NWS

National
Waterways
Study

# FINAL REPORT

# ENGINEERING ANALYSIS OF WATERWAYS SYSTEMS

PREPARED FOR THE

U.S. ARMY CORPS OF ENGINEERS
INSTITUTE FOR WATER RESOURCES
WATER RESOURCES SUPPORT CENTER
KINGMAN BUILDING
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## NATIONAL WATERWAYS STUDY
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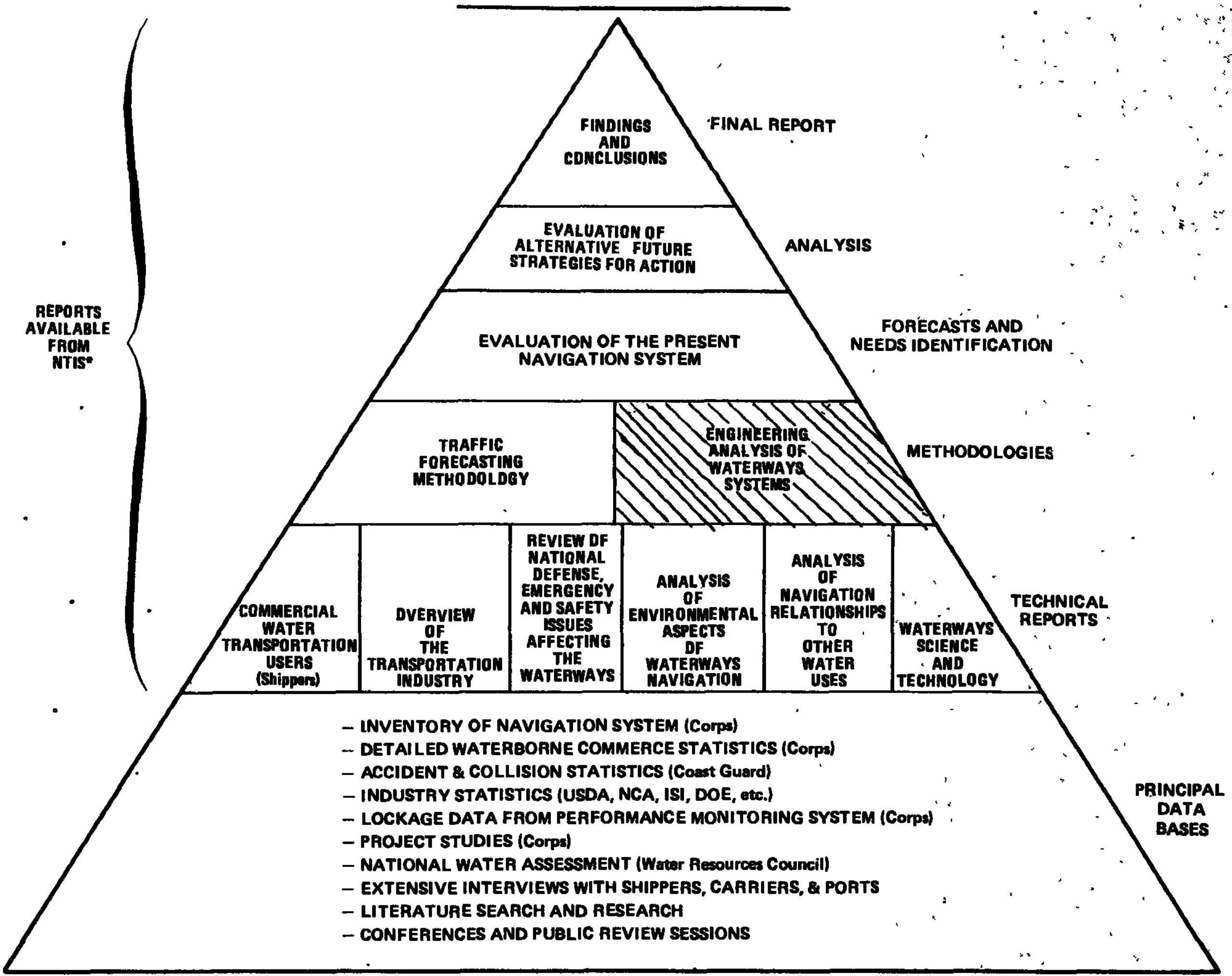

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This report, Engineering Analysis of the Waterways System, had two main objectives: 1) To assess the capability of the existing physical waterway system, and 2) To develop a methodology for assessing potential modifications to the existing system in response to strategies to meet future demand. The report addressed the physical waterway system in the following four major components: lock capacity, channel maintenance, channel conditions for fleet operation, and waterway availability.

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**THIS REPORT IS PART OF THE NATIONAL WATERWAYS STUDY AUTHORIZED BY CONGRESS IN SECTION 158 OF THE WATER RESOURCES DEVELOPMENT ACT OF 1976 (PUBLIC LAW 94-587). THE STUDY WAS CONDUCTED BY THE US ARMY ENGINEER INSTITUTE FOR WATER RESOURCES FOR THE CHIEF OF ENGINEERS ACTING FOR THE SECRETARY OF THE ARMY.**

# NATIONAL WATERWAYS STUDY

# ENGINEERING ANALYSIS OF WATERWAYS SYSTEMS

## PREFACE

This report is one of eleven technical reports provided to the Corps of Engineers in support of the National Waterways Study by A. T. Kearney, Inc. and its subcontractors. This set of reports contains all significant findings and conclusions from the contractor effort over more than two years.

A. T. Kearney, Inc. (Management Consultants) was the prime contractor to the Institute for Water Resources of the United States Army Corps of Engineers for the National Waterways Study. Kearney was supported by two subcontractors: Data Resources, Inc. (economics and forecasting) and Louis Berger & Associates (waterway and environmental engineering).

The purpose of the contractor effort has been to professionally and evenhandedly analyze potential alternative strategies for the management of the nation's waterways through the year 2000. The purpose of the National Waterways Study is to provide the basis for policy recommendations by the Secretary of the Army and for the formulation of national waterways policy by Congress.

This report forms part of the base of technical research conducted for this study. The main purpose of this report was to assess the capability of the existing physical waterway system. The results of this analysis were reviewed at public meetings held throughout the country. Comments and suggestions from the public were incorporated.

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This is deliverable under Contract DACW 72-79-C-0003. It represents the output to satisfy the requirements for the deliverable in the Statement of Work. This report constitutes the single requirement of this Project Element, completed by A. T. Kearney, Inc. and its primary subcontractors, Data Resources, Inc. and Louis Berger and Associates, Inc. The primary technical work on this report was the responsibility of Louis Berger and Associates, Inc. This document supercedes all deliverable working papers. This report is the sole official deliverable available for use under this Project Element.

National
Waterways
Study

# FINAL REPORT

# ENGINEERING ANALYSIS OF WATERWAYS SYSTEMS

## U. S. CORPS OF ENGINEERS

## ENGINEERING ANALYSIS OF THE WATERWAYS SYSTEM

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# EXECUTIVE SUMMARY

This report is structured according to the four major elements of waterways maintenance and operation: Lock Capacity, Channel Maintenance, Channel Conditions for Fleet Operations, and Waterway Availability. These elements are summarized below.

## LOCK CAPACITY

Because of the similarity in physical dimensions of so many of the locks in the United States, it was possible to develop a methodology whereby the capacity of a few locks representing each lock size and combination of lock sizes (where two chambers exist at a site) could be estimated and then adjusted for differences in lock service time, average vessel size, average load per barge, percent of empty barges, etc., in order to provide capacity estimates for other locks in the system. The method which was developed to allow the adjustment of capacity estimates under differing conditions is referred to as a sensitivity analysis. One of each size lock on each waterway was selected as representative of the locks of that size on the waterway. Capacity evaluations were then performed using the LOKCAP model in order to determine the technical and practical capacity of each representative lock in each lock group (class) under present navigation conditions, lock operating procedures, commodity pattern and fleet mix.

The method of sensitivity analysis which has been developed allows the capacity at any given lock, once it has been determined under present conditions, to be adjusted to provide estimates under assumed future conditions. The method develops mathematical relationships between capacity and lock service time, chamber size, average tow size, percent of empty barges, percent of double lockages, seasonality, recreation usage and downtime. Changes in the estimated capacity under assumed conditions can then be evaluated in terms of changes in any of the above factors, including changes in the individual elements of lock service time, approach time, chambering time, and extra time for double and setover lockages.

Alternatives for improvements of lock capacity are laid out segment by segment to show the extent of measures required to meet various levels of demand. The analysis of demand in other sections of the NWS sttudy formed the basis for preliminary selections of alternatives in this report. Alternative improvement options include minor structural and maintenance improvements, changes in operating policy, and structural replacement. Potential improvements currently under study are presented in generic form.

Approximate construction costs for locks and dams are provided as a function of several major physical parameters (lift, size, etc.), which can be readily determined site specifically from available information. Typical cost curves were obtained by evaluating a great number of Corps project costs for lock and dam construction. Operation and maintenance costs were compiled from Corps records systemwide. Costs associated with non-structural and low-cost measures to increase capacity are presented from available information.

## CHANNEL MAINTENANCE

Because the hydrology and morphology of every waterway is unique, the maintenance program undertaken on each waterway is specific to that waterway. In particular, it can be stated that basically different hydrological conditions exist for each major type of waterway: canalized rivers (with locks and dams), free-flowing rivers, canals, intracoastal waterways, lakes and coastal ports, or deep draft channels.

The determination of maintenance needs, specifically as a result of changed conditions, requires a great deal of experience on the waterway in question and detailed project level evaluation in order to reliably provide authorized dimensions at a minimum cost. This is due to the lack of available general evaluation measures and the great difficulty in determining the level of maintenance efforts required because of the complexity of the hydrological phenomena that define the need for maintenance. Therefore, because of the lack of generalized studies, the basis for the analyses presented herein is Corps project reports, operations records, and the expertise of Corps operational staff.

Authorized and controlling depths on the waterway system are reviewed and compared. The present maintenance program for each segment is then described so that areas of insufficient maintenance can be identified. For those segments having maintenance programs which are sufficient to maintain authorized depths, the current maintenance program and level of maintenance are outlined.

Segments which have maintenance programs which are insufficient to maintain authorized depths with the desired reliability are examined using available information in order to determine the nature and severity of the deficit.

The maintenance programs for inland channels and coastal ports are examined separately because of principal differences between the two, including different physical features (hydrology and morphology), different types of maintenance (different types of dredges and methods of dredging), and different structures of available operational data.

As the major component of channel maintenance, the current dredging fleet is examined with respect to its ability to adequately maintain the waterways in light of current requirements and constraints. A cost model is provided to aid in the evaluation of dredging costs in relation to possible future constraints or requirements.

In order to facilitate the selection of alternative maintenance programs to be proposed in response to potential future modifications, alternative channel maintenance programs which have been proposed in prior studies are presented.

## CHANNEL CONDITIONS FOR FLEET OPERATION

Most United States waterway channels have large reserves of capacity. This is because on most waterways the frequency of vessel passages is relatively low and the,maximum possible tonnage throughput is controlled by the service times of the locks. The service time is the time required for the lock to process each vessel. For example, if lock service time is 45 minutes and the average tow speed in the channel is 5 mph, then the average distance between tows would be 9 miles; however if the distance between tows is 8 miles under the same conditions, then the lock capacity would be exceeded. Yet 8 miles between tows does not overload the channel.

The condition of the current waterway system for navigation was investigated with respect to the operation of the current industry transportation fleet. In addition, functional relationships have been developed to allow the evaluation of the interaction between modified navigation conditions and fleet operation.

The major impact which channels have on system capacity is related to the maximum size tows which can safely or physically operate on the waterway. If the largest tow size which can operate on the waterway is small compared to the maximum size tow which can be efficiently handled by the lock, then the channel affects capacity. An evaluation of the maximum tow size which the waterway channel can accommodate was made by waterway segments. The degree of restriction of a waterway was then analyzed from the point of view of the largest tow commonly operating on that waterway. Existing channel conditions on each NWS segment were compared with the design standards which represent unrestrictive navigation for the common maximum tow size now operating on that segment. The relative importance of constraints on navigation in each segment is represented by an index of the constraining effect of sharp bends, the number of bridges with narrow navigable spans, and the density of marinas and commercial sites. The comparison of channel dimensions and constraint indicators describes each segment as unrestricted, partially restricted, or very restricted.

Tow speeds and segment transit times in relation to existing navigation conditions were evaluated. The evaluation begins with a discussion of the effects of resistance and thrust followed by an analytical formulation for estimating tow speeds that will account for these factors. Transit times under present navigation conditions of locks, channels and traffic levels are tabu- lated by analysis segment. Lock delays and service time are incorporated into the tabulation.

Finally, waterway transportation costs are analyzed as a function of navigation conditions. The sensitivity of waterway transportation costs to channel depth, width, frequency of oneway reaches, density of constraints (bridges, landings), lock utilization and level of traffic was developed. The sensitivity of transportation cost to waterway characteristics was determined by parametric analysis, varying the value of one parameter of the waterway at a time and holding all others constant. In this way, channel modifications, which may be suggested to increase waterway capability, can be analyzed in order to determine the magnitude of the improvement (reduction in constraints or changes in dimensions) offered in terms of cost impacts resulting from increased tow speeds and decreased transit time . These can be analyzed at any anticipated level or distribution of traffic in conjunction with lock oapacity and delay.

## WATERWAY AVAILABILITY

The report addresses closures to navigation due to lock downtime and weather, presenting the current average annual duration of traffic disruption by segments. The major emphasis regarding waterways availability is on current, ongoing, and anticipated programs to extend the navigation season. Techniques which are currently in use on waterways in the United States to make navigation possible under winter conditions are briefly described. Locations where these techniques have been or are expected to be applied to maintain locks and to keep channels open under winter conditions are presented. Alternatives which are laid out for extending the navigation season will form the basis for assessing the potential for increasing the availability of the waterways in response to future demands.

# I-INTRODUCTION

This report entitled "Engineering Analysis of the Waterways System," is composed of 14 separate yet interactive elements having the cllective objective to "Identify and Analyze Alternative Strategies for Providing a Navigation System to Serve the Nation's Current and Projected Transportation Needs."

The investigations presented in this report were undertaken simultaneously with six other elements which investigated commodity flows, water user operation, carrier and port issues, defense and emergency requirements, water resources demand and environmental impacts.

In the National Waterways Study overall objective, this report provides the following:

1. An assessment of the capability of the existing physical waterway system.

2. The development of a methodology to allow the assessment of potential modifications to the existing system in response to strategies to meet future demand.

The report addresses the physical waterway system in four major components. These comprise the four major sections:

- Lock Capacity.
- Channel Maintenance.
- Channel Conditions for Fleet Operation.
- Waterway Availability.

Figure I prints an outline of the major steps followed during the investigations for this report. Within each section, the current state of the waterways is investigated. The capacity and delays for existing locks under present conditions are established. An outline of current channel maintenance programs, authorized depths and the reliability of authorized depth, as well as the characteristics of the existing dredge fleet are provided. The effects of present channel dimensions and constraints to

# Figure I-1

## OUTLINE OF MAJOR STEPS FOLLOWED DURING THE INVESTIGATIONS FOR THE REPORT "ENGINEERING ANALYSIS OF THE WATERWAYS SYSTEM"

| Title | Assessment of the Present Waterways System | | Development of a Methodology to Assess Modifications | | Presentation of Improvement Alternatives |
|---|---|---|---|---|---|
| Lock Capacity | Analysis of lockage data for present system | Evaluation of lock capacity under present conditions | Evaluation of the sensitivity of lock capacity to major variables | Development of cost estimates for lock replacement and O&M | Alternative measures to increase lock capacity |
| Channel Maintenance | Assessment of deficiencies in authorized channel dimensions | Assessment of current channel maintenance programs | Evaluate dredging cost sensitivity to major factors | Evaluate methods to reduce the effect of adverse hydrological conditions | Alternative channel improvement options |
| Channel Conditions for Fleet Operation | Identification of accommodated tow size and navigation constraints | Evaluation of tow speeds and segment transit times under present conditions | Determination of the effect of channel improvements on transit times | Evaluation of the sensitivity of transportation costs to navigation conditions | |
| Waterway Availability | Assessment of present waterway availability | | Technology for the extension of the navigation season | | Alternatives for the extension of the navigation season |

navigation are investigated to show their effect on fleet operation. And, in the final section, normal periods of waterway closings are established.

Each section presents a methodology which can be used in later analysis to evaluate the effects of potential modifications to the existing waterway system in response to future conditions. The sensitivity of lock capacity to major performance parameters is established. A methodology is developed which will allow the determination of the cost and the effect on capacity of possible structural and non-structural lock improvements in response to future demands. Potential improvements to lock facilities are laid out to meet possible levels of future demand. Alternatives for potential channel improvements, maintenance and associated costs are laid out from existing projections to form the basis for evaluating the effects of future conditions on channel maintenance needs and capabilities. The sensitivity of dredging costs to major performance parameters is provided. The relationship between channel waterway constraints and segment transit times and the associated impact on transportation costs are established to allow the assessment of the effect of possible changes on conditions for fleet operation. Finally, alternatives for potential improvements to extend the navigation season are laid out from existing projections to form the basis for assessing the potential for increasing the availability of the waterways in response to future demands.

The final sections include conclusions and recommendations for further study and a bibliography. A discussion of information sources and data limitations is provided as Section II.

The overview of current maintenance programs and the present state of the waterways has been presented based on the most recent information available as provided by the U.S. Army Corps of Engineers and as obtained through interviews and discussions with Corps expert personnel. This report also used asn input the prior NWS element work which developed a computerized data base of physical and operational waterway characteristics.

This report does not pretend to provide conclusions as to the appropriateness of alternative measures presented, as this can only be done in conjunction with an analysis of potential demand.

The NWS report "Future Directions in Waterway Science and Engineering," is a logical extension to this report as it will provide an assessment of the most likely trends in the field of waterways science and engineering which may effect the future water transportation system.

## II-INFORMATION SOURCES AND DATA LIMITATIONS

Data sources for this report were primarily limited by the cope of the study to available published information. However, because of the study objectives, it was also necessary to obtain empirical information from several primary sources for further analysis, generalization and correlation.

Primary information sources included Performance Monitoring System (PMS) data records, waterway maintenance and operations records and costs, construction costs for locks and dams, navigation charts and project maps. The PMS data records were obtained in cooperation with the Engineer Data Processing Center of the U.S. Army Corps of Engineers, and was used as input for lock capacity evaluations. Unfortunately, sufficient data for the study purposes was not available for the locks in the New Orleans District and the North Pacific Division. For locks in these regions, alternative data sources or average values were used. In general, PMS data was found to be satisfactory and reliable for the purposes of the study. To aid in describing maintenance and operation practices, on which topic little published information is available, it was necessary to obtain maintenance records through interviews with the U.S. Army Corps of Engineers Districts. These records included periods of closure, project data, consolidated statements of dredge operation and hydrological and depth duration information. Maintenance, operation and first cost information was obtained from the Corps District records and from records of the Office of the Chief.

The published sources of information used to prepare this report were reports, studies, investigations and evaluations supplied by the United States Army Corps of Engineers. This information was obtained through interviews with personnel from nearly all Corps Divisions and Districts. In addition, information was provided by the staff of the following Corps Offices:

1. The Office of the Chief.

2. Institute for Water Resources.

3. The Board of Engineers for Rivers and Harbors.

4. The Dredging Division.

5. The Waterways Experiment Station.

6. The Cold Regions Research and Engineering Laboratory

As well as providing information sources, the interviews provided invaluable insight into operation and maintenance problems and constraints to improvements, allowed the incorporation of Corps expert knowledge on individual waterways and provided a basis for examining the relative effectiveness of current maintenance programs.

Reports of private companies or individuals were obtained from a vairety of sources including the National Technical Information Service, Engineering Journals and Publications and United States and European Research Centers.

The National Waterways Study Inventory of Physical Waterway Characteristics was a major source of physical information. The aid of the North Central Division in verifying this data is gratefully acknowledged. Unfortunately, the full potential could not be realized because of various problems with the Inventory. These problems include ambiguities in the definitions of data components, and information which was omitted from the report either inadvertently or because it was not collected. The major difficulties were associated with costs data. Costs, in particular, are very sensitive to the method used to calculate them. Communications with district personnel indicated that different methods were used in each district to determine the cost of dredging, for example. The differences render meaningful comparisons between districts difficult, if not impossible. In addition, several pieces of information which would be very useful for the NWS, or other studies, were not included in the Inventory and were very difficult to obtain from other sources. Deficiencies in the maintenance of authorized channel dimensions, for instance, would be more amenable to analysis if the frequency and duration of short-falls in channel dimensions were shown. Unfortunately, this very important information used for the assessment of channel maintenance efforts and the evaluation of the reliability of authorized depth, was missing not only from the Inventory but was limited in field records as well. Specifically, this information is not available for coastal approach channels.

First costs for locks and dams which were obtained from district records varied greatly due to physical differences between sites, however, accounting methods appear to be consistent. Downtime obtained from Corps districts and the NWS Inventory was of limited value because differences in accounting and recording methods made individual values incomparable. Only limited information associated with interactions between tow movements and channel navigation constraints was available. There are no consistent records relating channel bends and segment specific impacts to travel time. Limited observations performed by the contractor on the Ohio and Monongahela Rivers obviously was insufficient to fill data gaps in this area.

Due to the absence of general analytical methods, measures and costs to improve channel navigation conditions were obtained from Corps projections. This information was satisfactory. In general, the Corps has sufficiently studied areas with severe channel constraints.

Sources for tables and figures presented in this report are provided (in the text) whenever the material is taken directly from published reports. All other tables and figures were developed for inclusion in this report based on data in unpublished sources, principally, Corps of Engineers files and records. To maintain a high level of accuracy, information based on unpublished sources has been supplemented and updated using a variety of records spanning Corps districts, divisions and offices.

# III - LOCK CAPACITY

## METHODOLOGY

### (a) General

The capacity of a waterway is defined as the maximum tonnage which the waterway can pass per unit time, generally a year. While the capacity of its locks and the capability of its channel, it is almost always the locks which limit the waterway maximum tonnage throughput. This section assesses the capacity of existing locks under present conditions and presents the methodology by which lock capacity estimates can be made under conditions imposed by future modifications.

The capacity of a lock depends on the following parameters:

1. The physical lock dimensions.

2. The mix of vessel/tow sizes and configurations serviced by the lock.

3. The time required for the lock to service, individually and collectively, the mix of vessels/tows utilizing the lock.

4. The percentage of empty vessels/barges which are serviced by the lock.

5. The amount of time the lock must be closed due to factors such as maintenance, accidents, ice and adverse hydrological conditions.

6. The amount of time the lock is devoted to service recreational and other non-commercial craft.

7. The seasonality of traffic movements.

Because all of these parameters except physical dimensions change in time, lock capacity is not constant. Therefore, a limiting capacity only has meaning when presented along with explicit values for the above parameters.

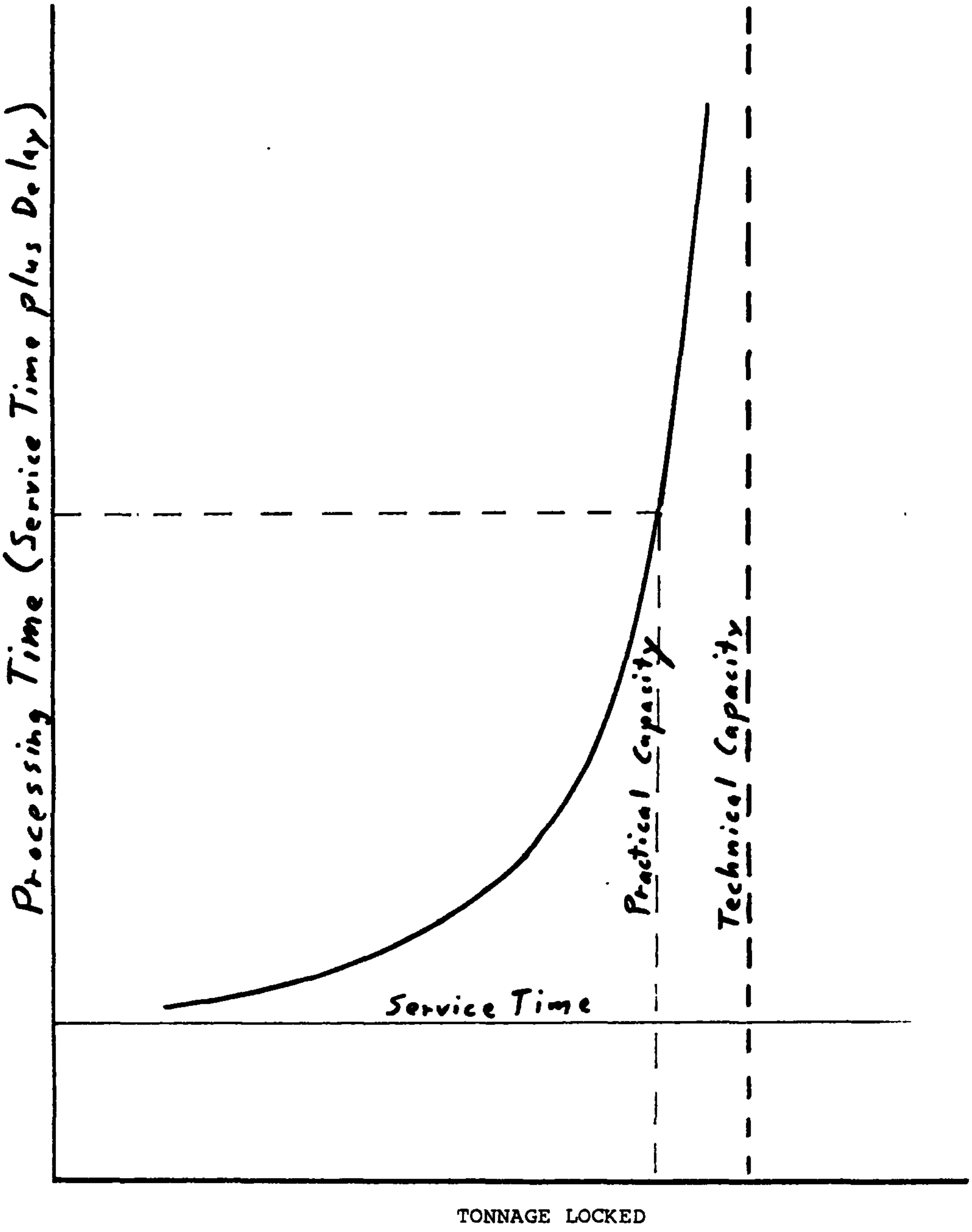
For the purposes of the National Waterways Study, two types of capacity are defined, technical capacity and practical capacity, both of which are functions of all of the above parameters.

Technical capacity is defined as the maximum tonnage which the lock can pass in one year irrespective of the level or economic impact of delays. Technical capacity is determined by assuming one value for each of the parameters listed above. In other words, technical capacity is calculated for a particular lock based on a given mix of vessels/tows, a given service time for each type of vessel (or each type and configuration of tow) and for each type of lockage (fly/exchange or turnback), a given percent of empty vessels/barges, a given amount of lock downtime, a given volume of recreational traffic, and a given variation in the seasonality of traffic movements.

The practical (or economic) capacity of a lock is determined in the same manner as the technical capacity but includes one additional factor. The practical capacity includes a consideration of the increased costs that waterway traffic can endure as a result of delays incured due to congestion at the lock. Figure III-A presents a generalized relationship between tonnage locked and expected delay at a lock. The value of delay which is "acceptable" at a given lock is dependent upon the transportation economics. In particular, the level of "acceptable" delay depends upon the differences in costs between waterway transportation and alternative modes of transportation for the complete range of commodity mix on the waterway. For project level evaluations, practical capacity must be defined based on economic and technical studies associated with lock replacement. For the purposes of the National Waterways Study practical capacities were evaluated based on calculated technical capacities, computed tonnage locked versus delay relationships and "reasonable" values of "acceptable" delay.

## FIGURE III - A

Generalized Curve Processing Time vs. Capacity



### (b) Methodology Employed to Develop Lock Capacity Estimates

Because of the general level of study required and the national scope of the analysis, encompassing more than 250 locks, a method of evaluation is required which can allow rapid capacity determinations. More importantly, however, a method is required which can provide adequate sensitivity to potential changes in waterway conditions under a number of possible futures by properly taking into account the parameters discussed above. A review of available methods of determining lock capacity was undertaken and the LOKCAP computer model was chosen as the most appropriate for use by the NWS, specifically because of its ability to directly utilize data collected by the Inland Navigation System Performance Monitoring System. It was recognized, however, that even using the LOKCAP MODEL, within the scope of the study too many computer runs would be required to evaluate the capacity of all locks under all possible modifications of the factors determining capacity due to potential change in the physical waterways system and traffic levels. To overcome this limitation, for the purposes of the National Waterways Study, several empirical relationships between lockage variables have been developed. (An example of this type of empirical relationship is tow size versus type of lockage: single, double, etc). The relationships obtained in this manner exhibit very stable correlations and, hence, the accuracy of this type of estimate is not sacrificed. The introduction of these relationships allows the substitution of a number of sensitivity relationships for a great number of computer runs in order to provide an efficient method to estimate the impact of any modification of major variables on lock capacity.

Although the model uses data as collected by the Performance Monitoring system (PMS data) as input, these data have only been collected for a few years at most sites. The accuracy with which the program was set up to verify the accuracy of the PMS data for those locks, which were selected for analysis using the LOKCAP model. The operating districts of these locks, having data which appeared to be inaccurate, unreliable or unavailable, were contacted to aid in the determination of appropriate values for input into the model.

Many locks in the United States have similar physical dimensions (width and length). This is, of course, not a coincidence, but the result of a conscious effort over the years to design locks to accommodate existing vessel sizes and, vice versa, on the part of industry to design vessels to make maximum use of available lock dimensions. It is generally found appropriate to provide locks of similar dimensions along the entire length of a waterway. Exceptions to this rule are waterways which have differing authorized channel dimensions in different reaches, waterways which are in an intermediate phase of lock replacement and waterways which have differing levels of traffic or differing vessel sizes in different reaches.

Because of the similarity in physical dimensions of so many of the locks in the U.S., it was possible to develop a methodology whereby the capacity of a few locks representing each lock size and combination of lock sizes (where two chambers exist at a site) could be estimated and then adjusted for differences in lock service time, average vessel size, average tow size and average load per barge, percent of empty barges, etc., in order to provide capacity estimates for other locks in the system. The method, which was developed to allow the adjustment of capacity estimates under differing conditions, is referred to as a sensitivity analysis. The sensitivity analysis allows the capacity at any given lock, once it has been determined under present conditions, to be adjusted to provide estimates under assumed future conditions, assuming, of course, that the future conditions, can be represented in terms of factors to which the method is sensitive, such as average load per tow and percent of empty barges.

The capacity of canalized or channelized waterway is usually the capacity of the most constraining or lowest capacity lock on the waterway.

One of each size lock on each waterway was selected as representative of the locks of that size on the waterway. An attempt was made to choose, as representative, the most constraining lock on the waterway on the basis of present delay time, present lock service time, and present traffic level. Where more than one lock of the same type appeared to be a potential bottleneck, more than one lock was chosen as representative. All of the representative locks were then grouped by lock size. Capacity evaluations were then performed using the LOKCAP model to determine the technical and practical capacity of each representative lock in each lock group (class) under present navigation conditions, lock operating procedures, commodity pattern and fleet mix. The estimates of practical capacity include an adjustment for seasonality, recreational use and downtime.

The sensitivity analysis which has been developed to allow the capacity estimates under present conditions to be adjusted for future conditions is presented in the section "Sensitivity Analysis of Lock Capacity and Delay." In short, the method develops theoretical mathematical relationships between capacity and lock service time, chamber size, average tow size, percent of empty barges, percent of double lockages, seasonality, recreation and downtime. Changes in the estimated value of capacity under assumed conditions can then be evaluated in terms of changes in any of the above factors, including changes in the individual elements of lock service time, approach time, chambering time, and extra time for double and setover lockages. The result is a set of sensitivity charts that can be used to adjust the capacity estimates for the representative locks under present conditions to obtain a hypothetical capacity estimate for any lock in the system.based on reasonable assumptions for future conditions.

While the methodology developed above allows the determination of capacity at any existing lock, it is also necessary to lay out alternatives for increasing the capacity of locks which may be unable to meet the year 2000 level of demand under future conditions. This report presents preliminary examples of lock constraints and alternative improvements. Actual lock constraints and proposed improvement alternatives will be developed in subsequent phases of this study and will be presented in a later report.

In order to determine which locks may have insufficient capacity to meet the year 2000 level of demand, a comparison was made between present lock capacities and the year 2000 maximum probable segment demand as determined in a preliminary analysis by Data Resources, Inc.

The year 2000 maximum probable segment demand is the highest demand expected under assumed future conditions.

In the section entitled "Estimates of Measures to Increase Lock Capacity by Segments," alternatives are laid out segment by segment to show what level of improvement would be required to meet all levels of demand between the present lock throughput and the hypothetical maximum probable demand. Improvement options for the various scenarios in later evaluations can be selected from the alternatives laid out in this section. At locks where the present capacity, under present conditions, is greater than the maximum probable demand, no improvement options are shown. At locks where the present capacity, under present conditions, may be insufficient to meet demands, improvement options are presented which include non-structural or low-cost measures to increase capacity and structural lock replacement. Non-structrual, or low-cost measures which can be employed to increase lock capacity are discussed in the section entitled "Alternative Measures to Increase Lock Capacity." Lock replacement and potential nonstructural alternatives are laid out segment by segment in the section entitled "Estimates of Measures to Increase Lock Capacity by Segments." present conditions of average tow size, empty backhaul, etc., at the locks. The alternatives as presented in the section entitled "Estimates of Measures to Increase Lock Capacity by Segment," will be adjusted for future conditions using the methodology developed in the earlier section.

To facilitate the choice of improvement alternatives, approximate costs for increased capacity alternatives are also shown. For each alternative presented in the section entitled "Estimates of Measures to Increase Lock Capacity by Segments," both the cost of the improvement and the capacity provided by the improvement are shown.

The methods used to determine approximate lock replacement costs and operation and maintenance costs are presented in the sections entitled "Approximate Method for Estimating Lock and Dam Construction Costs" and "Maintenance and Operation Costs for Locks and Dams," respectively. Approximate construction costs for locks and dams are provided as a function of several major physical parameters (lift, size, etc.), which can be readily determined site specifically from available information. Typical cost curves were obtained by evaluating a great number of Corps project costs for lock and dam construction. Operation and maintenance costs were compiled from Corps records system-wide. Unfortunately, however, due to great variations in methods used to allocate costs to Operation and Maintenance and wide variations in these expenses even for locks with similar physical parameters, only very rough approximations of O&M expenses were possible, where they could be identified at all. Costs associated with non-structural and low cost measures to increase capacity are presented in the section entitled "Alternative Measures to Increase Lock Capacity."

1. Review and Comparison of Available Methods for Lock Capacity Evaluation. Several methods are available to evaluate lock capacity:

Traditional/analytical methods use general average assumptions concerning lock performance characteristics. They are very useful when there is no specific data available for each phase of the lockage process. These methods do not provide any delay values and are not computerized. Even more importantly, these methods are not sensitive to some important variables, such as tow size or type of lockage.

Simulation methods such as the WatSim, and INSA models (sometimes called WAM, for Waterway Analysis Model) are well known waterway simulation models. These models can be useful, but they require a level of analysis and computation that is beyond the requirements and scope of the NWS.

Expected value computer models, such as the Lock Capacity Calculator (LOCALC) and the Lock Capacity Function Generator (LOKCAP) models, represent the most widely accepted examples of this method. These models use queuing theory and probability theory to arrive at predictions of locking time and delay at individual locks. The Corps of Engineers has been using these two models extensively. These type of analytical computer model are extremely useful as permit the combination of analytical, graphical, and simulation methods of capacity calculations specifically because of the availability of PMS data, which allows the application of a more detailed analysis than is possible with traditional/analytical methods. The

LOCALC model has been widely applied, but does not have the ability to provide information on delay or practical capacity. This information, however, is highly desirable because if fulfills the requirements of the NWS relative to transit time and helps establish the relationship between capacity reserves and cost to the towing industry.

The LOKCAP model provides the same information as the LOCALC model, but also provides the output necessary to conduct the NWS tasks and therefore appears to be the most appropriate method.

The following section assesses the ability of the LOKCAP model to provide logical results for the NWS by having sufficient sensitivity to the major variables which determine lock capacity.

The preliminary documentation of lock capacity analysis, issued by the Plan Formulation Branch of the Louisville District Planning Division, is the major source of information about the LOCALC and LOKCAP models. The findings of this study are briefly reviewed.

The study by the Louisville District was the first attempt to generate consistent capacity values over a wide range of lock facilities within one division (the Ohio River Division). Following the example of this effort, a similar task is now being conducted on a national basis for the NWS.

The Louisville study determined that the average capacity figures generated by the two models are comparable and differ by as little as 5 to 10% in some instances. However, Louisville personnel believe that the raw LOKCAP figures should be adjusted slightly toward the LOCALC figures, since the LOKCAP model (old version) did not automatically consider downtime or chamber interference in its calculations.

The study concluded that the results obtained are very similar to those obtained by using simpler calculations (purely analytical methods).

The Lock Capacity Function Generator (LOKCAP) model was originally designed to determine capacity and delay at single chamber locks. The model was recently modified (July 30, 1979) to handle double chamber locks and account for the effects of interference between chambers.

2. Review of the LOKCAP Model. The LOKCAP model applies queing theory to lock operations and is based on the following assumptions:

(a) Arrivals per unit time are distributed according to a Poison probability distribution.

(b) Lockage or service times are assumed to follow a normal distribution, with known mean and variance.

(c) Service time is assumed exponential only for purposes of turnback probability calculations.

(d) A one-up/one-down policy is assumed to prevail when there is a queue at the northbound and southbound sides of the lock. If specified, calculations can also be performed based on a m-up/n-down policy.

The model determines for as many traffic levels as specified the average queue length (number of tows), the average time in queue, the average tow interarrival time, and the probabilities of approach and exit conditions. Technical lock capacity is the traffic level that corresponds to an infinite delay time or queue length. In addition to providing the annual lock capacity in tons, the program also calculates the daily capacity in tows and in barges, and the lock delay parameter which is the expected delay per tow. This lock delay parameter is an increasing function of service time and the standard deviation of lock service time. The equations used to derive such an extensive set of results are too numerous and too detailed to be presented in the context of this report. Most of the equations used in the model are typical queuing equations such as the ones used to derive queue length and delay time. Other equations are based on probability theory to calculate for instance,the probability of turnback approaches for each level of lock utilization.

The input requirements include lockage time, barge, tow type and lockage type data. Lockage time means and standard dviation are needed for each phase of the lockage process and for each direction of travel. Barge data includes barge capacity/lading and large size compared to a jumbo barge to calculate daily capacity in reference barge equivalent. Tow type data includes the type of barges used, tow size, the frequency of each type, the percent of empty tows, and the number of cuts needed for every category of tows. Lockage type data includes the frequency of double, triple and setover lockages. The old and new versions of the model were reviewed. The following summarizes the findings of the review. The disappointment in the old version of the LOKCAP model, expressed by the Louisville District, is best explained by the programming errors identified below. The new version corrects several programming errors of the original version. Significant efforts have been made to identify these types of errors in both versions of the LOKCAP model.

Errors in two areas were detected in the old version of the model: the determination of the effect of recreation on lock capacity and the determination of turnback probability.

The equation used to assess capacity in the old version of the model was not properly interpreted with respect to recreation and service time.

The average service time should be the service time for tows and commercial vessels only, and not the overall service time,.including recreation. Instead of deducting the total time devoted to recreational lockages from total available time, the model was deducting the percent of time available for recreational lockages, assuming that this percentage was the percentage of recreational lockages. Obviously, there is no reason for these two percentages to be equal, especially when the commercial traffic is relatively low.

This error was discovered by running the model with and without recreation, then manually computing the capacity values and comparing these values to the computer output.

The calculation of turnback probabilities in the old version of the model appeared suspicious according to the Waterway and Rail Capacity Analysis Report.

A detailed analysis of turnback probability calculations conducted by the model is too complicated for the NWS but this analysis is not necessary because a new and more elaborate approach was adopted in the new version of the LOKCAP model to estimate turnback probabilities.

The new version of the LOKCAP model represents a definite improvement over the old version. The new version is designed to calculate capacity and delay at dual chamber locks, to account for interferences between chambers, and to incorporate downtime. The new version also corrects the programming errors discovered in the old version and its output is more useful for analysis.

Three programming mistakes were identified in the new version.

(a) Extra time for setover lockages was not properly incorporated.

(b) Lockage times for extra cuts of multiple lockages were not included in the calculation of average composite time (only the extra time for break-up and make-up time was included).

(c) Percent of time devoted to recreational lockages had no impact on capacity

These mistakes were corrected prior to usage of the model.

The revised version of the LOKCAP model does provide reasonable results. Moreover, it is the most suitable method presently available to meet NWS requirements for lock capacity calculations and sensitivity analysis.

The present form of the LOKCAP model is the state-of-the-art for preliminary types of lock capacity calculations. However, there is still room for improvement.

The limitations to the utilization of the model are as follows:

(a) Tow size distribution does not respond to traffic increases.

(b) Model cannot substitute for detailed simulation.

(c) Data were converted into expected values being used as input (expected value type of model).

(d) There is an independent arrival from both directions.

(e) Interaction between both directions is not taken into account (except for turnbacks).

(f) When handling double-chamber locks, model does not control for changes in chamber selection as traffic increases; model treats each lock separately and does not provide for interdependence within the lock system.

The most significant limitation is that the model does not control for variations in tow size distribution when traffic increases to capacity. This limitation requires that additional analysis (outside of the model) of future tow configurations as a function of traffic density and structure and technical trends in the towing industry be performed.

## ASSESSMENT OF DATA FOR INPUT INTO CAPACITY EVALUATIONS

### (a) Review of Existing Capacity Estimates from Prior Studies

A survey was made of existing estimates of lock capacity. The primary sources of information discovered were from the Corps of Engineers, the findings of the Freight Transportation Energy Use Study, and the Mid-America Port Study.

It was found that there is no generally accepted definition of capacity or method to evaluate capacity. Some studies present capacity in terms of available fleet volume and others in terms of tonnage. Definition of technical, practical, maximum technical and available capacity differ from one source to another and often include, to varying degrees, adjustments for downtime, recreation use and peak monthly use. Methods used to evaluate capacity include analytical, graphical and expected value and simulation methods.

Despite the variations observed, the findings of existing studies are very useful as they permit the identification of existing or potential bottlenecks in the waterway analytical segments.

Capacity estimates developed by the Corps of Engineers are generally presented as "practical capacity." Methods of calculation include: simulation (e.g., the Mississippi RiverIllinois Waterway 12-foot Channel Study); regression analysis (e.g., the Recreational Craft Locks Study - Upper Mississippi River); Great Lakes/Saint Lawrence Seaway Lock Capacity Model; LOCALC and LOKCAP models (e.g., the Ohio River Basin Lock Capacity Analysis and the Lower Ohio River Navigation Study); and analytical methods (e.g., the Lower Monongahela River Navigation System Study).

The Freight Transportation Energy Use Study presents lock capacity estimates which were made in a previous study for the DOT Transportation Systems Center (TSC) and were reported in "Freight Transportation Energy Use: Volume III, Freight Network and Operations Database (CACI, Inc. for DOT/TSC, October 1978). The results are reported in more detail than in the TSC report, and some new analyses are included.

The capacity calculations conducted for the Mid-America Ports Study provide only an order of magnitude estimate. Twenty-two locks were initially identified as being current or potential constraints, based on the INSA report and on responses to a TAMS questionnaire by district engineers in the study area.

As expected, lock capacity limits vary substantially from one source of information to the other. The variations are, however, understandable as the assumptions and methodologies that were used in the reports differ substantially.

In order to compare capacity estimates obtained from a number of sources and derived with a variety of assumptions, the various capacity estimates were evaluated and an attempt was made to adjust the figures to a common base. This was not completely successful in that the specifics of the assumptions and methodology employed were not always clearly stated. In addition, capacity values were often obtained with differing precision. For instance, the Corps estimates are often the results of longer and more detailed analysis than the capacity estimates calculated by the other sources.

In general, Corps estimates were found to be the most reliable. Estimates from the other three sources were found to be less reliable but were used as a cross-checking measure. Existing Corps estimates are compared with NWS estimates, in Sub-section (d) of the section entitled "Capacity and Delay for Existing Locks Under Present Conditions by NWS Segments."

Locks identified in the review as possible constraints to the system were subsequently selected to be analyzed. The review of existing capacity estimates aided in the selection of constraining and representative locks.

### (b) Verification of PMS Data

In order to evaluate the capacity of a lock, accurate information must be available from which lock service times can be determined. The Performance Monitoring System was set up by the Corps in order to gather data from which lock efficiency could be evaluated, including the elements of lock service time (i.e., approach time, entry time, chambering time, exit time, extra time for setover lockages and extra time for double lockages). If, over a period of time, sufficient PMS data have been collected at a lock to accurately measure the elements of lock service time for all types of vessel lockages and all types and sizes of vessels using the lock, then accurate estimates of lock capacity can be made.

The LOKCAP model, which was used by the NWS to evaluate lock capacity, uses as input lock service times as recorded by PMS. For this reason, it was necessary to insure that the lock service time data as recorded by PMS accurately reflected conditions at the lock sites. The following sections present an assessment of PMS data reliability and the results of a PMS data verification.

An attempt was made to identify all non-reliable or unavailable PMS data. The reliability of the PMS data was assessed by comparing the elements of lockage time at each lock to the elements of lockage time at other locks. In order to control differences in the length of lock approaches, all of the elements of lockage time were converted into vessel speeds, (approach speeds are obtained by dividing the length of the approach, as obtained from the INSA report, by the approach time recorded by PMS). Where data appeared to be "abnormal," the operating districts were contacted for verification. When data were found to be unreliable or unavailable, values based on judgment, limited field data or averages were substituted for use in capacity evaluation. Tow speeds for the approach, entry and exit phases of the lockage cycle under normal operating conditions are expected to be fairly similar for every lock as well as the extra time for setover and double lockages. PMS data reliability was assessed by constructing histograms of the approach, entry, and exit speeds and of the extra time for setover and double lockages for about 50 representative locks (see Figures III-B to III-F).

Empirical relationships were developed to calculate tow speed based upon time and distance and reciprocally to calculate time based upon tow speed and distance.

The histograms help to interpret five sets of data points. Any data point that falls outside a reasonable range was considered "abnormal" and was further investigated.

A reasonable explanation should be found for any value falling outside reasonable limits. Reasons for abnormal deviations from averages are unusual local conditions or deficiencies in the PMS data. In the former case, if speeds are found to be too low or extra time for setover or double lockages found to be too high, non-structural measures to increase capacity might be suggested. In the latter case, actual PMS data were discarded and replaced by the average values obtained with a normal set of PMS data.

The histograms, constructed for representative locks, were compared to histograms prepared based upon the Inland Navigation Simulation Run B26D conducted by the Pittsburgh District. In addition, the average values were compared to the data collected by the Consultant on a tow trip along the Monongahela River. These comparisons provided additional validation of the PMS data.

1. Assessment of PMS Data Reliability. Accurate and reliable recording of the input data required for the LOKCAP model at locks is essential to the success of the PMS. As stated in the report "Implementation of the Performance Monitoring System,"[2] the forms and procedures developed for the PMS have been designed to increase the usefulness of the data collected at the lock without significantly increasing the current data recording workload of the lock staff.

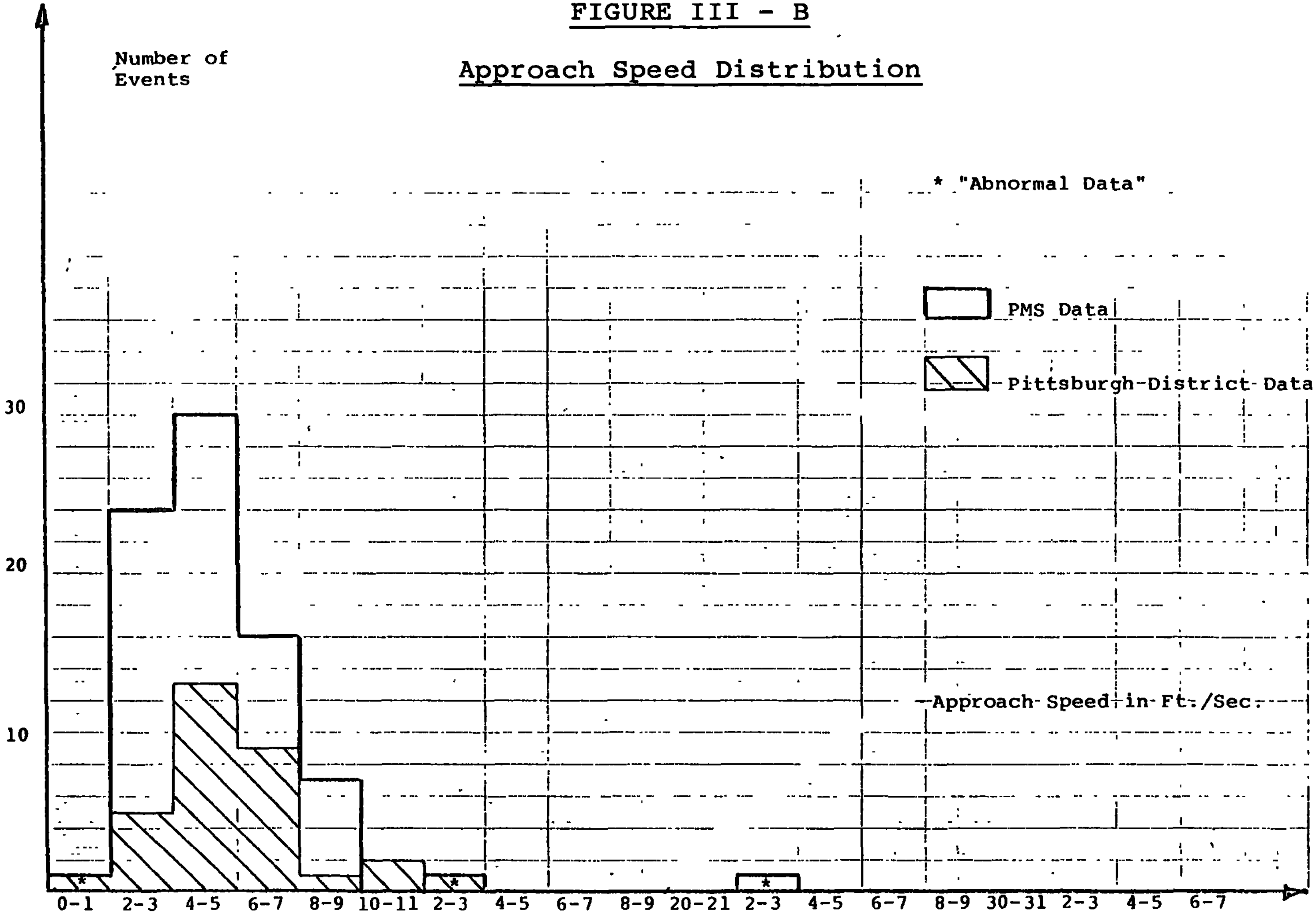
PMS data are not available for all locks. They are not available for Inner Harbor Lock, A.C.F. River locks, Bayou Teche River locks, Old River Lock, GIWW locks, Hudson River locks, N. Y. State Barge Canal locks, Columbia River locks, Willamette Canal locks and St. Mary River locks. The PMS data were not processed in 1976 for the New Orleans District; the Jacksonville District has nothing but February data recorded; for the Hudson River (Troy Lock), data recording started in 1977; there are no statistics for the New York State Barge Canal; the 1977 and 1978 PMS data are presently being updated for the Columbia-Snake River and cannot be used at the present time; and finally, no PMS data were recorded for the Great Lakes area and St. Lawrence Seaway.

Naturally, data are not available for locks presently under construction on the Red River and the Tennessee-Tombigbee Waterway.

Approach and exit times are the most difficult to monitor and to verify. The range of speed and time can be fairly large due to various conditions affecting the lockage process such as: site specific approach, entry

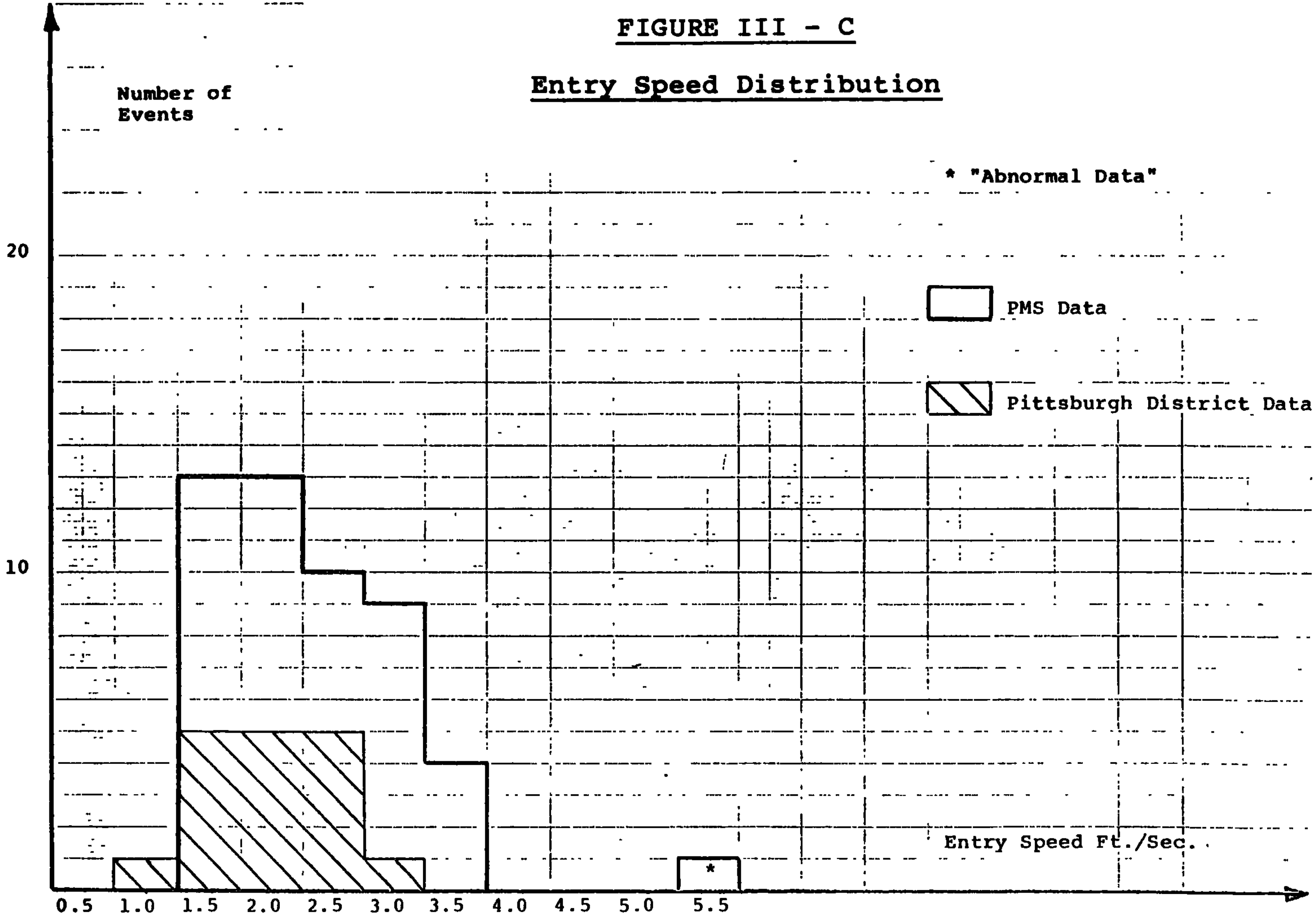
## FIGURE III - B

## Approach Speed Distribution



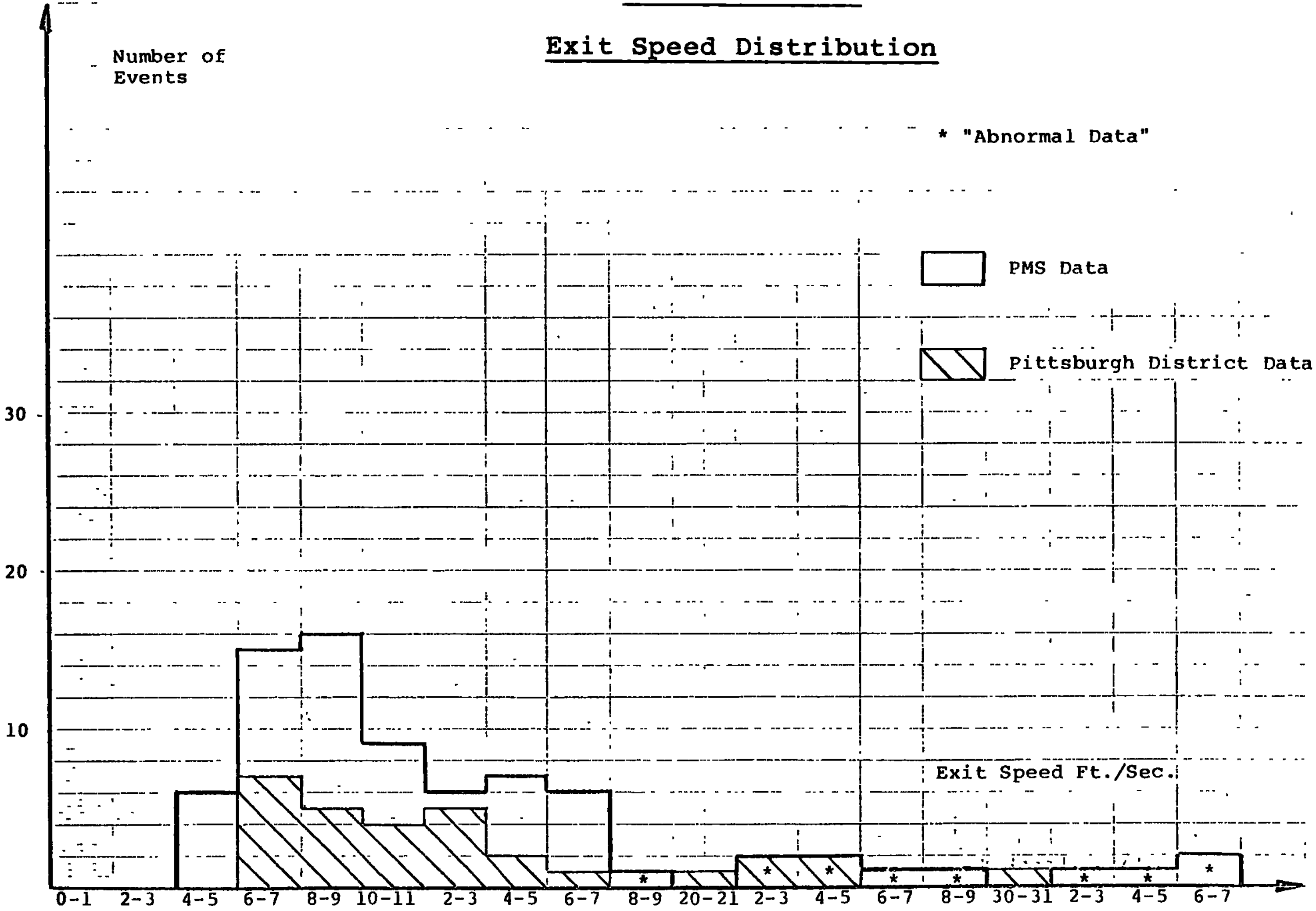
## FIGURE III - C

## Entry Speed Distribution



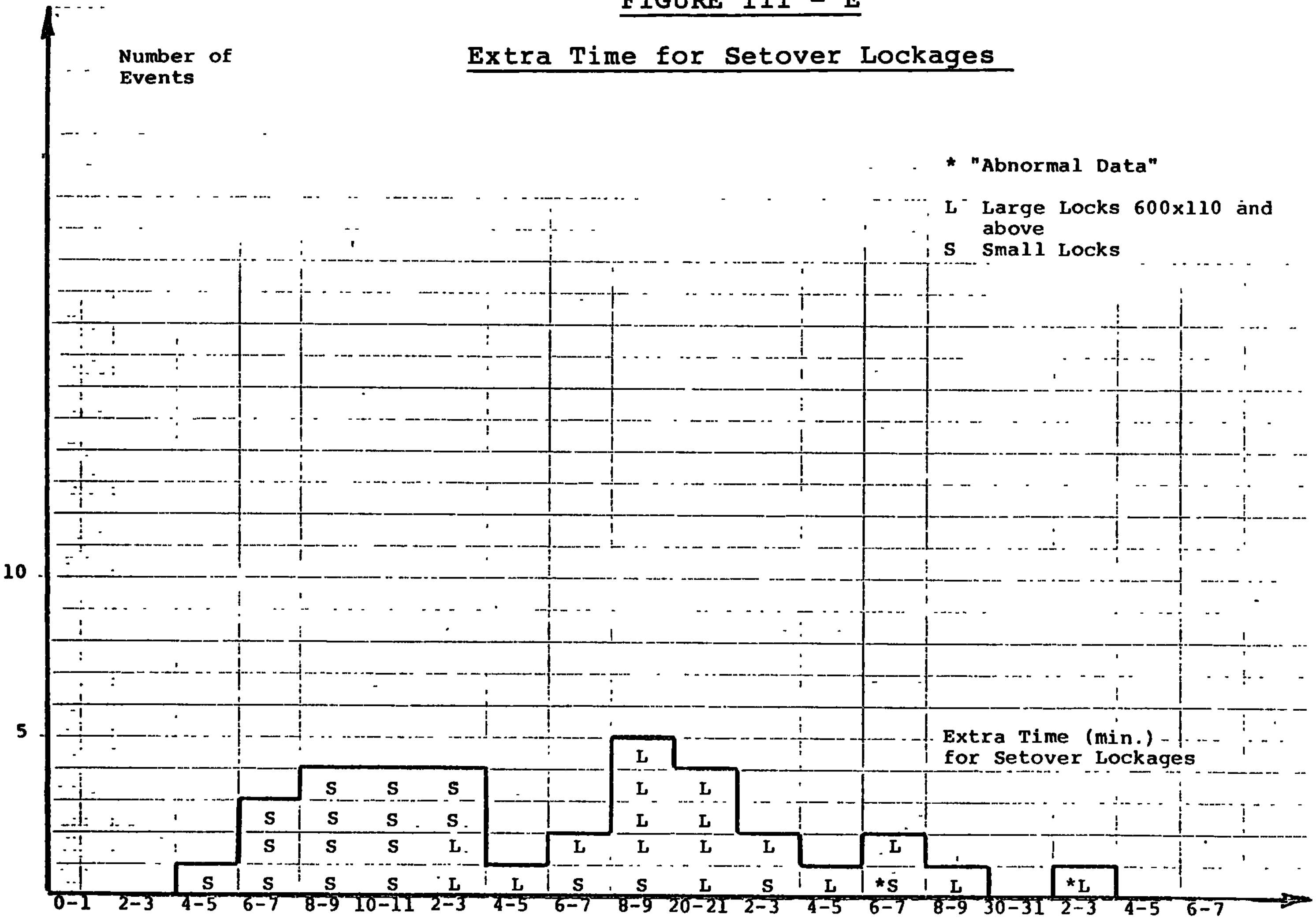
## FIGURE III - D

## Exit Speed Distribution



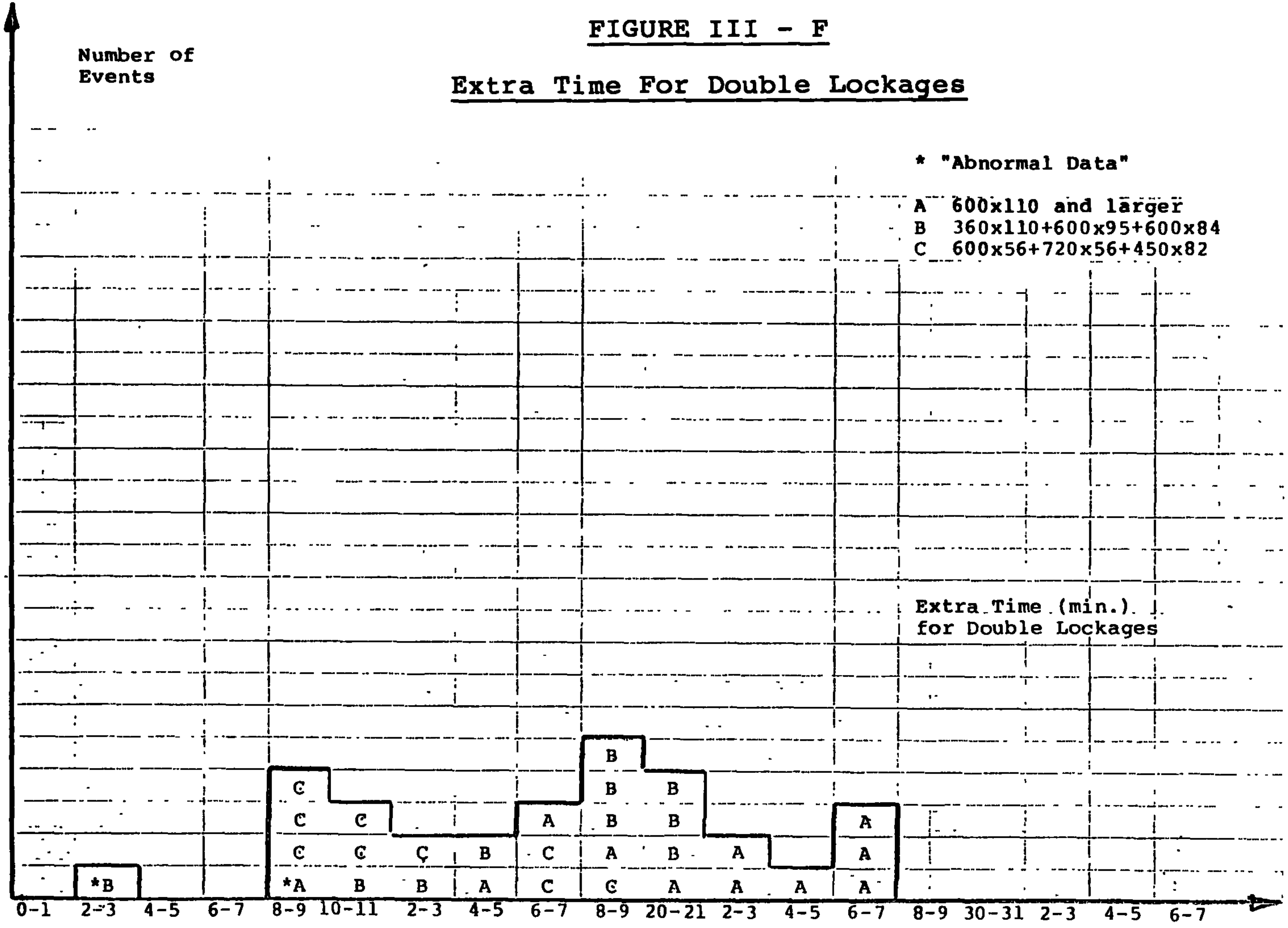
## FIGURE III - E

## Extra Time for Setover Lockages



## FIGURE III - F

## Extra Time For Double Lockages



and exit situations (presence of sharp bends, bridges, narrow channels, guiding walls, etc.), tow size, towboat power, weather, visibility (day/night), pilot experience, etc.

Nonetheless, as shown in the histograms presented in Figures III-B to III-D, for the majority of locks (65%), the approach speed falls in a narrow range (3 ft./sec. to 6 ft./sec.); similarly, for 90% of the locks the entry speed falls between 1.25 ft./sec. and 3.25 ft./sec.; and for 55% of the locks, the exit speed falls between 6 ft./sec.and 11 ft./sec. However, the shape of the histograms suggests that even larger ranges of speeds should be considered as normal. Specifically, 2 to 9 ft./sec. for approach speeds, 1.5 to 3.5 ft./sec. for entry speeds and 4 to 17 ft./sec. for exit speeds.

Subsequently, any approach speed lower than 2 ft./sec. and higher than 9 ft./sec. was considered suspicious and was given additional scrutinization. Similarly, any entry speed lower than 1.5 ft./sec. and higher than 4 ft./sec., and any exit speed lower than 4 ft./sec. and higher than 17 ft./sec., were further investigated.

The extra time for setover lockages follows a fairly flat distribution (see Figure III-E) with two peaks that correspond to times for large locks (600 x 110 and more) and small locks (less than 600'x 110). Figure III-E indicates that the extra time for setover lockages ranges from 6 to 13 min. for small locks (less than 600' x 110) and from 13 to 29 min. for large locks (600 x 110 and larger). This distinction between locks permits the identification of two locks with abnormal extra times for setover: Barkley L/D on the Cumberland River and L/D 26 on the Mississippi River.

The values of extra time for double lockages are fairly wide ranging see Figure III-E) and necessitated further analysis. It was found that the three peaks in the distribution are relative to three types of locks: Type A (600'x 110'and larger); Type B (360'x 110', 400'x 25', and 600'x 84), Type C (720 x 56 and smaller). Two locks were identified as having abnormal extra time for double lockages: Millers Ferry L/D on the Alabama River and L/D 27 on the Mississippi River.

2. Characteristics of Data Distributions. The mean, moment, and skewness of the lockage time data distributions represented by the histograms are presented in

Table III-1. The mean values are used in subsequent sections to determine the capacity of representative locks that do not have reliable or available PMS data. The second moment is the variance; this moment is used to measure the variability or dispersion of the data. The third moment is used to determine the degree of skewness of the distribution: if the skewness is zero, the distribution is symetric if the skewness is positive, the distribution is said to be positively skewed. The distribution is considered symmetric if -0.5 - skewness - 0.5; the distribution is highly skewed if this value exceeds 1.

As shown in Table III-1, the characteristics of the PMS distributions are very similar to the distributions derived from verified PMS data for September 1977 provided by the Pittsburgh District. The mean approach speeds are respectively 4.7 and 4.9 ft./sec.; the mean entry speeds are respectively 2.2 and 2.1 ft./sec.; the mean exit speeds are respectively 9.8 and 9.9 ft./sec. Again, the waiting distances are taken from the INSA report "Lock Physical Characteristics." These distances might not always represent actual distances, as suggested by the high values obtained for exit speeds. Therefore, the speed values should not be taken per se, but should be viewed merely as a means of identifying erroneous PMS data recordings for a particular lock.

Field data collected on the Monongahela River do not conflict with PMS averages. However, as expected, the timings do not match the PMS averages as closely as do the Pittsburgh data, because only one set of field data is available for comparison.

3. Results of PMS Data Verification. Monthly average lockage times were found to be fairly stable for various months in the year 1976. However, the locks in Table III-2 were found to have significant monthly variation in lockage time.

The variation were found to be due to the following factors:

L/D 24, 25, and 27: Approach distances are cited as nonavailable in the INSA report on "Physical Characteristics" and therefore it is likely that there are no fixed waiting areas and that tows wait at different locations depending upon the season.

## TABLE III - 1

## Mean, Variance, and Skewness of Distribution for PMS Data

| | | | Mean | s.d. | Variance | Skewness |
|---|---|---|---|---|---|---|
| Speed (ft./sec.) | Approach | PMS | 4.7 | 1.8 | 3.4 | 0.5 |
| | | P.D. | 4.9 | 1.6 | 2.5 | 0.1 |
| | Entry | PMS | 2.2 | 0.6 | 0.4 | 0.4 |
| | | P.D. | 2.1 | 0.5 | 0.2 | 0.2 |
| | Exit | PMS | 9.8 | 3.0 | 9.1 | 0.5 |
| | | P.D. | 9.9 | 3.0 | 8.7 | 0.4 |
| Extra Time (Min.) | Setover L | PMS | 19.6 | 4.4 | 19.1 | 0.2 |
| | S | PMS | 10.8 | 3.1 | 9.9 | 1.1 |
| | Double A | PMS | 21.9 | 4.6 | 21.4 | -0.4 |
| | B | PMS | 17.8 | 4.2 | 17.4 | -1.2 |
| | C | PMS | 12.3 | 3.4 | 11.7 | 0.5 |

Source: PMS Printout and lockage data analyzed by the Pittsburgh District.

## Table III - 2

## Locks with Unstable Data

| Lockage Parameter | Locks |
|---|---|
| F/E Approach Time | L/D 24 (Mississippi)<br>L/D 25 (Mississippi)<br>Columbia (Ouchita/Black)<br>Watts Bar (Tennessee) |
| F/E and TB Approach Time | L/D 8 (Mississippi)<br>L/D 9 (Mississippi)<br>L/D 10 (Mississippi) |
| Entry Time | L/D 27 (Mississippi)<br>(Main Chamber) |

L/D 8, 9, 10: Approach distances are significantly longer than usual, and therefore, depending on seasonality and flow conditions, the designated distances might not always be respected.

Columbia and Watts Bar L/D: Fewer than 20 tows are recorded monthly. Therefore, monthly averages cannot be as stable as expected.

Other possible reasons for fluctuations in monthly data are alterations caused by lock maintenance, rehabilitation work (L/D 27, for example, was undergoing construction in 1976) and accidents. Still, for the large majority of locks operating, conditions in 1976 (the year chosen as representative) appeared to be normal.

Three types of "abnormal" data verification were conducted for the abnormal data identified in Figures III-B and III-F. (Table III-3 presents a summary list of representative locks with their abnormal data.)

(a) If the "abnormal" data were averages of a significantly large number of events, or if there were any other obvious explanation, the data were not rejected for use in the LOCKAP model for capacity estimates.

# TABLE III - 3

## List of Representative Locks with "Abnormal Data"

| Discrepancies | River | District | Locks | Speed | | | | | Extra Time | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Approach | | Entry | Exit | | | |
| | | | | Up. | D. | | Up. | D. | Setover L. | Double L |
| Approach Speed | Mississippi | Rock Island | L/D 19 | 1.2* | 2.4 | 2.5 | 8.3 | 4.1 | - | - |
| | B. Warr. Tomb. | Mobile | Coffeeville | 7.8 | 12.1* | 3.3 | 13.8 | 9.3 | 13 | - |
| | A.C.F. | Mobile | Woodruff | 22.5* | 6.7 | 2.5 | 10.4 | 24.6* | 7 | 19 |
| Entry Speed | Illinois | Chicago | T.O'Brien | 7.7 | 7.7 | 5.6* | 16.7 | 16.7 | - | - |
| Exit Speed | Mississippi | St. Paul | L. St. Anthony | 9.3 | 2.5 | 1.5 | 10.8 | 21.6* | 7 | 10 |
| | Kanawha | Huntington | Winfield | 4.9 | 5.3 | | | | | |
| | | | (Main 1) | | | 2.0 | 33.4* | 35.9* | 11 | 13 |
| | | | (Main 2) | 5.3 | 6.3 | 3.0 | 50.2* | 53.8* | 9 | 13 |
| | Ohio | Louisville | Cannelton | 3.7 | 7.5 | | | | | |
| | | | (Main) | 4.4 | 6.9 | 3.1 | 23.3* | 17.5 | - | - |
| | | | (Aux.) | | | 2.5 | 37.3* | 24.0* | 26 | - |
| | Monongahela | Pittsburgh | L/D 2 (Main) | 4.1 | 4.2 | 3.4 | 25.2* | 15.6 | 18 | 19 |
| | | | (Aux.) | 6.0 | 6.8 | 3.0 | 33.5* | 26.8* | 9 | 17 |
| Extra Time for Setover Lockages | Cumberland | Nashville | Barkley | 3.0 | 2.9 | 1.8 | 7.4 | 13.7 | 33* | 26 |
| | Mississippi | St. Louis | L/D 26 (Aux.) | - | - | 3.0 | - | - | 27* | 21 |
| Extra Time for Double Lockages | Mississippi | St. Louis | L/D 27 (Aux.) | - | - | 2.0 | - | - | 14 | 9* |
| | Alabama-Coosa | Mobile | Millers Ferry | 3.3 | 3.3 | 1.8 | 10.7 | 8.9 | 12 | 3* |

* "Abnormal Data"

(b) If the "abnormal" data for locks in the Ohio River Division were supported by the findings of the Pittsburgh District, relative to lockage times, the data were not rejected.

(c) For the remaining "abnormal" data, the operating Corps Districts were contacted to determine whether or not the data should be discarded.

(d) If the PMS data were finally discarded or if field data were unavailable for a selected lock, average values were assumed.

Approach Speed

L/D 19: The approach distances used were confirmed as correct (i.e. 2,600 ft. for upper pool and 800 ft. for lower pool). The reason for the downstream approach speed being so low is due to the presence of an ice-breaking structure that slows down the tows. The Rock Island District's opinion is that there is a need to eliminate part of that structure to facilitate approaches.

For the other three locks (Lower St. Anthony, Coffeeville, and Woodruff) the approach distances actually represented are different from those presented in the INSA report. Therefore, the PMS data for these locks are normal and used for speed calculation.

Accordingly, modifications were made as follows in Table III-4:

Table III - 4

| Locks | Approach Distance (ft.) INSA | | Approach Distance (ft.) Actual | | Actual Approach Speeds ft./sec. | |
|---|---|---|---|---|---|---|
| | U. | D. | U. | D. | U. | D. |
| L. St. Anthony | 500 | 1800 | 800 | 600 | 4.2 | 3.3 |
| Woodruff | 1500 | 5000 | 1600 | 1000 | 5.8 | 6.7 |
| Coffeeville | 5400 | 3800 | 2640 | -- | - | 6.3 |

T.O'Brien Lock: The entry speed is substantially higher than average. The reasons are:

1. The lock length is 1000 ft.
2. The average tow size is only 2.19 barges
3. There are almost no multiple lockages (only .5%)

Therefore, a tow does not need to cover the whole length of the lock and requires less time to enter. Hence, the data relative to T. O'Brien Lock are not rejected.

## Extra Time for Setover Lockages

Barkley L/D: Only sixteen tows experienced a setover lockage in 1976 at Barkley L/D. The number of events is too low to justify keeping the data. Therefore, the average extra time for setover (19.6 min. for large locks) can be used (see Table III-1).

L/D 26: The situation is reversed for L/D 26. The number of events, or number of tows, that experienced a setover lockage is about 270. This number is too high and the data point is not rejected. Twenty-seven minutes is therefore the best estimate of the extra time for setover at the auxiliary chamber on L/D 26.

## Extra Time for Double Lockages

L/D 27: A 9 min. extra time for double lockages is significantly lower than the average of 22 min. for 600' x 110' locks. L/D 27 was undergoing construction in 1976 and traffic had to be shifted to the auxiliary chamber. The data were discarded and the new average extra time for double lockages is taken as 22 min. (see Table III-1).

Millers Ferry: A 3 min. extra time for double lockage is significantly lower than the average obtained for locks of similar size. Moreover, the number of events was very small (less than 30 tows experienced a double lockage in

1976). Therefore, the data were discarded and the new average is taken as 18 min. (see Table III-1).

PMS "abnormal" data and the Pittsburgh District analysis conducted for the locks located in the Ohio Basin, Cannelton L/D on the Ohio River, Winfield L/D on the Kanawha River, and L/D 2 on the Monongahela River are comparable. For these locks, the Pittsburgh analysis of September 1977 supports 1976 PMS data. Therefore, the data are considered reliable.

## REPRESENTATIVE LOCKS AND LOCK CLASSIFICATION

There are over 250 locks in the United States inland waterways system. Because of the great number of locks in the system, it was not considered possible to perform a detailed capacity analysis for each, nor was it necessary. Lock capacity varies as a function of several physical parameters. The effort that most of these parameters, such as service time, average load per barge, average tow size, etc., have on capacity, however, can be evaluated at each lock by using the lock sensitivity analysis presented in the section entitled "Sensitivity Analysis of Lock Capacity and Delay."

The only parameter which requires an independent evaluation at each lock is lock size (length and width). Fortunately, there are a limited number of lock sizes and lock size combinations (two chambers at a site) in existence.

First, one lock on each waterway was chosen as representative of all the other locks of the same size on the waterway. Where more than one lock size exists on a waterway, a different lock was chosen to represent each size. These representative locks are shown in Table III-5 along with all the locks they represent.

An attempt was made to choose, as the representative lock, the lock which is the most constraining on the waterway. In this manner, when capacity is determined for the representative locks, it will represent the minimum

## TABLE III - 5

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 1 | U. Miss. R | L. St. Anthony | L. St. Anthony | 400x56 | | 3.2 |
| | | U. St. Anthony | | 400x56 | | NA |
| 1 | U.Miss. R | L/D 14 | L/D 15 | 600x110 | 320x80 | 17.4 |
| | | L/D 15 | | 600x110 | 18.2 | |
| 1 | U. Miss. R | L/D 19 | L/D 19 | 1200x110 | | 23 |
| 1 | U. Miss. R | L/D 2 | L/D 22 | 600x110 | | 11.2 |
| | | L/D 3 | | 600x110 | | 11.0 |
| | | L/D 4 | | 600x110 | | NA |
| | | L/D 5 | | 600x110 | | 11.4 |
| | | L/D 5A | | 600x110 | | 11.5 |
| | | L/D 6 | | 600x110 | | 12.1 |
| | | L/D 7 | | 600x110 | | 12.2 |
| | | L/D 8 | | 600x110 | | 12.5 |
| | | L/D 9 | | 600x110 | | 13.1 |
| | | L/D 10 | | 600x110 | | 13.1 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage of Tons per year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| | | L/D 11 | | 600x110 | | 15.0 |
| | | L/D 12 | | 600x110 | | 15.1 |
| | | L/D 13 | | 600x110 | | 15.1 |
| | | L/D 16 | | 600x110 | | 19.7 |
| | | L/D 17 | | 600x110 | | 19.9 |
| | | L/D 18 | | 600x110 | | 21 |
| | | L/D 20 | | 600x110 | | 23 |
| | | L/D 21 | | 600x110 | | 24 |
| | | L/D 22 | | 600x110 | | 25 |
| | | L/D 24 | | 600x110 | | 24.6 |
| | | L/D 25 | | 600x110 | | 24.8 |
| 1 | U. Miss. R | L/D 1 | L/D 1 | 400x56 | 400x56 | 3.4 |
| 1 | L. U. Miss. R. | L/D 26 | L/D 26 | 600x110 | 360x110 | 58 |
| 2 | Mid. Miss. R | L/D 27 | L/D 27 | 1200x110 | 600x110 | 65 |
| 2 | Mid. Miss. R. | Kaskaskia | Kaskaskia | 600x84 | | 1 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 4 | Ouachita R. | L/D 8 | L/D 8 | 268x55 | | 0 |
| | | L/D 6 | | 268x55 | | 0 |
| 4 | Ouachita | Columbia | Columbia | 600x84 | | 1 |
| | | | Jonesville | 600x84 | | 1 |
| 4 | Red R. | L/D 9 | L/D 1 | 685x84 | | - |
| | | L/D 8 | | 685x84 | | - |
| | | L/D 7 | | 685x84 | | - |
| | | L/D 6 | | 685x84 | | - |
| | | L/D 5 | | 685x84 | | - |
| | | L/D 4 | | 685x84 | | - |
| | | L/D 3 | | 685x84 | | - |
| | | L/D 2 | | 685x84 | | - |
| | | L/D 1 | | 685x84 | | - |
| 4 | Atchafalaya R. | Keystone | Keystone | 162x36 | | - |
| 4 | " | Berwick | Berwick | 300x45 | | - |
| 4 | " | Old River | Old River | 1190x75 | | 5.4 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 4 | Baton Rouge & Morgan City | Bayou Sorrel | Bayou Sorrel | 760x56 | | 19.6 |
| | " | Port Allen | Port Allen | 1198x84 | | 19.4 |
| 5 | Illinois w/w | Lockport | Marseilles | 600x110 | | 22.5 |
| | | Brandon Rd. | | 600x110 | | 23 |
| | | Dresden Is. | | 600x110 | | 25.4 |
| | | Marseilles | | 600x110 | | 26 |
| | | Starved Rock | | 600x110 | | 27.2 |
| | | Peoria | | 600x110 | | 33.2 |
| | | Lagrange | | 600x110 | | 30.7 |
| 5 | Illinois w/w | Chicago | Chicago | 600x80 | | 1 |
| 5 | Illinois w/w | Tom O'Brien | Tom O'Brien | 1000x110 | | 6 |
| 7 | U. Ohio R. | Emsworth | Emsworth | 600x110 | 300x56 | 24 |
| | | Dashields | | 600x110 | 300x56 | 24 |
| | | Montgomery | | 600x110 | 300x56 | 23 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 7 | U. Ohio R. | New Cumberland | Hannibal | 1200x110 | 600x110 | 26 |
| | | Pike Island | | 1200x110 | 600x110 | 28 |
| | | Hannibal | | 1200x110 | 600x110 | 32 |
| | | Willow Island | | 1200x110 | 600x110 | 33 |
| | | Belleville | | 1200x110 | 600x110 | 34 |
| | | Racine | | 1200x110 | 600x110 | 35 |
| 7 | Mid. Ohio R. | Gallipolis | Gallipolis | 600x110 | 360x110 | 41 |
| 7 | Mid. Ohio R. | Greenup | Markland | 1200x110 | 600x110 | 34 |
| | | Meldahl | | 1200x110 | 600x110 | 30 |
| | | Markland | | 1200x110 | 600x110 | 35 |
| 7 | L. Ohio R.III | McAlpine | McAlpine | 1200x110 | 600x110 | 44 |
| | | Cannelton | | 1200x110 | 600x110 | 45 |
| | | Newburgh | | 1200x110 | 600x110 | 43 |
| 7 | L. Ohio R.III | Uniontown | Uniontown | 1200x110 | 600x110 | 51 |
| 7 | L. Ohio R.III | Smithland | Smithland | 1200x110 | 600x110 | 51 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| 7 | L. Ohio R.I. | L/D 52 | L/D 52 | 1200x110 | 600x110 | 30 |
| 7 | L. Ohio R.I. | L/D 53 | L/D 53 | 600x110 | - | 30 |
| 7 | Monongahela R. | L/D 2 | L/D 2 | 720x110 | 360x56 | 23 |
|  | " | L/D 3 | L/D 4 | 720x56 | 360x56 | 25 |
|  | " | L/D 4 |  | 720x56 | 360x56 | 19 |
| 7 | " | Maxwell | Maxwell | 720x84 | 720x84 | 18 |
| 7 | " | L/D 7 | L/D 7 | 360x56 |  | 7 |
| 7 | " | L/D 8 |  | 360x56 |  | 9 |
|  |  | Morgantown | Morgantown | 600x84 |  | 2 |
|  |  | Hildebrand |  | 600x84 |  | 1 |
|  |  | Opekiska |  | 600x84 |  | 0.2 |
| 7 | Allegheny R. | L/D 2 | L/D 2 | 360x56 |  | 4 |
|  |  | L/D 3 |  | 360x56 |  | 3 |
|  |  | L/D 4 |  | 360x56 |  | 2 |
|  |  | L/D 5 |  | 360x56 |  | 1 |
|  |  | L/D 6 |  | 360x56 |  | 0.1 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | L/D 7 | | 360x56 | | 0.1 |
| | | L/D 8 | | 360x56 | | 0 |
| | | L/D 9 | | 360x56 | | 0 |
| 7 | Kanawha R. | London | Winfield | 360x56 | 360x56 | NA |
| | | Marmet | | 360x56 | 360x56 | NA |
| | | Winfield | | 360x56 | 360x56 | 13 |
| 7 | Kentucky R. | L/D 1 | L/D 1 | 145x38 | | 0 |
| | | L/D 2 | | 145x38 | | 0 |
| | | L/D 3 | | 145x38 | | 1 |
| | | L/D 4 | | 145x38 | | 1 |
| | | L/D 5 | | 145x38 | | 1 |
| 7 | Kentucky R. | L/D 6 | L/D 6 | 148x52 | | 0 |
| | | L/D 7 | | 148x52 | | 0 |
| | | L/D 8 | | 148x52 | | 0 |
| | | L/D 9 | | 148x52 | | 0 |
| | | L/D 10 | | 148x52 | | 0 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | L/D 11 | | 148x52 | | 0 |
| | | L/D 12 | | 148x52 | | 0 |
| | | L/D 13 | | 148x52 | | 0 |
| | | L/D 14 | | 148x52 | | 0 |
| 7 | Green R. | L/D 1 | L/D 1 | 600x84 | | 14 |
| | | L/D 2 | | 600x84 | | 14 |
| 7 | Green R. | L/D 3 | L/D 3 | 138x36 | | 0 |
| 7 | Cumberland R. | Cordell Hull | Old Hickory | 400x84 | | 0 |
| | | Old Hickory | | 400x84 | | 0.3 |
| 7 | Cumberland R. | Cheatham | Barkley | 800x110 | | 4.2 |
| | | Barkley | | 800x110 | | 6.2 |
| 8 | U. Tenn. R. | Melton Hill | Melton Hill | 400x75 | | 0 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 8 | U. Tenn. R. | Ford Lounden | Chickamauga | 360x60 | | 0.3 |
| | | Watts | | 360x60 | | 0.5 |
| | | Chickamauga | | 360x60 | | 4 |
| 8 | U. Tenn. R. | Nickajack | Nickajack | 600x100 | | 4 |
| 8 | U. Tenn. R. | Guntersville | Wheeler | 600x110 | 400x60 | 5.3 |
| | | Wheeler | | 600x110 | 400x60 | 7 |
| 8 | U. Tenn. R. | Wilson | Wilson | 600x110 | | 8 |
| 8 | L. Tenn. R. | Kentucky | Kentucky | 600x110 | | 21 |
| | | Pickwick | Pickwick | 600x110 | | 8.4 |
| 9 | Arkansas R. | Newt Graham | Norrell | 600x110 | | 1 |
| | | Chouteau | | 600x110 | | 1 |
| | | Webber Falls | | 600x110 | | 1.4 |
| | | Kerr | | 600x110 | | 1.6 |
| | | Mayo | | 600x110 | | 1.5 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | L/D 13 | | 600x110 | | 1.8 |
| | | Ozark | | 600x110 | | 1.7 |
| | | Dardanelle | | 600x110 | | 1.7 |
| | | L/D 9 | | 600x110 | | 1.7 |
| | | Toad Suck Ferry | | 600x110 | | 1.7 |
| | | Murray | | 600x110 | | 1.7 |
| | | D. Terry | | 600x110 | | 3 |
| | | L/D 5 | | 600x110 | | 3 |
| | | L/D 4 | | 600x110 | | 3.5 |
| | | L/D 3 | | 600x110 | | 4 |
| | | L/D 2 | | 600x110 | | 4 |
| | | Norrell | | 600x110 | | 4 |
| 10 | GIWW W. -I. | Harvey | Harvey | 415x75 | | 5 |
| 10 | GIWW W. -I. | Algiers | Algiers | 760x75 | | 25 |
| 10 | GIWW W. -I. | Vermilion | Vermilion | 1182x56 | | 42 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Lock | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| 10 | GIWW W. -I. | Calcasieu | Calcasieu | 1194x75 | | 45 |
| | | Bayou Boeuf | | 1148x75 | | 23 |
| 11 | GIWW E. -I. | Inner Harbor | Inner Harbor | 640x75 | | 28 |
| 11 | Pearl R. | L/D 1 | L/D 1 | 310x65 | | NA |
| | | L/D 2 | | 310x65 | | NA |
| | | L/D 3 | | 310x65 | | NA |
| 11 | Okeechobee W/W | St. Lucie | St. Lucie | 250x50 | | 45 |
| | | Moore Haven | | 250x50 | | 45 |
| | | Ortona | | 250x50 | | 45 |
| 11 | Okeechobee W/W | Franklin | Franklin | 400x56 | | 45 |
| 11 | A/C/F R. | George | Woodruff | 450x84 | | 0.1 |
| | | Andrew | | 450x84 | | 0.3 |
| | | Woodruff | | 450x84 | | 1 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| 12 | Black Warrior R. | Demopolis | Demopolis | 600x110 | | 12 |
| | | Coffeeville | | 600x110 | | 12 |
| 12 | Black Warrior R. | Oliver | Oliver | 460x95 | | 12 |
| 12 | Black Warrior R. | Bankhead | Bankhead | 600x110 | | 10 |
| | | Holt | | 600x110 | | 12 |
| | | Warrior | | 600x110 | | 12 |
| 12 | Alabama R. | Jones Bluff | Millers Ferry | 600x84 | | 0.1 |
| | | Millers Ferry | | 600x84 | | 1 |
| | | Claireborne | | 600x84 | | 1 |
| 12 | Tenn-Tom W/W | Gainesville | Bay Springs | 600x110 | | NA |
| | | Aliceville | | 600x110 | | NA |
| | | Columbus | | 600x110 | | NA |
| | | Aberdeen | | 600x110 | | NA |
| | | L/D A | | 600x110 | | NA |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mils. of Tons per Year |
|---|---|---|---|---|---|---|
| | L/D B | | | 600x110 | | NA |
| | | L/D C | | 600x110 | | NA |
| | | L/D D | | 600x110 | | NA |
| | | L/D E | | 600x110 | | NA |
| | | Bay Springs | | 600x110 | | NA |
| 13 | Cross Fl. Canal | H.H. BUckman | H.H. Buckman | 600x84 | | NA |
| | | Inglis | | 600x84 | | NA |
| 13 | Canaveral H. | Canaveral | Canaveral | 600x84 | | 0 |
| 13 | Okeechobee W/W | St. Lucia | St. Lucia | 310x50 | | 0 |
| 13 | Okeechobee W/W | Moore Haven | | 250x50 | | 0 |
| 13 | Okeechobee W/W | Ortona | | 250x50 | | 0 |
| 13 | Okeechobee W/W | Franklin | | 443x56 | | 0 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 13 | Savannah R. | Savannah Bluff | Savannah Bluff | 360x56 | | 0.1 |
| 13 | Cape Fear R. | L/D 1 | L/D 1 | 200x40 | | 0 |
| | | L/D 2 | | 200x40 | | 0 |
| 13 | Cape Fear R. | Huske | Huske | 300x40 | | 0 |
| 14 | AIWW | Great Bridge | Great Bridge | 600x75 | | 1.6 |
| 14 | AIWW | Deep Creek | Deep Creek | 300x52 | | 0 |
| 14 | Hudson R. | Troy | Troy | 493x44 | | 2 |
| 14 | NY State W/W | Locks C1-C12 | Lock C1 | 310x45 | | 2 |
| | | Locks E2-E27 | | 310x45 | | 2 |
| | | Utica Harbor Lock | | 310x45 | | 2 |
| | | Locks 01-03 | | 310x45 | | 2 |
| | | Locks 05-08 | | 310x45 | | 2 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | Locks E28 A&B | | 310x45 | | 2 |
| | | Locks E29-E30 | | 310x45 | | 2 |
| | | Locks E32-E35 | | 310x45 | | 2 |
| | | Locks C/S1-C/S4 | | 310x45 | | 2 |
| 16 | St. Lawrence S. | St. Lambert | Snell | 730x80 | | 54 |
| | | Cote St. Catherine | | 730x80 | | 55 |
| | | L. Beauharnois | | 730x80 | | 55 |
| | | U. Beauharnois | | 730x80 | | 55 |
| | | Snell | | 730x80 | | 55 |
| | | Eisenhower | | 730x80 | | 55 |
| | | Irequois | | 730x80 | | 55 |
| 16 | Welland Canal | L/D 1 | L/D 1 | 730x80 | | 64 |
| | | L/D 2 | | 730x80 | | 64 |
| | | L/D 3 | | 730x80 | | 64 |
| | | L/D 7 | | 730x80 | | 64 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size Main | Chamber Size Aux | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| 16 | Welland Canal | L/D 4 | L/D 4 | 730x80 | 730x80 | 64 |
| | | L/D 5 | | 730x80 | 730x80 | 64 |
| | | L/D 6 | | 730x80 | 730x80 | 64 |
| 16 | Welland Canal | L/D 8 | L/D 8 | 1148x80 | | 64 |
| 16 | St. Marys R. | MacArthur | MacArthur | 800x80 | | 40 |
| 16 | St. Marys R. | New Poe | New Poe | 1200x110 | | 50 |
| 16 | St. Marys R. | Davis | Davis | 1350x80 | | 3 |
| | | Sabin | | 1350x80 | | 1 |
| 18 | Col-Snake W/W | Bonneville | Bonneville | 500x76 | | 6 |

## Table III-5 (continued)

## U.S. Navigation Locks' Physical Characteristics

| Reporting Region | Segment Name | Lock Name | Representative Lock | Chamber Size | | 1976 Tonnage Mil. of Tons per Year |
|---|---|---|---|---|---|---|
| | | | | Main | Aux | |
| 18 | Col-Snake W/W | The Dalles | McNary | 675x86 | | 5 |
| | | John Day | | 675x86 | | 5 |
| | | McNary | | 675x86 | | NA |
| | | Ice Harbor | | 675x86 | | 2 |
| | | L. Monumental | | 675x86 | | 2 |
| | | Little Goose | | 675x86 | | 2 |
| | | L. Granite | | 675x86 | | 1 |
| 18 | Willamette R. | Willamette | Willamette | 4@ 210x40 | | 1 |
| 19 | Sacr. Ship C. | W.G. Stone | W.G. Stone | 600x86 | | NA |
| Totals | | 280 | 86 | | | |

capacity on the waterway. To achieve this goal for each waterway, the representative locks were selected on the basis of present delay time, present lock service time, present traffic level lock lift (when service times were not available), and proximity to the "mouth" of the waterway. For situations where the relative level of traffic was not available, the proximity to the mouth of the segment was used assuming that higher traffic levels occur in the lower waterway reaches.

An attempt was made to select a representative lock for all the locks in the waterway system. The locks that were chosen as representative include both present and potential bottlenecks, as well as other locks that, although not constraining, are necessary for analysis of tow travel time in channelized systems. In most cases, choosing the representative lock was fairly straightforward as most ranking criteria were not contradictory. In a few instances (for example Upper Mississippi and L/D 22, 24 and 25), the choice of a representative lock was ambiguous because lockage time, delay time, traffic density, or lift are very close for each lock (within 10%); in these few instances, the available evaluations of capacity were used as the determining factor for the choice of representative locks.

Moreover, there are waterways for which more than one lock was chosen as representative. That occurred when locks were identified as potential bottlenecks (Illinois Waterway) or when the selection criteria and additional analysis (capacity estimates) were insufficient to identify the most constraining lock.

Finally, 22 different classifications of lock size or combinations of lock size (with two chambers at a site) were identified for the 81 representative locks. These lock classes are presented in Table III-6. Lock sizes and the representative locks in each lock classification are shown.

Thus, in order to determine the capacity of any lock in the waterway system, detailed capacity analyses were only performed for 22 lock classifications. The capacities determined for these locks under present conditions, as determined in the section entitled "Capacity

## Table III-6

## List and Classes of Locks Selected for Analysis

| Lock Class | Lock Size | | Locks Selected for Analysis | Other Representative Locks |
|---|---|---|---|---|
| 1 | 1200x110 | 600x110 | MacAlpine* | |
| | | | Uniontown* | Hannibal |
| | | | | Markland |
| | | | L/D 52 (Ohio)[2] | |
| | | | L/D 27 (Miss.) | |
| 2 | 1200x110 | - | L/D 19 (Miss.) | |
| | | | T. O'Brian[1] | |
| 3 | 800x110 | - | Barkley | |
| 4 | 720x110 | 360x 56 | L/D 2 (Mon.) | |
| 5 | 600x110 | 360x110 | L/D 26 (Miss.) | |
| | | | L/D 15 (Miss.)[1] | |
| | | | Gallipolis | |
| 6 | 600x110 | 360x 56 | Emsworth | Wheeler |
| 7 | 600x110 | - | Marseilles | |
| | | | L/D 22 (Miss.)[1] | |
| | | | Kentucky | Nickajack, Wilson |
| | | | Pickwick | |
| | | | Demopolis | Gainsville, Norrell |
| | | | Bankhead | |
| | | | L/D 53 | |
| 8 | 460x 95 | - | W. B. Oliver | |
| 9 | 1198x 84 | - | Port Allen | |
| 10 | 720x 84 | 720x 84 | Maxwell | |

## Table III-6 (Continued)

## List and Classes of Locks Selected for Analysis

| Lock Class | Lock Size | | Locks Selected for Analysis | Other Representative Locks |
|---|---|---|---|---|
| 11 | 600x 84 | - | L/D 1 (Green) | L/D 1 (Red), Chicago |
| | | | Morgantown | Buckman, Kaskaskia, Stone<br>Canaveral |
| | | | McNary[2] | Jonesville[2], Millers Ferry[2] |
| 12 | 450x 82 | - | Old Hickory | |
| | | - | Woodruff[1] | |
| 13 | 1194x 75 | - | Calcasieu | Old River |
| 14 | 760x 75 | - | Algiers | |
| 15 | 640x 75 | - | Inner Harbor | |
| 16 | 500x 76 | - | Bonneville | |
| 17 | 415x 75 | - | Harvey | |
| | | | Melton Hill | |
| 18 | 1182x 56 | - | Vermilion | |
| 19 | 720x 56 | 360x 56 | L/D 4 (Mon.) | |
| 20 | 760x 56 | - | Bayou Sorrel | |
| 21 | 360x 56 | 360x 56 | Winfield | |
| | | | L/D 1 (Miss.) | |
| 22 | 360x 56 | - | L/D 7 (Mon.) | L/D 2 (All.),<br>L. St. Anthony, Chicamauga,<br>Sav. Bluff, L/D 1 (Pearl),<br>Franklin |

[1] Short Service Time compared to other representative locks in same size class.
[2] Long Service Time compared to other representative locks in same size class.

and Delay for Existing Locks Under Present Conditions by NWS Segments," can be adjusted to apply to any lock under any assumed condition using the sensitivity analysis presented in the section entitled "Sensitivity Analysis of Lock Capacity and Delay."

Representative locks which are smaller than 360' x 56', although identified, have not been examined further because projected traffic levels are very low at these sites. These locks include:

- 14 locks on the Kentucky River.
- Locks six and eight on the Ouachita River.
- Keystone and Berrick Locks in Segment 26.
- Three locks on the Cape Fear River.
- Troy Locks on the Hudson River.
- 58 locks on the New York State Waterway.
- The locks on the Willamette River.

The 19 deep draft locks on the St. Mary's River, the Welland Canal and the St. Lawrence Seaway are classified separately.

All of the representative locks identified as constraining were selected for capacity evaluation. In addition, several representative locks were included in the list of selected locks for LOKCAP model evaluation if their average service time for straight single lockages (with F/E approach and F/E exit) was substantially different from the service time calculated for the selected locks in the same size class, and if year 2000 preliminary estimates of demand indicated that they were likely to become bottlenecks.

## CAPACITY AND DELAY FOR EXISTING LOCKS UNDER PRESENT CONDITIONS BY NWS SEGMENTS

The LOKCAP computer simulation model was used to provide estimates of capacity and delay under present conditions as presented in this section.

As stated in the section entitled "Lock Classification," any representative lock identified as being constraining (or likely to become constraining) was selected for capacity evaluation.

For all other locks, evaluation using the LOKCAP model was not necessary. For these locks, sensitivity relations generated in the section entitled "Sensitivity Analysis of Lock Capacity and Delay" provide traffic delay curves based upon adjustments of the results obtained in this section for locks of similar size (same size class).

Capacities of existing locks are estimated for present navigation conditions, lock operational procedures, commodity pattern and fleet mix. The sensitivity analysis presented in the section entitled "Sensitivity Analysis of Lock Capacity and Delay" can be used to provide different capacities for modified input corresponding to future conditions.

PMS data was used whenever possible, or substituted by field data or average values. Another source of information (concerning average barge load only) could also have been used since the towing industry reports tonnages to the Waterborne Commerce Statistics Center (WCSC). However, the tonnages reported to the WCSC might be lower than the tonnages recorded by the lock personnel because some movements are not reported to the WCSC by shippers and because WCSC traffic density calculations assume "straightline" flows between origin and destination, which is not always valid. (Some movements are actually routed indirectly and may even pass upbound and downbound through the same lock facility without being considered.) Battelle, Inc.'s study of traffic flows for Projections of Ohio River Traffic[3] found PMS information to be significantly more reliable than WCSC. They concluded that this was a result of the procedure of collecting in a virtually continuous process at each locking (PMS) as opposed to collecting information at the end of each month (WCSC). The repetitive nature of the PMS collection process provides a check of the data as well.

### (a) Estimates of Practical Capacity

Estimates of technical and practical capacity are provided in Table III-7.

Practical capacity is taken as 90% of net maximum technical capacity (for infinite queue length) after deductions for recreation downtime and seasonality, as determined using the LOKCAP model. A value of 90% was selected as a point on the delay curve where delay would be at or approaching unacceptable levels which is equivalent to about a five hour delay per tow for transiting a lock. This delay threshold evidently varies significantly depending upon site specific situations. The estimates of practical capacity are presented in Table III-7 and are adjusted for the effects of seasonality, downtime and recreational usage. Therefore, the practical capacity provided is not an upper limit for traffic. Higher traffic levels under present conditions can be achieved, but delay times would be dramatically increased. In addition, practical capacity depends on so many variables that a change in any one of them would generally provide a proportional change in the capacity estimate. For example, an increase in tow size in the average tonnage per loaded barge, or in the percent of loaded barges, would increase capacity. Similarly, a higher utilization of the auxiliary chamber, a reduction in downtime, recreational usage or in seasonality would also increase capacity.

The input data utilized for capacity evaluation were 1976 data (Table III-8) to allow for a rapid checking of major input data and for easy comparison of input between locks. These average data (tons per loaded barge, tow size, percent of double lockages, percent of loaded barges and service time) were obtained from the PMS data, processed for 1976 by EDPC.

These estimates of practical capacity, based on 1976 data, will be refined in upcoming NWS tasks to account for any increases in tow size, in percent of loaded barges, etc. In this manner, year 2000 final estimates of segment demand will be compared to year 2000 capacity.

Some estimates of capacity under present conditions required immediate revision for evaluation of lock replacement alternatives in the section entitled "Estimates of Measures to Increase Capacity by NWS Segments." This is the case for dual 1200' x 110'/600' x 110' locks on the Ohio River and for the locks where traffic is likely to be modified due to the opening of the Tennessee Tombigbee Waterway. The 1976 technical capacities calculated for these locks cannot be considered as an upper limit for traffic since an increase in average tow size or the utilization of the auxiliary chamber would substantially increase capacity.

As previously stated, practical capacity estimates presented include adjustments for seasonality, downtime and recreational usages.

The impact of differing traffic levels, from season to season, on capacity was calculated based on the monthly 1976 PMS data according to the seasonality coefficient.

$$ks = (T/4)/\text{Max ST}$$

where,

T = annual tonnage
Max ST = maximum seasonal tonnage(peak three month period)
ks = coefficient of seasonality

This function implicitly takes downtime due to winter closing as well as seasonal commodity fluctuations into account by dividing the total annual tonnage by four times the maximum tonnage during the peak three month season. The seasonality coefficient can then be used to calculate capacity where significant seasonal variations in tonnages occur, including zero tonnage movement as occurs in seasonal closings.

## Table III-7

## Estimates of Technical and Practical Capacities for Representative Locks

(Million Tons)

| Lock Class | Lock Name | Annual Technical Capacity | | Annual Technical Capacity | | Monthly Practical Capacity (No Seas. & Max. Rel.) | |
|---|---|---|---|---|---|---|---|
| | | Main | Aux. | Main | Aux | Main | Aux. |
| 1 | McAlpine | 81 | 13 | 59 | 8 | 5.5 | 0.8 |
| | Uniontown | 106 | 21 | 82 | 13 | 7.6 | 1.2 |
| | L/D 52 (Ohio) | "61" | "33" | "49" | "22" | 4.3 | 2.2 |
| | L/D 27 (Miss.) | 94 | 54 | 77 | 43 | 6.8 | 3.7 |
| 2 | L/D 19 (Miss.) | 78 | - | 45 | - | 4.9 | - |
| | T. O'Brien | 41 | - | 23 | - | 2.5 | - |
| 3 | Barkley | 52 | - | 38 | - | 3.4 | - |
| 4 | L/D 2 (Mon.) | 54 | 15 | 44 | 8 | 3.9 | 0.7 |
| 5 | L/D 26 (Miss.) | 59 | 22 | 47 | 17 | 3.8 | 1.4 |
| | L/D 15 (Miss.) | 61 | 15 | 38 | 7 | 4.3 | 0.8 |
| | Gallipolis | 52 | 20 | 40 | 9 | 3.5 | 0.8 |

## Table III-7 (Continued)

## Estimates of Technical and Practical Capacities for Representative Locks

(Million Tons)

| Lock Class | Lock Name | Annual Technical Capacity | | Annual Technical Capacity | | Monthly Practical Capacity (No Seas. & Max. Rel.) | |
|---|---|---|---|---|---|---|---|
| | | Main | Aux. | Main | Aux | Main | Aux. |
| 6 | Emsworth | 41 | 11 | 32 | 5 | 2.9 | 0.5 |
| 7 | Marseilles | 38 | - | 26 | - | 2.4 | - |
| | L/D 22 (Miss.) | 48 | - | 29 | - | 3.2 | - |
| | Kentucky | 41 | - | 30 | - | 2.7 | - |
| | Pickwick1) | 39 | - | 26 | - | 2.4 | - |
| | Demopolis1) | 42 | - | 35 | - | 2.9 | - |
| | Bankhead1) | 41 | - | 31 | - | 2.8 | - |
| | L/D 53 (Ohio) | "48" | - | "34" | - | 3.3 | - |
| 8 | W.B. Oliver1) | 36 | - | 27 | - | 2.5 | - |
| 9 | Port Allen | 36 | - | 29 | - | 2.4 | - |
| 10 | Maxwell | 55 | 25 | 43 | 20 | 3.6 | 1.7 |
| 11 | L/Dl (Green) | 68 | - | 55 | - | 4.9 | - |
| | Morgantown | 34 | - | 55 | - | 4.9 | - |
| | McNary | 51 | - | 27 | - | 3.3 | - |

## Table III-7 (Continued)

## Estimates of Technical and Practical Capacities for Representative Locks

(Million Tons)

| Lock Class | Lock Name | Annual Technical Capacity | | Annual Technical Capacity | | Monthly Practical Capacity (No Seas. & Max. Rel.) | |
|---|---|---|---|---|---|---|---|
| | | Main | Aux. | Main | Aux | Main | Aux. |
| 12 | Old Hickory | 17 | - | 12 | - | 1.0 | - |
| | Woodruff | 20 | - | 15 | - | 1.4 | - |
| 13 | Calcasieu | "66" | - | "54" | - | 4.0 | - |
| 14 | Algiers | 31 | - | 27 | - | 2.3 | - |
| 15 | Inner Harbor | 32 | - | 26 | - | 2.1 | - |
| 16 | Bonneville | 17 | - | 9 | - | 1.1 | - |
| 17 | Harvey | 11 | - | 9 | - | 0.8 | - |
| | Melton Hill | 7 | - | 6 | - | 0.5 | - |
| 18 | Vermilion | "54" | - | "44" | - | 3.3 | - |

## Table III-7 (Continued)

## Estimates of Technical and Practical Capacities for Representative Locks

(Million Tons)

| Lock Class | Lock Name | Annual Technical Capacity | | Annual Technical Capacity | | Monthly Practical Capacity (No Seas. & Max. Rel.) | |
|---|---|---|---|---|---|---|---|
| | | Main | Aux. | Main | Aux | Main | Aux. |
| 19 | L/D 4 (Mon.) | 43 | 13 | 33 | 7 | 3.1 | 0.6 |
| 20 | Bayou Sorrel | 27 | - | 22 | - | 1.8 | - |
| 21 | Winfield | 16 | 16 | 11 | 9 | 1.1 | 0.8 |
| 22 | L/D 7 (Mon.) | 21 | - | 16 | - | 1.4 | - |

NOTE - " " indicates open pass situation

1) Shown present capacity is expected to increase when Tennessee-Tombigbee becomes operational

Downtime was obtained from Section VI. Precise values for downtime were available for the Ohio River Division. Corps District offices were contacted for missing information, most particularly from the New Orleans District.

Recreational information was obtained from the 1976 PMS data. The percent of recreation that appears on Table III-8 is the percent of time devoted to recreational lockages and is the product of the total number of recreational lockages by the average recreational lockage time. Only recreational lockages were taken into account. Recreational craft include small pleasure boats, fishing boats, government vessels, etc. The crafts which lock together with commercial vessels were excluded from the time dedicated to recreational use.

Time devoted to recreational usage is calculated on an annual basis and also for the peak summer season. Whenever peak season for commodity flow and recreation do not coincide, the annual capacity is calculated by deducting the annual percent of recreation. Whenever both peak demands occur simultaneously (in the same season), annual capacity is calculated by deducting peak recreational demand. Peak demands occur simultaneously for the following representative locks: L/D 1, L/D 15, L/D 19, L/D 22 (on the Mississippi River), Bonneville L/D and McNary L/D (on the Columbia/Snake Waterway), and Pickwick L/D (on the Lower Tennessee River).

### (b) Delay Function

Based on queuing theory, the delay function, representing the average tow delay time at any lock, can be presented as follows:

$$D = kt/(Q - t)$$

where,

D = delay at lock (min.)
t = traffic at lock (tons)
Q = capacity(tons)
k = lock delay parameter (min./tow)

## Table III-8

## Summary Input Data

| Lock Class | Lock Name | Coefficients of Reduction |  |  |  | Averages for Present Conditions |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | % Seas. | % Down. | % Rec. P.S. | % Rec. An. | Tons Loaded Barges | Average Tow Size | % of Double Lockages | % of Loaded Barges | Service Time (min.) |
| 1 | McAlpine | M 10 | 3 | 13 | 7 | 1550 | 7.8 | 0 | 62 | 49 |
|  |  | A 10 | 19 | 2 | 1 | 1780 | 2.3 | 0 | 36 | 63 |
|  | Uniontown | M 11 | "3" | 1 | 1 | 1590 | 9.4 | 0 | 62 | 46 |
|  |  | A 11 | "19" | 8 | 5 | 1598 | 3.5 | 0 | 30 | 41 |
|  | L/D 52 (Ohio) | M 15 | 2 | 2 | 3 | 1546 | 8.8 | 0 | 62 | 73 |
|  |  | A 15 | 9 | 4 | 3 | 1655 | 3.7 | 0 | 45 | 45 |
|  | L/D 27 (Miss.) | M 5 | 2 | 3 | 2 | 1513 | 7.8 | 0 | 66 | 43 |
|  |  | A 5 | 2 | 7 | 6 | 1480 | 7.3 | 53 | 62 | 63 |
| 2 | L/D 19 (Miss.)1) | 24 | "6" | 11 | 5 | 1212 | 2.2 | 0 | 61 | 21 |
|  | T. O'Brien | 21 | "6" | 38 | 15 | 1212 | 2.2 | 0 | 61 | 21 |
| 3 | Barkley | 10 | 6 | 8 | 4 | 1673 | 10.7 | 60 | 50 | 89 |

## Table III-8 (Continued)

## Summary Input Data

| Lock Class | Lock Name | | Coefficients of Reduction | | | | Averages for Present Conditions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | % Seas. | % Down. | % Rec. | | Tons Loaded Barges | Average Tow Size | % of Double Lockages | % of Loaded Barges | Service Time (min.) |
| | | | | | P.S. | An. | | | | | |
| 4 | L/D 2 (Mon.) | M | 7 | "3" | 0 | 0 | 1014 | 6.5 | 9 | 55 | 35 |
| | | A | 7 | "33" | 10 | 5 | 815 | 1.6 | 0 | 44 | 19 |
| 5 | L/D 26 (Miss.) | M | 8 | 3 | 1 | 1 | 1457 | 10.4 | 72 | 65 | 99 |
| | | A | 8 | 3 | 9 | 6 | 1578 | 3.5 | 48 | 52 | 74 |
| | L/D 15 (Miss.)1) | M | 27 | "3" | 3 | 2 | 1495 | 7.6 | 49 | 71 | 69 |
| | | A | 27 | "3" | 25 | 9 | 1494 | 1.3 | 0 | 34 | 25 |
| | Gallipolis | M | 7 | 9 | 0 | 0 | 1368 | 9.4 | 60 | 59 | 77 |
| | | A | 7 | 43 | 4 | 2 | 1072 | 4.1 | 28 | 45 | 52 |
| 6 | Emsworth | M | 9 | 5 | 1 | 1 | 1046 | 6.8 | 13 | 55 | 49 |
| | | A | 9 | 32 | 21 | 11 | 910 | 2.0 | 8 | 43 | 37 |
| 7 | Marseilles1) | | 15 | "6" | 11 | 6 | 1543 | 5.9 | 29 | 61 | 77 |
| | L/D 22 (Miss.) | | 24 | 3 | 8 | 3 | 1478 | 9.2 | 62 | 68 | 101 |
| | Kentucky | | 10 | 6 | 8 | 4 | 1516 | 6.9 | 37 | 58 | 76 |

## Table III-8 (Continued)

### Summary Input Data

| Lock Class | Lock Name | | Coefficients of Reduction | | | | Averages for Present Conditions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | % Seas. | % Down. | % Rec. P.S. | % Rec. An. | Tons Loaded Barges | Average Tow Size | % of Double Lockages | % of Loaded Barges | Service Time (min.) |
| 7 | Pickwick1)4) | | 10 | "6" | 13 | 6 | 1584 | 7.7 | 45 | 56 | 92 |
| | Demopolis4) | | 0 | 6 | 2 | 1 | 1490 | 3.5 | 0 | 67 | 44 |
| | Bankhead4) | | 9 | "6" | 2 | 2 | 1502 | 3.6 | 0 | 65 | 45 |
| | L/D 53 | | 15 | "6" | 2 | 2 | 1552 | 8.2 | 56 | 61 | 84 |
| 8 | W. B. Oliver4) | | 9 | 6 | 3 | 2 | 1508 | 3.4 | 15 | 67 | 50 |
| 9 | Port Allen3) | | 0 | 10 | 0 | 0 | 1850 | 2.4 | 6.4 | 71 | 51 |
| 10 | Maxwell | M | 7 | 3 | 10 | 4 | 921 | 6.0 | 0 | 31 | 40 |
| | | A | 7 | 3 | 8 | 3 | 906 | 6.0 | 0 | 77 | 36 |
| 10[1] | L/D 7 (Welland[5] | | 36 | "6" | 0 | 0 | 13362 | 1.0 | 0 | 79 | 44 |

## Table III-8 (Continued)

### Summary Input Data

| Lock Class | Lock Name | Coefficients of Reduction | | | | Averages for Present Conditions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | % Seas. | % Down. | % Rec. P.S. | % Rec. An. | Tons Loaded Barges | Average Tow Size | % of Double Lockages | % of Loaded Barges | Service Time (min.) |
| 11 | L/D 1 (Green) | 8 | 2 | 1 | 1 | 1497 | 3.8 | 0 | 50 | 22 |
| | Morgantown | 7 | "7" | 5 | 2 | 917 | 3.9 | 0 | 50 | 26 |
| | McNary1) | 32 | "6" | 8 | 3 | 2276 | 3.0 | 0 | 52 | 34 |
| 12 | Old Hickory | 13 | "6" | 15 | 7 | 1914 | 1.6 | 40 | 51 | 48 |
| | Woodruff | 9 | "6" | 3 | 2 | 997 | 2.0 | 3 | 49 | 25 |
| 13 | Calcasieu3) | 0 | 10 | 0 | 0 | 1851 | 2.5 | 11 | 71 | 30 |
| 14 | Algiers3) | 0 | 3 | 0 | 0 | 1736 | 2.4 | 65 | 64 | 43 |
| 15 | Inner Harbor3) | 0 | 10 | 0 | 0 | 1485 | 2.6 | 87 | 59 | 38 |
| 16 | Bonneville1) | 32 | 4 | 8 | 3 | 1728 | 3.0 | 34 | 58 | 89 |

## Table III-8 (Continued)

### Summary Input Data

| Lock Class | Lock Name | Coefficients of Reduction | | | | Averages for Present Conditions | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | % Seas. | % Down. | % Rec. P.S. | % Rec. An. | Tons Loaded Barges | Average Tow Size | % of Double Lockages | % of Loaded Barges | Service Time (min.) |
| 17 | Harvey3) | 0 | 6 | 0 | 0 | 1133 | 1.3 | 77 | 54 | 37 |
| | Melton Hill | 0 | "3" | 3 | 2 | 1083 | 1.5 | 0 | 29 | 29 |
| 18 | Vermilion3) | 0 | 10 | 0 | 0 | 1928 | 2.4 | 33 | 56 | 25 |
| 19 | L/D 4 (Mon.) | M 11 | 7 | 0 | 0 | 909 | 5.8 | 3 | 52 | 33 |
| | | A 11 | 33 | 9 | 4 | 897 | 1.9 | 3 | 48 | 27 |
| 20 | Bayou Sorrel3) | 0 | 10 | 0 | 0 | 1485 | 2.1 | 54 | 49 | 35 |
| 21 | Winfield2) | M 16 | 8 | 1 | 1 | 1288 | 4.6 | 91 | 59 | 117 |
| | | A 16 | 33 | 3 | 2 | 1137 | 4.1 | 82 | 46 | 69 |
| | L/D 1 (Miss.) | M 44 | "6" | 22 | 9 | 1271 | 1.8 | 3 | 50 | 34 |
| | | A - | - | - | - | - | - | - | - | - |

## Table III-8 (Continued)

### Summary Input Data

| Lock Class | Lock Name | Coefficients of Reduction |  |  |  | Averages for Present Conditions |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | % Seas. | % Down. | % Rec. |  | Tons Loaded Barges | Average Tow Size | % of Double Lockages | % of Loaded Barges | Service Time (min.) |
|  |  |  |  | P.S. | An. |  |  |  |  |  |
| 22 | L/D 7 (Mon.) | 7 | 7 | 4 | 2 | 909 | 4.7 | 76 | 51 | 26 |

1) Peak demand for commodity flows and recreation occurs simultaneously.
2) Multicut lockages with more than two cuts
3) The percent of multiple and setover lockages is included in the percent of double lockages.
4) Shown capacity expected to increase significantly when Tennessee-Tombiggee is operational
5) Data based on Volume II, GL/SLS Lock Capacity Analysis, Arctec, Incorporated (Practical Capacity = 75. million tons.
6) Peak seasonal
7) Annual.

The lockage delay parameter (k) is calculated by the LOKCAP model as a function of service times and the standard deviation of the service times at the lock. The parameter (k) increases when the service time increases or the standard deviation in service times increases. It can be noted that (k) is generally high at congested locks (L/D 26, L/D 22 (Mississippi River), Pickwick, Winfield, Gallipolis, Marseilles, etc.). This can be attributed to a shift towards a higher percentage of double lockages with high utilizatin, (i.e., both average service time and standard deviation between single and double lockage times increased). Peak tow lockage delay when peak commercial traffic corresponds to peak recreational traffic is given by the following formula (a):

$$D = kt/(kR \times kd \times Q - t) \qquad \text{(a)}$$

here,

k = lock delay parameter (same as above)
kR = reduction coefficient for peak recreational utilization
kd = reduction coefficient for downtime
t = peak seasonal traffic
Q = technical seasonal capacity

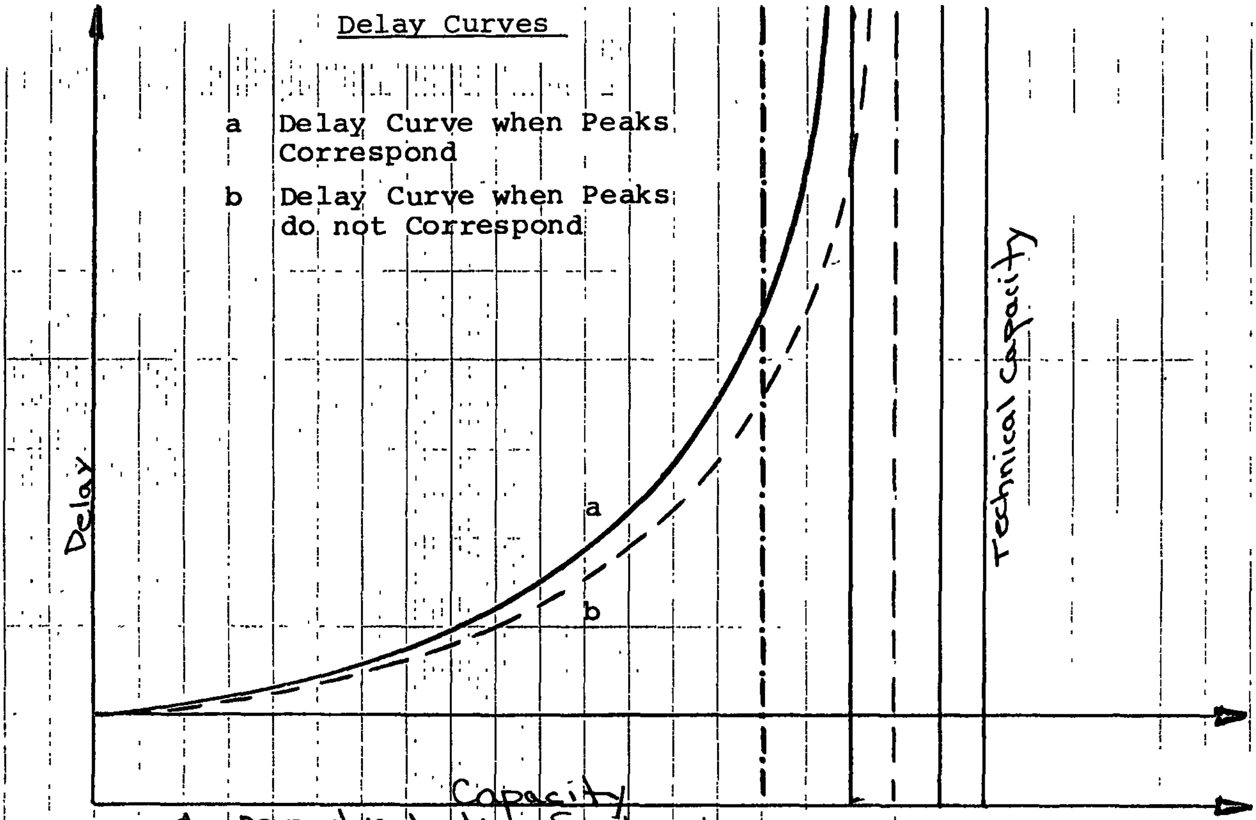
Lock delay parameter is unchanged since it is assumed that the curve is proportionally adjusted between given capacity tonnages and zero level traffic. This assumption is reasonable since technical capacity forms the asymptote of the tonnage delay curve and the curve must go through the point zero delay/zero capacity on the graph.

When commercial traffic does not correspond to peak recreational traffic, peak tow delay can be estimated using equation (a) with kr = reduction coefficient for annual recreation instead of peak recreation, as shown in formula (b).

$$D = kt/(kr \times kd \times Q - t) \qquad \text{(b)}$$

When equations (a) and (b) are used with annual traffic and capacity, tow delay time is the average annual delay time.

Figure III-G



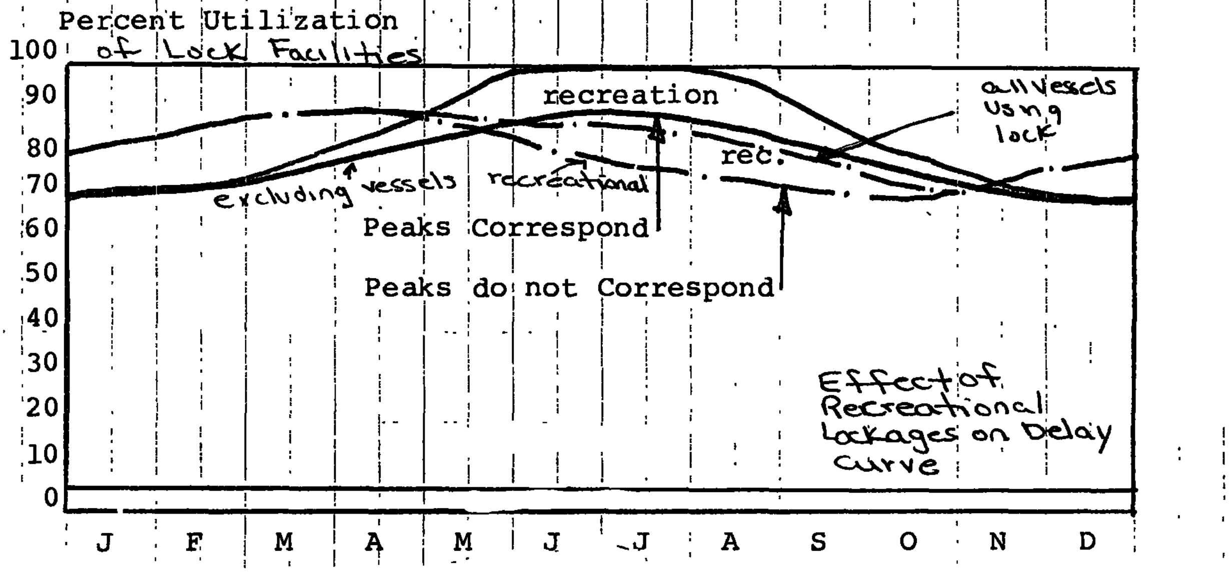
s R r d

d = percent reduction for downtime

r = percent reduction for recreation when the peak recreation season does not correspond to the peak traffic season

R = percent reduction for recreation when the peak recreation season corresponds to the peak traffic season

s = percent reduction for seasonality



When traffic reaches technical capacity after adjustment for downtime, recreation and seasonality, the annual delay would still be finite. However, delay would become infinite at the peak period. The graphical representation of delay curves is presented in Figure III-G.

All values required to use the above equations for representative locks are provided in this task. Lock delay parameters are provided in Table III-9 and the reduction coefficients can be found in Table III-8. Calculated delay is also reported in Table III-9 for each representative lock.

### (c) Existing Bottlenecks

According to the estimates of practical capacity for 1976, the following representative locks (most utilized in the segment) appear to have reached 60% or more utilization of practical capacity under present lock operating conditions: L/D 26 (Mississippi River), Inner Harbor Lock, Vermilion Lock, Calcasieu Lock, Algiers Lock, Gallipolis L/D, Marseilles L/D, L/D 22 (Mississippi River), Bonneville L/D, Winfield L/D and Kentucky L/D. Inner Harbor, with 1976 delays of 11.5 hours, is operating above practical capacity (i.e., capacity correspondent to a delay of approximately five hours). For L/D 26, practical capacity shown includes switchboat operation at the locks. Presently, practical capacity at this lock has been further extended up to 64 million tons by extensive use of operations policy measures such as 4 up/4 down lockages.

Table III-10 presents the 1976 tonnage, capacity, delay from the NWS Inventory and from delay calculated according to queuing theory for each one of these locks. Inventory delay and calculated delay are very close considering that these locks are approaching capacity and that small variations in traffic and capacity generate wide variations in delay (vertical portion of the delay/traffic curve).

## Table III-9

## Lock Delay Paramters

| Lock Class | Lock Name | Delay Parameter (Min./Tow) Main | Aux. | Main & Aux. | Calculated Delay for 1976 Traffic (hrs.) |
|---|---|---|---|---|---|
| 1 | McAlpine | 25.3 | 39.3 | 27.2 | 39 |
| | Uniontown | 23.7 | 22.7 | 23.6 | 22 |
| | L/D 52 (Ohio) | 37.3 | 26.2 | 33.5 | Open Pass |
| | L/D 27 (Miss.) | 23.0 | 37.0 | 28.1 | 27 |
| 2 | L/D 19 (Miss.) | 29.8 | - | 29.8 | 25 |
| | T. O'Brien | 10.8 | - | 10.8 | 3 |
| 3 | Barkley | 49.4 | - | 49.4 | 8 |
| 4 | L/D 2 (Mon.) | 20.7 | 11.4 | 18.6 | 12 |
| 5 | L/D 26 (Miss.) | 52.8 | 39.3 | 49.0 | 474 |
| | L/D 15 (Miss.) | 41.6 | 15.0 | 36.2 | 20 |
| | Gallipolis | 43.6 | 29.4 | 39.6 | 125 |
| 6 | Emsworth | 28.7 | 21.2 | 27.1 | 38 |
| 7 | Marseilles | 44.6 | - | 44.6 | 387 |
| | L/D 22 (Miss.) | 56.0 | - | 56.0 | 175 |
| | Kentucky | 48.7 | - | 48.7 | 85 |
| | Pickwick | 56.8 | - | 56.8 | 149 |
| | Demopolis | 21.9 | - | 21.9 | 10 |
| | Bankhead | 23.0 | - | 23.0 | 10 |
| | L/D 53 (Ohio) | 49.0 | - | 49.0 | Open Pass |
| 8 | W. B. Oliver | 27.7 | - | 27.7 | 18 |
| 9 | Port Allen | 27.7 | - | 27.7 | 46 |
| 10 | Maxwell | 29.9 | 6.8 | 13.2 | 6 |

## Table III-9 (Continued)

## Lock Delay Paramters

| Lock Class | Lock Name | Delay Parameter (Min./Tow) Main | Aux. | Main & Aux. | Calculated Delay for 1976 Traffic (hrs.) |
|---|---|---|---|---|---|
| 11 | L/D 1 (Green) | 11.2 | - | 11.2 | 3 |
| | Morgantown | 13.9 | - | 13.9 | 1 |
| | McNary | 14.5 | - | 14.5 | 3 |
| 12 | Old Hickory | 29.0 | - | 29.0 | 0 |
| | Woodruff | 13.4 | - | 13.4 | 1 |
| 13 | Calcasieu | 12.1 | - | 12.1 | 68 |
| 14 | Algiers | 20.6 | - | 20.6 | 103 |
| 15 | Inner Harbor | 25.9 | - | 25.9 | 725 |
| 16 | Bonneville | 36.2 | - | 36.2 | 54 |
| 17 | Harvey | 27.1 | - | 27.1 | 27 |
| | Melton Hill | 14.0 | - | 14.0 | 0 |
| 18 | Vermilion | 16.6 | - | 16.6 | 100 |
| 19 | L/D 4 (Mon.) | 16.9 | 16.9 | 17.0 | 13 |
| 20 | Bayou Sorrel | 22.6 | - | 22.6 | 113 |
| 21 | Winfield | 66.3 | 37.4 | 51.2 | 83 |
| | L/D 1 (Miss.) | 18.3 | 18.3 | 18.4 | 5 |
| 22 | L/D 7 (Mon.) | 28.2 | - | 28.2 | 32 |

### (d) Comparison of National Waterways Study Capacity Estimates to Existing United States Corps of Engineers Estimates

In almost all cases, National Waterways Study estimates of capacity do not differ by more than 15% from existing Corps estimates. Special care was taken to compare capacity values based on similar assumptions.

Since the Corps of Engineers capacity estimates account for downtime and recreation, they are compared, in Table III-11 to National Waterways Study technical capacities, as presented in Table III-2 after adjustments for downtime and recreation. Coefficients used for adjustment are provided in Table III-8. The table also indicates the references used for the Corps capacity estimates.

Explanations for the observed differences are summarized below:

## Table III - 10

### Most Constraining Representative Locks

| Lock Name | 1976 Tonnage ($10^6$T) | 1976 Practical Capacity* ($10^6$T) | 1976 Delay** (Min.) | Calculated Delay |
|---|---|---|---|---|
| L/D 26 (Miss.) | 58 | 58 | 510 | 474 |
| Inner Harbor | 28 | 26 | 692 | 725 |
| Vermilion | 42 | 44 | 246 | 348 |
| Calcasieu | 45 | 48 | 110 | 68 |
| Algiers | 25 | 27 | 96 | 103 |
| Gallipolis | 41 | 49 | 178*** | 125 |
| Marseilles | 26 | 26 | 169 | 387 |
| L/D 22 (Miss.) | 25 | 29 | 105 | 175 |
| Bonneville | 6 | 9 | 55 | 54 |
| Winfield | 13 | 20 | 59 | 83 |
| Kentucky | 21 | 30 | 194 | 85 |

NOTE: *Ninety percent of Technical Capacity, adusted for seasonality downtime and recreation.
**From United States Army Corps Inventory Report on locks.
***Not available in Inventory; taken from report "Capacity Studies of Gallipolis Locks," 1978.

At L/D 26 on the Mississippi River, National Waterways Study capacity, adjusted for a 4-up/4-down policy and accounting for the partial elimination of the extra time (make-up time) for double lockages, is within 5% of the Corps of Engineers estimate.

Capacity estimates for Gallipolis compare well with Corps estimates when the latter is adjusted for differences between tonnages reported by the towing industry to the Waterborne Commerce Statistics Center, and tonnages recorded in PMS records. The adjusted factor is provided in the Corps of Engineer report "Capacity Studies of Gallipolis Locks, Ohio River," May 1978.

National Waterways Study estimate of capacity for locks on the Monongahela River are slightly higher than the Corps estimates. A possible explanation is that the Corps estimate was derived using one month of data

## Table III-11

## Comparison of Existing Corps of Engineers Estimates to National Waterways Study Technical Capacities

| Lock Class | Lock Name | Technical Cap. Net of Down & Rec. |  | Corps Estimates |  | References | Percent Differences[4] |
|---|---|---|---|---|---|---|---|
|  |  | Main | Aux. | Main | Aux. |  |  |
| 1 | McAlpine | 73 | 10 | 83 | 16 | a | (16) |
|  | L/D 52 (Ohio) | 58 1) | 29 1) | 65 | 39 | b | Open Pass |
|  | L/D 27 (Miss.) | 90 | 50 | 148 |  | d | ( 5) |
| 3 | Barkley | 47 | -- | 42 | -- | a | (12) |
| 5 | L/D 26 (Miss.) 2) | 52 | 19 | 73 |  | d | ( 4) |
|  | Gallipolis | 47 | 11 | 45 | 11 | 6 | 4 |
| 6 | Emsworth | 39 | 7 | 34 | 5 | a | 18 |
| 7 | Marseilles | 34 | -- | 32 | -- | 11 | 6 |
|  | L/D 22 (Miss.) | 43 | -- | 41 | -- | 11 | 4 |
|  | Kentucky | 37 | -- | 31 | -- | a | 19 |
|  | Pickwick 3) | 32 | -- | 31 | -- | e | 3 |
|  | Demopolis 3) | 39 | -- | 44 | -- | e | (11) |
|  | Bankhead 3) | 38 | -- | 40 | -- | e | ( 5) |
|  | L/D 53 (Ohio) | 44 1) | -- | 117 | -- | b | Open Pass |
| 8 | W. B. Oliver 3) | 33 | -- | 35 | -- |  | ( 6) |

## Table III-11 (Continued)

## Comparison of Existing Corps of Engineers Estimates to National Waterways Study Technical Capacities

| Lock Class | Lock Name | Technical Cap. Net of Down & Rec. | | Corps Estimates | | References | Percent Differences[4] |
|---|---|---|---|---|---|---|---|
| | | Main | Aux. | Main | Aux. | | |
| 9 | Port Allen | 32 | -- | 30 | -- | d | 8 |
| 11 | L/D 1 (Green) | 66 | -- | 59 | -- | a | 12 |
| | Morgantown | 31 | -- | 25 | -- | c | 24 |
| 13 | Calcasieu | 59 | -- | 66 | -- | d | (10) |
| 14 | Algiers | 30 | -- | 30 | -- | d | 0 |
| 15 | Inner Harbor | 29 | -- | 30 | -- | d | ( 4) |
| 16 | Bonneville | 15 | -- | 13 | -- | 20 | 15 |
| 17 | Harvey | 10 | -- | 10 | -- | d | 0 |
| 18 | Vermilion | 49 | -- | 50 | -- | d | ( 3) |
| 19 | L/D 4 (Mon.) | 40 | 8 | 36 | 10 | a | 4 |

## Table III-11 (Continued)

## Comparison of Existing Corps of Engineers Estimates to National Waterways Study Technical Capacities

| Lock Class | Lock Name | Technical Cap. Net of Down & Rec. | | Corps Estimates | | References | Percent Differences[4] |
|---|---|---|---|---|---|---|---|
| | | Main | Aux. | Main | Aux. | | |
| 20 | Bayou Sorrel | 24 | -- | 25 | -- | d | ( 4) |
| 21 | Winfield | 15 | 10 | 13 | 9 | 19 | 14 |
| 22 | L/D 7 (Mon.) | 19 | -- | 16 | -- | a | 22 |

NOTE:
1) Capacity after adjustment for downtime and recreation assuming no open pass.
2) Capacity estimates at L/D 26 includes seasonality factor.
3) Shown capacity expected to increase significantly when Tennessee-Tombigbee Waterway is operational.
4) References are either numerical and refer to footnotes at the end of the report, or alphabetical (a through e), and refer to the following sources:
   a. Ohio River Basin Lock Capacity Analysis, November 1978.
   b. Lower Ohio River Navigation Study, May 1979.
   c. Grays Landing Lock and Dam Point Marion Lock, Monongahela River, GDM, September 1975.
   d. Lock Capacity Data Memorandum for the National Waterways Study by LMVD, July 1979.
   e. Minutes from National Waterways Meeting in Mobile, SAD, August 1979.

(September 1976) versus one year of data for the National Waterways Study (1976).

The Corps estimate of capacity at Winfield L/D was taken from the report "Capacity Studies of Winfield Locks, Kanawha River," 1977. The estimation provided there (22 million tons), do not match the estimate of 13 million tons provided in the Corps documentation, "Ohio River Basin, Lock Capacity Analysis," 1978. The Huntington District confirmed that the latter estimate should be discarded. Therefore, the National Waterways Study technical capacity of 25 million tons is only slightly higher than the retained Corps estimate of 22 million tons.

For locks where significant changes of commodity pattern and fleet configuration are expected, differences in capacity evaluation are explained in the following section as capacity adjustments.

### (e) Preliminary Adjustments of Capacity for Future Conditions

The NWS estimates based on present conditions, in general, are likely to be lower than for future conditions when traffic and, therefore, tow sizes will increase. As mentioned above, adjustments for future conditions will be made in later sections. However, there are two situations where the impact of future conditions is most obvious. That is the case of the 1200' x 110' + 600' x 110' locks on the Ohio River and the locks where traffic patterns will be completely changed when the new Tennessee-Tombigbee Waterway opens.

Practical capacities calculated for McAlpine and Uniontown Locks on the Ohio River are underestimated because of the present low utilization of their auxiliary chambers. Capacity at year 2000 is expected to be substantially higher. An approximate estimate will show the order of magnitude of capacity at year 2000 demand levels as forecasted year 2000 data are presently unavailable.

One way to adjust these capacities is to start from L/D 27 capacity (L/D 27 has a higher auxiliary chamber utilization) and to adjust it using the service times and coefficients of regression for downtime and recreation of the Ohio River locks. Adjusted for seasonality, downtime and recreation, the preliminary estimate of practical capacity for 1200' x 110' + 600' x 110' locks on the Ohio River is 104 million tons. This capacity value is used in later sections to determine necessary capacity expansion measures to satisfy future demand. As mentioned above, this estimate will be further refined to account for forecasted tow sizes, average load for barge, and percent of loaded barges according to NWS Scenarios.

Practical capacities provided for the locks on the Tennessee, Black Warrior and Tombigbee Rivers are presented in Tables III-7, under present conditions (1976) in order to be consistent with the rest of the network. However, capacities are likely to increase at these locks when the Tennessee-Tombigbee Waterway opens. Mean tow sizes are expected to increase substantially at these locks and the variances are expected to decrease to account for a homogenization of the fleet. Therefore, sensitivity analysis will be used to provide estimates of future capacity for Bay Springs and Demopolis, as well as for all other affected locks. The largest increase of capacity is expected to occur at Demopolis L/D because of the presently small average tow size (3.5). This tow size is expected to increase to 4.5 (conservative estimate) in the future. The practical capacity at this tow size (45 million tons) is nearly equal to the existing Corps estimate.

The capacities of Bankhead and W. B. Oliver Locks will also increase for the same reason, but to a lesser degree. Pickwick and Kentucky lock capacities are also expected to increase not because of an increase in tow size (already 7.7 and 6.9 at Pickwick and Kentucky, respectively), but because of a homogenization of the fleet. A 1000' x 110' lock is under construction at Pickwick Lock and will provide an even larger capacity to accommodate traffic from the Tennessee River and Tennessee-Tombigbee Waterway. When demand values become available, Kentucky Lock will probably emerge as the most constraining lock on the Tennessee River.

The maximum tow size that will be accommodated on the divide section of the Tennessee-Tombigbee Waterway is eight jumbo barges. A tow size of eight would not require any double lockage for a 600' x 110' lock. Therefore, assuming an average tow size of six (conservative estimate) for the waterway to account for fleet diversity, and assuming 0% double lockages (reference SAMPD-S memo dated November 15, 1979), technical capacity for Bay Springs Lock is 79 million tons. After deduction of 5% for seasonality, 6% for downtime and 1% for recreation (as for Pickwick L/D), technical capacity is 70 million tons and practical capacity (traffic at an average of five hours of delay per tow and approximately 90% of practical capacity) is 63 million tons. The NWS assessment is 14% higher than the Corps estimate of 55 million tons provided for Bay Springs Lock, considered representative on this portion of the Tennessee-Tombigbee Waterway.

## SENSITIVITY ANALYSIS OF LOCK CAPACITY AND DELAY

This section provides a sensitivity analysis for lock capacity and delay evaluation under various lock conditions as a result of potential changes in commodity pattern, of modifications in the waterway system and of changes as a result of structural and non-structural measures to increase lock capacity for the existing lock system.

Lock capacity is evaluated as a function of major operational variables, such as tow configuration, chamber size, mix of single and double lockages, empty backhaul, recreational traffic and downtime, time necessary to perform different phases of the lockage process, and operating policy. The results of the sensitivity analysis, thus obtained, provide a basis for rapidly revising lock capacity estimates, given the estimated capacity under present conditions as determined in the previous section, and anticipated changes in lock operation and traffic characteristics. This, in turn, permits comparisons between forecasted commodity flows and capacity, adjusted for corresponding future lockage conditions.

Although the capacity estimates presented are based on the LOKCAP model evaluation of capacity for representative locks, the approach presented eliminates the necessity of additional computer runs. The nomographs and equations developed for the NWS lock capacity sensitivity analysis also provide an efficient and quick way to evaluate lock capacity for any given set of assumptions. For the sake of brevity, only one complete set of nomographs is presented herein. This is included in order to illustrate the usage. Nomographs for all of the representative locks considered in the 22 lock classes have been prepared and will be used for subsequent analyses.

Table III-8, in the previous section, provided data for the base conditions upon which the sensitivity analysis is conducted. These data, including service time and capacity, are provided for 39 carefully selected representative locks divided into 22 lock size classes.

The approach taken is to consider the basic equations relating lock service time and capacity to more fundamental variables. The effects of variations in these fundamental inputs are then studied systematically. The results are presented first in mathematical form and then graphically, both for ease of application and to illustrate the sensitivity of the relationships derived. The intent of this presentation is to document the analysis, rather than to provide detailed user instructions. However, the knowledgeable analyst will be able to apply this material to practical problems with little additional instruction.

The impacts of average tow size and percent of double lockages on capacity and service time were immediately identified as the most complex to investigate since these two variables are directly related. Therefore, special care was taken to identify, precisely, the empirical relationship between these two variables.

The impact of the other variables were easier to analyze. For instance, capacity is directly proportional to the percent of loaded barges. Reduction coefficients for downtime and recreation are also simple to derive and apply. The impact of all variations in the timing of phases of the lockage process can be obtained rapidly by computing the variation in service time (and therefore capacity) due to specific time savings due to improvements.

The impact of lock operating policy on service time, and therefore capacity is also presented. The graphical results enable rapid identification of the locks for which an N-up/N-down policy has the potential of increasing capacity.

Finally, sensitivity to the percent of multiple-vessel lockages is also provided for application to locks with long chambers and small average tow size. Port Allen Lock is taken as being typical of this case, where an increase in the percent of multiple-vessel lockages would substantially increase capacity.

Note that for dual locks the capacity and sensitivity analyses were conducted separately for individual chambers. To obtain results for the lock facility as a whole, it is necessary to analyze each chamber separately under appropriate tow size assumptions and then manually combine the results, allowing for the effects of tow interference in the lock approach areas. The exact assumptions and procedures used will be explained as specific cases arise.

Detailed explanations of each element of the sensitivity analysis are provided in the following section.

### (a) Definition of Variables

To aid the reader with the mathematical formulations to follow, a list of variables is presented below.

Major Input Variables

$T$ = average service time (minutes)
$N$ = number of minutes per year = 365 x 24 x 60

$s$ = average tow size (number of barges per tow)
$L$ = average tonnage per loaded barge (tons)

$k_1 = 1 - \alpha_1$, with $\alpha_1$ = frequency of empty barges
$k_2 = 1 - \alpha_2$, with $\alpha_2$ = frequency of downtime
$k_3 = {}_1 - \alpha_3$, with $\alpha_3$ = seasonality factor
$k_4 = {}_4 - \alpha_4$, with $\alpha_4$ = percentage of time used for recreational lockages

### Timings (min.)

$A_{f,t}$ = (fly/exchange, turnback) approach time
$X_{f,t}$ = (fly/exchange, turnback) exit time
$E$ = entry time
$F$ = chambering time
$S$ = extra time for setover lockages
$D$ = extra time for double lockages
$T_{f,t}$ = service time for straight single (with F/E approach and exit, turnback approach and exit
$T_n$ = service time for N-up/N-down policy
$H = A_f + X_f - A_t - X_t - F$
$M$ = make-up time = $kD$, with $k$, a constant

### Capacities (tons)

$C_t$ is "technical capacity," before adjustments for downtime, recreation and seasonality, as it appears in the computer output. $C_t$ is calculated for present conditions ($N_{pc}$, $L_{pc}$, $s_{pc}$, $k_{1pc}$).

### Lockage Type Frequency

$P_d$ = frequency of double lockages
$P_m$ = frequency of multivessel lockages
$P_s$ = frequency of setover lockages

### Remarks

$\Delta$ - indicates variations

subscript pc - indicates present conditions

### (b) Sensitivity of Lock Capacity to Variations in Base Data

In the following sections, a mathematical analysis of the sensitivity of lock capacity to selected operational variables is presented first. This is followed by a graphical display of the results.

For the purposes of sensitivity analysis, no distinction will be made between upstream and downstream lockages. Therefore, the capacity formulas used will only include as variables averages of the upstream and downstream data.

The capacity and service time equations (for one-up/one-down policy and no multiple-vessel lockages) are as follows:

$$T = A_f + E + F + X_f + P_d\ (A_t + E + X_t + 2F + D) + P_s S \qquad (1)$$

$$C = (1/T)\ N \times L \times s \times \prod_{i=1}^{4} ki \qquad (2)$$

C = yearly capacity (tons)
T = average service time (minutes)

or,

$$C = C_t \times k_2 \times k_3 \times k_4 \qquad (3)$$

and,

$$C_t = (1/T)\ N \times L \times s \times k_1 \qquad (4)$$

Sensitivity analysis was performed for all variables necessary to estimate capacity. The following sections present the sensitivity of lock capacity to changes in average tow size (and percent of double lockages), chamber size, percentage of empty barges, downtime, recreational lockages, seasonality, lockage time elements, operating policy, and percent of multiple-vessel lockages.

1. *Determination of Revised Capacity Estimates Using Present Capacity as a Base.* Assuming changed lockage conditions, a revised capacity estimate may be computed from the present capacity as follows:

$$C = C_{tpc} \times \frac{L}{L_{pc}} \times \frac{s}{s_{pc}} \times \frac{k_1}{k_{1_{pc}}} \times \prod_{i=2}^{4} ki/(1 + \frac{\Delta T}{T_{pc}}) \qquad (5)$$

with,

$$\Delta T = \Delta A_f + \Delta F\,(1 + 2P_{dpc}) + \Delta DP_{dpc} + \Delta P_d\,((A_t + E + X_t + 2F + D)_{pc} + \Delta D + 2\,\Delta F) \qquad (6)$$

These equations are complete. Their use is substantially simplified if one attempts to calculate the effects of only a few input variables on capacity.

The most difficult case occurs when average tow size increases, since this variable is related to the prevalence of double lockages. For convenience, the effect of consistent changes in average tow size and frequency of double lockages on technical capacity may be expressed as follows:

$$C_t^{'} = C_{tpc} \times \frac{s}{s_{pc}} \times \frac{T_{pc}}{T'} \qquad (7)$$

A separate analysis, described later, provides $C_t^{'}$ and T'. The effect of modification of any other variable can then be computed with respect to $C_t^{'}$ and T' rather than the initial $C_t$ and T, as follows:

$$C = C_t^{'} \times \frac{L}{L_{pc}} \times \frac{k_1}{k_{1_{pc}}} \times \prod_{i=1}^{4} ki/(1 + \Delta T/T') \qquad (8)$$

with,

$\Delta T = \Delta A_f + \Delta F \ (1 + 2P_d) + \Delta D \times P_d$, because $\Delta P_d =$ 0 between (s, C', T') and (s, C, T).

The advantage of using a previously calculated capacity is substantial when only one or two determining variables are investigated. If all variables change, it is advisable to recalculate capacity altogether by using equation (1) and (2).

Table III-12 verifies this approach by demonstrating that equations (1) and (2) provide the same results (within one or two percent) as the NWS computer model, even though the formulas neglect upstream and downstream differences.

2. Capacity as a Function of Chamber Size. Technical capacities of all locks selected for evaluation by the LOKCAP model were plotted on a capacity versus chamber size chart (see Figure III-H). Least squares regression analysis (coefficient of regression = 0.96) provided the following equation:

$$\text{Cap} = -6.4 + 0.76\ A$$

where,

Cap = technical capacity
A = chamber area

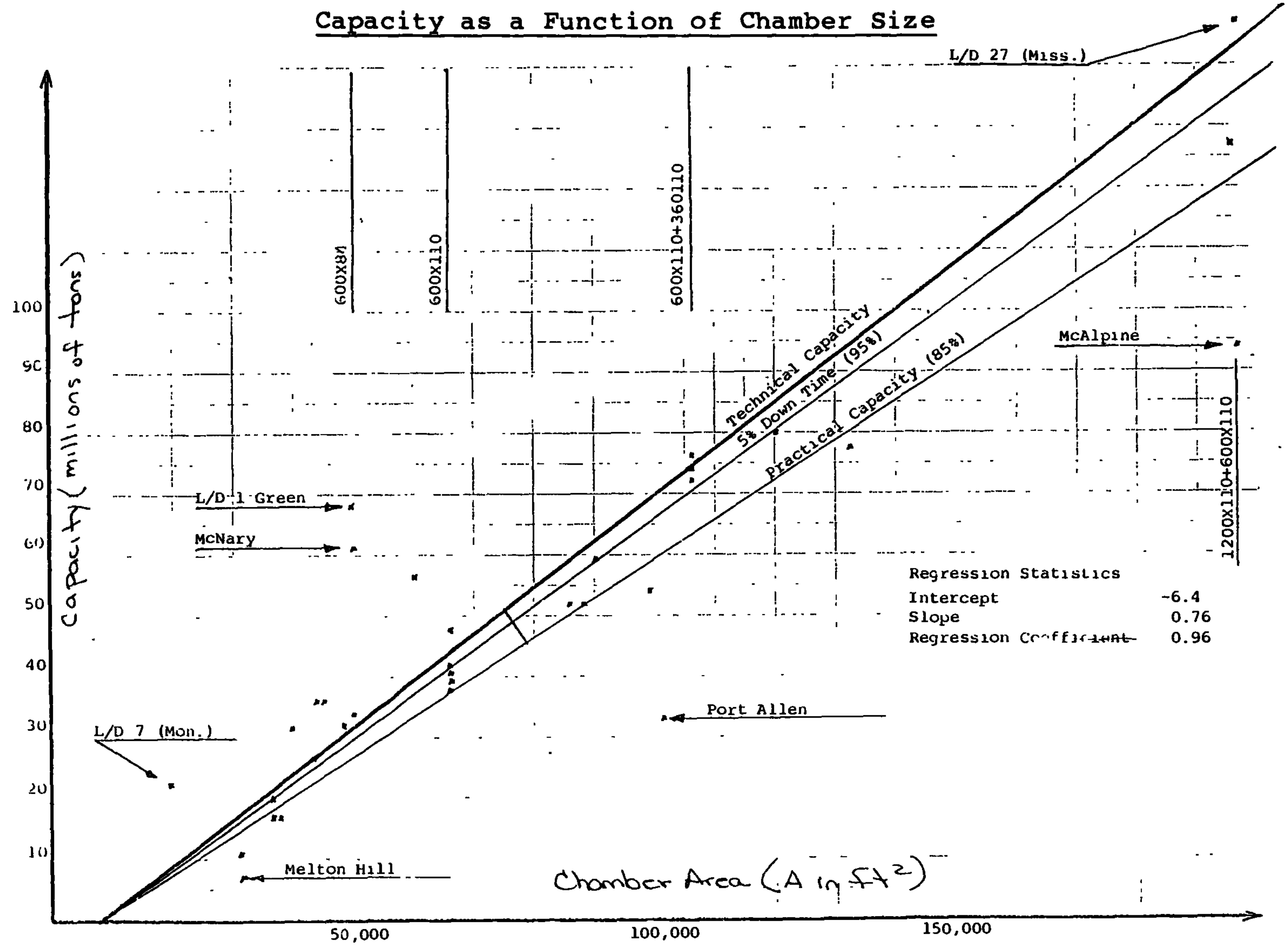
Data for most locks plot very close to the regression line.

The chart suggests that there is a definite linear relationship between capacity and chamber area, regardless of site specific assumptions and input data. This chart also justifies the grouping of locks into size classes for sensitivity analysis of capacity.

Deviation from the regression line can be logically explained. For instance, higher than average capacity at L/D 1 on the Green River is due to its short service time (22 minutes) and to the perfect match between chamber size and predominant tow size. On the contrary, the relatively low capacity of Port Allen Lock in the GIWW can be explained by the fact that tow size configuration

# Figure III-H

## Capacity as a Function of Chamber Size



## Table III -12

### Comparison of NWS Capacity Evaluation and Estimations by Using Simplified Capacity Formula

| Lock Name | Processing Time at Capacity Minutes | | Capacity ($10^6$T) | |
|---|---|---|---|---|
| | NWS Run | Formula | NWS Run | Formula |
| L/D 19 | 59.6 | 59.5 | 78.3 | 78.2 |
| L/D 26 (Main) | 98.7 | 98.5 | 52.7 | 52.4 |
| Gallipolis (Main) | 77.0 | 76.9 | 52.5 | 51.9 |
| Demopolis | 43.6 | 43.6 | 42.3 | 41.5 |

and chamber dimensions are poorly matched. Low capacity of McAlpine L/D on the Ohio River is due to the present underutilization of the auxiliary chamber. Obviously, as soon as the utilization of this lock increases, larger tows will lock through the auxiliary chamber and the calculated capacity will increase substantially.

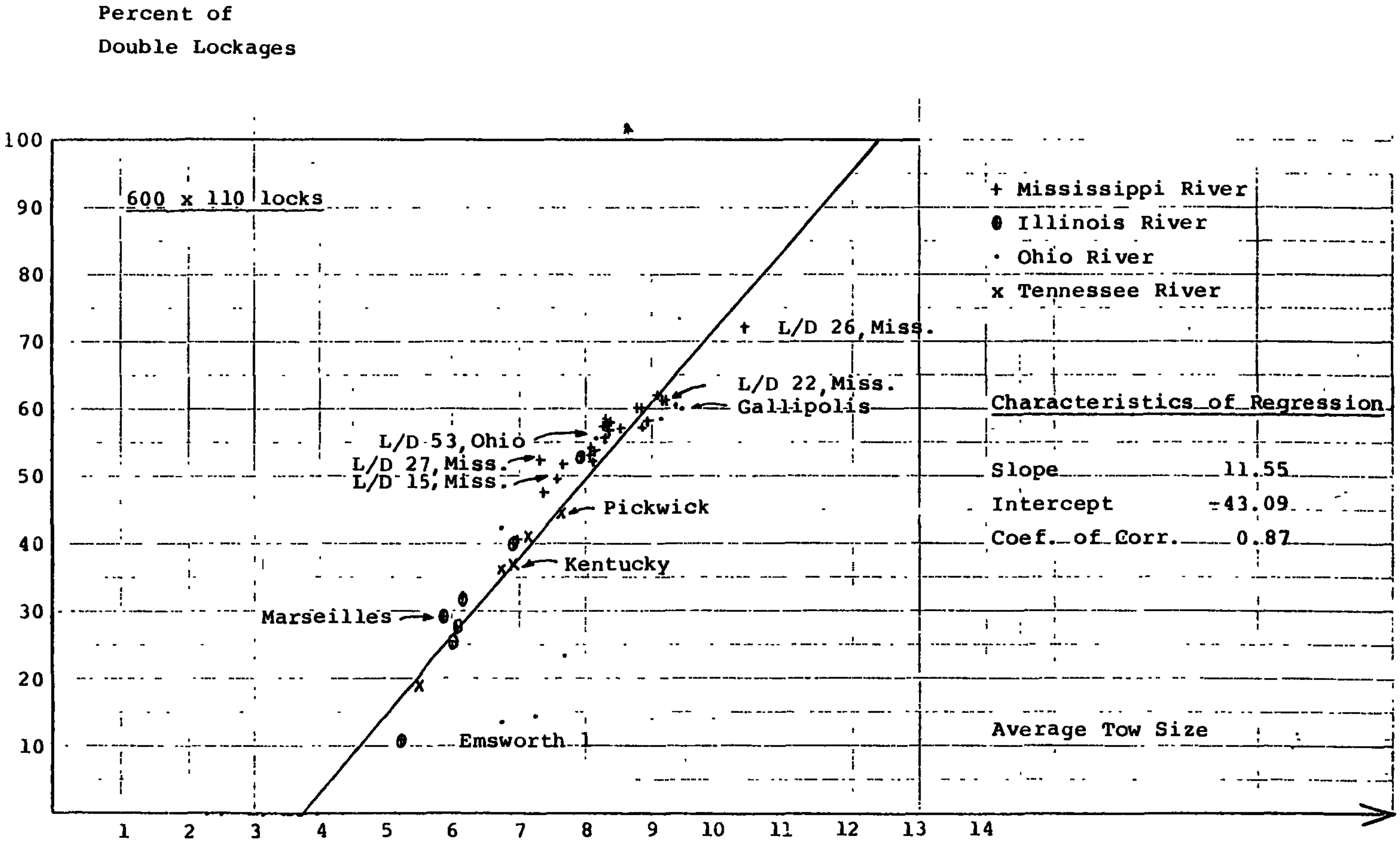
3. Relationship between Average Tow Size and Type of Lockage. Empirical data gathered for every lock suggest the existence of a direct relationship between percent of double lockages ($P_d$) and average tow size(s). This relationship permits the elimination of one determining variable, percent of double lockages, since this variable can be expressed as a function of average tow size.

Detailed analysis was performed for 600' x 110' and 360' x 56' locks because of the large number of data points available.

Figure III-I, based on PMS data, relates the percent of double lockages to average tow size for each 600' x 110' lock. A single well-defined and statistically significant relationship appears for locks on the Mississippi River, the Illinois Waterway, the Ohio River, and the Tennessee River. This indicates that tow size distribution is similar on these waterways. For a given average tow size, if the tow size distribution were to become more tightly clustered about the mean (i.e., if the variance in tow size becomes smaller), the percent of double lockages would be reduced. However, for this fixed average tow size, capacity would be increased. The high capacity estimate is explained by these facts, i.e., there would

## Figure III-I

## Percent of Double Lockages as a Function of Average Tow Size for 600x110 Locks



not be any double lockages there (tow size limited to eight), but average tow size would still be as high as six barges per tow.

Three exceptions to the general relationship are - Emsworth L/D, Dashields L/D, and Montgomery L/D. The fleet composition and tow size distribution at these locks are influenced by those on the Allegheny and Monongahela Rivers. This reemphasizes the need to adjust the relationship between percent of double lockages and average tow size for specific tow size distributions.

Figure III-J provides the results for 360' x 56' locks. Again, all locks on the Kanawha River, the Monongahela River, the Allegheny River, the Ohio River and the Mississippi River follow a single well-defined linear relationship.

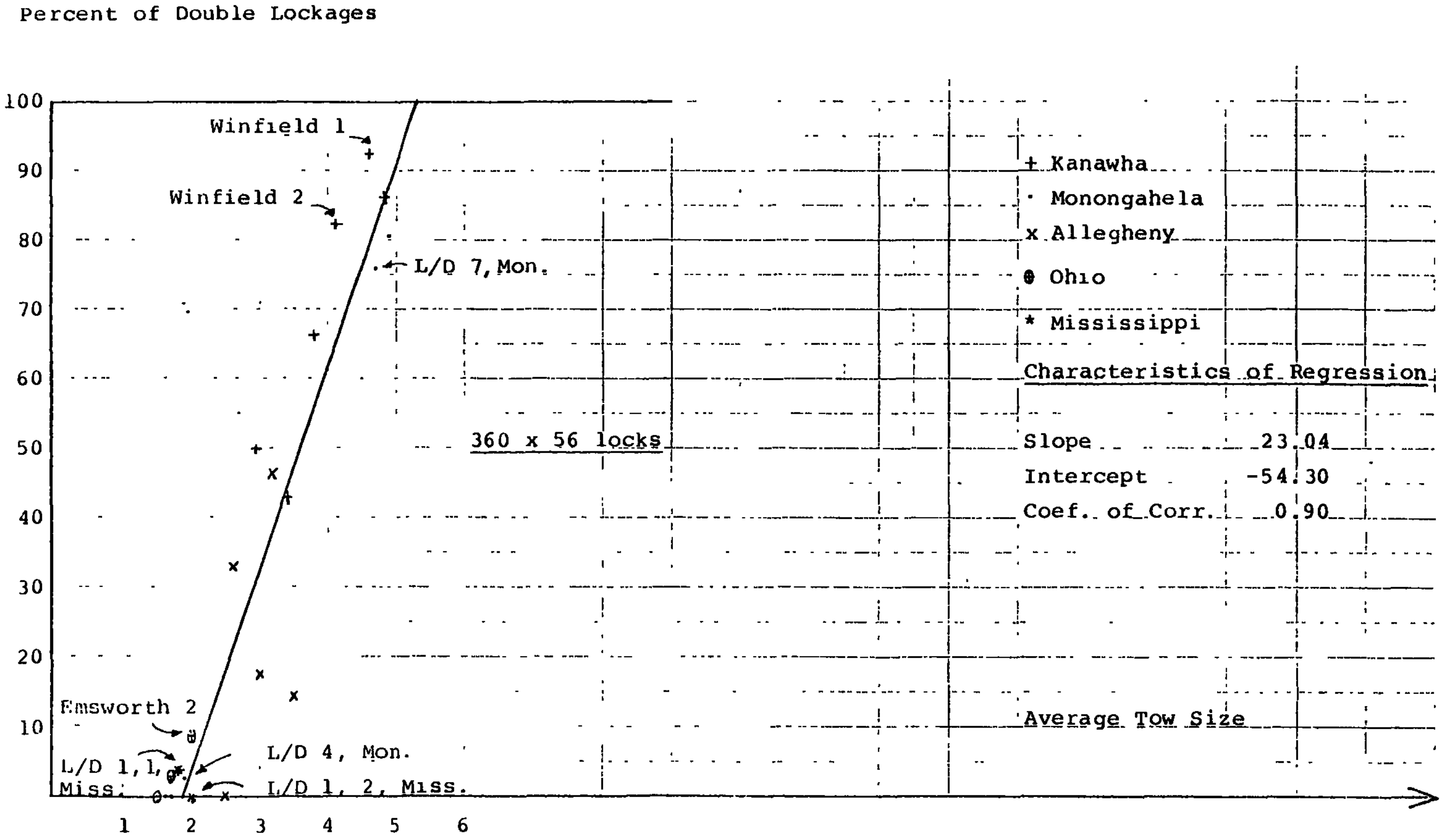
The correlation coefficients are very high for both curves and confirm once again the reliability of the PMS data. The strong correlations suggest that the relationships developed can be successfully applied for future conditions unless drastic changes are likely to occur (i.e., new Tennessee-Tombigbee Waterway).

Fewer points were available for other lock sizes. The outcome of all research is presented in Figure III-K. This figure contains the "percent of double lockages/average tow size" relationships for locks of the following sizes: 360' x 56', 360' x 110', 600' x 84', 600' x 110', 720' x 110' and 800' x 110'. For 1200' x 110' locks, there is no need to present a curve since double lockages are not allowed. One can observe that slope decreases as chamber size increases.

The linear relationships between percent of double lockages and tow size suggests that it is legitimate to fit a smooth curve through the capacities obtained for 0% double lockages and 100% doubles, and their corresponding average tow sizes, to estimate capacity at any intermediate tow size. The point representing existing conditions, for example, will lie on this curve, except when there are presently no double lockages. In this case, the capacity/tow size curve will pass through the point representing present conditions and the point representing the maximum average tow size for 0% double lockages.

## Figure III-J

## Percent of Double Lockages as a Function of Average Tow Size for 360x56 Locks



Based upon this analysis, additional NWS runs corresponding to 0% and 100% of double lockages were performed for one lock in each major class. The tow size corresponding to 0 and 100% double lockages were determined by passing a line through the point corresponding to present conditions (when there are presently double lockages), and parallel to the average line for locks of a similar size class (see Figure III-K). Table III-13 presents the average tow sizes that were utilized for these runs, along with the 1976 tow size and the slope of the regression line between percent of double lockages and average tow size.

The results of the runs corresponding to 0% double lockages and to 100% double lockages are shown in Table III-14. Respective tow sizes used were ($s_0$) and ($s_1$) (see Table III-13), defined as

$s_0$ = maximum average tow size for which no double lockages are required
$s_1$ = minimum average tow size for which all lockages are double

In most cases, three different values were obtained, one for capacity under present conditions, one at 0% double lockages and one at 100% double lockages.

Since,

$$Pd = 0 \text{ for } s < s_0$$
$$Pd = 1 \text{ for } s > s_1$$

and,

$$Pd = (s - s_0)/(s_1 - s_0) \text{ for } s_0 < s < s_1$$

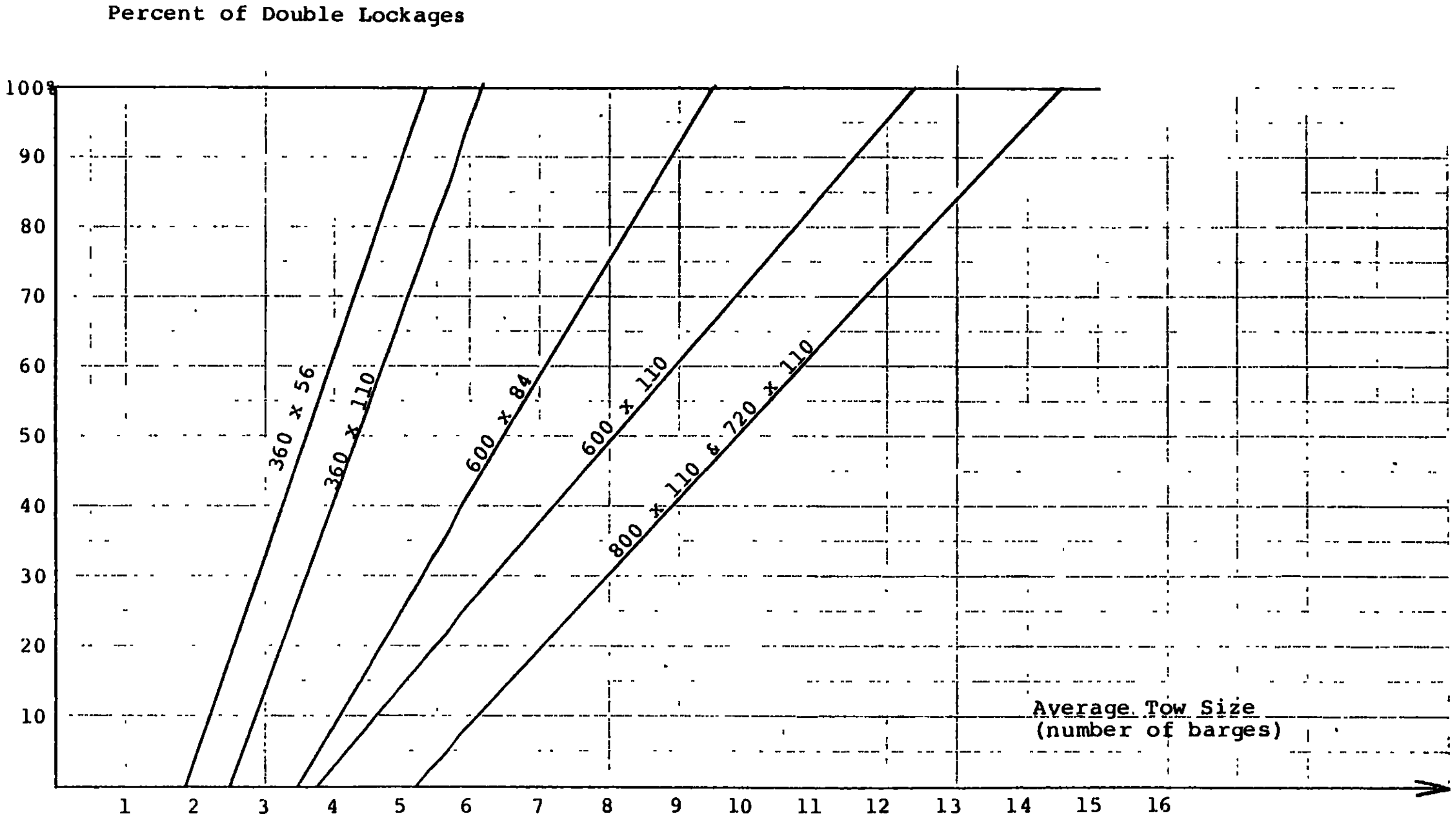
capacity becomes,

$$C = NLs \prod_{i=1}^{4} ki/(T_f + P_s S),\ s < s_0 \tag{9}$$

$$C = NLs \prod_{i=1}^{4} ki/(T_f + P_s S + \frac{s - s_0}{s_1 - s_0}(T_t + F + D = P_s S)) \qquad s_0 < s < s_1 \tag{10}$$

## Figure III-K

## Percent of Double Lockages as a Function of Average Tow Size for Various Chamber Dimensions



$$C = NLs \prod_{i=1}^{4} ki/(T_f + T_t + F + D), \; s = s_1 \qquad (11)$$

where, $T_{f,t}$ = service time for straight single (with F/E approach and exit, turnback approach and exit).

There is no need to investigate cases where $s \geq s_1$ since the lock would then have triple lockages. In actuality, there are very few locks for which the percent of double lockages reaches 80%. At Winfield Locks, both chambers experience multiple lockages over 80% of the time, and over 50% of the lockages are triple.

The theoretical relationships given above should not be used for tow sizes exceeding 11 barges for 600' x 110' locks, and exceeding 4.5 barges for 360' x 56' locks. If average tow size does get higher, service time would increase substantially and capacity no longer increases and eventually decreases. Very large increases in delay time would also occur, completely offsetting any marginal capacity increase.

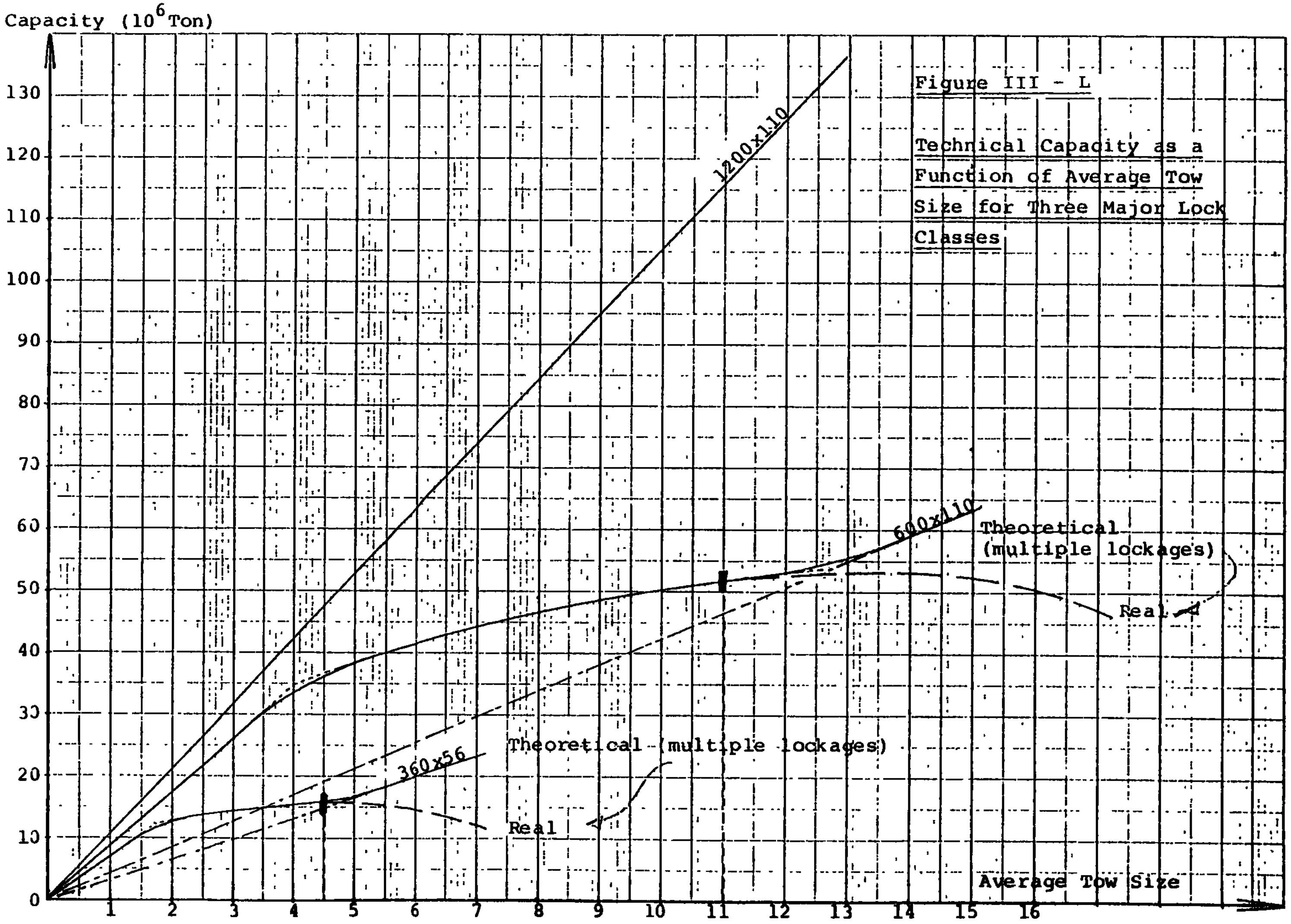
Moreover, in some instances, such as L/D 1 on the Green River and Maxwell and L/D 4 (Main) on the Monongahela River, the increase in service time with increasing double lockages decreases capacity sufficiently so as to negate the increase in capacity from the larger average tow size. In such cases, the peak capacity occurs when there are no double lockages. This phenomenon can possibly be explained by the fact that for these locks chamber configurations are not particularly suitable for double lockages.

The capacity/tow size relationships are, in general, very similar for locks that belong to the same class.

Figure III-L presents the capacity versus tow size curves derived by the methods outlined above for 1200' x 110', 600' x 110', and 360' x 56' locks. Similar relationships can be developed for other lock sizes as well. In accordance with equations (9) to (11), capacity increases linearly with tow size for $s < s_0$ (hence the single straight line for 1200' x 110' locks) and then follows a curve with decreasing slope up to s = s. The straight line passing through the origin and $s_1$ indicates theoretical capacity increases for further increases

# Figure III-L

## Technical Capacity as a Function of Average Tow Size for Three Major Lock Classes



## Table III-13
## Average Tow Size Utilized for Sensitivity Runs

| | | Main Chamber | | | | Auxiliary Chamber | | | |
|---|---|---|---|---|---|---|---|---|---|
| Class | Lock Name | Pres. Cond. | 0% Double | 100% Double | (Slope)[1] | Pres. Cond. | 0% Double | 100% Double | (Slope)[1] |
| 1 | McApine | 7.8 | - | - | - | 2.3 | 3.7 | 12.4 | 8.7 |
| 1 | L/D 27 (Miss.) | 7.8 | - | - | - | 7.3 | 2.8 | 11.5 | 8.7 |
| 2 | L/D 19 (Miss.) | 8.8 | - | - | - | - | - | - | - |
| 3 | Barkley | 10.7 | 5.1 | 14.4 | 9.3 | 1.6 | 1.9 | 5.3 | 3.4 |
| 4 | L/D 2 (Mon.) | 6.5 | 5.6 | 14.9 | 9.3 | - | - | - | - |
| 5 | L/D 26 (Miss.) | 10.4 | 4.1 | 12.8 | 8.7 | 3.5 | 2.0 | 5.5 | 3.5 |
| 5 | Gallipolis | 9.5 | 4.2 | 12.9 | 8.7 | 4.1 | 3.1 | 6.6 | 3.5 |
| 6 | Emsworth | 6.8 | 5.6 | 14.3 | 8.7 | 2.0 | 1.7 | 5.1 | 3.4 |
| 7 | Kentucky | 6.9 | 3.7 | 12.4 | 8.7 | - | - | - | - |
| 8 | W. B. Oliver | 3.4 | 2.6 | 7.1 | 4.5 | - | - | - | - |
| 10 | Maxwell | 6.0 | 6.5 | 15.0 | 8.5 | 4.7 | 6.5 | 15.0 | 8.5 |
| 11 | L/D 1 (Green) | 3.8 | 3.8 | 9.8 | 6.0 | - | - | - | - |
| 12 | Old Hickory | 1.6 | 1.0 | 3.0 | 2.0 | - | - | - | - |
| 19 | L/D 4 (Mon.) | 5.8 | 5.5 | 11.0 | 5.5 | 1.9 | 1.8 | 5.2 | 3.4 |
| 21 | Winfield | 4.6 | 1.4 | 4.8 | 3.4 | 4.1 | 1.3 | 4.7 | 3.4 |
| 22 | L/D 7 (Mon.) | 4.7 | 2.1 | 5.5 | 3.4 | 4.1 | 1.3 | 4.7 | 3.4 |

## Table III -14

## Capacity ($10^6$T) and Service time (min.) for Zero and One Hundred Percent of Double Lockages

| | | % of Double Lockages | | 100 % Double Lockages | |
|---|---|---|---|---|---|
| Lock Name | | Serv. T. | Cap. | Serv. T. | Cap. |
| McAlpine | M | 49 | 51 | "49" | "134" |
| | A | 62 | 23 | 145 | 33 |
| L/D 27 (Miss.) | M | 43 | 48 | "43" | "157" |
| | A | 35 | 38 | 87 | 64 |
| L/D 19 | | - | - | "60" | "116" |
| Barkley | | 46 | 46 | 118 | 52 |
| L/D 2 (Mon.) | M | 30 | 54 | 79 | 55 |
| | A | 19 | 18 | 55 | 18 |
| L/D 26 (Miss.) | M | 54 | 38 | 113 | 56 |
| | A | 44 | 20 | 101 | 23 |
| Gallipolis | M | 42 | 43 | 96 | 58 |
| | A | 38 | 21 | 83 | 21 |
| Emsworth | M | 41 | 41 | 96 | 45 |
| | A | 34 | 10 | 76 | 14 |
| Kentucky | | 51 | 33 | 110 | 51 |
| W.B. Oliver | | 42 | 58 | 99 | 39 |
| Maxwell | M | 40 | 58 | 99 | 55 |
| | A | 36 | 28 | 90 | 26 |
| L/D 1 (Green) | | 22 | 68 | 62 | 62 |
| Old Hickory | | 32 | 15 | 73 | 20 |
| L/D 4 (Mon.) | M | 32 | 44 | 74 | 37 |
| | A | 26 | 13 | 60 | 16 |
| Winfield | M | 40 | 14 | 123 | 17 |
| | A | 25 | 16 | 79 | 16 |
| L/D 7 (Mon.) | | 26 | 19 | 60 | 22 |

NOTE: "" indicates no double lockages

in average tow size, assuming an absence of triple lockages. The short dashed segments simply provide smooth curvilinear transitions at the knees of the curves. The vertical lines mark the recommended limits of applicability of the equations for 600' x 110' and 360' x 56' locks. The dashed curves for average tow sizes between these limits indicate the practical real world capacity relationship, where capacity peaks at $s = s_1$ and decreases thereafter.

4. Capacity as a Function of Empty Barges, Downtime, Recreational Traffic and Seasonality. Capacity is linearly related to percent of empty barges, downtime, recreational traffic and seasonality. For convenience in application, the relationships can be expressed as follows:

$$C = C_o \prod_{i=1}^{4} ki = C_o(1 + \Delta C/C_o)$$

where,

$$C_o = C_t/k_{1_{pc}}$$

$C_t$ = technical capacity before adjustment for seasonality, downtime and recreational traffic (base conditions).

$k_{1pc}$ = percentage of loaded barges (present conditions) divided by 100.

Then, expressing the percent change in capacity in terms of the capacity coefficients,

$$\frac{\Delta C}{C_o} = \frac{C - C_o}{C_o} = \left( \prod_{i=1}^{4} ki \right) - 1 \qquad (12)$$

Note that the term in parentheses is simply the product of the complements of the factors expressing the percentages of capacity devoted to activities other than passing tonnage.

Although this is simple enough to compute arithmetically, Figure III-M shows how to evaluate $\Delta C/C_o$ graphically for a set of data.

# Figure III-M

## Capacity as a Function of Empty Barges, Downtime, Seasonality and Recreational Traffic

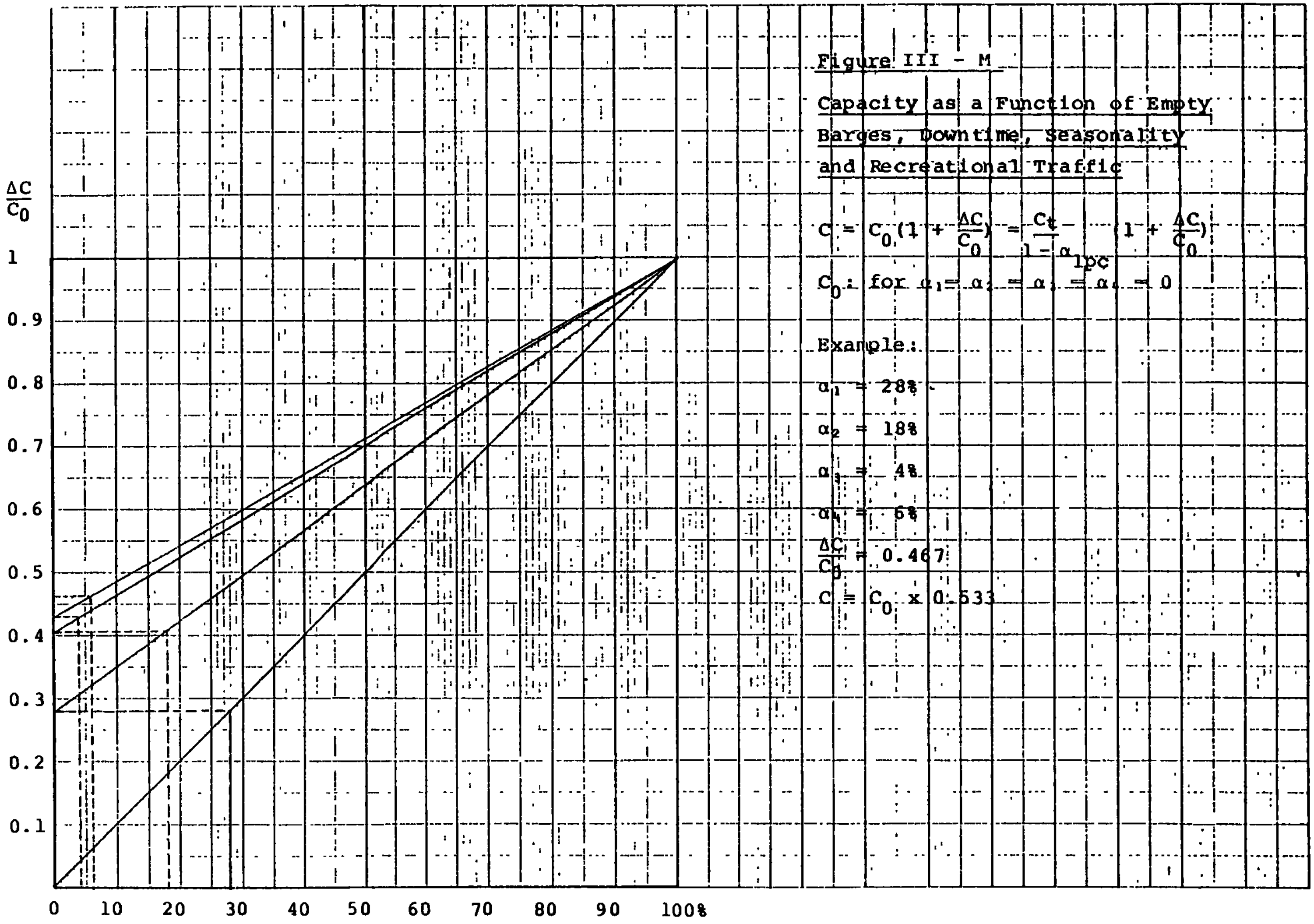


Figure III - M

Capacity as a Function of Empty Barges, Downtime, Seasonality and Recreational Traffic

$$C = C_0(1 + \frac{\Delta C}{C_0}) = \frac{C_t}{1 - \alpha_{1pc}}(1 + \frac{\Delta C}{C_0})$$

$C_0$: for $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 0$

Example:

$\alpha_1 = 28\%$

$\alpha_2 = 18\%$

$\alpha_3 = 4\%$

$\alpha_4 = 6\%$

$\frac{\Delta C}{C_0} = 0.467$

$C = C_0 \times 0.533$

Expressing the capacity directly, one obtains

$$C = \frac{C_t}{k_{lpc}} \prod_{i=1}^{4} ki \qquad (13)$$

5. Capacity as a Function of Chambering Time, Approach Time and Extra Time for Setover and Double Lockages. Any relative variation of average service time produces an equal relative variation in capacity,

$$\frac{\Delta C}{C} = \frac{-\Delta T}{T + \Delta T}$$

where, $T = T_f + P_d(D + F + T_t) + P_sS$

or in expanded form:

$$T = F(1 + 2P_d) + A_f + DP_d + X_f + E(1 + P_d) + P_d(A_t + X_t) + P_sS$$

The following relationships can readily be derived:

(i) Any change, $\Delta A_f$, in the F/E approach time leads to a relative variation of capacity as follows:

$$\frac{\Delta C}{C_o} = -\Delta A_f/(T_o + \Delta A_f)$$

(ii) Similarly, any change, $\Delta F$, in chambering time leads to:

$$\Delta C/C_o = -(1 + 2P_d)\,\Delta F/(T_o + (1 + 2P_d)\,\Delta F)$$

If $P_d = 0$

$$\Delta C/C_o = -\Delta F/(T_o + \Delta F)$$

If $P_d = 1$

$$\Delta C/C = -3\,\Delta F/(T_o + 3\,\Delta F)$$

Interpolation produces sufficiently precise results for $0 \leqslant P_d \leqslant 1$.

(iii) Any change of $\Delta D$ in the extra time for double lockages lead to the following:

$$\Delta C/C_o = P_d\, \Delta D/(T_o + P_d\, \Delta D)$$

If $P_d = 1$

$$\Delta C/C_o = - \Delta D/(T_o = \Delta D)$$

There is obviously no change in capacity for Pd = 0. Again, interpolation can be used for intermediate cases.

(iv) Any change of S in the extra time for setover lockages leads to the following:

$$\Delta C/C_o = -P_s\, \Delta S/(T_o + P_s\, \Delta S)$$

If $P_s = 1$

$$\Delta C/C_o = - \Delta S/(T_o = \Delta S)$$

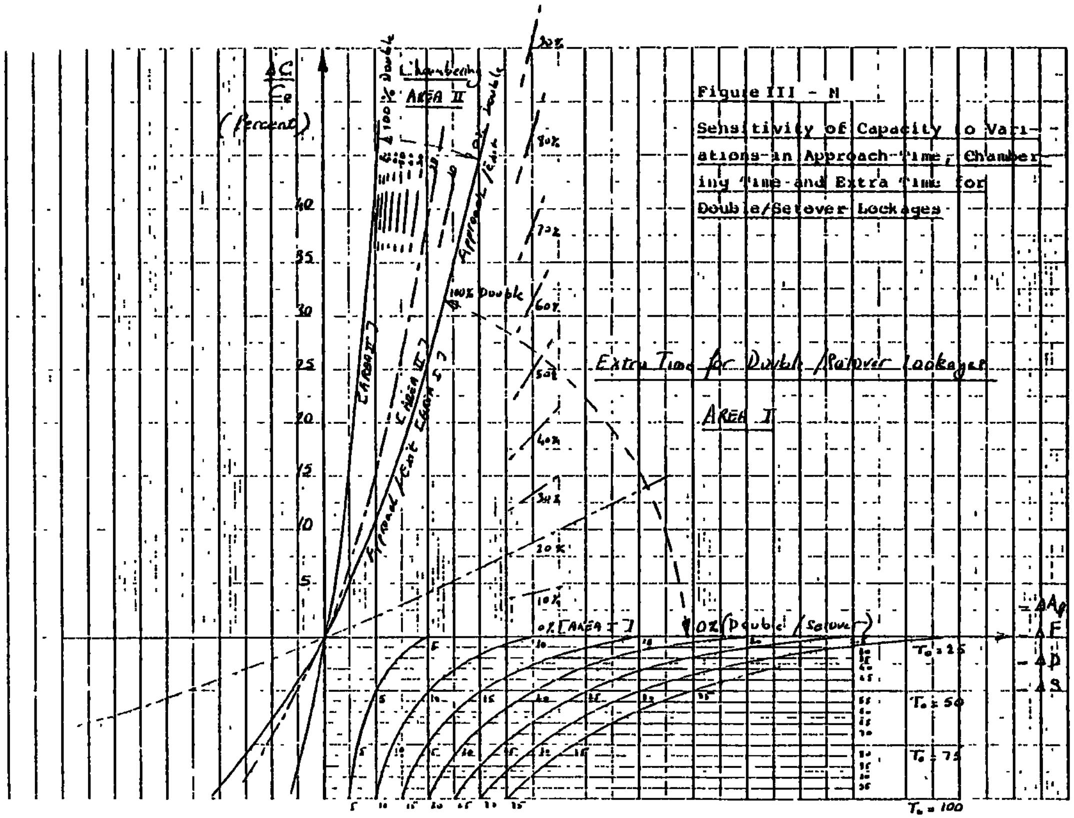
and again interpolation applies.

Figure III-N presents these results in an easy to use graphical form. The various curves in the figure relate the percent increase in capacity to the percent decrease in lock processing time. The lower portion of the first quadrant, area I, contains curves for reductions in tow make/break times and related activities for double and setover lockages for various percentages of such lockages. The variations in approach/exit times are represented by the curve separating area I from area II. The upper portion of the quadrant, area II, provides the capacity sensitivity curves for reductions in approach time and chambering time. Note that both sets of curves extend back into the third quadrant, thus covering cases where the lockage time elements increase rather than decrease.

The curves in the lower right quadrant provide a convenient means of converting discrete changes in $A_f$, F, D or S, expressed in minutes, into the corresponding percentages of base service time, $T_o$. To use the graph, enter at the right at the current $T_o$ and proceed horizontally to the curve labeled with the desired reduction, in minutes, in a lockage time element. From this point, dropping vertically to the line for $T_o = 100$ yields the percentage of service time and rising vertically to the

## Figure III-N

Sensitivity of Capacity to Variations in Approach Time, Chambering Time and Extra Time for Double/Setover Lockages



curve for the appropriate lockage time element and percentage of double (or setover) lockages yields the relative change in capacity.

Figure III-N indicates that reducing the chambering time has the largest effect on capacity. For 0% double lockages, a reduction in approach or exit time would be as effective as a reduction in chambering time.

Finally, a reduction in extra time for setover or double lockages provides good results when the percent of such lockages is significant.

In general, chambering time depends on chamber size and lift. The larger the chamber size or the lift, the longer the chambering time.

Three empirical curves presented in Figure III-O show chambering time as a function of lift for 1200' x 110', 600' x 110' and 360' x 56' locks. These curves permit the identification of locks that have inefficient hydraulic systems and may also be useful for estimating unknown times.

The empirical curves for 1200' x 110' and 600' x 110' locks coincide whereas the theoretical curves derived by the United States Army Corps of Engineers indicate that these curves should differ. This phenomenon is due to the more efficient hydraulic systems placed on the recent 1200' x 110' locks.

No lock currently in service has a data point below the theoretical curves. These theoretical curves can therefore be considered as lower limits on chambering time.

6. <u>Sensitivity of Capacity to Operating Policy</u>. Given $C_1$ and $T_1$, the capacity and service time for 1-up/1-down policy define $C_n$ and $T_n$ for the N-up/N-down policy as follows:

$$C_n = C_1 + \Delta C$$

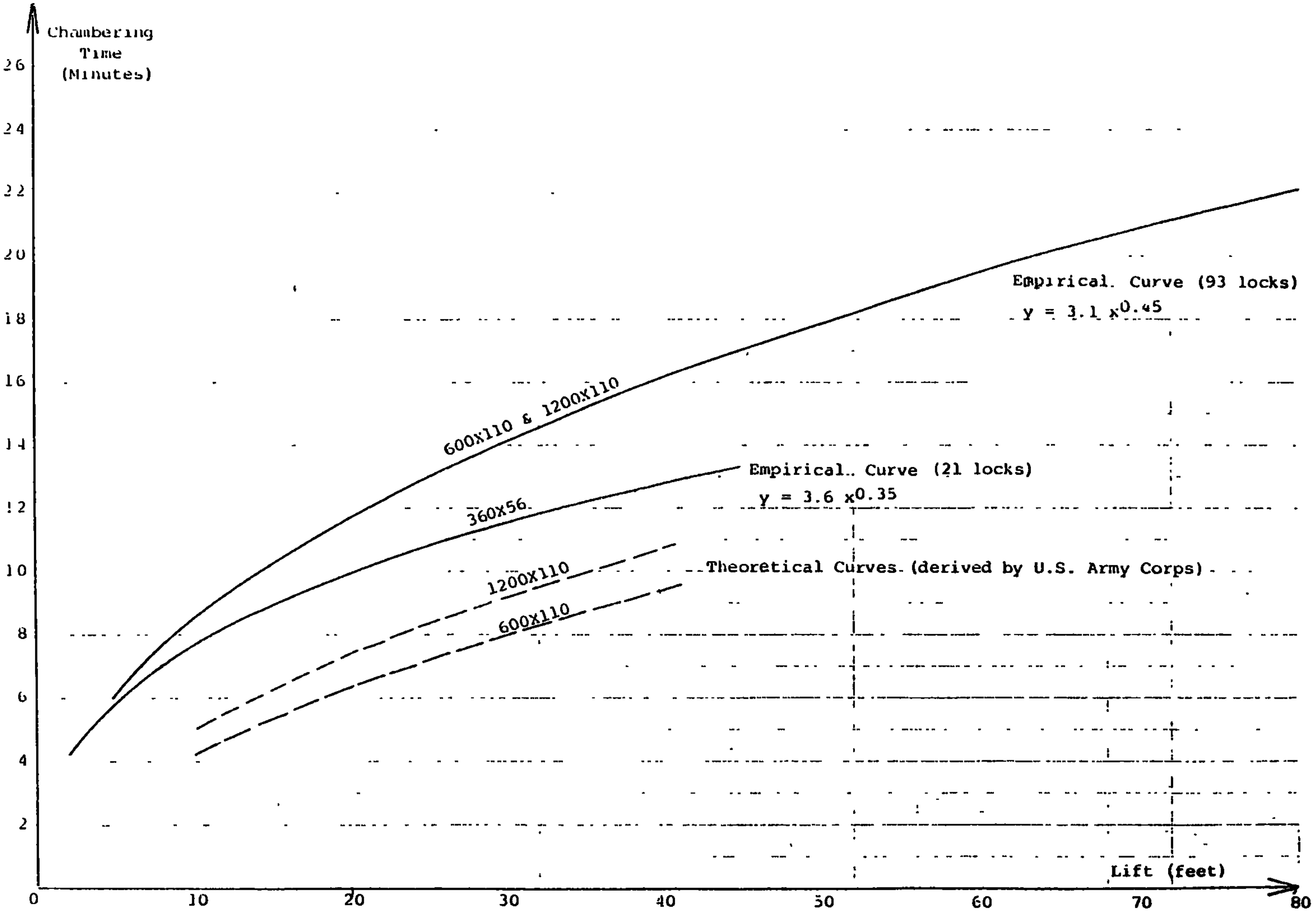
$$T_n = T_1 + \Delta T$$

Also note that:

$$\Delta C/C_1 = - \Delta T/(T_1 + \Delta T)$$

Figure III-O

Chambering Time as a Function of Lift



Then,

$$\text{given, } H = A_f + X_f - A_t - X_t - F$$

the time saved by a tow executing a turnback lockage is:

$$\Delta T = -((n - 1)/n)\ (H + MP_d))$$

where,

$M$ = make-up time = kD (k a constant). Introducing make-up time here assumes that this process occurs simultaneously with the empty chamber turnback.

Then,

$$\Delta T = -((n - 1)(H + kDP_d))/n$$

and,

$$\Delta C/C_1 = (n - 1)\ (H + kDP_d)/(n((1 - k)DP_d + (P_d + 1)\ (A_t + X_t + 2F + E)) + H + kDP_d)$$

Keeping all other variables constant, the formula indicates that the relative increase in capacity as n increases is bounded. The limit for large values of n is given by the following equation.

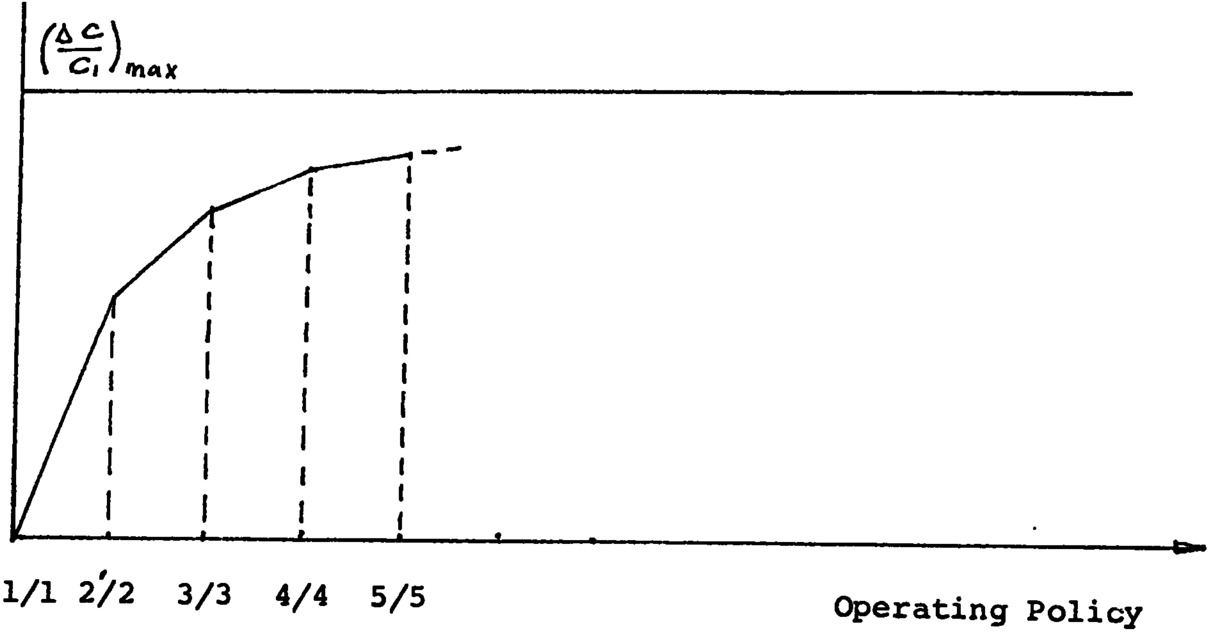
$$\frac{(\Delta C)}{C_1 \ \text{max.}} = (H + kdP_d)/((1 - k)DP_d + (P_d + 1)\ (A_t + X_t + 2F + E))$$

The general relationship between capacity increase and operating policy is as presented in Figure III-P.

Detailed curves of the relative variation of capacity as a function of H for n = 2, 3, 4, and 5 are presented in Figure III-Q for 0, 50 and 100% double lockages. Interpolation can be used for intermediate values of the percent of double lockages. These curves also assume that make-up time is two-thirds of extra time for double lockage (k = .667) which is a good average for most locks.

Figure III-P

General Relationship Between Capacity and Operating Policy



Technically, the relationship between capacity and operating policy also depends upon the specific values at $A_t$, $X_t$, E and F. However, the first three of these each take on a value of about five minutes for virtually all locks, and the relationship is not particularly sensitive to variations in chambering time. Hence, for sensitivity analysis purposes, the approximate relationships in Figure III-Q can be applied with confidence to all waterways.

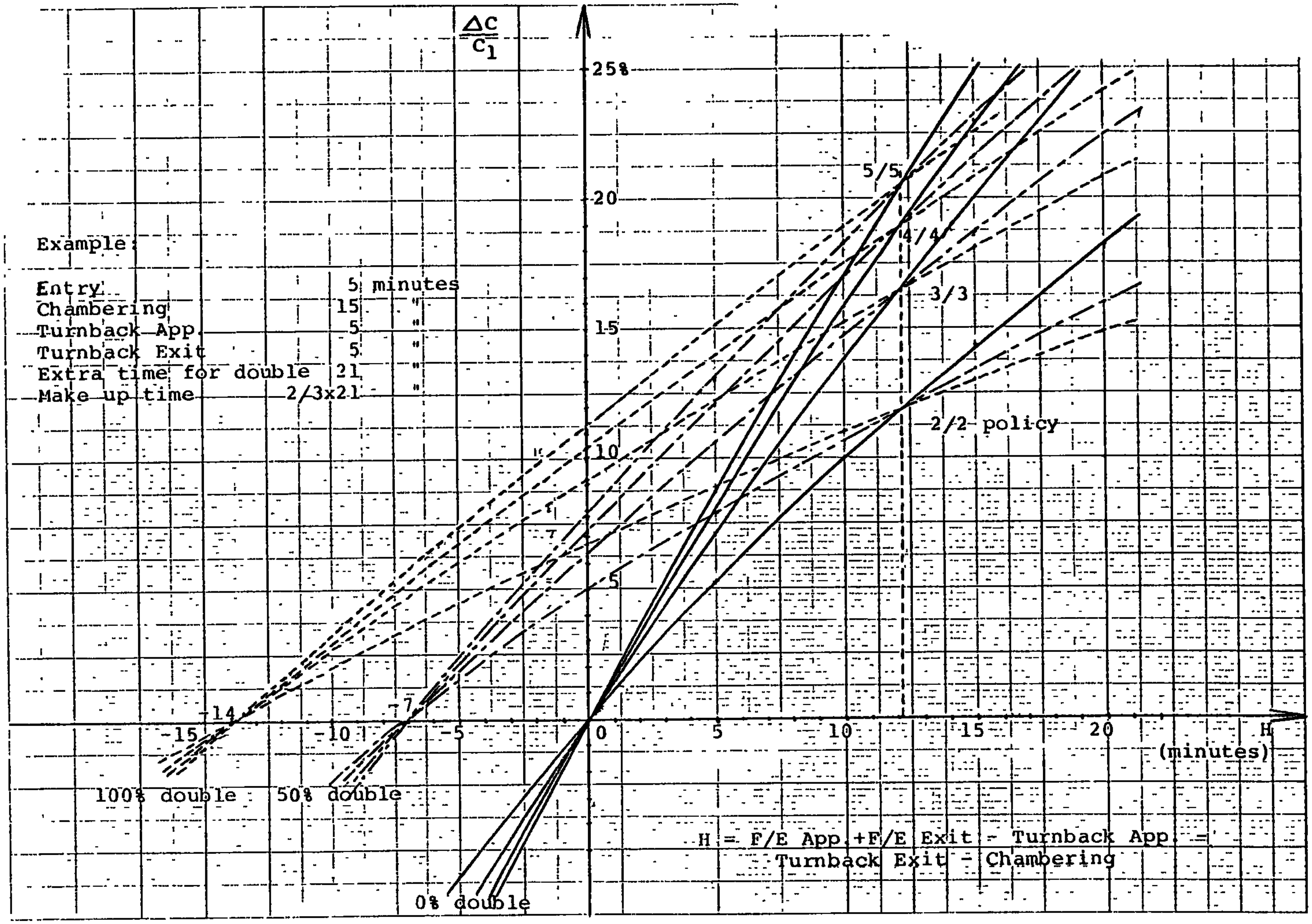
Of course, if $(H + kDP_d)$ is negative, implementation of N-up/N-down $(n > 1)$ policy would reduce capacity.

7. Sensitivity of Capacity to Percent of Multi-vessel Lockages. To analyze the sensitivity of capacity to the percent of multivessel lockages (Pm) it is assumed that only two tows are locked together for small values of Pm and that three tows are locked together for large values of Pm.

Figure III-R presents the case of Port Allen Lock, which is presently underutilized. The average number of barges per lockage is presently 2.4 for 6% of multi-vessel

## Figure III-Q

## Sensitivity of Lock Capacity to Operating Policy



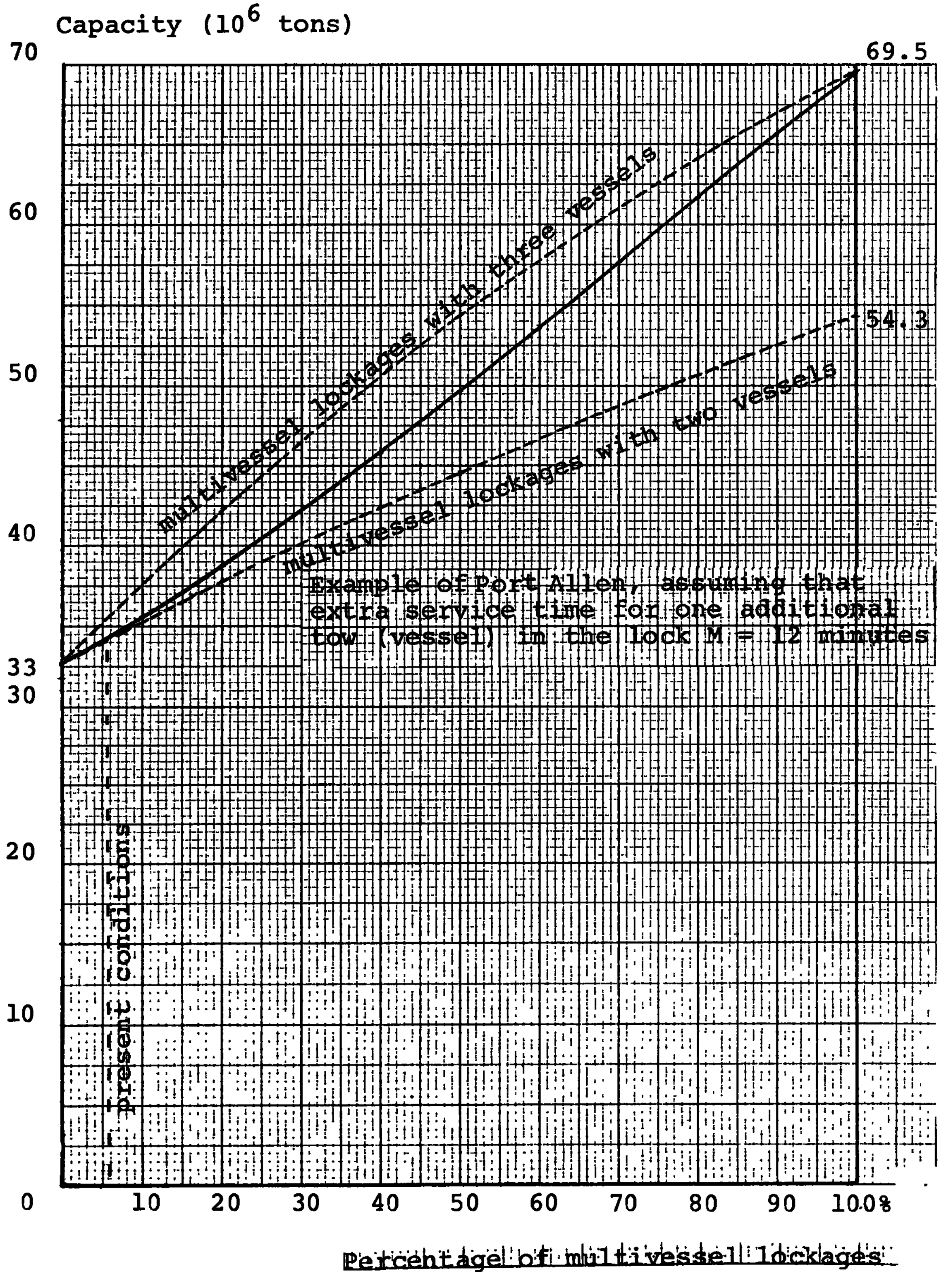
Example:

| | | |
|---|---|---|
| Entry | 5 | minutes |
| Chambering | 15 | " |
| Turnback App. | 5 | " |
| Turnback Exit | 5 | " |
| Extra time for double | 21 | " |
| Make up time | 2/3x21 | " |

H = F/E App.+F/E Exit - Turnback App. - Turnback Exit - Chambering

## Figure III-R

## Capacity of a Function of Percentage of Multivessel Lockage for Underutilized Chambers



lockages. The figure indicates that capacity would be greatly increased by increasing the percent of multi-vessel lockages (better chamber utilization).

This analysis is supported by the following assumptions and mathematical formulation:

It is assumed that the percent of multi-vessel lockages with three vessels (tows) is $Pm^2$ and with two vessels (tows) is $Pm - Pm^2$. (As justification for this model, note that $Pm^2$ approaches Pm as Pm approaches 1.0).

Therefore, service time increases by the following:

$$\Delta T = ((Pm - Pm^2) + 2Pm^2)M = (Pm^2 + Pm)M$$

where,

M = extra time for one additional tow in the chamber 12 minutes for Port Allen according to PMS data).

Assuming no double lockages (1200' long chamber at Port Allen) and no setovers, capacity becomes:

$$C = \frac{N \times L \times s \times (1 + Pm + {}^{2}Pm) \times \prod_{i=1}^{4} ki}{A_f + E + F + X_f + (Pm + Pm^2)M}$$

Assuming that s does not vary while Pm does, capacity for Pm = o is:

$$C_o = N \times L \times s \times \prod_{i=1}^{4} ki/T_s$$

for Pm = 1,

$$C_1 = N \times L \times s \times 3 \times \prod_{i=1}^{4} ki/(T_s + 2M)$$

where,

$T_s$ = service time for straight single.

This analysis depends heavily on the characteristics of individual locks, particularly on chamber size, average tow size and extra time for multi-vessel lockages, so no generalized nomograph can be readily developed. The methodology presented here, however, can easily be applied to any lock. The empirical results for this particular lock indicate that capacity is very sensitive to the percentage of multi-vessel lockages for cases where average tow size is lower than chamber size by a factor of two or more.

### (c) Lock Capacity Sensitivity Charts

The results of this analysis are summarized in the form of a set of lock capacity sensitivity charts prepared using the methods detailed in previous sections. Charts were prepared for the representing major lock classes. Most of these locks have two chambers, and charts were prepared for each chamber.

All of the capacity sensitivity charts are not presented in this report for the sake of brevity. However, all of the charts were prepared for use in later analysis and the charts for Kentucky Lock are presented herein for illustrative purposes. The only variables not included on the charts are operating policy and percent of multi-vessel lockages, as the charts would become extremely cumbersome with these added. All other variables are included. The effects of simultaneous variations in all of these on capacity may be determined with a single application of the chart. Of course, chart usage is much simpler if only a few variables are considered.

The following is a step by step explanation of how to use the sensitivity charts with Kentucky Lock as an example.

Two sets of conditions, present and modified, are presented below to aid in the use of the sensitivity charts for Kentucky Lock provided in Figures III-S and III-T. Figure III-U is an enlargement of a portion of Figure III-T. For each set of conditions, the corresponding capacity and service time are shown as obtained by using the step by step method.

Present conditions with 0% downtime, 0% seasonality adjustment, 0% recreation:

| | | |
|---|---|---|
| Average tow size: | 6.9 | Service time at capacity: 77 min. |
| Percent of double lockages: | 37 | Capacity: 41 x $19^6$ tons |
| Average tonnage per loaded barge: | 1,516 | |
| Percent of empty barges: | 42 | |

with, 0% double lockages:

| | | |
|---|---|---|
| Same except: | | Service time at capacity: 51 min. |
| Average tow size: | 37 | Capacity: 33 x $10^6$ tons |
| Percent of double lockages | 0 | |

with, 100% of double lockages:

| | | |
|---|---|---|
| Same except: | | Service time at capacity: 110 min. |
| Average tow size: | 12.4 | Capacity: 51 x $10^6$ tons |
| Percent of double lockages: | 100 | |

Modified conditions:

| | | |
|---|---|---|
| Average tow size: | 8.0 | Service time at capacity: 68 min. |
| Average tonnage per loaded barge: | 1,700 | Capacity: 39x $10^6$ tons |

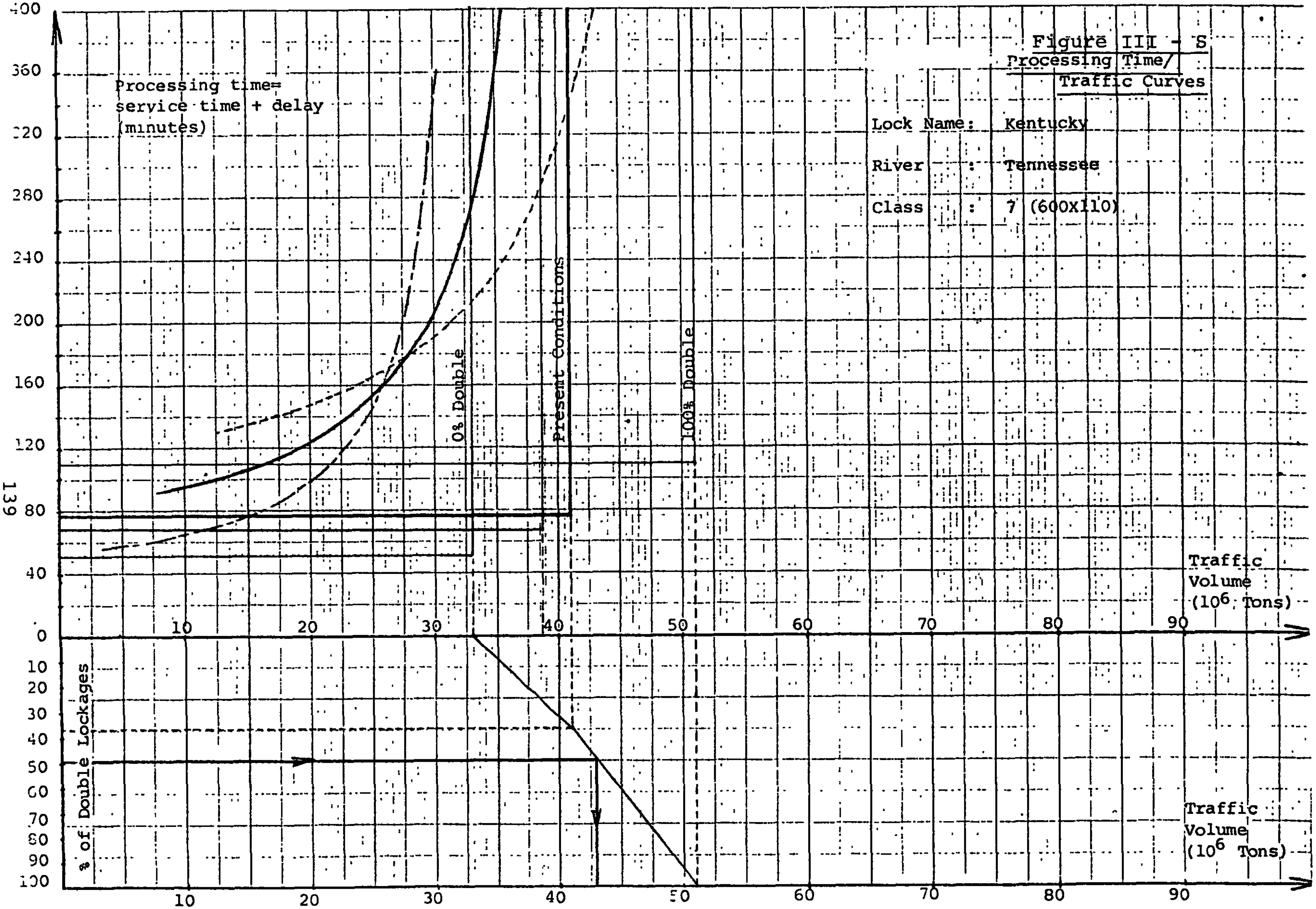
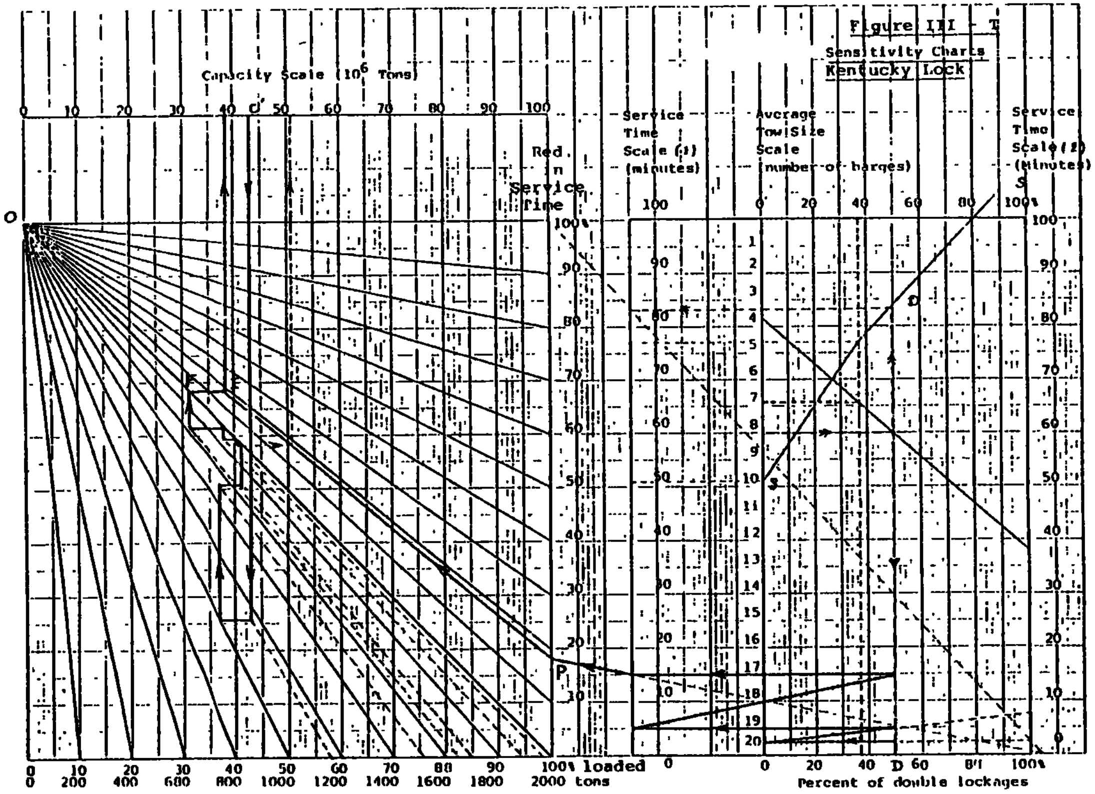


Figure III - 5
Processing Time/
Traffic Curves

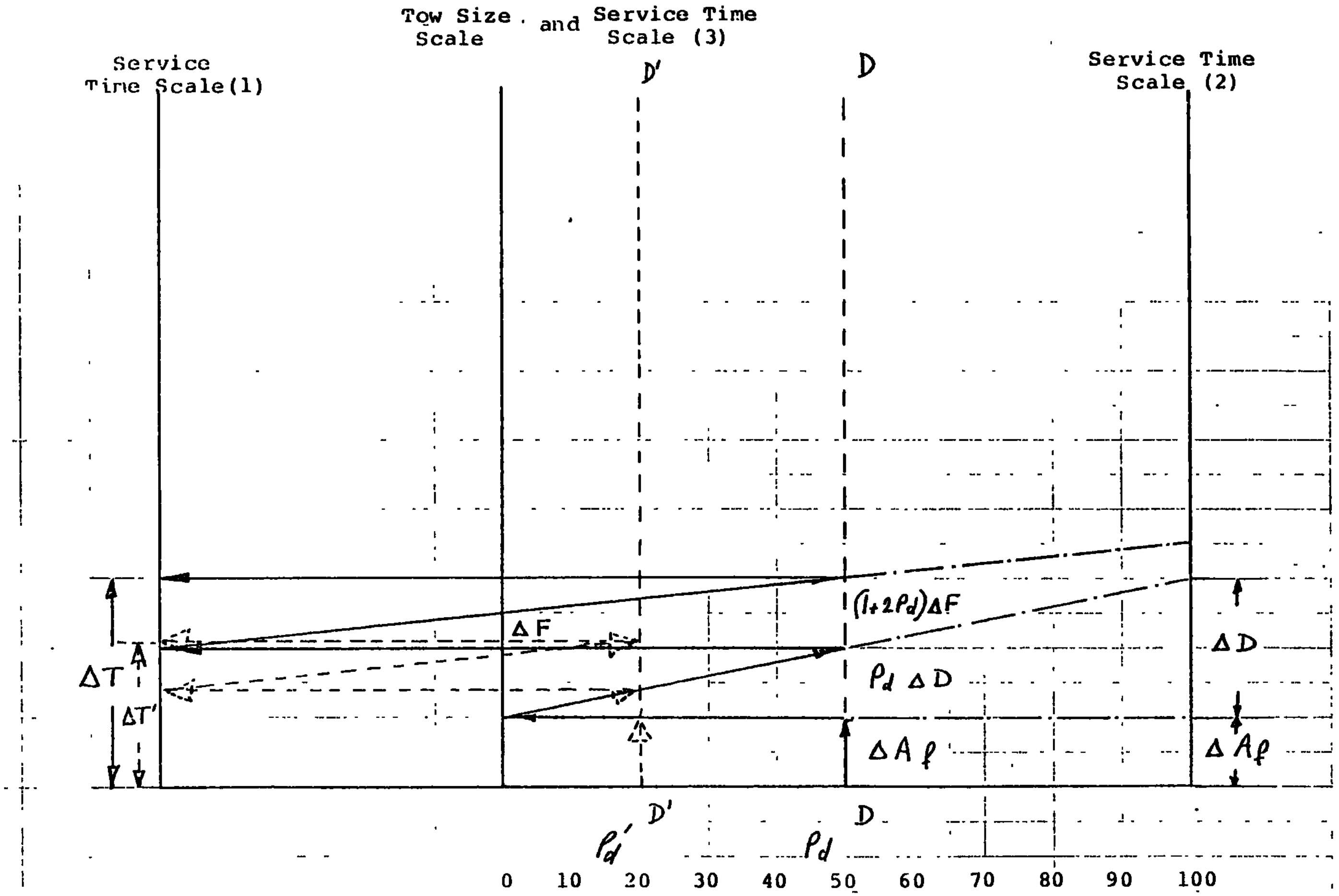
## Figure III-T

## Sensitivity Charts
## Kentucky Lock



## Figure III-U

## Chart for Determination of Variation in Service Time



| | |
|---|---|
| Percent of empty barges: | 50 |
| Percent downtime: | 18 |
| Percent seasonality: | 2 |
| Percent recreational: | 6 |
| Hydraulic improvement: | 5 min. on chambering time |
| Reduction of approach time: | 2.5 min. |
| Reduction of time for double (switchboat or operating policy: | 5 min. |

The capacity and service time under modified conditions, mentioned above were obtained using the sensitivity graphical charts. A special LOKCAP run with these modified inputs produced service time at capacity = 68 min. and capacity = 39.7 x 10 tons. These two sets of results are in agreement, thus demonstrating the validity of the capacity sensitivity charts.

Step 1: Modified Tow Size and Percent of Double Lockages (Figure III-T) as follows:

1. Set the new average tow size (8.0) on the average tow size scale.

2. Read corresponding percentage of double lockages (50%) on one of the two horizontal scales.

3. Draw the line (DD) corresponding to the new percent of double lockages between the two percent of double lockages scales.

Step 2: Determination of Capacity (C') According to New Tow Size (Figure III-S) as follows:

1. Use the new percentage of double lockages to determine the new value of capacity (C') by interpolation between capacities obtained for 0 and 100% of double lockages as well as capacity under present conditions. (Enter

the bottom part of Figure III-S on the left at 50%, read over and down to C' = 43 million tons.)

2. Report this capacity (C') on the capacity scale located on the left hand side of Figure III-T.

Step 3: Determination of Service Time (T') According to New Tow Size (Percent of Double Lockages) (Figure III-T) as follows:

Read T' corresponding to the new percent of double lockages on service time scale (1). (Look for the intersection of SS and DD lines and obtain T' = 83 min.)

Step 4: Calculate Variations of Service Time (Figure III-T) as follows: Variations in service time are due to variations in approach time, chambering time (due to hydraulic improvements) or in extra time for double lockages (break-up plus make-up time).

The total variation in service time, after adjustment for the new average tow size and percent of double lockages becomes,

$$\Delta T = \Delta A_f + P_d \, \Delta D + \Delta F(1 + 2P_d)$$

1. Report the variation in approach (or exit) time starting from the bottom of line DD and follow the arrows as in the enlargement in Figure III-U. The enlargement presents the paths corresponding to $P_d$ = 50% of double lockages and $P_d$ = 20% of double lockages. The spacing of service time scale (1), the tow size scale and service time scale (2) is the same for each lock. The spacing is such that the distance between the tow size scale and service time scale (1) is half of the distance between the tow size scale and service time scale (2). These distances were determined from purely geometric considerations - for instance, if $\Delta D$ is reported on service time scale (2), $P_d \, \Delta D$ is obtained by proportionality on line DD. Similarly, if $\Delta F$ is reported on service line scale (3) (also tow size scale), $(1 + 2P_d) \, \Delta F$ is obtained directly on line DD.

The total decrease in service time ($\Delta T$) is reported on service time scale (1) ($\Delta T$ = 15 minutes for

50% of double lockages and $\Delta T$ = 11 minutes for 20% double lockages.)

2. Convert $\Delta T/T'$ as a percentage. Once again, purely geometrical considerations are used to convert $\Delta T$ in service time scale (1) into a percentage (see point P in Figure III-T).

3. Join point P to the origin (0) of all oblique lines (line OP).

Step 5: Variations of Capacity (C') due to Changes in Fleet Data (Percent of Loaded Barges and Average Tonnage per Loaded Barge) - Left hand side of Figure III-T as follows:

1. Draw a line vertically from C' to the intersection with the line corresponding to the percent of loaded barges (present conditions = 58%), on the horizontal percentage scale.

2. Move horizontally to the oblique line corresponding to the revised percent of loaded barges (50%). If there are no other variations, move up to the 100% oblique line.

3. Proceed the same way for the average tonnage per loaded barge, and move up to the 100% oblique line.

Step 6: Capacity Adjustments for Downtime, Recreation and Seasonality as follows:

Reduce capacity graphically to account for reduction coefficients by using the horizontal percentage scale. Come back to 100% line (point F).

Step 7: Determine Final Estimate of Capacity as follows:

1. Determine intersection of line OP and horizontal line that goes through point F (intersection I).

2. From intersection I, move up to capacity scale and read the final estimate of capacity under the new set of assumptions.

3. If necessary, correct this estimate to account for operating policy by using Figure III-Q.

## ALTERNATIVE MEASURES TO INCREASE LOCK CAPACITY

### (a) Non-Structural or Low Cost Measures to Reduce Tow Processing Time

The tow processing time of a lock is that amount of time during which a tow controls the lock, i.e., prevents the lock from being used or readied for use by another tow. It is that time from when a tow finds, upon the exit of the tow ahead, that it can proceed into the lock, be locked, and depart to that point at which the opposite bound tow may start to enter the lock or at which time the lock may be readied to accept the next tow in the same direction. To keep tow processing time as short as possible and thereby increase the number of lockages in a given time period to maximize the practical tonnage capacity, it is important that all elements of that time interval be kept at their minimum. The tow processing time varies with the type lockage - single, double, setover or knockout - and the type of entry/exit - fly exchange or turnback.

At existing locks only the chambering time, which is the time required to open and close the gates and to fill and empty the chamber, is under the direct control of the Corps lock personnel. All other elements of the lockage interval time are primarily under industrial control and are only affected by Corps operating personnel in as much as lockage procedures can be established and enforced, additional facilities (such as mooring cells and switchboats) can be provided, or approach channel design can be improved.

For the most part, the tow processing time is a function of the lock design and location. During the design phase, the lock should be physically aligned such that crosscurrents and other unfavorable approach conditions are avoided. In addition, the lock should be designed with adequate clearances to insure speedy entry and exit and with filling system portals located for rapid and safe operation.

However, approach distances at many existing locks are very long because hazardous conditions exist which cannot be economically rectified. On the other hand, many older locks often suffer from difficult approaches and long chambering and gate operating times as a result of insufficient knowledge at the time of construction and inefficiencies due to age and lack of modernization. Inefficiencies and difficulties which act to reduce the overall lock processing time are generally not investigated for improvement and investment until such time as traffic delays are encountered. When traffic delays do occur, they are often relieved by employing techniques already employed at other locks. Thus, the state of modernization or the level of non-structural improvement of existing locks generally varies from lock to lock as a function of traffic.

Three levels of improvement are considered: minor structural and maintenance improvements or modernization, changes in operating policies, and potential improvements under study.

Minor Structural and Maintenance Improvements: These improvements primarily include low cost measures which can be employed to increase the efficiency of the lockage process and the introduction of low oost auxiliary facilities or equipment to speed tow movement. Specifically, such items as improved valved efficiency, minor approach modifications, provision of fenders and energy absorbers and provision of tow haulage equipment are included. These measures would be expected to provide only minor savings except in isolated cases and their implementation would depend upon the current level of modernization.

Changes in Operating Policy: These improvements primarily include low cost measures which can be employed to increase lock capacity and which represent a change in current lock operating policy. Specifically, such items as instituting an N-up/N-down or Ready-To-Serve policy or providing switchboards are included. These items have been found to provide savings at high traffic levels and often include the provision of auxiliary facilities, such as mooring cells and extended guide walls for implementation.

Potential Improvements Under Study: These improvements primarily include measures which could theoretically provide increased lock capacity or increased capacity throughout a lock system, but to date, have not been employed in the United States. Specifically, these include institutional changes within the industry and improvements which have been considered, but not implemented, for one reason or another, at locks currently experiencing high traffic levels.

The following sections describe several non-structural and low cost methods which can be, and in some cases are, employed to increase lock capacity by decreasing tow processing time. Many of the descriptions are taken from the following documents:

1. Potential Non-Structural or Low Cost Waterway System Improvements, Misc. Paper 0-71-1 by Frederick M. Anklam - June 1971, for WES.[4]

2. Evaluation of Operational Improvements at Locks and Dam 26, Mississippi River - July 1975, prepared by Peat, Marevick, Mitchell & Co. for LMVD, United States Corps of Engineers.[5]

3. Capacity Studies of Gallipolis Locks, Ohio River, West Virginia, Tech. Report H-78-6, by L. L. Daggett and R. W. McCarley, WES.[6]

Some of the improvements discussed are purely speculative and have yet to be proven effective.

1. Minor Structural and Maintenance Improvements. The allocation of personnel resources for lock operation under a full traffic condition could be improved in both quantity of authorized personnel and the grade of the position to insure that modern up-to-date operations and coordination may be carried on.

It has been the experience of a number of knowledgeable observers that a few locks and their filling systems are not operated in accordance with their design. Technical personnel making inspection visits to several such projects have noticed problems such as dangerous air blowouts in water passages, lock chamber surges which move tows toward the gates under overstressed hawsers, excessive vibrations in valves and structures, and other such dangerous hydraulic phenomena. Considering the natural forces and volumes, the investment, and the potential for accidents, each lock should have an operating procedure prominently displayed before or above the place where the operator handles controls. Such operating guides generally do not exist. The correct sequence of operations for a variety of conditions, both usual and emergency, should be displayed. Trouble indicators and the potential problem behind them should be displayed so that emergency procedures or requests for technical assistance can be initiated when serious problems arise. Improper valve operation of filling systems can cause dangerous disturbances of tows or pleasure craft in the lock, trapping of air and blowing off of gratings, water hammer, and many other such potentially destructive problems. In particular, some filling systems require very close coordination of valve operations to handle large amounts of water efficiently and rapidly and for the safety of the craft in the locks. Such problems are frequently not recognized or, if recognized, are not brought to the attention of technical personnel who can provide assistance.

Increased staffing could be combined with improved communications between Corps operations, engineering and planning.

Increased staffing at some locks could lead to somewhat decreased entry, chambering and exit times. This improvement would be most valuable for high levels of traffic.

An alternative to increased staffing is automation and control centralization.

Centralized and Automated Controls: locks have been designed for many years with the idea that personnel should visually inspect the entrance, exits, and outlet ports before operating gates or valves. As a result, controls in many places are located on opposite ends of 600 to 1200 ft. of lock wall and sometimes one person is required to move from one end to the other on foot or with scooters to operate the lock. Considering modern control and industrial management processes, it may be worthwhile to consolidate all controls into one location and use closed-circuit television monitors for visual scanning.

Installation of a closed circuit television covering the lower discharge area with receivers in both the upper and lower control stands and position indicators that would depict the exact position of all the valves would provide the lock operator with a continuous view of the discharge valves from the upper control stand.

Another improvement which offers considerable promise would be that of automatically controlled cycling of filling and operating sequences. Rather than have a variety of controls, modern industrial facilities today provide for automatic sensing and sequencing of steps in an operation. In this manner, large valves and heavy gates can be much more carefully and properly controlled by manual operation. This might result in faster cycle times and less damage to lock components. The cost of the automated equipment must be measured against the savings of decreased personnel, the benefits to the towing industry at a given location, and the potential longer structure life through safer operation.

On the Welland Canal, by improving valves, automating certain functions, centralized traffic control and alert operation of vessels, it was possible to gain one more lockage per day.

Improvement of Lock Equipment: Investment in new or modern hydraulic operating equipment or improvement of equipment could in many instances decrease entry, exit and chambering times.

Because of the age of the equipment at most locks which have developed to the point of having high traffic levels, the existing machinery is understandably inefficient.

Floating bollards are another useful improvement to the equipment of locks. In particular, provision for such equipment would reduce the time required to secure tows in the chamber. Further, they would tend to reduce the demands upon the time of the lockmen, thereby enabling them to expedite operations.

Time can also be saved by requiring tows to stay sufficiently clear of lock filling and emptying system intakes and outlets so that the chamber filling and emptying time could be reduced to a minimum.

Install Replaceable Fenders, Energy Absorbers and/or Rolling Fenders at Critical Sites on Lock Walls: From observations of damage at Lock and Dam 27 and other locations, there may be an opportunity to improve passage through a lock by providing replaceable fenders, energy absorbers, and/or rolling fenders at critical points on the lock walls.

The aims of this installation are as follows:

(a) To control the alignment of the vessel during entries and exits and, for example, to counteract wind forces acting on the ship.

(b) To externally apply a braking force on entering vessels thus allowing greater entry speed or shorter entry time than if the vessels had to rely solely on the braking capacity of their propeller.

(c) To provide flexible mooring, enabling a safe use of hydraulic assist during downbound exits.

Improve Approach Channels: Approach conditions affected by poor channel alignment, adverse currents, and improperly designed guard and guide walls can cause considerable delay ranging from a few minutes to several hours because of the maneuvering required. Ideal approach conditions would permit fully loaded tows to become aligned for approach into the lock some distance upstream of the lock, and then drive or drift toward the guide or guard wall with little or no maneuvering or engine reversal required.

Modifications that can be made in the lock approaches and the benefits obtained will depend on conditions at each lock and might include: realignment of the approach channel upstream and downstream, river training structures, additional maneuver area, provision or modification of auxiliary walls, elimination of obstructions affecting the movement of tows, provision of mooring cells, and additional navigation aids.

At Lock 24 in the St. Louis District, a dike was constructed upstream of the lock, which greatly improved the navigation conditions experienced by tows as they approached the lock. The dike enabled faster approaches and shorter service times. There is also a serious problem with drift debris at this lock, and a 100 ft. extension of the dike is to be made to alleviate this problem.

Keeping the approaches, particularly the lower approach, at a depth that would allow the most efficient entry of tows into the chambers would decrease entry and exit times. A rather serious shoaling problem exists in the approach channels to the Gallipolis Locks, particularly in the lower approach. There has been no major dredging of these channels for many years because of the interference such operations have with the traffic passing the locks. The reduced depth has thus had a hydraulic effect on tows entering the lock and tends to slow vessel approach. An analysis of entry time savings that may be realized by dredging the channel approaches could possibly be estimated from past research on the effects of reduced channel dimensions on tow transit times. In some cases, a submerged wing dike has proved useful in reducing or stopping shoaling in lock approaches. Such a solution would eliminate lost time at the lock during dredging operations. The increase in lock capacity, solely from this option, is considered to be negligible at Gallipolis Lock; however, it is possible that some benefit could be recognized from this at other sites.

The possibility of shoaling due to dike construction in an alluvial stream cannot be ignored and should be studied for each location where a dike is proposed.

At some locks (such as Gallipolis), the upper approach could be improved by placing guard cells angled toward the center of the river upstream from the river guard wall. These cells would be spaced so as to prevent a tow or small boat from passing through the space between the cells but far enough apart that the water flow would pass through them. The cells would provide tows protection from being swept by the current around the end of the river guard wall and into the gates of the dam. The angle of cells should be such that tows will have an adequate maneuvering area for approaching the locks. A submerged wing dike could be constructed off the end of the downstream river guard wall to reduce the current toward lock approach and the shoaling in the approach channel.

Tow Haulage Equipment: At locks which are not already so equipped, tow haulage equipment can be used to reduce the time required for double lockages. For some years, various locks have used a cable assembly to pull the first half of a split tow out of a lock, thus permitting the towboat and second half to follow through immediately behind.

A system of wheeled, movable mooring posts (a traveling kevel) can be useful in moving tows into, through, and out of locks. This system would reduce the time required for double lockages by pulling the first half of the split tow out of the lock, like the cable assemble, but can also be used to speed entry. By providing positive control to the tow, the reduction in time, particularly for large tows, and the consequent reduction in damage to walls and corners appear to make this a worthwhile item for consideration at some locations.

In locations where tows longer than the lock do appear, but there is no waiting line, such devices are helpful. At locations where waiting lines develop, the advantage afforded by haulage equipment is reduced because the tow must remake while blocking the gates. Use of an extended guide wall and an N-up/N-down procedure in conjunction with tow haulage equipment would allow tows to remake while not interfering with the operation of the gates for turnback lockages.

Greater Use of the Auxiliary Chamber: Increased use of auxiliary chambers should come about naturally as main chambers become more heavily utilized and the delays to tows increase. It will then be advantageous for smaller tows to double lock in the auxiliary chamber, rather than wait for the larger main chamber.

Certain factors often discourage the use of the auxiliary chamber by most tows. Multiple lockage tows would require as many as six lockages in the auxiliary chamber, whereas the same tow could transit the main chamber as a double lockage. The processing of multiple lockage tows through the auxiliary chamber can also create unsafe approach and exit conditions for other tows using the main chamber. In addition to small size, the lack of adequate guide walls or guard walls to assist tows while they enter the auxiliary chamber and remake after lockage may contribute to low utilization. For example, the auxiliary lock at Gallipolis cannot be used by tows at certain times when the main chamber is in use. The present entrance conditions are such that the entire channel must be occupied by the tows entering and exiting from the main chamber. In addition, interference to operations in the auxiliary chamber is caused by portions of tows secured on the main chamber guide walls during double lockages.

If interference with operation of the main chamber is not a problem, or if structural modifications, such as the extension of the center guide wall, can be made, then nonstructural measures to increase lock capacity, discussed herein, would be equally applicable to the auxiliary chamber.

At high levels of traffic, improved scheduling can potentially increase the usage of the auxiliary chamber.

Use of a Ready-to-Serve policy, which would insure that all tows requiring double cut lock as two singles, would probably increase the number of tows able to use the auxiliary chamber and thus increase utilization.

2. Changes in Operating Policy, N-Up/N-Down Policy. Currently most locks operate on a First In, First Out schedule (FIFO). This simply means that the tows are serviced in the order of their arrival and that no restriction is placed on their barge configuration (tow makeup) or size as they approach the lock; i.e., no remake or reconfiguration of the barges is required until after the lockage process begins.

If the time required to reverse the lock to make a turnback entry is greater than the time required for a fly exchange entry, then an alternate rule could be involved where a 1-up/1-down procedure would be followed. Under this rule, tows in queue on each side of the lock are served alternately. That is, after a tow traveling in a given direction is locked through, a tow traveling in the opposite direction is next to be locked, thereby eliminating the time required to reverse the lock.

These rules are commonly followed at most locks where waiting lines are not too long. At higher traffic levels, a Multi-up/Multi-down policy can often increase capacity.

The so-called N-up/N-down rule is effective only if the sum of average times for a turnback exit, a turnback, and a turnback entry is much less than the time for an exchange exit and entry. When this is the case, the lock may be reversed and a new tow can enter the chamber faster than two tows can exchange use of the lock. Even though this may result in more efficient use of the lock, it often causes increased average delay times, because longer waiting times are imposed on tows that arrive at the lock sooner than the tows being locked ahead of them, and is only beneficial if the queue is present at the locks most of the time.

Additional savings can be made if an extended guide wall is provided to allow tows to remake without interfering with turnback gate operation.

At Locks and Dam 26 in the St. Louis District, the locks are operated under what is known as a 4-up/4-down rule. Under this rule, four upbound tows are locked consecutively followed by four downbound tows, or vice versa. If the queue in the pool from which tows are being locked empties prior to reaching the maximum of four vessels, tows from the other pool are then selected. For this policy, it is assumed that the last three tows in sequence will approach the lock and, therefore, their entry will be of the turnback (or short) entry type.

Though it appears to be wasteful since the lock must be filled without a tow in it (the downstream traffic is being passed while the upstream traffic waits), there is a considerable time savings due to certain characteristics of floating craft. The susceptibility of tows to the influence of the current, the stern steering characteristics of water craft, and the great length of the modern tows make it easier for one tow to follow another in line than to have two opposing tows pass each other. Therefore, the so-called N-up/N-down rule sometimes allows several tows moving in one direction to move through a lock in a shorter period of time than can the same number of tows that must pass each other in opposite directions. These one-way rules could also be modified to 3-up/5-down depending on waiting line configurations at a given time.

There is, at the present time, in effect a 5-up/5-down rule at Vermilion Lock in the New Orleans District. N-up/N-down rules have also been employed at Bonneville, Inner Harbor, Calcasieu and Port Allen Locks.

At Gallipolis Lock, the N-up/N-down rule was found to be ineffective at increasing lock capacity because tows waiting for a turnback entry block access to the auxiliary chamber.

During high water periods at some locks, lock turnback times are sometimes shorter because of the smaller difference in water elevation, thus indicating there may be some advantage to implementing this rule at certain times of the year.

The choice of the N-up/N-down policy to be used should consider the probability of having a smaller tow available to lock as the last tow in the series. Tows requiring only a single lockage would not need to be recoupled on guard walls, and thus the first of a series of N tows traveling in the opposite direction could begin its entry much sooner. A priority system could also be instituted to give high priority to single tows as the last in the series.

Switchboat: Where heavy traffic conditions occur frequently, it has been demonstrated that the use of an extra towboat at the lock has been very effective in passing traffic. The lockage procedures for this type of operation requires the switchboat to extract the unpowered cuts from the chamber and to secure the unpowered cuts at a mooring where the recoupling of the powered and unpowered cuts does not interfere with the operation of the lock. A reduction in the exit and clear times for both the unpowered and powered cuts of double lockage tows is possible.

Setover single and knockout single lockage tows can also improve their exit and clear times by having the switchboat extract the unpowered string of barges. The tows would then be required to move, either under their own power or with the help of the switchboat, to a mooring area before reconfiguring for river travel. The following benefits could be anticipated from a lockage procedure in which the switchboat removed the unpowered strings of double, setover and knockout lockage tows to a mooring sufficiently far from the lock that lock operations would not be impeded by the reconfiguration operation:

(a) exit and clear time for the powered and unpowered strings is reduced since the powered string would not be required to maneuver back into the chamber to complete recoupling; and

(b) recoupling of the tow can be accomplished at a mooring where the recoupling operation does not preclude lock operations.

In addition to the normal lock facilities, the Switchboat operation requires the use of switchboats and moorings located outside the approaches to the main chamber.

Where an auxiliary chamber is available, a single switchboat can be used in both the upper and lower pools. The switchboat should be given priority service in the auxiliary chamber so that it will be available to extract the unpowered cut of the first tow in sequence after it has completed extracting the unpowered cut of the last tow in the preceding sequence in the opposite direction.

An alternative to this operation is to provide a switchboat in the upper pool and an extended guide wall in the lower pool. When combined with a N-up/N-down policy, this alternative provides nearly the same benefit as having a switchboat in the lower pool while affording downbound tows the added safety of remaking on the lower guide wall instead of at a downstream mooring area.

Switchboats can also be employed when a Ready-to-Serve policy is in effect. Under this policy, sufficient switchboats would be required at the locks at all times to assist the larger tows in their locking process. The switchboats would attach to separate unpowered cuts of large multicut tows and serve as the towboat until the barges have been moved to the mooring area on the opposite side of the lock. It was estimated in "Locks and Dam No. 26 (Replacement) Design Memorandum No. 11" that five switchboats would be required at Locks and Dam No. 26 to implement this policy. The exact number of switchboats would depend on the length of queues and the percentage of tows requiring assistance.

The Industrial Canal Lock in New Orleans has had an operating rule which requires that the second half of a split tow move to the end of a waiting line. As a result, the towing industry pays for the use of an extra towboat to carry through the front half of a split tow at the same time.

Guide Wall Extension with an N-Up/N-Down Policy: At some locks (such as Gallipolis) there could be some specific disadvantages, in terms of safety and industry desires, to reassembling barges outside the lock chamber, especially in the lower pool. Reassembling in a downstream mooring area could be hazardous because of the required tow maneuvers. Tows usually approach a moored cut when heading upstream. Since they will be headed downstream upon exit, each tow would have to turn 180 degrees in midstream. They would then approach the moored cut from downstream, recouple, and execute another 180 degree turn with the full tow.

An alternative to reassembling in the downstream approach is to provide an extended guide wall for reassembling (the landward guard wall or the guard wall between the main and auxiliary chamber could also be extended).

The effective capacity of a lock with extended guide walls in an approach would be about the same as employing a switchboat, as long as a N-up/N-down procedure is followed and haulage equipment is provided. In order to achieve the same capacity with guide wall extension, the last of a series of one-directional lockages should be a single lockage in order to minimize delay to the tow approaching from the opposite direction.

The guide wall extension should be long enough for an entire tow to moor along the wall and clear the mitre gates and the filling and emptying system outlets. Delong Piers, a floating boom or a concrete cap on sheet pile cells could be used in lieu of a conventional concrete wall.

Extension of the landward guard wall would probably cause less interference to traffic during construction than extension of the riverward guide wall. Where an auxiliary chamber is available, extension of the guide wall between the two chambers could reduce approach blockages.

In approaches which are already restricted, extending the guide wall may not be feasible as maneuvering room may be decreased.

Ready-To-Serve Policy: The Ready-to-Serve operating policy prohibits the break and remake of tows within or in the vicinity of a lock chamber. Each separate cut of a large tow is assumed to lock immediately following one another and is considered to be independently powered. The tow would be required to appear at an initial point for lockage some distance from the lock, prepared to move through without further changes in tow configuration. Tows appearing at that point would be denied waiting line position if they were not able to move through the lock without splitting the tow, rearranging barges, or other time-consuming modifications prior to entry into the lock itself. This policy would require several switchboats at the lock at all times to assist in the locking operations and mooring facilities.

The number of switchboats required would be reduced if knockout and setover type lockages were allowed to continue locking in an unrestricted manner. Towboats of tows waiting in line could be used in lieu of switchboats.

All of the items discussed under "Changes in Operating Policy" have been found to shift the delay capacity curve downward and to the right, providing a much lower level of traffic delay at high levels of utilization.

3. Potential Improvements Under Study. Provide Waiting Areas: There are a number of locations where lengthening of approach walls or providing tie-off areas close to the lock would enable towboats to line up close to the lock entrance as they await their turn. Considerable reductions in service time can be experienced in these cases. Most European locks provide an offset waiting location close to the lock entrance. A flared-angle waiting wall may permit tows to wait close to the lock and provide passing room for the exiting tow. This type of waiting improvement requires increased tow maneuverability through the use of bow-steerers or mechanical devices, such as a swinging arm from the Lock wall which would grasp the tow and enable it to move out into line with the lock entrance. Such changes would eliminate the need for N-up/N-down rules and permit two-way tow passage for each filling and emptying of a single lock.

Tie-off areas are provided at Lock 7 on the Welland Canal and the Brandon Road Lock upper approach on the Illinois Waterway. Research has been conducted to determine the best design for such offsets and is presented in the paper "Navigation Locks for Push Tows" by I.C. Kooman, 1973. However, provisions for such vessel exchanges are not generally incorporated into the design of United States locks. In our opinion, in certain situations tie-off facilities near the lock gates can provide a very efficient method to increase the capacity of existing locks.

Longitudinal Hydraulic Assistance: At several locks on the Welland Canal, it has been found feasible to increase downbound exit speeds by providing hydraulic assistance. This feature provides the inclusion of water into the upper end of the lock to assist a downbound vessel in leaving. This procedure is particularly helpful when large blockage ratios (the ratio of the submerged area of the tow to the cross sectional area of the lock) are experienced. At three locks on the Welland Canal an average of 26 seconds was gained in overall lockage time as a result of this procedure.

Give Priority to Faster Locking Tows: In many instances, lockage times are long because the tows are not operating very efficiently. In order to encourage tows to become more efficient during the lockage process, rules could be developed for maneuverability such that arrivals at an initial point for a given lock would gain priority according to their ability to move rapidly through the lock when waiting lines exist.

Three areas of current technology if universally applied would have a significant effect on lock transit speeds.

The first possible improvement is an increase in towboat horsepower. There have been various reports of tows, especially very large or underpowered ones, having considerable difficulty in executing necessary locking maneuvers. Large tows operating with small clearances in lock areas require very precise steering, and most tows are difficult to control if lock approaches and exits are complicated by crosscurrents, wind, or heavy traffic. Increased power is generally synonymous with increased speed and maneuverability.

The second possible improvement, which is now being used to a limited extent is the bow steerer or "bow thruster" These independent power units mounted at the head of a long tow allow propulsion of the bow in any direction and thus greatly increase the maneuverability of an otherwise somewhat sluggish (especially at slow speeds) vehicle. While some of these units are permanently fixed to a barge, and thereby dictate special care in fixing the configuration of the assembled tow, others are independent units and can be fairly easily attached to a forward barge of almost any tow.

In view of the problems frequently encountered in maneuvering tows around and into locks, it would seem that bow steerers could be economically employed to a much greater extent than they are at the present time. Such devices could also provide the towboat pilot with a much greater degree of steering flexibility and resultant safety when navigating under other adverse conditions of weather, traffic, or channel conditions, as well as greatly simplifying dockings and landings.

The third improvement which would seemingly be worthwhile and highly profitable would be the development of a simple, quick operating, and universally adaptable coupler for joining barges. At the present time, moorings and barge couplings are made by traditionally effective but slow methods which are quite time-consuming when tows must be disassembled and reassembled. Mounted on all sides of all barges, the coupling devices suggested could greatly speed up the assembly and disassembly operation of tows. Considering the time this would save during pickup and delivery switching and particularly in breaking tows for multiple lockages (where a few minutes saved by each tow greatly increases lock capacity), such devices should prove vastly more economical than traditional rigging and lashings. Alternatively, hand winches could be employed which can be operated much faster than the ratchet and cable method and allow the outside lines of the tow to be secured, permitting the tow to clear the lock while deckhands are securing the remaining cables.

A successful example of change in rules which resulted in major benefits to the shipping industry is available in the Welland Canal studies. In the Welland Canal, careful study revealed that when a waiting line formed for any reason, a slow ship would impede the progress of any ship if it were near the head of the line. When faster ships were allowed through the lock ahead of slower ships, the slower ship arrived at its destination at essentially the same time without delaying the faster vessels. The result then was a greater passage of tonnage per unit time through the entire system.

Increased Use of Radar or Use of Tow Guidance Systems: Under bad weather conditions, tows equipped with radar are often able to traverse the locks whereas tows not so equipped cannot. The installation of radar reflectors in approach channels can aid operations at night and during periods of poor visibility.

It would appear entirely beneficial to provide a tow pilot with a lock entrance electronic guidance system similar to those used by aircraft in approaching an airport landing runway. Such a system would guide the tow's pilot in maintaining a proper attitude and speed on approaching and entering the lock and would notify him of any deviations from the desired approach path. Because this guidance system would potentially be expensive, the system could be fixed at the lock and the lock personnel would relay corrections to the tow pilot. No system of this kind is known to exist today.

Establishment of More Responsive and Flexible Scheduling Procedures: A rigid scheduling procedure of a given number of tows up and a given number down could result in inefficiencies in some instances. In this context, the key is to develop a responsive and flexible scheduling algorithm to establish which chamber a tow will use, the order of turn in which the tow will be served, and the lockage procedures which the tow must adhere to. The solutions provided by this scheduling algorithm would vary depending on the length of the queue, the mix of lockage types and vessels desiring service, the origins and destinations of the tows, the elevations of the upper and lower pools, and possibly a number of other factors.

Because the situation at most locks is dynamic and substantial changes in traffic demands and queue length can occur in short time periods, the scheduling rules and lockage procedures should be flexible enough to be applied as the situation warrants. For example, during extremely light traffic, a first come, first served scheduling rule might be used. As traffic increases, a three up, three down scheduling rule might be instituted and setover rules might be put into effect. If the queue grows even longer (24 hours or more), more restrictive procedures might be used (e.g., a four up, four down scheduling rule, no decoupling of doubles within the lock, mandatory scheduling of tows for the auxiliary chamber). Such flexibility implies the use of some form of dynamic, or semi-realtime scheduling mechanism. Such a system, which could be queried and invoked several times a day, could then produce some form of interactive scheduling and lockage procedures.

The flexible scheduling procedures can only be invoked if the lock staff has a tool available to it for arriving at a more optimal scheduling procedure for a given set of circumstances. The following was suggested for use at Locks No. 26: a tool to provide flexible and responsive scheduling of tows could be achieved initially through written scheduling rules using algorithms and ultimately through mechanized systems using computers. If a small on-site computer or a time sharing computer service were used, the shift chief could input key information about each arriving tow, and the system would display the scheduling and lockage procedures to be followed for both chambers. The procedures could be modified or updated with each arriving and departing tow.

At locks with auxiliary chambers, a more responsive and flexible scheduling mechanism could increase the ability of both chambers to serve increased traffic. If tows could be selected from a waiting queue to effectively use the time available (when the approach channel is not blocked) to enter and exit from the lock and during periods when the channel is blocked by operations in the main chamber, to break, chamber, remake, and perform other processing operations that do not require approach or exit of the tow through the channel, then the auxiliary chamber might possibly be utilized a higher percentage of the time.

Wind Deflectors: In some locations, wind has an adverse effect upon the availability of tows, especially empties, to approach locks. Corrective structural additions or revised procedures may be required. One such location is at Lock and Dam 27 in the St. Louis District where the lockmaster has films that show significant wind effects on tows entering the lock.

Future Industry Improvements: In the area of long-term industry planning, many types of hardware changes are possible. Special consideration of hydraulic and aerodynamic characteristics of barges may result in lower drag forces on barges and improved handling under rough current and wind conditions. In applications where the one-way movement of empty barges is unavoidable, it may be possible to stack empty barges one on top of another and cut the required area of the tow in half. Although this would require complex handling equipment, hydraulic drag would be reduced, and double lockage could be eliminated at most places on the return trip of tows which required double lockages in their loaded configuration. Further increases in towboat horsepower as well as improved steering and propulsion methods are also likely.

A towboat system that has been used in Europe and which might find favorable application in this country is the "automotive coupled unit." In this system each tow is propelled by two independent towboats whose controls can be coupled and operated by a single pilot in the master towboat. This system is somewhat more maneuverable than a single towboat system because of the spacing between the two boats which push side by side at the stern of the tow. The biggest advantage in such a combination would be the convenience of having two towboats available for switching operations. The tow could normally be operated by a single pilot who could be assigned by special pilots permanently stationed at locks and ports. When double lockages are necessary, the tow could be split up and remade far enough from the lock to avoid any traffic interference and the two independent parts of the tow could pass through the lock in the same manner as any single-lockage tow. Thus the need for a local switchboat at each location would be eliminated and the full capability of each towboat could be utilized at all times.

Even with all of the available electronic and special devices to simplify navigation, the most modern of towboats is far from automatic. As such, their operation requires well trained pilots. An agency could be established to further new pilot training and provide veteran pilot refresher training. Pilot and equipment licensing and inspection might go along with this. It may be questioned whether the individual tow operators would institute such restrictions as these upon their own operations, but if they realized that such measures would be beneficial to a good majority of the operators, then it should be possible to make a majority of operators accept them. A logical industry-wide type of agency to promote greater cooperation among various operators might be found in the American Waterway Operators, Inc.

There are some locations which may only be able to pass the necessary traffic under intensive waterway management procedures. This procedure would be similar to an air traffic control area surrounding a busy complex of airports. This intensive management area would have a centralized control over one or more locks and river entrances to insure that they operate in the best coordination. A system to identify traffic coming into this area and predict problems prior to their occurrence would be essential. Such activities as reporting of positions, changes of course, and exit from the special area would be required of tows. Ground-based radar reporting points, entrance and exit reports, and powerful communications are required to make such centers effective. The area surrounding Locks and Dams 52 and 53 can be considered for such comprehensive control as an alternate to temporary construction. This type of activity may be applied intermittently in busy locations when heavy traffic builds up or bad weather appears. It may also serve to pass more traffic through very difficult and restrictive reaches of the rivers, not necessarily at locks.

At Barkley and Kentucky Locks, a communication feature utilizing a dispatching program and computerized data was considered to obtain optimum usage of both locks in the 1972 "Reconnaissance Investigation Improvements of Navigation Conditions in the Lower Cumberland-Tennessee Rivers Below Barkley Canal."[1] Using the program, the following four steps would be followed:

(a) Kentucky lockmaster would receive an information request from an Upper Ohio River tow nearing the mouth of the Cumberland River and bound for Nashville.

(b) The lockmaster would obtain the horsepower of the towboat, number and configuration of barges, and whether or not they are equipped with bow thrusters from the towboat operator.

(c) He would then check the number and size of tows awaiting lockage at Kentucky, flow releases from both Kentucky and Barkley, and the prevailing wind direction and velocity.

(d) Data would be fed into a computer and within seconds the lockmaster could tell the tow operator the approximate time it would take to reach the Cumberland end of the canal going through either of the locks.

Benefits accruing to navigation from the use of the computerized dispatching system would relate to a possible shift of traffic from the Tennessee River to the Lower Cumberland. The possibility of a shift would be enhanced since the information provided to the pilot would evaluate delays for both routes and remove some of the assumptions of risk and other uncertainties of the Lower Cumberland.

In terms of long-range planning, the use of better traffic monitoring and coordination could be greatly expanded and improved. The progress made by the railroads in recent years in the areas of automatic electronic traffic monitoring and control should serve as an example of some of the possibilities in this area. The future possibility of fully automated barge navigation certainly exists; it may be by total electronic control and guidance, or by underwater rails which may either physically guide floating craft or provide directional information to sensors which control the craft's steering. Such concepts may first be adopted in difficult river reaches and lock approaches. Continuous monitoring and updating of lock operation, fleet scheduling, and commodity flow could greatly increase the realized capacity of the waterways.

4. Combining Alternatives. Naturally, increased time savings can be achieved in many cases by providing two or more improvement alternatives simultaneously. Many of the alternatives, however, provide similar benefits or must be combined to provide any benefits.

For example, while an N-up/N-down policy can provide some savings at some locks, combining the N-up/N-down procedures with an extended guide wall can further reduce lockage time. Combining the N-up/N-down procedure with switchboat operation and mooring facilities can reduce lockage time even further. However, an extended guide wall is of little value without an N-up/N-down policy.

### (b) Improve Towing Industry Technology-Tow Configuration and Operational Patterns

Barge types, tow sizes and configurations used to transport cargo on a waterway are highly dependent upon the nature of the commodities moved over the waterway as well as channel constraints. Tow configuration is highly important for utilization of lock chamber area. On cases where lock size is not matched with chamber lateral size, capacity is severely reduced. In determining capacities, variations in tow size distribution and configuration are generally reduced to the more manageable parameters of average tow size and average load per barge.

These figures include both loaded and unloaded barges. On most waterways, more commodities are usually transported in one direction than the other. Since capacity is measured in terms of tonnage, the lockage of an empty barge detracts from the time the lock is available to lock loaded barges. In an extreme case where equipment is completely dedicated such that barges always return empty, lock capacity would be reduced by one-half. Thus, an evaluation of practical capacity must include assumptions as to tow size distribution, tow configuration and percent of empty backhaul.

At the low traffic levels, there are often inefficiencies in chamber usage because tows are often made up in the configuration which will speed transit between locks when lock delays are minimal. However, as traffic levels increase and delays at locks become longer, tow operators have an incentive to make larger tows which make better use of available lock dimensions even if transit times between locks increase somewhat. This is especially true where existing channel dimensions allow larger tow configurations than present lock dimensions.

On waterways which carry a wide variety of commodities in several types of barges, inefficiencies are often unavoidable. This is because locks which were originally constructed to pass one or two types of barges in specific configurations are now passing many more types of barges in configurations which were unforeseen at the time of construction of the lock.

It is highly likely that future barge types and tow configurations will continue to be a function of commodity movement, where not limited in growth by channel or lock dimensions. Even when the maximum accommodated tow size cannot be increased due to channel limitations, the average tow size may increase due to shifts in tow size distributions. It may also be possible to increase present and future lock capacities by the adoption of standardization measures, improved equipment utilization and in some cases improved traffic control.

The adoption of standardized lock sizes throughout the waterway system would provide incentive for barge companies to construct standard barges which would make optimum use of lock dimension. This measure is already widely adopted.

There is also the opportunity for the industry to improve itself through closer cooperation of individual operators. This could include assistance in the determination of the maximum practical size of tows to be used on the waterways as well as regulation of such size once it is determined. The Corps of Engineers could also take an active part in the regulation of tow sizes.

Another important gain of this type could be achieved through more cooperative scheduling and sharing of equipment through greater cooperation among different operators. The opportunity for this is evidenced by the two-way empty barge traffic noted on some reaches of the waterways system. Where empty barges are similar in these instances, there appears to be no reason other than lack of willingness to share equipment preventing the movement of only full barges of that type in at least one direction. The savings in wasted energy as well as the resultant share of gains to overall system efficiency should more than offset any associated increase in management costs. Along with this general idea goes the possibility that a sort of industry-wide clearing-house could be established to keep track of waterways equipment.

Several types of highly efficient automated cargo handling equipment have been put into use for handling bulk materials; further advances in this area can be expected. A major shift to containerization within the barge industry can also be expected, especially as increased emphasis on intermodal transportation coordination develops. Shipper ownership of barges, especially dedicated equipment, sometimes restricts their full time utilization, but this may be resolved through cooperative agreements. Another concept aimed at reducing empty barge traffic would be the development of hybrid equipment types where the nature of the cargo permits. As an example, the adaptation of some sort of inflatable bladder would allow a barge to transport liquids within the bladder on trips in one direction while hauling general dry cargo on the return trip.

An extension to this type of operation could require tows to break out barges and combine them with other tows in order to fill the lock chamber. To obtain any measurable benefit from this procedure, tows of the proper configuration must be present at the same time with enough time available to them prior to lockage to perform the reassembling necessary. Factors such as legal responsibility and insurance liability for the vessels and cargo may make implementing such a plan difficult, and the benefits would be limited.

### (c) Even Out Seasonal Distribution

There is a considerable effect on lock utilization due to the seasonal nature of commodity production, recreational use and the weather effects in the northern parts of the nation.

The effect is that while delays may occur during one month, the lock may be underutilized in other months. (This effect can be compounded if time devoted to recreational lockages corresponds to times of higher than average utilization by tows.) In these cases, the practical annual capacity, which is the summation of the practical monthly capacities, would be lower than if tow arrivals were evenly distributed throughout the year.

There would appear to be little potential to improve the seasonal nature of many commodity movements; however, it should be recognized that the practical annual capacity is lower where seasonality exists. There are several programs underway to extend the navigation season, as described in Section VI.

### (d) Separate Facilities for Recreational Craft

At places where recreational craft appear in considerable quantities, the introduction of separate handling facilities may be worthwhile. This is particularly true when the period of peak recreational demand corresponds to the period of peak commodity movement. Such separate facilities could be canvas slings or steel tanks to lift the craft from one level to another, separate small locks out of the main navigation channel, or an inclined plane moving lock such as has been used in Europe and in the early canal development in the United States. Separation of recreational traffic from towboat traffic would also appear to be a safety improvement.

Analysis of alternative small craft lifts were considered at Kentucky Lock and indicated that the inclined plane type would be more feasible from the standpoint of economics and operation. The inclined plane would be laid out on a steel superstructure that would carry the tracks on a uniform grade up the downstream side of the embankment to an elevation permitting adequate clearance over the railroad and highway. The superstructure would then convey the tracks across the top of the dam to a similar inclined plane on the upstream side. The boat would ride in a tub which would accommodate one craft 24 ft. or less in length. An inclined plane small craft lift able to accommodate one craft 25 ft. or less in length was estimated to cost $1,000,000 with $162,000 average annual O & M in 1971 dollars in the 1972 Cumberland-Tennessee Report. The cost would be roughly $1,600,000 with $260,000 annually for O & M in 1977 dollars.

As part of the 1977 "Recreational Craft Locks Study Stage II Planning Report," for the Upper Mississippi

River, several alternatives for providing separate facilities for recreational craft were considered. These included the following:

- a 110' x 360' auxiliary chamber.
- a 110' x 400' auxiliary chamber.
- a mobile floating lock.
- a small-scale steel lock.
- a differential railway lift.
- a steel tank on inclined rails.
- a steel tank lift crane.
- a mobile boat carrier.
- an inclined channel lift.
- an inclined plane lift.

Twenty of the Upper Mississippi River Locks have partial provisions for a second lock chamber, 100' x 360'. These provisions include an upper gate sill, upper portion of the river wall, and recesses in the intermediate wall for the lower mitre gate and gate machinery. Completion of this lock chamber would involve damming and dewatering the chamber area; removing accumulated debris and scour protection measures; constructing the river wall and chamber floor; removing and rehabilitating the upper mitre gate, and installing gates, valves, operating machinery, and appurtenances. Commercial traffic would also be able to use the new lock if the main chamber fails.

Eighteen of the 20 Upper Mississippi River locks with partial provisions for a second lock chamber include either a roller or tainter flood control gate adjacent to the river wall. At these 18 locks, the completion of a 400 ft. auxiliary lock would be possible. The 400 ft. chamber would be built by extending the river wall, Dam Pier 2, and possibly the intermediate wall downstream. A new mitre gate and tainter gate would be built in a monolith at the lower end of the chamber. The wall and pier extensions would be made from steel sheetpile cells. The extension of the dam pier and any extension of the intermediate wall would be a solid cell wall. The river wall would be steel sheet-pile cells spaced with 10 ft. clearances between cells. The monolith would be keyed into the intermediate wall and the dam pier extension. The area between the river wall and the dam pier extension would function as a flume to fill the lock chamber (the area between the river wall and the intermediate wall). Commercial traffic would be able to use the new chamber if the main chamber fails. As most barges on the Upper Mississippi River are 195 ft. long, the 110' x 400' chamber could hold six barges at one time compared to three barges in the 110' x 360' lock chamber.

A mobile floating lock is a self-contained, fully operational lock structure which can be positioned behind the existing upper mitre gates for the auxiliary chamber. This device would be approximately the size of three barges abreast (105' x 200'). The lock is a steel vessel similar to a dry dock. The sides would be floating tanks housing the operating machinery and controls. The upper and lower gates, integral parts of the dock, would be permanently mounted within the outside tanks. The upper and lower gate types have not been determined but would probably be submerging tainter gates or hinged drop gates, depending on the available depth in the chamber. Filling and emptying would be done through ports in the chamber floor.

The small-scale steel lock, 25' x 80', would be a doublewall steel structure of 3/8-inch plate with adequate diaphragms. The upper gate bay would include a vertical lift gate and an emptying system. The upper sill elevations would be set to accommodate sailboats up to 40 ft. long.

The 25' x 80' concrete and sheet-pile lock would be a concrete Uframe structure on a sand foundation. The structure would include a concrete upper gate bay monolith, a lower concrete gate bay monolith, and a lock chamber of sheet-pile walls with a revetment floor. The inside face of the cofferdam would act as the outer form for the concrete gate bay monoliths and would be constructed on site.

The differential railway lift consists of a steel tank (pan) carried up an inclined plane, over a crest, and down a reverse plane without being tilted. The pan is rigidly suspended from a carriage equipped with two sets of wheels to travel on a system of track elevated over the earth dike. The outer set of wheels maintains the pan horizontally while the carriage travels above the downstream face of the dike on a 2.5-horizontal to 1-vertical incline. The inner set of wheels maintains the pan horizontally while the carriage travels above the upstream face of the dike on a reverse 2.5-horizontal to 1-vertical incline. Both sets of wheels are used as the carriage travels above the crest on a double set of differential rails.

The steel tank on inclined rails consists of a steel tank (pan) carried up an inclined plane, rotated on a turntable, and lowered down a reverse plane. The pan is rigidly suspended from a carriage equipped with wheels to travel on a system of tracks elevated over the earth dike. The carriage would be propelled by wire rope cables wound on an electric-hydraulic winch mounted on a turntable on top of the dike. The turntable would rotate 180 degrees on a circular track to position the carriage for lowering the tank down the opposite side of the dike. No clearance problems are anticipated; however, the boats must depart stern first.

The steel tank lift crane is a steel tank (pan) supported by an overhead crane at each corner. The cranes lift the tank vertically out of the water, travel horizontally along rails across the dike, and lower the tank into the water on the other side. The crane trolleys on each rail are structurally separated from the trolleys on the other rail and each uses one drive wheel. The four lift motors and both crane drives are electrically synchronized, eliminating overhead clearance restrictions.

The mobile boat carrier system is based on a mobile boat carrier presently used for launching certain pleasure craft. The slings could be replaced with a tank (pan) for holding the boats being transported. The modified boat carrier would lift the tank out of the water, travel along a horizontal track across the dike, and lower the tank into the water on the reverse side. The carrier cross member would restrict the overhead clearance. Additional studies would be required to determine if the slings could be safely adapted to various boat shapes.

The inclined channel lift is similar to a device in operation at Montech, near Toulouse, France, connecting two canals. Two water levels in the canal are joined by a 480 ft. flume or concrete ramp having a U-shaped section. Water at the upper level is held back by a tilting gate. The boat on the lower level enters the approach basin. A large plate at the end of two arms is lowered into the water behind the boat, forming a wedge-shaped body of water in which the boat floats. The plate is then pushed forward by two 1,000 hp diesel-electric locomotives, one on each bank.

The inclined plane lift resembles Belgium's Ronquieres ship lift located near Brussels. This single structure is 4,700 ft. long and raises and lowers craft 225 ft. Two inclined planes raise and lower 1,500-ton barges 225 ft. in 22 minutes. Barges enter a tank (pan) with gates at either end and are pulled or lowered by six 125-kilowatt electric motors connected to the tanks by eight 2-inch-diameter cables. When loaded, the tanks weigh between 5,500 and 6,280 tons. Counterweights weighing 5,733 tons run up and down in recesses between the tank rails. The tanks measure 49' x 300' and are 14 ft. deep. Both tanks and counterweights ride springsuspended on flangeless wheels running on steel rails.

The version considered for the Upper Mississippi River would have one tank approximately 26' x 80' and maintain a depth of about four or five ft. The system would be operated by remote control from the main lock and monitored by television and two-way radio communication.

Cost estimates were provided for all of the alternatives considered for the Upper Mississippi locks in the 1977 Recreational Craft Locks Study, with the exception of the inclined channel lift and the inclined plane lift. The costs determined for the various alternatives and approximate 1979 updated costs are provided in Table III-15.

## Table III-15

## Cost Estimates for Providing Separate Facilities for Recreational Craft

| Facility | 1977 Cost |
|---|---|
| 110'x360' Auxiliary Lock | $ 14,240,000 |
| 110'x400' Auxiliary Lock | 29,000,000 |
| Mobile Floating Lock | 3,769,000 |
| 25'x 80' Steel Lock | 6,240,000 |
| 25'x 80' Concrete Lock | 5,470,000 |
| Differential Railway Lift | 2,000,000 |
| Steel Tank on Inclined Rails | 1,440,000 |
| Steel Tank Lift Crane | 840,000 |
| Mobile Boat Carrier | 580,000 |

### (e) Increase Lock Availability

In order to increase lock availability, measures must be employed to decrease the time a lock is not available to process tows. This includes time during which the lock is unavailable to tows because it is being used to process recreational craft. Currently, lock downtime is due to a number of factors; dredging in approach channels, routine and emergency maintenance, ice, high water, low water, fog and accidents. The subject of lock downtime is discussed in detail in Section VI. Measures to reduce approach channel dredging requirements (Improved Approach Channels) and methods to navigate in fog (Increased Use of Radar) were discussed as measures which increase tow speeds. Low water conditions can be mitigated (by additional dredging for instance) only within certain limits. High water accidents and emergency maintenance are occurrences which cannot be directly avoided. Routine maintenance is currently scheduled to interrupt traffic as little as possible. Therefore, the major measure which could be expected to considerably decrease downtime is associated with increasing lock availability during ice conditions.

Major increases in capacity can often be obtained at locks where the navigation season has traditionally been less than 12 months. This can be done by extending the usable period of the lock into the winter season.

The winterization of lock equipment, provision of de-icing equipment and provisions of air bubbler systems to keep floating debris out of critical locations have been used at several locks and are discussed further in Section VI.

Improving lock capacity by providing separate facilities for recreational craft are discussed in Subsection (d).

### (f) Increased Authorized Dimensions and Increased Reliability of Authorized Dimensions

The maximum dimensions of any lock in a natural channel are governed by the maximum size tow that can safely navigate a channel in the waterway. Provision of locks of larger dimensions is only practical if the channel dimensions, depth, width and bend radii are enlarged. In such a case, the cost of the new lock would include the cost of channel enlargement as well. The relationship between channel dimensions and the maximum tow size that can be accommodated are discussed in Section V.

On the majority of United States waterways, present channel dimensions can accommodate larger tow sizes than the associated locks. When this is the case, larger replacement locks can often be provided without incurring excessive costs for channel modifications. On the other hand, when larger channel dimensions are available, barge companies often try to utilize the maximum channel dimensions and process through the system locks in double cuts. This causes longer average delay times per tow.

It should also be recognized that actual channel dimensions can be highly variable. At any given time, the available draft in a channel and the width of the channel at that draft is a function of the flow at that time. Authorized dimensions, depth and width, occur on most waterways with a very high probability. The relationship between authorized dimensions and the flow at which they occur are discussed in Section IV. The capacity of a lock in terms of average load per barge is often dependent upon the ability of the barge industry to load to drafts which take full advantage of the available flow. Thus, on some waterways, the average load per barge can also be seasonal (i.e., higher during high flow periods). In this sense, increasing the probability that authorized dimensions are available can also increase lock capacity.

### (g) Structural Lock Replacement

The most obvious means to increase segment capacity is by construction of additional lock chambers or replacement of the existing locks with new, larger locks. This alternative measure to increase segment capacity is included because of the understanding that all of the measures discussed heretofore can provide only limited increases in practical capacity, on the order of a few percent in most cases. Lock replacement, of course, requires substantial initial costs and provides sharp increases in capacity. The necessary high investment costs and the long design and construction time required to make lock projects operational are major difficulties in providing economic justification for lock replacement or new construction. To reduce immediate capital investment and provide more gradual increases in capacity, it is feasible, in some cases, to provide several stages of lock replacement. For instance, first a recreational lift, then an additional chamber and finally, two chambers can be constructed sequentially.

### (h) Cost of Minor Structural and Non-Structural Improvements

While many of the costs associated with the various alternatives discussed herein cannot be directly evaluated, those costs directly associated with additions to the lockage facilities can be estimated.

The estimated annual operating cost of switchboats including depreciation, is shown in the following table. The table was taken from the document "Estimated Operating Costs of Towboats on the Mississippi River System, January 1978," distributed by Alex Shwaiko, Chief Planning Division, Directorate of Civil Works. The costs were converted to 1977 dollars by reducing the 1978 cost figures by 10%.

| Switchboat Horsepower | Total Annual Cost |
|---|---|
| 400- 600 | $ 274,500 |
| 800-1200 | 514,500 |
| 1400-1600 | 622,900 |
| 1800-2000 | 808,200 |
| 2800-3400 | 1,158,200 |
| 4000-4400 | 1,370,900 |

During switchboat tests at Locks No. 26, a 1,140 hp towboat was used.

Conventional tow haulage equipment costs $300,000 per lock equipped plus $3,900 per year for operation and maintenance according to the "Tow Haulage Feasibility Study," March 1979, of the Ozarks Regional Commission for the McClellan-Kerr Arkansas Navigation Project. This would be about $250,000 and $3,250, respectively, in 1977 dollars.

A traveling check post was installed at Guntersville Lock. Based on a length of rail of 470 ft. and the cost at Guntersville, a traveling check post was estimated to cost $75,000 in 1971 dollars (with $10,000 annual O & M) in the report "Improvement of Navigation Conditions in the Lower Cumberland-Tennessee River Below Barkley Canal,"[8] November 1972. In 1977 dollars, the cost would be about $125,000 (with $17,000 annual O & M) or about 270 per foot. For Locks 26 in the 1975 report on operational improvements, the cost of a traveling kevel was estimated at about $500 per foot of rail for either 600 or 1800 ft. alternatives. This would be about $550 per foot in 1977 dollars.

A 30 ft. diameter remote mooring cell was estimated to cost $50,000 in 1971 dollars in the 1972 Cumberland-Tennessee Report. The cost would be about $80,000 in 1977 dollars. In the same report, tie-off cells which serve the dual purpose of dissipating cross currents in the approach channel as a result of powerhouse and spillway operations, and of providing a waiting area for tows near the lock gates, were estimated to cost $1,120,000 in 1971 dollars for the lower pool. The cost in 1977 dollars would be about $1,800,000.

The cost of installing a closed circuit television covering the lower discharge area and indicators showing the exact position of all valves were estimated to be $46,000 with $6,000 annual O & M in 1971 dollars according to the 1972 Cumberland-Tennessee Report. The cost would be about $74,000 and $10,000 in 1977 dollars. The installation of a computerized dispatching system was estimated to cost $20,000 in 1971 dollars in the same report. This would be about $32,000 in 1977 dollars.

Three types of guide wall extensions were considered for use in the lower pool of Kentucky Lock in the 1972 Cumberland-Tennessee Report: a solid concrete approach wall, a concrete wall founded on steel sheet pile coffer cells, and a floating boom anchored at the end by cables attached to underwater anchors. The first alternative was estimated to cost $9,500 per foot of extension in 1971 dollars. The other alternatives were estimated to cost $4,000 per foot of extension in 1971 dollars. The costs would be about $15,300 and $6,400 per foot of extension, respectively, in 1977 dollars.

The cost of a sheet pile guide wall extension for the upper pool of Locks 26 was estimated in the 1975 report, "Evaluation of Operational Improvements at Locks and Dam

No. 26, Mississippi River.[9] The cost was estimated to be roughly $3,700 per foot of extension for the 15 ft. lift lock in 1974 dollars. This would be about $5,300 per foot in 1977 dollars. Delong piers were also examined for use as guide wall extensions in the upper pool at an estimated cost of roughly $1,700 per foot of extension in 1974 dollars. This would be about $2,100 1977 dollars.

In the Cumberland-Tennessee Report, the cost of a computerized dispatching system was estimated to be $20,000 in 1971 dollars. The cost would be about $32,000 in 1977 dollars.

The cost of providing recreational lockage facilities was presented in the section entitled "Separate Facilities for Recreational Craft."

## APPROXIMATE METHOD FOR ESTIMATING LOCK AND DAM CONSTRUCTION COSTS

This section presents a model for the determination of lock and dam construction costs.

The vast majority of locks built in the United States are built on the inland and intracoastal waterways. These are typically concrete monolith structures built specifically for shallow draft tows and are of primary concern in this report. Cost estimates for several embankment type locks for shallow draft tows on the Gulf Intracoastal Waterway West are also included. In addition, locks for deep draft vessels are used on the Great Lakes, on the Saint Lawrence Seaway and in the Port of New Orleans. Cost estimates for these locks, which are not so numerous, are also provided. Dam costs are presented in the final sections.

### (a) Lock Construction Cost Estimates for Inland Locks

1. Cost Estimating Methodology. Data on construction costs for 90 lock projects built in the last 30

years were collected, and the costs for 68 of them were used to develop generalized cost curves. The costs shown on the generalized curves represent the cost of construction of the lock (or locks) only at each project as a function of lift and foundation type. Costs of such items as lands and damages, relocations, reservoir clearing, dams, ponds, channels and canals, levees, recreation facilities, buildings, grounds and utilities, engineering and design, supervision and administration are not included. All structures, mechanical and electrical equipment, costs of cofferdams, control of water in the work area, and any appurtenances required for the lock (or locks) are included. It should be noted that at any particular site there are factors related to site and operational requirements other than lift and foundation type which can make cost for projects of similar dimensions vary significantly from locale to locale. For example, dewatering costs can be a significant construction cost and in no way related to lift or foundation type. The cost curves presented, therefore, reflect only average costs to provide rough estimates for the NWS project purposes.

The cost data used in this study were obtained from Corps of Engineers Division and District offices. All costs were adjusted to a 1977 base level by application of the ratio of 1977 construction cost indices to the indices that existed at the time (date) the cost estimates were made. Cost indices were obtained from the "Engineering News Record" magazine composite cost indices for similar type work. In some instances, costs represent contract bid prices and in some instances costs were obtained from general design memo studies or other recent engineering reports. The costs for 22 projects that were not used were rejected because of the following:

(a) inapplicability for use in a generalized study, i.e., the project had some special features that made it different.

(b) inability to verify the source and accuracy of the data.

(c) lack of accurate information on the date of the estimate.

Since most of the locks are of gravity construction founded on rock, there were few data to develop general costs of locks with different types of foundations. Of the 68 locks used, only 16 utilize either pile foundations or "u" frame design.

When competent rock on which to found lock walls is not available at a site, alternate methods of foundation construction are employed. In some cases, end-bearing or friction piles can be driven into the earth to support the gravity walls. In other cases, lock walls are constructed continuous with the lock floor and classified as "u" frame design. In still other cases, such as Overton Lock, the "u" frame lock is supported on piles. In any event, these alternative types of construction generally represent significant increases in construction costs. The figures presented in the following sections include separate curves for locks founded on rock and for locks with alternate foundation types.

2. Relationship Between Lock Costs, Lift, Size and Foundation Type. The construction cost of locks varies with the horizontal dimensions, the lift, the type of foundation required and, to some extent, the region in which the project is located. The curves developed in this study reflect the first three parameters, but do not include any factors to show regional effects. Such effects would have to include a detailed study of labor costs, material costs, transportation costs and general level of economic activities that existed at the time the project was built or studied. All of the above factors affect contractors' bid prices on a project. Also, to try to segregate out the differences in costs of building a lock of a certain size in one region compared to costs of the identical lock in another region would require a much larger array of data (projected costs) than could possibly be obtained. However, the problem of effects of regional differences in costs is not as serious as it appears. It must be recognized that the data (for the most numerous size locks) are from projects located on a number of different waterways in different regions of the country. Further, any new or additional projects are apt to be in these same general locations. Since the plotted points of the curves already represent a fairly wide geographic sampling, and the curves are drawn with due consideration for the diversity of samples, it is believed that a fair representation of the costs, nationwide, is portrayed. However, it is suggested in applying these curves to a

specific location, that the construction costs at that location be compared with national average costs and adjustments be made in accordance with this comparison. A set of Regional Cost Factors are provided for this purpose for all reporting segments in Table III-16. The factors were obtained from the "Engineering News Record" Magazine indices for similar type work.

As the lift of a lock increases, the construction cost increases because more concrete is required; usually, though not always, more excavation is necessary; and cofferdam and dewatering costs increase. Filling system costs may also increase rapidly if lifts exceed about 30 feet. Current Corps' criteria specify that locks must have filling times of 6-10 minutes for lowlift locks, 7-10 minutes for medium lift locks, and 8-12 minutes for high lift locks (EM 1110-2-1604), and that mooring line stress (as determined in a model) shall not exceed 5 tons. Twelve minutes may not be adequate for filling locks having lifts much greater than 100 feet. These criteria have been developed over the past 40 years of lock design and operation and have proven very satisfactory. The most simple system, the wall culvert side port system, can be used for lifts up to about 30 feet for 1200 foot locks and can be used for lifts slightly greater for 600 foot locks. For lifts in excess of 30 feet, more elaborate and costly filling systems have to be provided. The cost curves generally reflect this effect, so there is no specific need to show a breakdown of cost adjustments for filling systems.

Another source of general increase in lock construction costs during the past 15 to 20 years arises from: (1) greater emphasis on safety; (2) heavier usage - both in size and number of tows; (3) more automation to reduce personnel requirements; and (4) general advances in the state of the art. This last item includes more reliable foundation design, more durable structures, better quality mechanical and electrical equipment, and finally, communication equipment that was not available 20 years ago.

Attempts have been made to develop similar methodologies, (i.e., development of lock costs as a function of lift and size). However, their results were not found to be directly applicable and therefore were not used. (1) Lock costs as a function of lift and chamber size were developed as part of the recent Trinity River Project, Texas, General Design Memorandum, however, costs presented included more than just the cost of the lock

## Table III-16

## Reporting Region Cost Index

| Reg. No. | Segment Name | Description | ENR* Regional Factors | Relative Cost Factors |
|---|---|---|---|---|
| 1 | Upper Mississippi | Mineapolis, Minn. to mouth of Illinois River | 175 | 0.92 |
| 2 | Lower Upper Mississippi | Illinois River to Cairo, Ill. | 185 | 0.97 |
| 3 | Lower Mississippi | Cairo, Ill. to Baton Rouge, La. | 140 | 0.74 |
| 4 | Baton Rouge to Gulf | Baton Rouge, La. (including port) to Mouth of Passes | 125 | 0.66 |
| 5 | Illinois River | Chicago Ill. (Guard Lock) to mouth of Illinois River | 185 | 0.97 |
| 6 | Missouri River | Head of navigation to mouth | 165 | 0.87 |
| 7 | Ohio River | Head of navigation to Mississippi River | 160 | 0.84 |
| 8 | Tennessee River | Head of navigation to mouth | 130 | 0.68 |
| 9 | Arkansas River | Head of navigation to mouth | 145 | 0.76 |
| 10 | Gulf Coast West | New Orleans, La. to Brownsville, Tex. | 155 | 0.82 |

## Table III-16 (Continued)

## Reporting Region Cost Index

| Reg. No. | Segment Name | Description | ENR* Regional Factors | Relative Cost Factors |
|---|---|---|---|---|
| 11 | Gulf Coast East | New Orleans, La to Key West, Fla. | 115 | 0.61 |
| 12 | Tombigee-Alabama Coosa-Black Warrior River | Heads of navigation to mouth including Tennessee-Tombigee Waterway | 100 | 0.53 |
| 13 | South Atlantic Coast | Key West, Fla. to North Carolina/Virginia Line | 120 | 0.63 |
| 14 | Middle Atlantic Coast | North Carolina/Virginia Line to New York/ Connecticut Line | 175 | 0.92 |
| 15 | North Atlantic Coast | Hudson River: Waterford to mouth; New York/Connecticut Line to St. Croix River, Maine | 190 | 1 |
| 16 | Great Lakes/Saint Lawrence Seaway/ New York State Waterways |  | 195 | 1.03 |

### Table III-16 (Continued)

### Reporting Region Cost Index

| Reg. No. | Segment Name | Description | ENR* Regional Factors | Relative Cost Factors |
|---|---|---|---|---|
| 17 | Washington/Oregon Coast | Puget Sound to California-Oregon Line | 200 | 1.05 |
| 18 | Columbia-Snake Waterway/Williamette River | Lewiston, Idaho to mouth | 200 | 1.05 |
| 19 | California Coast | California-Oregon Line to Mexican Border | 215 | 1.13 |
| 20 | Alaska | | - | |
| 21 | Hawaii and Pacific | | 185 | 0.97 |
| 22 | Carribean, including Puerto Rico and Virgin Islands | | - | |

*From Engineering News Record, September 1979.

structure and the most common sizes, 110' X 600' and 110' X 1200' were not included and (2) Lock works, volume of concrete and excavation as a function of lock dimensions were developed in the paper "Technical and Economic Assessment of Waterway Dimension,"[10] by G.M. Matlin, Moscow 1959, but the lock dimensions considered were generally smaller and the lock lifts were generally higher than those on United States Waterways.

3. Future Lock Sizes. The maximum horizontal dimensions of any lock in a natural channel (river) will probably be governed by the maximum size tow that can safely navigate a channel in the waterway without incurring excessive channel work. While this does not mean that a lock must be sized to accommodate the maximum size tow, it does provide an upper limit. Since 1945 there have been over 100 new locks built. Most of these have been in three sizes: 110' X 600', 84' X 600', and 110' X 1200'. Other sizes have been built, but the common denominator of most of them is the width. Over the years the barge industry has built equipment to make up tows of various numbers of barges that will operate satisfactorily in 110' X 84', 86', and even 75' wide locks, so that barge sizes and lock sizes are in relative harmony. In the past, lock chambers with dimensions of 56' X 360' or 400' have been built, but they will probably not be built in the future as this size cannot provide enough capacity for a viable project. In summary, the sizes and combinations of sizes covered by the curves are believed to be the sizes that will be used in the foreseeable future. To move to another size would entail an enormous cost in towing practice and equipment.

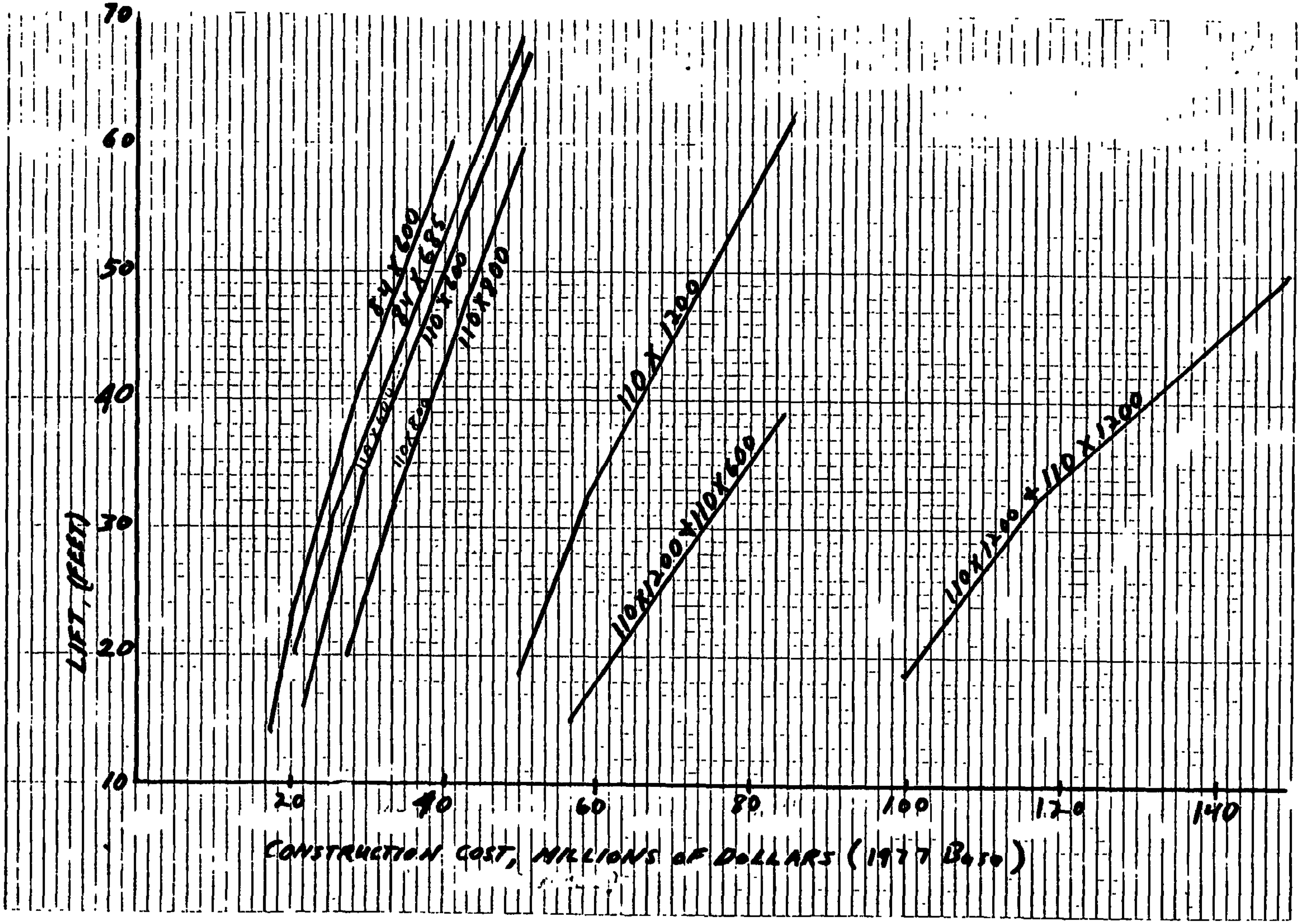
4. Cost Curves. Figures III-V and III-W present cost curves for locks as a function of lift for various sized locks founded on rock and/or soil (refer to item "Cost Estimate Methodology" for source of data, page 179).

Figure III-X presents the relationship between costs, length, and lift for 110 ft. wide locks founded on rock.

The cost of dual 1200 ft. locks on rock foundations are shown as approximately double the cost of a single 1200 ft. lock. First of all, the one lock project having dual 1200 ft. chambers is insufficient to establish a generalized curve. Secondly, it is felt that to eliminate congestion caused by adjacent chambers of such large size, future dual chambers will probably be separated

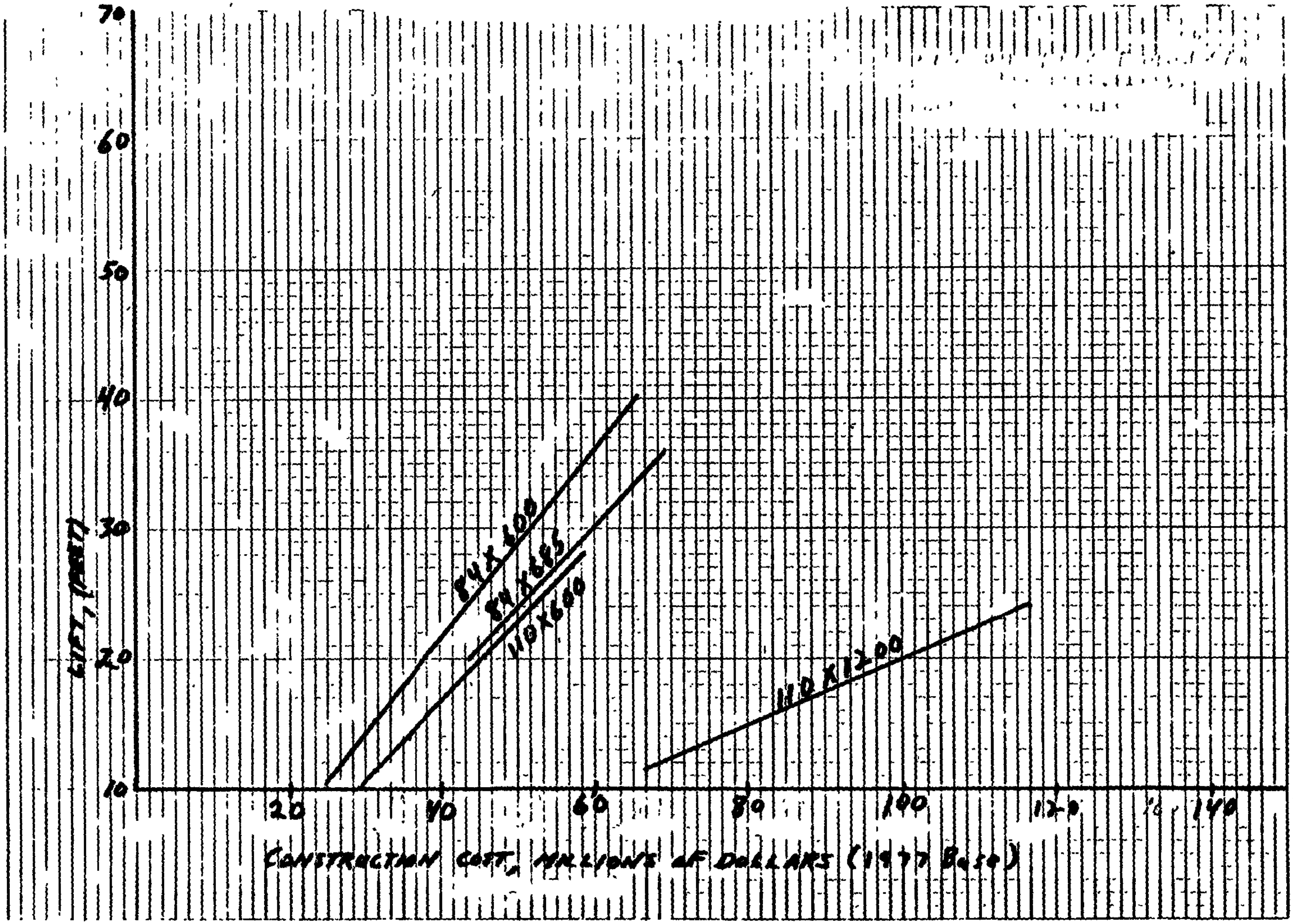
Figure III-V

Lock Costs on Rock Foundation



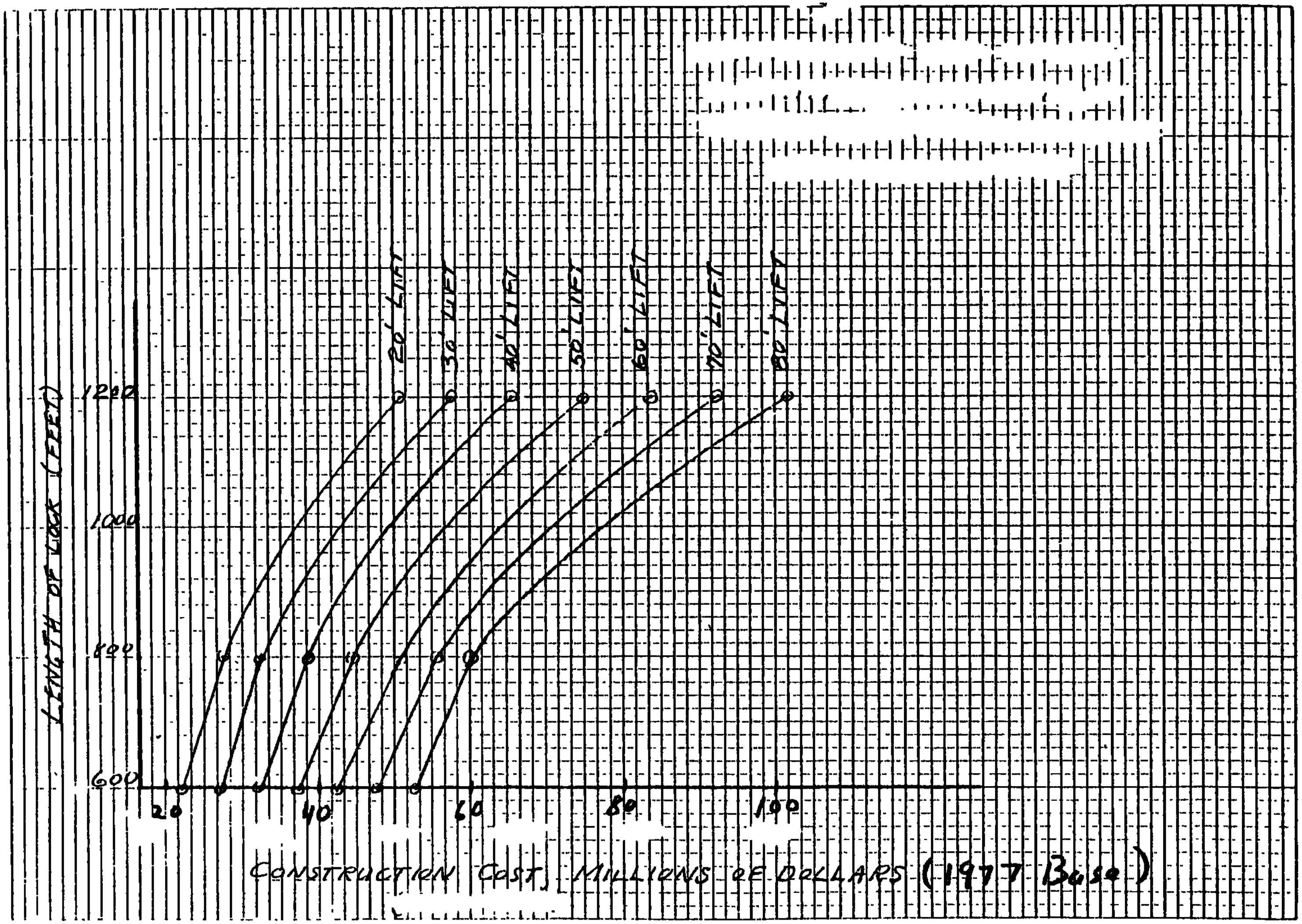
## Figure III-W

## Lock Costs on Soil Foundations



## Figure III-X

## Construction Cost v. Lift for Different Lengths of 110 Foot Width Single Locks Founded on Rock



whenever local conditions allow. For the development of the generalized curve this conservative assumption was used.

5. Embankment Locks. In additional to the concrete monolith locks constructed on inland waterways, at several locations on the Gulf Intracoastal Waterway West low lift (below 5 ft.) embankment locks have been constructed; specifically, Vermilion, Calcasieu and the Colorado River Locks. Because of the low lift and rather simple earthen design, the locks are relatively less expensive than concrete locks. While no locks of this type have been constructed in the last 25 years, an estimate of the cost of construction of this type of lock is available from the 1976 report "Vermilion Locks, Louisiana-Replacement, Design Memorandum No. 1." According to the report a 75' X 1200' lock of this type was estimated to cost $7,405,000 in 1975 dollars. A 110' X 1200' lock of this type was estimated to cost $11,939,000 in 1975 dollars. In 1977 dollars the costs would be approximately $7,930,000 and $12,790,000, respectively.

### (b) Construction Cost Estimates for Locks for Deep Draft Vessels

Locks for deep draft vessels currently exist on the Great Lakes, on the St. Lawrence Seaway and in the Port of New Orleans. Fortunately, recent cost estimates have been previously prepared for the replacement of all of the existing locks in the same manner as presented here for inland waterway locks (i.e., as a function of width, length, and accommodated draft). Because the estimates are for specific locks, the relationships developed are for the lift of the specific lock. Both rock and pile foundations are represented.

Estimated initial lock construction costs for 13 existing locks, one proposed lock and for two sites which combine the lift of two existing consecutive locks were prepared in the draft report "Great Lakes - St. Lawrence Seaway Locks Cost Estimate Study for North Central Division," dated October 1977. The locks range in lift from 2 to 91 feet. Costs were prepared for locks which could accommodate vessels of 940' X 105', 1200' X 130', 1300' X 130', 1300' X 175', and 1500' X 175' length and width and with drafts ranging from 25.5 to 36 feet. Costs are presented in Table III-17 in order of increasing lift. Costs are in September 1977 dollars. Lock walls were assumed to be of the gravity type founded on rock.

The estimating scheme used by the Corps in evaluating the costs required each lock to be separated into component parts. The parts were then individually estimated and regrouped to determine the total lock cost at each site. Sizing of some components was not possible by proportioning data from existing locks or previous studies. In these instances, sufficient design was performed to obtain an estimate. Major components designed were sector gates, bulkheads, mass concrete gravity lock walls, and approach guide walls.

Estimated initial construction cost curves for the replacement of Inner Harbor Lock were prepared by the New Orleans District in a memorandum dated March 1979. The lift of Inner Harbor Lock is generally less than 10 feet. The cost curves were prepared for lock widths ranging from 75 to 150 feet and for ship drafts ranging from 12 to 55 feet for a constant length of 1200 feet as shown in Figure III-Y. Costs were also prepared for 110 and 75 feet, widths for 12 foot ship drafts and lengths from 675 to 1200 feet, as shown on Figure III-Z. The cost shown in Figure III-Z can be adjusted to 1977 levels by dividing by a factor of about 1.2. The lock is not founded on rock and its site specific design for the low head makes its costs incomparable with other inland locks founded on piles.

### (c) Dam Construction Cost Estimates

1. Cost Estimating Methodology. The cost of dam construction was estimated in a manner very similar to the method used to estimate lock costs. The data collection efforts, however, were not as exhaustive.

## Table III-17

## Lock Estimated Initial Construction Cost
(thousands of dollars)

| | | Draft | | | |
|---|---|---|---|---|---|
| Location | Vessel Size | 24.5 | 28.0 | 32.0 | 36.0 |
| Iroquois, St. Clair River - 2', 5' Lift | | | | | |
| | 940x105 | 43,109 | 48,937 | 52,974 | 64,119 |
| | 1200x130 | 58,402 | 65,978 | 71,848 | 85,971 |
| | 1300x130 | 61,892 | 69,167 | 76,179 | 91,257 |
| | 1300x175 | 72,069 | 81,803 | 89,598 | 87,682 |
| | 1500x175 | 78,827 | 89,360 | 97,783 | 116,741 |
| Welland Canal "E" - 3' Lift | | | | | |
| | 940x105 | 42,747 | 48,095 | 52,111 | 62,657 |
| | 1200x130 | 57,605 | 64,933 | 70,173 | 83,971 |
| | 1300x130 | 61,007 | 68,786 | 74,329 | 89,028 |
| | 1300x175 | 70,316 | 79,373 | 86,319 | 103,232 |
| | 1500x175 | 77,237 | 87,099 | 94,628 | 113,081 |
| St. Lambert - 16' Lift | | | | | |
| | 940x105 | 57,237 | 62,879 | 67,320 | 79,518 |
| | 1200x130 | 77,338 | 84,737 | 90,738 | 106,641 |
| | 1300x130 | 81,998 | 89,850 | 96,202 | 113,127 |
| | 1300x175 | 95,279 | 104,426 | 112,299 | 131,243 |
| | 1500x175 | 104,821 | 114,766 | 123,314 | 144,013 |
| Soo - 21' Lift | | | | | |
| | 940x105 | 57,763 | 63,559 | 68,579 | 80,710 |
| | 1200x130 | 77,768 | 83,028 | 92,177 | 107,949 |
| | 1300x130 | 78,587 | 90,660 | 97,821 | 114,654 |
| | 1300x175 | 91,943 | 106,176 | 112,986 | 134,239 |
| | 1500x175 | 105,694 | 116,065 | 125,602 | 146,528 |
| Cote St. Catherine - 34' Lift | | | | | |
| | 940x105 | 68,642 | 72,175 | 81,207 | 93,522 |
| | 1200x130 | 91,828 | 101,210 | 108,499 | 124,489 |
| | 1300x130 | 97,522 | 107,517 | 15,256 | 132,332 |
| | 1300x175 | 113,063 | 124,612 | 134,044 | 153,503 |
| | 1500x175 | 123,821 | 136,346 | 146,554 | 164,935 |
| | 1500x175 | 170,989 | 186,948 | 200,535 | 22,452 |

SOURCE: Great Lakes-St. Lawrence Seaway Locks Cost Estimates Study.

## Table III-17 (Continued)

### Lock Estimated Initial Construction Cost (Cont.)
(thousands of dollars)

| Location | Vessel Size | Draft | | | |
|---|---|---|---|---|---|
| | | 24.5 | 28.0 | 32.0 | 36.0 |
| Welland Canal "B" - 81" Lift | | | | | |
| | 940x105 | 99,031 | 108,634 | 116,356 | 128,879 |
| | 1200x130 | 130,148 | 141,416 | 150,165 | 168,433 |
| | 1300x175 | 138,383 | 151,076 | 162,135 | 179,263 |
| | 1300x175 | 156,409 | 170,084 | 180,002 | 201,652 |
| | 1500x175 | 170,989 | 186,948 | 200,535 | 222,452 |
| Welland Canal "C" - 81' Lift | | | | | |
| | 940x105 | 99,427 | 109,022 | 116,641 | 129,296 |
| | 1200x130 | 130,670 | 142,950 | 152,814 | 169,005 |
| | 1300x130 | 142,936 | 152,045 | 162,565 | 179,822 |
| | 1300x175 | 157,209 | 170,798 | 183,088 | 203,340 |
| | 1500x175 | 171,763 | 187,736 | 201,165 | 222,313 |
| Welland Canal "D" - 81 Lift | | | | | |
| | 940x105 | 134,877 | 146,520 | 154,268 | 167,902 |
| | 1200x130 | 180,037 | 194,835 | 204,862 | 222,653 |
| | 1300x130 | 191,157 | 206,928 | 217,619 | 236,579 |
| | 1300x175 | 221,570 | 238,982 | 251,453 | 272,569 |
| | 1500x175 | 243,863 | 262,949 | 276,579 | 299,708 |
| Welland Canal "A" - 83' Lift | | | | | |
| | 940x105 | 114,540 | 125,719 | 131,486 | 143,080 |
| | 1200x130 | 151,447 | 165,564 | 173,398 | 190,588 |
| | 1300x130 | 160,968 | 176,034 | 184,269 | 202,692 |
| | 1300x175 | 183,173 | 200,036 | 209,776 | 230,315 |
| | 1500x175 | 200,815 | 219,291 | 233,914 | 252,611 |
| Eisenhower and Snell Combined - 91' Lift | | | | | |
| | 940x105 | 115,420 | 126,841 | 134,028 | 147,674 |
| | 1200x130 | 150,729 | 165,304 | 74,683 | 192,108 |
| | 1300x130 | 160,703 | 176,353 | 186,350 | 204,994 |
| | 1300x175 | 182,286 | 199,788 | 211,574 | 232,984 |
| | 1500x175 | 199,534 | 218,609 | 231,426 | 254,734 |

NOTE: September 1977 prices. All dimensions are in feet. All figures are in thousands of US dollars and do not include any contingencies.

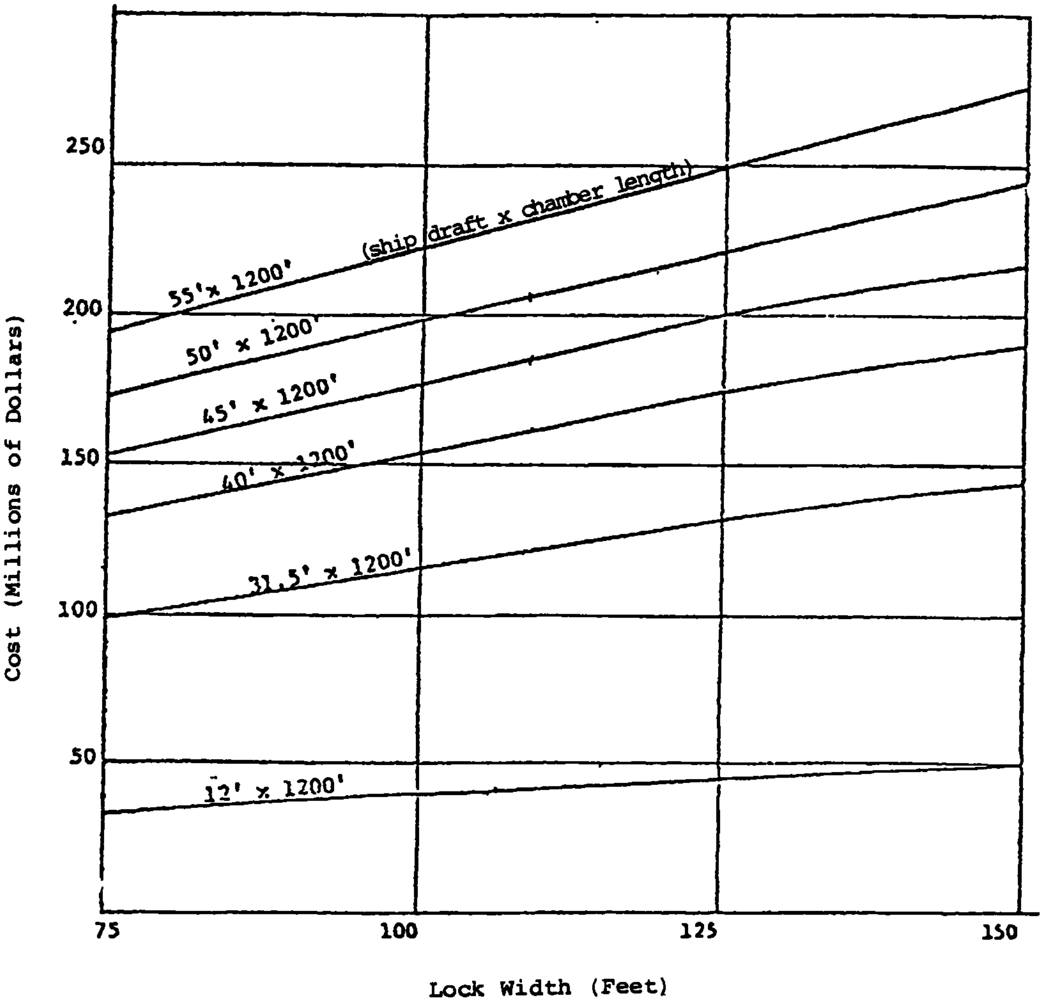
## Table III-17 (Continued)

## Lock Estimated Initial Construction Cost (Cont.)
(thousands of dollars)

| | | Draft | | | |
|---|---|---|---|---|---|
| Location | Vessel Size | 24.5 | 28.0 | 32.0 | 36.0 |
| Upper Beauharnois - 38' Lift | | | | | |
| | 940x105 | 86,930 | 94,929 | 100,427 | 113,890 |
| | 1200x130 | 114,343 | 124,990 | 132,412 | 149,656 |
| | 1300x130 | 121,691 | 132,882 | 139,690 | 159,010 |
| | 1300x175 | 143,301 | 155,993 | 165,384 | 186,343 |
| | 1500x175 | 157,118 | 170,909 | 181,078 | 203,881 |
| Lower Beauharnois - 40' Lift | | | | | |
| | 940x105 | 84,238 | 92,332 | 97,006 | 110,664 |
| | 1200x130 | 116,213 | 127,107 | 133,804 | 152,029 |
| | 1300x130 | 117,724 | 128,494 | 135,193 | 153,017 |
| | 1300x175 | 140,549 | 153,129 | 161,457 | 182,291 |
| | 1500x175 | 154,663 | 168,362 | 177,489 | 198,074 |
| Eisenhower - 42' Lift | | | | | |
| | 940x105 | 73,251 | 81,209 | 87,484 | 102,059 |
| | 1200x130 | 101,134 | 111,158 | 116,877 | 135,609 |
| | 1300x130 | 107,399 | 118,318 | 124,158 | 144,212 |
| | 1300x175 | 124,974 | 136,572 | 144,430 | 167,168 |
| | 1500x175 | 136,426 | 149,685 | 157,939 | 182,693 |
| Snell - 49' Lift | | | | | |
| | 940x105 | 69,398 | 75,408 | 79,910 | 91,319 |
| | 1200x130 | 91,696 | 99,595 | 105,479 | 119,993 |
| | 1300x130 | 97,147 | 105,558 | 111,815 | 127,531 |
| | 1300x175 | 109,361 | 118,591 | 125,865 | 143,550 |
| | 1500x175 | 120,209 | 130,249 | 138,143 | 157,468 |
| Upper and Lower Beauhornois Combined - 78' Lift | | | | | |
| | 940x105 | 128,174 | 140,281 | 147,596 | 162,548 |
| | 1200x130 | 170,959 | 186,099 | 197,446 | 213,063 |
| | 1300x130 | 181,445 | 198,068 | 207,770 | 226,840 |
| | 1300x175 | 211,090 | 229,682 | 241,223 | 262,843 |
| | 1500x175 | 226,450 | 251,727 | 264,268 | 287,863 |

## Figure III-Y

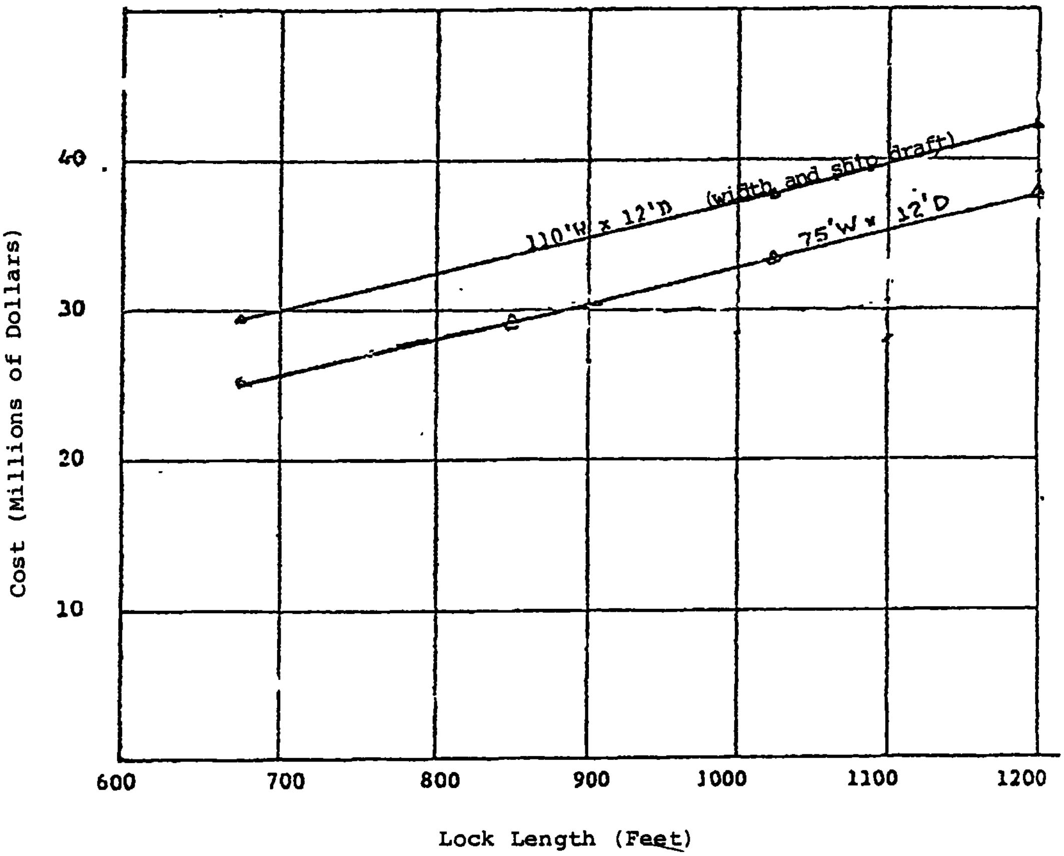
## Inner Harbor Lock Site
## Conventional Construction



SOURCE: Memorandum, New Orleans District, March 1979.

## Figure III-Z

## Inner Harbor Lock Site
## Conventional Construction



SOURCE: Memorandum, New Orleans District, March 1979.

Data on type of dam, construction costs, dam heights and dam lengths were collected from Corps Districts and Divisions. Of the costs gathered, 19 were used to develop generalized cost curves. The document sources of the dam costs are the same as for the associated locks discussed in the previous section. The costs shown on the generalized curves represent the cost of construction of the dam only at each project. All costs were adjusted to a 1977 base level by using the same indices as for locks. Regional costs can be adjusted in the same manner as for locks.

Many dams were not included because of the inapplicability of the costs or base data in developing generalized curves. The costs of the dams on the Ohio and Arkansas Rivers were used mainly because the dams are long enough so that miscellaneous costs associated with dam construction represents only a minor part of the total dam cost.

2. Relationship Between Dam Costs, Type of Dam, Dam Height and Dam Length. Most dams on United Inland Waterways consist of a gated spillway section and an overflow or non-overflow fixed weir section. The length of the gated spillway section required depends upon the flow which the dam must pass and should be estimated at each individual site. Overflow fixed weir sections are generally employed with lowlift locks where water is ponded with the limits of the flood plain and where the waterway is sufficiently wide so that gated or controlled sections are not required for the full length of the dam. Non-overflow sections are generally used to pond large areas of water beyond the limits of the flood plain, generally in conjunction with high lift and multipurpose type reservoirs. On most navigable waterways the gated sections dominate both the river width and the overall cost.

Because the length of the dam is dependent upon the width of the river, and the length of the gated or fixed weir sections is dependent on flow characteristics, the generalized cost curves are presented in terms of a cost per linear foot.

The generalized curves are presented in terms of total dam height (bottom of concrete to top of concrete). The total height of a dam is a function of the maximum height of water level fluctuations and the depth to bedrock at the site. The range of water level fluctuations is readily available for most United States waterways. For example, this type of information was recorded as part of the INSA Program. No apparent relationship could be found between dam costs and lift at a site. For gated sections, the total height of the gated section is selected to locate the gate machinery above a selected high water level so that the gates in their fully raised position will not interfere with flow during high flow periods. For example, the top elevation of the gated dams on the Ohio River range between 60 to 80 feet above normal pool elevations. On the McClellan - Kerr Arkansas River Navigation System the top elevation of the gated sections averages 40 feet above normal pool elevations.

The crest of an overflow fixed weir dam is generally placed at the desired upper pool elevation at low flow. The crest of a nonoverflow fixed weir dam is generally placed several feet above a specific high water level.

Curves are shown both for gated dams founded on rock and gated dams not founded on rock. As a general rule when the depth to rock is less than 40 feet below the gate sill, the concrete below the gate sill is usually extended to the rock surface. When the depth to rock is greater than about 40 feet, a minimum amount of concrete is placed under the sill and a sheet pile cutoff is provided. Designs, for gated sections, to provide positive cutoff and a stable structure that will not be undermined on foundations other than rook can substantially increase the dam cost.

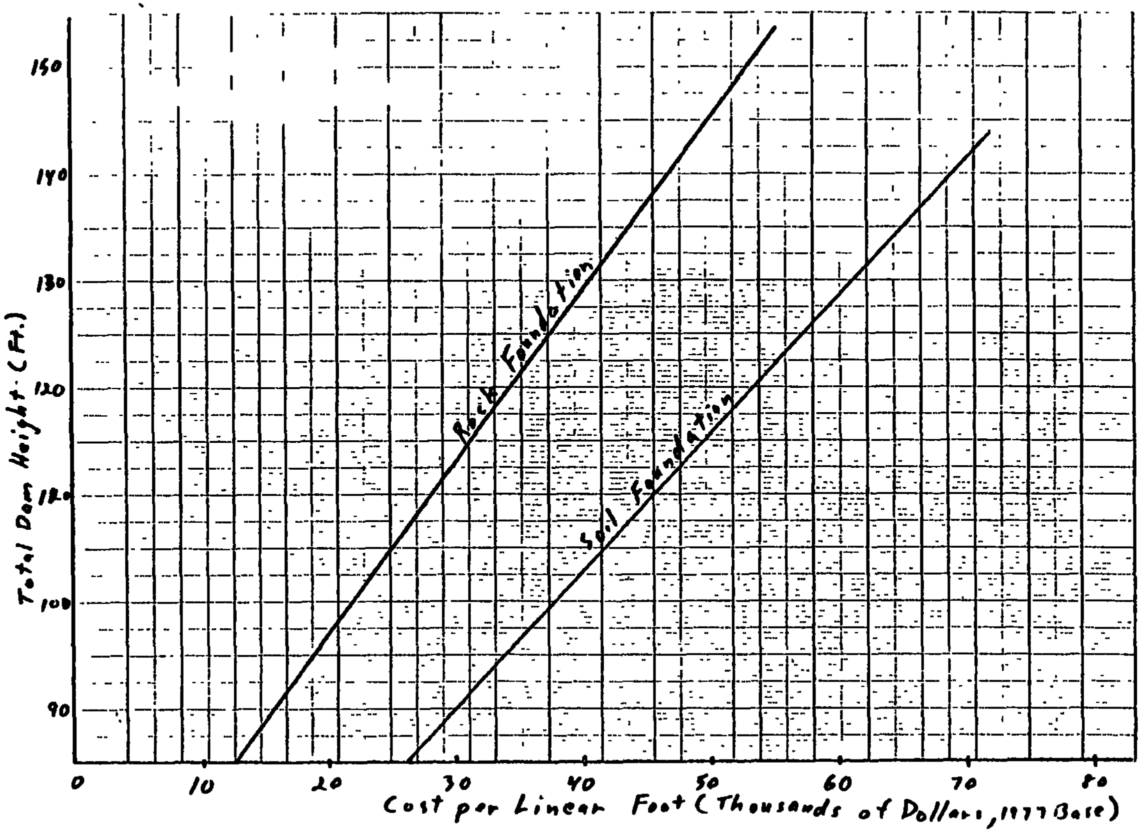
3. Costeurves. Representative cost curves for gated spillway and overflow fixed weir section dams are presented in Figures III-AA and III-BB.

While the dams shown on Figure III-AA were selected because they are of typical design, individual cost can vary considerably from the "average" curve. This is because gate sizes and thicknesses of concrete under the gate will vary from site to site with flow, water level fluctuations and depth to bedrock for a given total dam height. Figure III-AA represents "average" depth conditions between riverbed and bedrock.

For overflow fixed weir dam sections, a very wide variety of dam types and cross sections can be employed,

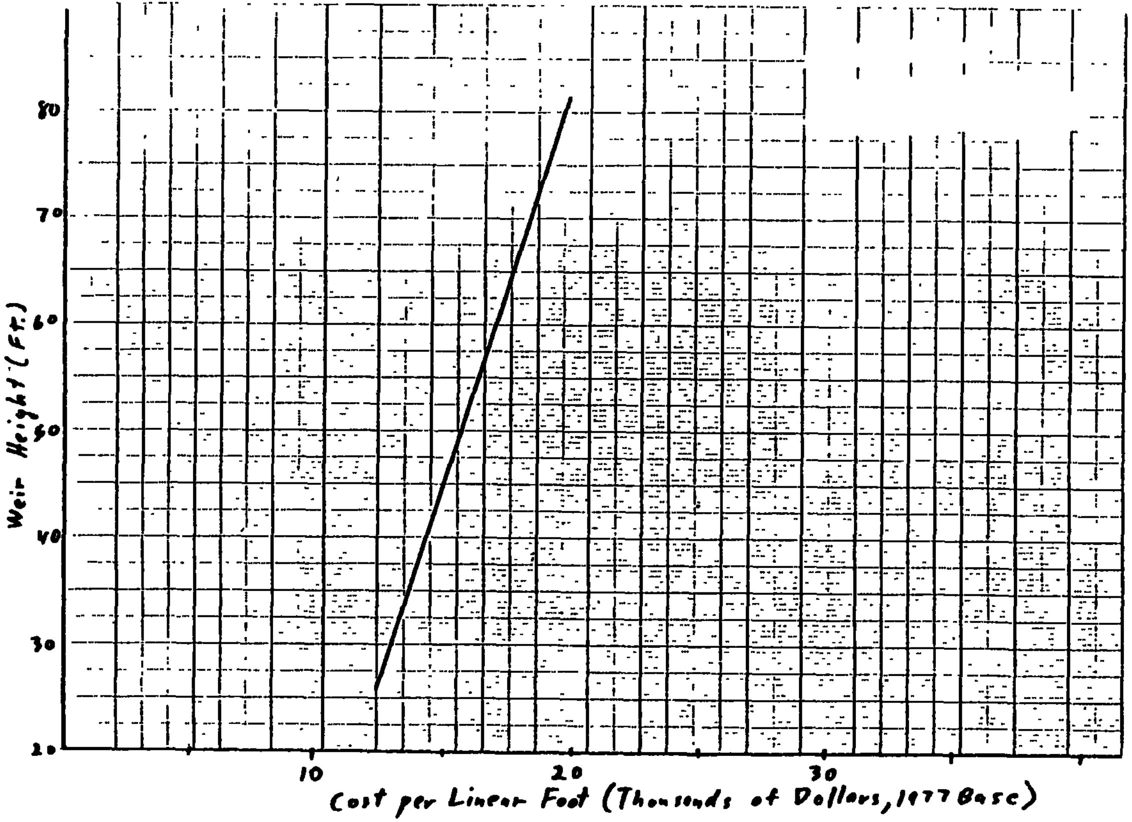
Figure III-AA

Cost of Dam Gated Spillway Sections



## Figure III-BB

Cost of Overflow Fixed Weir Dam (soil foundation positive cut-off provided)



ranging from protected embankments to cellular cofferdams to simple or highly elaborate concrete structures. While the curve of Figure III-BB was drawn based on three different fixed overflow weir types, the costs give an indication of the probable level of cost for this type of structure and are adequate for the purpose of this study.

Non-overflow dams are generally of the concrete gravity or earth fill types. A set of simplified cost curves for non-overflow dams is available from the Bureau of Reclamation for use in making reconnaissance estimates (Reclamation Instruction Series 150 - 10/27/69, Appendix A - Estimating Data).

### (d) Total Project Costs

The total project cost in addition to dams and locks, includes such items as lands and damages, relocations, reservoir clearing, powerplant, roads, channels and canals, levees, pumping plants, recreation facilities, buildings, grounds and utilities, engineering and design, and supervisor and administration.

The major cost items on new waterways are generally the costs of relocations, dams, locks and channels and canals. On waterways which are planned on rivers that are already equipped with dams, or for replacements, the major cost is generally for the locks. Engineering and design and supervision and administration account for about 10% of the total project cost.

Table III-18 presents an approximate breakdown of the total project cost attributable to locks and dams for several recent or planned waterways projects with new locks and dams. The breakdown is provided as an illustrative example. For the projects shown, lock costs account for about 30% of the total project cost for the canal section of the Tennessee-Tombigbee Waterway to 25% of the total project cost for the relatively wide Arkansas River.

## Table III-18

## Percentage of Total Project Cost Attributable to Locks and Dams

| Waterway | Locks (%) | Dams (%) | Locks & Dams (%) |
|---|---|---|---|
| McClellan-Kerr | 28 | 25 | 53 |
| Trinity River | 31 | 7 | 38 |
| Red River (Estimated) | 30 | 22 | 52 |
| Tennessee-Tombigbee | | | |
| River Section | 34 | 13 | 47 |
| Canal Section | 35 | 2 | 37 |

### MAINTENANCE AND OPERATION COSTS FOR LOCKS AND DAMS

Past operation and maintenance costs are consolidated in this section. They are used to develop typical lock and dam operation and maintenance estimates for the segments included in the National Waterways Study.

Operation and maintenance expenditures for over 100 locks and dams were compiled from various sources. The major sources of information were records obtained from the Operational Division, Office of the Chief, and reports and data supplied by District Offices. Different Corps Divisions and Districts have different methods of compiling and reporting O & M data, as became evident from "Operations" headings which imply operations and maintenance; O & M figures for the lock and dam, which include O & M of the pool or the entire waterway portion to the next dam upstream; maintenance data reported in terms of L.R.S. Job Order Costs, excluding "major plant costs;" apparent differentiation between normal maintenanoe, major maintenance, extraordinary maintenance, and emergency maintenance; O & M costs which are consolidated for a given district and then averaged over all locks in the district operation costs, including condition studies, etc.; and an unclear distinction between major maintenance and rehabilitation. Reliable data for analytical segments were not available, but enough data are available to reveal some basic correlations and to allow general conclusions to be drawn.

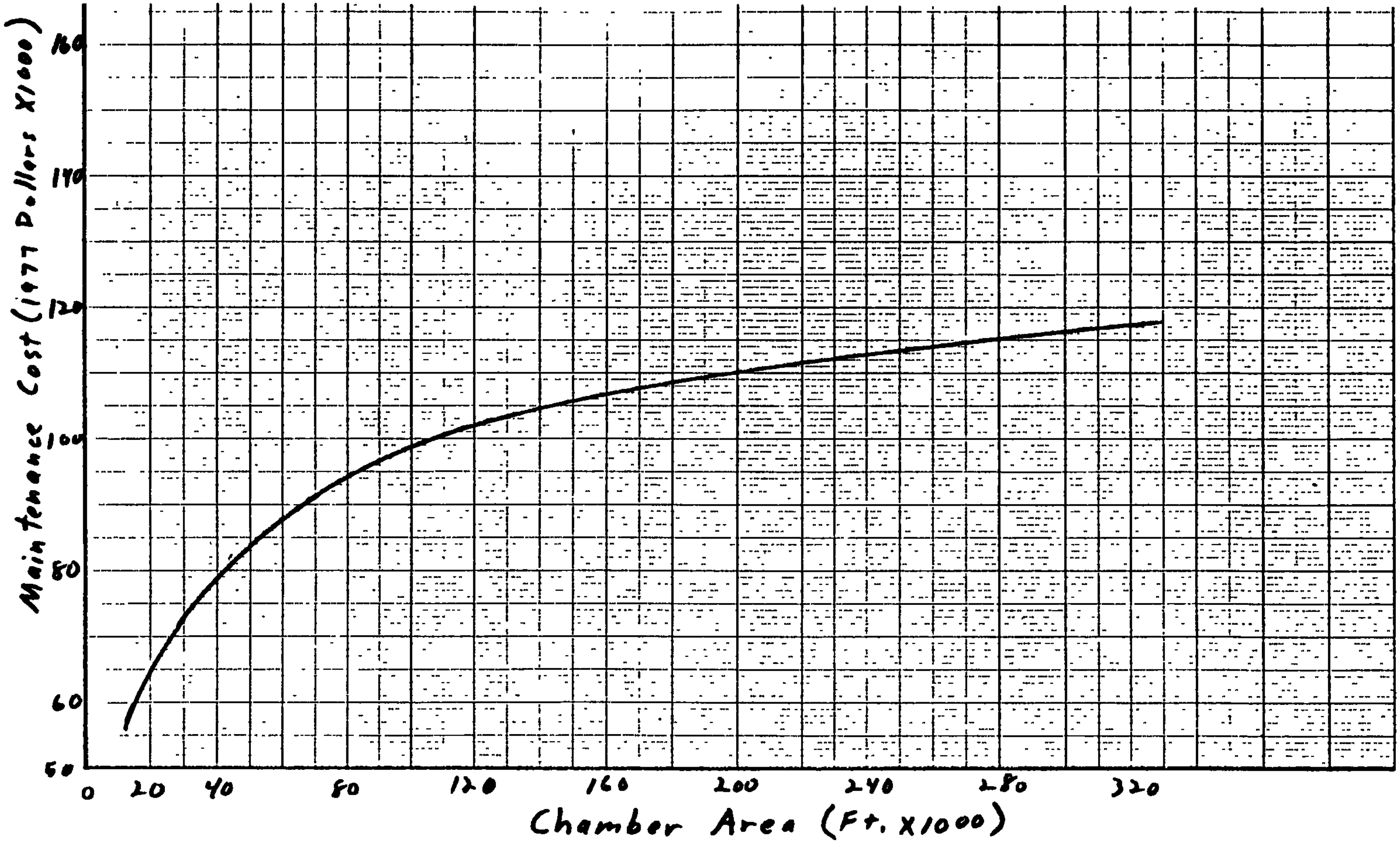
Unless otherwise noted, O & M data are annual values and represent a three to five year average, the last year of which is 1978. As used here, base operational costs encompass all non-dredging costs directly related to routine operation of a given lock and dam, including labor wages, utilities, and any "unanticipated" operational costs that may be expected to occur at least once during any given 10 year period. These costs exclude condition studies, environmental impact statements, etc., and any operational costs include all labor, materials, and supplies directly related to routine maintenance, repair, and cleaning of a given lock and dam and exclude any dredging or other pool-related maintenance. To this base maintenance cost is added the average yearly cost of major, extraordinary, unanticipated, or emergency maintenance, including periodic dewatering expected to occur during any given 10 year period, however, major or extraordinary maintenance include major rehabilitation as defined by the Corps, which usually incurs costs greater than $1,000,000 and occasionally above $10,000,000, and requires extended downtime for the lock.

Once data were collected for as many locks and dams as possible, correlations were sought between O & M costs and lockage, lock size, and lock utilization. Unfortunately, records of past major rehabilitations of locks are not readily available, so it as not possible to determine effective ages for most of the locks. In the absence of those data, O & M costs were plotted against actual age of locks and showed no significant correlation.

O & M costs were then plotted against lock size, expressed as lock surface area, or length x width. Various plots were prepared, including one searching for regional significance in the points plotted. A useful correlation, however, was found only between maintenance costs and lock size (Figure III-CC) and this relationship is described further below.

## Figure III-CC

O & M Costs vs. Lock Chamber Area (Total chamber area includes the area of both main and auxiliary chambers, where applicable.)



Finally, O & M costs were plotted against lock utilization, expressed as the number of lockages in 1976, which is an average year for the O & M data used.

However, a significant correlation was only found between operational costs and lock utilization, shown in Figure III-DD, which is described in more detail below. This correlation can be logically expected due to increasing utility requirements with increasing lock utilization.

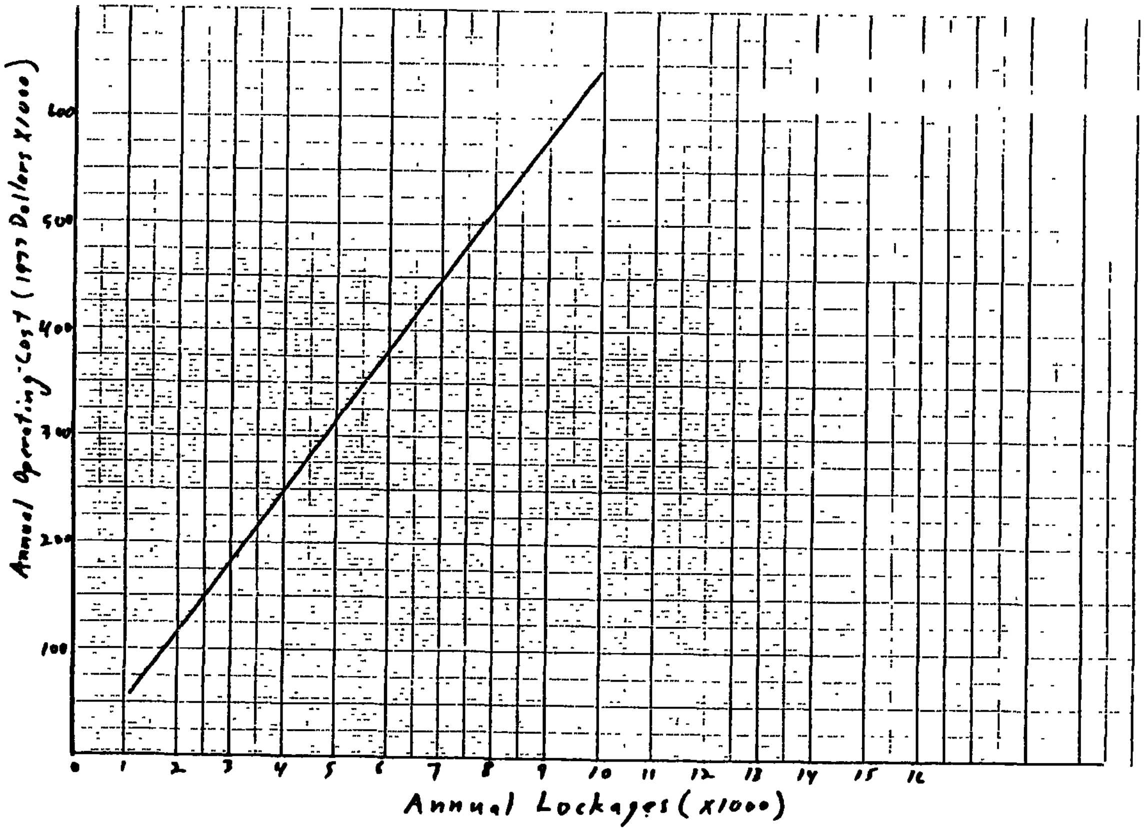
For the correlation between maintenance district cost and lock size, shown in Figure III-CC, data primarily from district interviews and records of the Operations Division of the Office of the Chief were plotted. These data can be made to exclude "major" and/or "extraordinary" maintenance because most of the data were specifically obtained to show costs under fairly consistent accounting methods. Additional major/extraordinary/emergency maintenance was found to vary from about $70,000 to $120,000 per year and is summarized along with annual maintenance costs from Figure III-CC in Table III-19. Although available data do not show a strong correlation, it was considered appropriate to group the locks into three size categories as they relate to maintenance costs. It should be noted that points for the Arkansas River locks and dams were determined to be unreliable for the purposes of this analysis since many of these O & M costs have been consolidated for all locks on the river and then divided evenly among the locks. The result is that all locks on the river share the burden of the O & M costs associated with the several hydropower installations and the correspondingly complex regulation procedures. A few other spurious points have likewise been ignored for similar reasons.

For the correlation between operational costs and lock utilization shown in Figure III-DD, all applicable data were plotted, although the Arkansas River points and a few others had to be ignored again for reasons mentioned above. The data presented in this figure were adjusted to 1977 dollars.

Since O & M costs are comprised primarily of labor costs and since labor costs are known to vary greatly from

## Figure III-DD

## Operating Costs vs. Lock Utilization



## Table III-19

## Annual Lock Maintenance Costs

| Lock Size (Ft.$^2$ Surface Area) | Yearly Maint. ($1977) | Add Major/ Extraord./ Emerg. Maintenance | Total Average Annual Maint. Cost ($1977) |
|---|---|---|---|
| less than 45,000 | $ 80,000 | 70,000[1] | $150,000 |
| more than 45,000 | 115,000 | 95,000 | 210,000 |
| multiple locks | 175,000 | 120,000 | 295,000 |

[1]NOTE: excludes major rehabilitation.

one area of the United States to another, it is necessary to account for these variations when developing O & M estimates.

The data points from which the correlations have been developed are predominantly North Central (Upper Mississippi River and Illinois River) and Ohio River (Ohio River, Cumberland River, Allegheny River) Division data, which suggest a, base labor index for O & M estimates from Table III-16 of between 156 and 175. Costs for other regions should be adjusted according to the cost indices provided in Table III-16.

A summary combining annual maintenance costs from Figure III-CC, additional major/extraordinary/emergency maintenance from Table III-19 and operation costs from Figure III-DD is presented as Table III-20. This table represents the total Operation and Maintenance costs for locks and dams for use in the NWS.

It must be remembered that estimates provided in Table III-20 are very general because of varying assumptions inherent in various classes of data, as mentioned earlier, and because of the many variables that have not been considered to affect O & M costs, including differences in

## Table III-20

## Estimated O & M Costs (in thousands of $ 1977) For Locks

| Annual Lockages | 45,000 | 45,000 | Multiple |
|---|---|---|---|
| 1,000 | 200 | 260 | 345 |
| 2,000 | 270 | 330 | 415 |
| 3,000 | 345 | 405 | 490 |
| 4,000 | 415 | 475 | 560 |
| 5,000 | 470 | 530 | 615 |
| 6,000 | 525 | 585 | 670 |
| 7,000 | 600 | 660 | 745 |
| 8,000 | 660 | 720 | 805 |
| 9,000 | 725 | 785 | 970 |
| 10,000 | 795 | 855 | 940 |

regulation procedures among locks, the skill level of the labor required to maintain older locks versus newer locks, the variations in lift among locks, the costs incurred due to ice conditions in some districts, the ratio of recreational lockages to commercial lockages, etc. It has been assumed that these factors are not generally important enough to significantly affect the estimates computed above, but the fact that they must have some effect cannot be denied.

## ESTIMATES OF MEASURES TO INCREASE LOCK CAPACITY BY NWS SEGMENTS

The purpose of this section is to lay out and define discrete phases of alternate measures to expand segment capacity. A segment capacity for one set of fleet mix, recreational demand and commodity flow pattern corresponding to existing conditions, is presented. The methodology used to develop these measures is presented first. The methodology used follows several steps which combine or bring together the efforts of previous sections.

Capacities introduced in this section assume the continuation of present lockage conditions. Preliminary capacity estimates for future replacement alternatives are presented to provide a starting point for final capacity analysis for the NWS Scenarios when the various factors affecting lock capacity (average tow size, average load per barge, etc.) become available. The methodology Lock Capacity and Demand," which will allow the rapid determination of capacities according to NWS Scenarios using the assumptions for capacity evaluation provided herein as starting conditions for adjustment.

It has been shown in previous sections that the capacity of a lock is related to:

1. the size of the lock (physical dimensions).

2. the time required to process a tow.

3. the distribution of tow sizes and tow configurations using the lock.

4. the percentage of empty backhaul.

5. time lock availability for commercial operation.

Any of the following improvements would therefore increase lock practical capacity:

1. decreased tow processing time.

2. improved tow arrangements and tow size distribution.

3. evened out seasonal distribution.

4. increased lock availability.

5. replacement lock provision.

6. improved channel by increased authorized channel dimensions, or increased reliability or authorized dimensions, and as a result, increased accommodated tow size/tonnage.

It should be emphasized that none of the possible improvements noted in this section are recommendations for implementation or meant to preempt other alternative solutions. Obviously, such conclusions could be reached only after detailed feasibility studies are undertaken. The improvements are shown only to indicate the areas where system capabilities may fall short of future demands on portions of the system, and indicate the order of magnitude of that short-fall. The possible improvements presented are for illustrative purposes of methods to expand system capabilities and are shown without prejudice toward alternative solutions that would require investigation during a feasibility study.

For the analysis to follow, only those segments having locks which may not have sufficient capacity to meet projected demands (determined in other NWS sections) are investigated.

### (a) Basis of the Selection of Improvement Options

A stepped method of increasing segment capacities is presented in the following section; however the basis of the selection of improvement options is outlined. First, the representative lock for each lock type on the segment is selected for improvement because it is the most constraining lock (lowest practical capacity) of its size in the segment. Second, low cost options, such as nonstructural policy options and the provision of separate facilities for recreational traffic, are evaluated for the representative lock to attempt to increase its practical capacity. Practical capacities for the representative locks are determined in the section entitled "Capacity and Delay for Existing Locks Under Present Conditions by NWS Segments," assuming present conditions (average tow size, average load per barge, etc.). Third, to provide further increases in segment capacity, the smallest locks in the segment are replaced by larger and larger locks until either all the locks in the segment are large enough to meet levels of demand determined in other NWS sections (in this manner the number of alternatives investigated could be kept from becoming unweidly.

Also, on major waterways, two chamber lock alternatives for two-way traffic were presented as a condition for a first rate waterway system.

1. NWS Analysis Segments Considered for Improvements to Increase Capacity. Based on the evaluation of present lock capacities provided in the section entitled "Capacity and Delay for Existing Locks Under Present Conditions by NWS Segments," a comparison was made between existing lock capacities under present conditions and levels of demand determined in other NWS sections. For the purpose of the preliminary estimate, demand was considered to be of uniform intensity throughout each segment. For segments where the present lock capacities are higher than expected levels of demand, no further evaluation to develop measures to increase segment capacity was deemed necessary. For segments where no locks are present, channel capabilities, in terms of tow transit/delay times will be discussed in Section V.

The NWS reporting region which, according to the above criteria, subject to evaluation to increase capacity are 1,2,4,5,7,8,10,11,12,18.

2. Basis of Estimates for Non-Structural or Low Cost Improvements. An evaluation of minor structural and maintenance improvements and of non-structural policy options which could be used to increase capacity was performed for the representative locks.

There is evidence that many of the minor structural and maintenance improvement options, in combination (discussed in previous sections) can provide significant increases in capacity at most locks. Using information developed in previous sections, it was possible to identify the areas of lockage operation where current inefficiencies exist for representative locks. The areas investigated include approaches, entries, filling/emptying systems and chamber interference. While it is not possible to state uncategorically that minor structural and maintenance improvements of the types discussed can feasibly be implemented at a given lock (at a reasonable level of cost), it is possible to estimate the approximate magnitude of increased capacity which would be obtained if lockage operation can be improved to normal levels.

For example, if at a given lock current approach speeds are very low (due to poor channel alignment, high crosscurrents, obstructions, etc.) then the possibility of improving the approach channel to allow greater tow speeds when traffic levels increase may exist.

The magnitude of the effect of potential improvements are indentified by segments in this section. Whenever possible, existing studies are used to identify both specific measures which can be implemented and the associated increase in capacity possible at specific locks.

Previously, locks were chosen as representative because they were the most constraining locks on the waterway. If it is found that a certain percentage increase in capacity is possible for a representative lock, improvements are therefore suggested for the representative locks and all the locks they represent to provide a uniform level of capacity.

It should be noted that the evaluations of the effectiveness of the above measures to increase capacity are based on data compiled in previous sections where not obtained directly from existing studies. As such, the accuracy of the estimates is only as good as the data used.

Non-structural policy options were investigated for each representative lock in order to assess the magnitude of capacity increases possible at each lock under present conditions by implementing the policy options.

Many of the non-structural policy options which were discussed in the section entitled "Alternatives Measures to Increase Lock Capacity," increase lock capacity by decreasing the processing time for double lockages. refer to that section for descriptions of Ready-to-Serve, N-up/N-down and switchboat alternatives). The maximum capacity increase which is attainable by this type of option is provided by invoking a Ready-to-Serve policy. The Ready-to-Serve policy completely eliminates double lockages by making each tow requiring a double lockage lock through as two consecutive single cuts in the same direction. At each of the representative locks a comparison was made between the time required for a double lockage and the time required for two consecutive single lockages in the same direction. Any time savings attained by the comparison multiplied by the current percentage of double lockages in order to obtain the potential increase in practical capacity at the lock under present tow size distrubution conditions due to invoking a Ready-to-Serve policy. Locks not currently experiencing double lockages are unaffected by this policy. Other policy measures using switchboats or traveling kevil were also assessed. Because these options are less costly than implementing a full Ready-to-Serve policy, they are selected for use where the additional increase in capacity due to a Ready-to-Serve policy would be small. The cost for full implementation of a Ready-to-Serve-Policy (5 switchboats) would be $2,000,000 to $3,000,000 per year.

Invoking an N-up/N-down policy can sometimes provide increases in practical capacity where approach distances are long or chambering times are short. For each of the representative locks, a comparison was made between the time required for a series of tows to transit the lock using a 1-up/1-down policy and the time required for a number of tows to transit the lock in one direction and then in the other direction. The comparison was made assuming the present tow size distribution at the locks. With locks currently experiencing double lockages, an extended guide wall was also assumed as a non-structural improvement so that much of the extra time for double lockages could also be eliminated, increasing the effectiveness of the N-up/N-down policy.

At locks which now experience multivessel lockages, increases in the average number of vessels per lockage can be expected at high traffic levels. For these locks, the increase in capacity which may be attainable by increasing the percentage of multivessel lockages is assessed.

In short, for each NWS segment, the capacity increase which can be obtained by the following measures was assessed for the representative locks:

(a) Minor Structural Improvements.

(b) N-up/N-down Policy.

(c) Use of Switchboats or a Traveling Kevil.

(d) Reduce Chamber Interference.

(e) Provide Separate Recreational Facilities.

(f) Increase Percentage of Multivessel Lockages.

If more than one of the above improvements are found to increase capacity at a given lock their effects are combined (as appropriate for the measures) and the increases in capacities shown in the appropriate tables are cumulative. Where several of the improvements are applicable at a given site, the order of their implementation shown in the tables to follow is somewhat arbitrary but a general rule of selection was followed whereby relatively inexpensive measures which provide major capacity increases are selected before relatively more expensive measures which provide smaller capacity increases.

On some segments both locks with and without auxiliary chambers exist. While non-structural measures may be effective in increasing the capacity of the locks with auxiliary chambers, the locks without the auxiliary chambers will generally be constraining, and therefore, non-structural measures can rarely be considered for the lock with the auxiliary chamber prior to replacement alternatives for the lock with the auxiliary chamber. It is further assumed that replacement locks will be constructed in a manner that will preclude the use of non-structural or low cost measures to increase capacity.

"Possible Improvements Under Study" as presented in the subsection entitled "Non-Structional or Low Cost Measures to Reduce Tow Processing Time," are not considered.

Table III-21 presents data which were used to evaluate non-structural alternatives for representative locks. Most of the data were obtained from 1976 PMS data compiled by ADPC and from limited observations where PMS data were unavailable. The percentage of double lockages and the extra.time required for double lockages was used to evaluate the increase in capacity possible by using a Ready-to-Serve policy. The time savings possible by using a 4-up/4-down policy was used to determine potential increase capacities possible for that option. Abnormal chambering times at two locks, Marseilles in Segment 9 and L & D 19 in Segment 1, were identified from the PMS data. Decreasing processing time at Marseilles Lock was considered under non-structural measures to increase capacity

# Table III-21

## Data Used to Evaluate Non-Structural or Low Cost Alternatives

| Analysis Segment | Representation Lock | % Doubles[1] | Extra Time For Doubles[1] | Time Savings Using 4-up/ 4-down[1] | % of Annual Time Devoted to Recreation | % of Peak Time Devoted to Recreation | Extra Chambering Time' | Extra Time for Approach/ Entry |
|---|---|---|---|---|---|---|---|---|
| | | | (min.) | (min.) | Main/Aux. | | (min.) | 2 |
| 1 | L & D 1 | 3 | 15.5 | - | 9/0 | $22^5$/0 | $0^6$ | 2 |
| | L & D 15 | 49 | 22.5 | 4.0 | 2/9 | $3^5$/25 | 1 | 15 |
| | L & D 19 | 0 | - | - | 5 | $11^5$ | 5 | 12 |
| | L & D 22 | 62 | 17.5 | 18.0 | 3 | $8^5$ | 0 | 2 |
| 2 | L & D 26 | 72 | 15.0 | 13.0 | 1/6 | 1/9 | 3 | 0 |
| 3 | L & D 27 | 0 | - | - | 2/6 | 3/7 | 0 | 0 |
| 9 | Marseilles | 29 | 22.0 | - | 6 | 11 | 6 | 0 |
| 11 | Emsworth | 13 | 19.0 | - | 1/11 | 1/21 | 4 | 0 |
| | Hannibal | 0 | - | - | 0/4 | 0/9 | 3 | 0 |
| 12 | Markland | 0 | - | 1.5 | 8/0 | 20/0 | 0 | 0 |
| | Gallipolis | 60 | 20.0 | - | 0/2 | 0/4 | 0 | 3 |
| 13 | McAlpine | 0 | - | 2.5 | 7/1 | 13/2 | 0 | 0 |
| 14 | Uniontown | 0 | - | 5.0 | 1/5 | 1/8 | 0 | 0 |
| 15 | L & D 52 | 0 | - | - | 2/3 | 2/4 | 0 | 0 |
| | L & D 53 | 56 | 9.0 | 8.5 | 2 | 2 | 2 | 0 |
| 16 | L & D 2 | 9 | 19.0 | - | 0/5 | 0/10 | $1^6$ | 0 |
| | L & D 4 | 3 | 10.5 | - | 0/4 | 0/9 | $0^6$ | 0 |
| | L & D 7 | 76 | 8.0 | - | 2 | 4 | 0 | 0 |
| 18 | Winfield | 91 | $25.0^7$ | 12.0 | 1/2 | 1/3 | 0 | 0 |
| 20 | L & D 1 | 0 | - | - | 1 | 1 | $0^6$ | 0 |
| 23 | Kentucky | 37 | 25.0 | - | 4 | 8 | 0 | 9 |
| | Pickwick | 45 | 28.5 | - | 6 | $13^5$ | 0 | 0 |

## Table III-21 (Continued)

## Data Used to Evaluate Non-Structural or Low Cost Alternatives

| Analysis Segment | Representation Lock | % Doubles[1] | Extra Time For Doubles[1] | Time Savings Using 4-up/ 4-down[1] | % of Annual Time Devoted to Recreation | % of Peak Time Devoted to Recreation | Extra Chambering Time[7] | Extra Time for Approach/ Entry |
|---|---|---|---|---|---|---|---|---|
| | | | (min.) | (min.) | Main/Aux. | | (min.) | |
| 27 | Bayou Sorrel | 25 | -[4] | -[4] | - | - | - | - |
| | Port Allen[2] | 0 | 18.0 | -[3] | - | - | - | - |
| 28 | Harvey[2] | 15 | 18.0 | - | - | - | - | - |
| | Algiers[2] | 10 | 18.0 | - | - | - | - | - |
| | Vermilion[2] | 0 | 18.0 | -[3] | - | - | - | - |
| | Calcasieu[2] | 0 | 18.0 | -[3] | - | - | - | - |
| 31 | Inner Harbor[2] | 15 | 18.0 | -[3] | - | - | - | - |
| 35 | Demopolis | 0 | - | - | 1 | 2 | 0 | 0 |
| | Oliver | 15 | 14.5 | - | 2 | 3 | 0[6] | 5 |
| | Bankhead | 0 | - | - | 2 | 2 | 0 | 0 |
| 51 | Bonneville[2] | 34 | 18.0 | -[3] | 3 | 8[5] | - | - |

1 Main chamber only
2 Data based on limited observations
3 Have used N-up/N-down policy
4 No data available
5 Peak recreation corresponds to peak commodity flow
6 Estimated
7 Includes a high percentage of lockages requiring three or more cuts

in the 1975 Duplicate Lock GDM. According to Chicago District operating personnel, improvements have not yet been implemented. Lock and Dam 19 has the only 1200' x 110' chamber in the segment, so that replacement of most of the other locks in the segment would be required before L & D 19 would be constraining even with the abnormally high filling time.

In this section, both minor structural and maintenance improvements and policy options are presented by segments. Most capacity improvements are additive and are presented as sequentially increasing capacity, (the increase in capacity due to individual improvements can then also be identified). The exception to this rule is the N-up/N-down policy which is not directly additive and, as such, is shown independently.

3. Basis of Replacement Lock Size Selection. The maximum lock size which was chosen for a segment was selected based on the maximum tow size and configuration that was considered to be able to safely transit the segment based on analysis in Section V of this report. Only standard lock sizes between the present lock size and the maximum lock size were considered. The largest lock size considered for any segment was 1200' x 110', the largest lock size currently in use on United States inland waterways. The maximum level of capacity provided for a segment was two locks per site of the maximum size considered possible for the existing channel or assuming modifications which are currently authorized or under consideration.

On a segment basis, consideration was also given to lock sizes which are already in existence. Emphasis was placed on providing uniform lock sizes throughout the segment. For the analysis of NWS Scenarios, consideration will be given to providing graduated lock sizes according to variations in demand at individual locks in a segment. For example, locks in upper waterways reaches often have lesser demand than in the lower reaches. A breakdown of demand by lock will be provided at a later date.

Since locks having dimensions smaller than 600' x 84' can provide only small increases in capacity compared to existing capacity, but could represent major costs, locks of these dimensions were not considered.

Under present conditions, the capacity of a lock includes both the main and auxiliary chambers. When lock replacement is required, maintaining the existing lock as an auxiliary chamber should also be considered if the extra capacity is needed and if the cost of maintaining or rehabilitating the existing lock is not too high-providing separate approaches can be maintained. In the following section, lock replacement is evaluated with and without maintaining the existing lock as an auxiliary chamber. This option is provided in the event it should prove feasible.

4. Basis of Channel Estimates. On many United States inland waterways, the present dimensions of the channel preclude safe navigation by fully loaded 15 barge tows. Tows consisting of fully loaded 15 jumbo barges make optimum use of a 1200' x110' lock chamber. Therefore, on these waterways, locks of smaller chamber dimensions are preferred unless channel dimensions (depth, width and bend radius) or other restrictions (such as bridges) can be economically enlarged.

An evaluation of the maximum tow size which can safely navigate the existing inland waterways was performed in Section V. In the following sections, evaluation of the availability of channel dimensions form the basis for the segment by segment estimate of alternative lock sizes. Areas where the possibility exists to enlarge channel dimensions and areas where authorized dimensions are not maintained are identified in Section IV. These possibilities are also discussed on a segment by segment basis in the following section.

Increases in the channel dimensions of width and bend radius generally increase the maximum of barges per tow that can safely navigate the segment. The related increase in capacity can then be calculated on the basis of increased average number of barges per tow. For example, when the Tennessee-Tombigbee-Waterway will be operational, the average tow size at Demopolis Lock is expected to be about 35% larger than at present. Consequently, the capacity of this lock will also be 35% higher than under present conditions.

An increase in channel depth, or in the reliability with which channel depth is maintained, provides the opportunity for tow operators to increase the average load per barge by loading to deeper drafts. Increases in the average load per barge can be calculated using the following formula:

$$\text{Projected average barge load} = \left( \frac{Dpr-De}{Dp-De} \right) \times \text{Present average barge load}$$

where, DPR = Projected average Tow Draft loaded
Dp = Present average Tow Draft loaded
De = Draft empty

The projected average tow draft loaded must be evaluated considering both the draft of barges originating on the deepened waterway and the draft of barges originating on tributaries which may have shallower depths. The effect of light or low density commodities should also be considered.

5. Basis of Capacity Estimates. In the previous section it was shown that the practical capacity of a given lock is highly dependent upon a number of factors including average number of barges per tow, average load per barge, percent of empty barges, tow processing time, the distribution of two arrival times, seasonality, and the time when the lock is unavailable to process tows.

The practical capacity determined for any given lock must include an assumption for each of the above variables and is only valid insofar as the assumptions are recognized. The determination of practical capacity is further complicated by the fact that many of the above factors are a function of the level of utilization of the lock. For example, as traffic levels increase the average number of barges per tow is also likely to increase as tow operators experience increased delays at locks and the auxiliary chamber of a presently underutilized lock, which is used mainly for recreational craft would serve commercial tows. Obviously, the present and future accommodated tonnage of this chamber would be quite different. The problem is especially acute in determining the capacity of replacement locks. If an existing 360' x56' lock with an average tow size of two barges is replaced by a 600'x 110' lock, the average number of barges per tow on the waterway will obviously increase. If it does not, the new capacity could be the same as or close to the old capacity.

The capacities which are presented in the following sections are for the purpose of providing a starting point from which actual capacity estimates can be made. As soon as the factors required to determine lock capacities for the various NWS Scenarios are defined, such as future average load per tow and average number of barges per tow for future commodity levels, the final capacities will be determined. The methodology developed in the section entitled "Sensitivity Analysis of Lock Capacity and Delay," will allow the rapid evaluation of practical capacity using the capacities presented herein as a starting point after the factors required to determine lock capacities have been defined.

As presented in the following sections, the capacities at existing locks were determined in the section entitled "Capacity and Delay for Existing Locks Under Present Conditions by NWS Segments," assuming present conditions. Capacities of replacement locks are presented as first estimates, based on lock classifications presented in the section entitled "Lock Classification" without precise evaluation of future average tow sizes and as such are semifictitious.

Capacity estimates include both main and auxiliary chambers. In some instances high interference between the chambers can decrease capacity. This factor must also be considered in future evaluations.

6. Increased Lock Availability. The evaluation of measures to decrease normal downtime at individual locks is beyond the scope of the study. Increases in capacity which may be attainable by lengthening the navigation season require an evaluation of winter traffic which has not yet materialized and therefore this study must rely on existing assessments.

7. Separate Facilities for Recreational Craft. Each representative lock was evaluated to determine any potential increases in capacity which could be obtained by eliminating recreational traffic. The amount of lock time devoted to the present level of recreational traffic was determined and the additional number of commercial tows which could be serviced during this period was used to determine the potential increases in practical capacity. Increased capacities associated with eliminating recreational traffic are based on the average annual time the

locks are currently devoted to recreation with the exception that the percent of peak time devoted to recreation was used when the peak recreation traffic and peak commodity movements coincided as indicated in Table lII-21. Whenever the elimination of recreational traffic provided a non-negligible increase in practical capacity under present conditions, this alternative is presented in the following section.

8. Basis of Cost Estimates. Cost estimates presented for the lock replacement alternatives considered in the following section were developed based on the lock cost estimating procedure presented in the section entitled, "Approximate Method for Estimating Lock and Dam Construction Costs." The costs presented are only for the locks and not total project costs. Some cost estimates were also taken from Corps studies which considered replacement alternatives similar to those presented in the following section.

Cost estimates for non-structural alternatives and for recreational locks are provided in the section entitlied "Alternative Measures to Increase Lock Capacity." In the following section, the cost of non-structural alternatives are designed as minimal compared with structural replacement.

Cost estimates for twin locks at the same site were taken as 90% of the cost of both locks combined to account for savings when constructing adjacent locks. Cost estimates for twin 1200' x 110' locks were considered to be twice the cost estimate for a single lock of the same size. This is because locks of such large size may not be constructed adjacent to each other in the future.

## (b) Reporting Region 1. Upper Mississippi River

1. Upper Mississippi River. This segment includes the Mississippi River (and tributaries) north of its confluence with the Illinois Waterway. Few capacity problems are currently being experienced in this segment, although some small delays are being incurred at locks on the southern portion of this segment. Possible expansion programs for this segment will be considered in the Upper Mississippi River Master Plan mandated PL 52-502.

Non-Structural Alternatives: At L/D 22, introduction of an N-up/N-down policy and use of switchboats or a traveling kevil would increase capacity by about 25%. Use of N-up/N-down and a Ready-to-Serve policy at L/D 22 would increase its capacity by about 40%. Use of N-up/N-down Ready-to-Serve policy and improvements to allow normal approach speeds would increase the capacity of L/D 22 by over 50%. At L/D 19, (1200' x 110'), which is currently the largest lock in the segment, a 40-45% increase in capacity may be possible by improving both approaches and by improving chambering time to provide normal approach speeds and chambering times. This alternative would not be required, however, prior to increasing the other locks on the segment to 1200' x 110' at which time L/D would become constraining. In Table III-21 the values include a reduction for present seasonality effects.

Most of the locks in this segment could increase capacity through the use of nonstructural policy alternatives. The two exceptions to this are Locks and Dam No. 19, a 1200' x 110' lock, and Locks and Dam No. 1. These locks presently have no double lockages and N-up/N-down policy would be of no value. The remaining locks could generally experience an increase in capacity of 10%-40% through the use of switchboats and/or an N-up/N-down lockage policy, depending on the physical characteristics of the lock and tows utilizing the lock.

Channel Improvements: Generally, the existing channel is adequate for present navigation purposes. There are, however 16 bridges which restrict traffic to one-way and 43 additional bridges which are restrictive. Reduced dredging programs due to environmental constraints resulted in depressed reliability of channel maintenance. However, although with restrictions, a 15 barge tow can be accommodated by the channel, it is unlikely that any channel modifications would significantly affect the capacity of the system without modification to the locks on the segment. The one exception is the channel in the extreme northern portion of the segment above Lock and Dam 2 which is only 200 feet wide.

Widening of the channel would allow larger tows to use the waterway reach without undue interference if demand were sufficient to warrant this step. Under present channel conditions, below Lock and Dam 2, lock sizes to accommodate 15 barge tows could be installed without requiring significant channel modifications to provide the increased segment capacity. Above Lock and Dam 2, the maximum lock size possible without increasing channel dimensions is a size which may accommodate 10 barge tows.

Two possible channel modifications have been investigated that could greatly expand the capacity of this segnent. One would be implementation of a 12 foot channel. This would reguire dredging, wideninq the river to 400 feet and lock modifications, and in the 1972 "Mississippi River-Illinois Waterway 12 Foot Channel Study"[11] was found not economically justified. Inplementation of this alternative would increase capacity of the segment by up to 37.5% because of the extra draft availability. The total cost of this alternative was presented as $1,068,055,000 and $77,471,000 in annual charges in the 1972 report. This would be about $1,950,000,000 and $140,000,000 in 1979 dollars. The second possibility would be extension of the navigation season of this segment. This segment is currently closed to navigation for approximately 2-3 months per year so that capacity could be increased approximately 25% by extension of the navigation season. According to the 1979 "Draft Economic Analysis of Year-Round Navigation on the Lower Mississippi River,"[12] the cost to extend the navigation season by four weeks at Locks 11 to 25 would be about $12,600,000. This includes both capital costs and O & M costs discounted over a 50 year period. The cost would be about $54,000,000 for year round navigation. Neither measure is sufficient by itself to increase capacity to meet year 2000 demand levels, although they would make significant contributions towards meeting these demands. It should be noted that these alternatives are prohibited by PL 52-502 until Upper Mississippi River Master Plan is completed.

Lock Replacement Alternatives: Projected demand on this segment will exceed its present capacity. While it is expected that traffic levels will decline as one moves northward on the segment, specific projections for each lock are not currently available. For purposes of this analysis it is assumed that each lock in the segment will be required to meet the projected demand for the entire segment.

Current main chamber sizes in Segment One are 600'x110'and 1200'x110' below Lock and Dam 1. Because the entire segment below Lock and Dam 2 is suffficiently wide to pass two-way traffic consisting of 15 barge tows, if is assumed that replacement lock sizes up to 200'x110' are possible. The present lock size at Lock and Dam 1 is 360'x 56'. Due to the narrowness of the channel in this reach maximun lock size without channel modification should not be much larger than the present size for two-way traffic. However, current practice in this reach provides for one-way traffic. Under this condition lock sizes up to 600'x110' could be employed. Table III-22 presents the minimum system practical capacity and the associated cost for various levels of improvements to increase segment capacity.

The possible alternatives selected are predicated on expanding the lock with the lowest capacity. Improvements 2 and 3 would provide recreation locks at the constraining lock L & D 1 and a minimum lock size of 600'x110' throughout the segment increasing capacity to approximately 29,000,000 tons annually. Improvements 6 and 7 are non-structural measures that could be implemented at minimal cost at the constraining lock L & D 22. Improvements 8 through 12 are structural measures that would increase the size of the navigation locks. Projected high demand requires a 1200'x110' lock with a 600'x110' auxiliary chamber throughout the segment except for Locks and Dam No. 1 where channel restrictions are limiting. The practical capacity at Lock and Dam 19 is 45,000,000 tons annually assuming the present average tow size. An annual tonnage of 77,000,000 at L & D 19 and throughout the system assumes a much higher future average tow size.

### (c) Reporting Region 2 - Lower Upper Mississippi

1. Lower Upper Mississippi River. The major capacity constraint within this segment is Locks and Dams No. 26. Significant delays have been experienced over the past decade and the existing structure was authorized for replacement with a single 1200'x110' lock in PL 52-502. Construction for the new structure commenced in Fy 1980, so that thisnew lock is considered as a component of the existing waterway.

Non-Structural Measures: While implementation of nonstructural policy alternatives of the authorized structure for Locks and Dam No. 26 would have only negligible

## Table III-22

## Potential Improvements to the Upper Mississippi River in Region 1 to Increase Capacity

| | Improvements | Minimum System Cap. (x$10^6$) | Cost (x$10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 14 @ L/D 1 | | |
| 2. | Provide recreation lock at L/D 1 | 17 @ L/D 1 | $ 2 | 0 |
| 3. | Provide 600'x110' lock at L/D 1 | 29 @ L/D 22 | $ 32 | 1 |
| 4. | Institute 4-up/4-down policy at L/D 22 | 33 @ L/D 22 | $ 0 | 0 |
| 5. | Provide switchboats or traveling kevils in addition (2). | 35 @ all 600'x110' locks | $ 1 | 0 |
| 6. | Provide recreation lock at all locks | 38 @ all 600'x110' locks | $ 33 | 0 |
| 7. | Provide 1200'x110' throughout, and dual 600'x110' at L/D 1 | 60 @ L/D 1<br>45 @ L/D 19<br>64 @ all other locks | $1,089 | 23 |
| 8. | Provide 1200'x110' throughout dual 600'x110' at L/D 1 and improve L/D 19 | 60 @ L/D 1<br>64 @ all other locks | $1,307 | |
| 9. | Provide 1200'x110' throughout, keeping existing 600'x110' chambers and 2-600'x110' at L/D 1 | 60 @ L/D 1<br>100 @ all other locks | $1,121 | 24 |
| 10. | Provide new 1200' and 600' throughout with 2- 600' at L/D 1 | 60 @ L/D 1<br>100 @ all other | $1,322 | 49 |
| 11. | Provide 2- 1200'x 110' throughout, keeping existing at L/D 19 | 60 @ L/D 1<br>128 @ all other locks | $2,187 | 49 |

impact on lock capacity, several of these alternatives are in use at the existinq structure to allow more efficient lock utilization. The alternatives involved include extended guide walls, a 4-up/4-down lockage scheduling sequence, the use of switchboats and operating policies that discourage knockout and setover lockages. These procedures have proved quite effective and have already allowed the lock to process more tonnage than the estimated capacity of the lock without any non-structural alternatives undertaken.

Prior to implementation of these procedures, their possible effects were analyzed in two studies. One by Peat, Marwick, Mitchell & Co., the other by the United States Arny Corps of Engineers. Both studies indicated that increases in capacity on the order of approximately 20% could be realized with these alternatives. Recent experience would appear to support these conclusions, as the capacity of 64 million tons was developed based on the 4-up/4-down policy presently in use.

Channel Improvements: The channel within this segment is adequate for current navigation requirements and is generally well-maintained. Channel depth and bend radii present no problems for navigation and it is not envisioned that modifications to the channel can increase the capacity of this segment without modifications to the locks on the Mississippi River and the Illinois Waterway.

As with Segment 1, the evaluation of a 12 foot channel was undertaken in the Mississippi River-Illinois Waterway 12 Foot Channel Study",[13] for this segment in combination with Segment 3. The project, as evaluated, assumed that a 12 foot channel was already in existence throughout this segment and also assumed that twin 1200 foot locks would also be operational at Locks 26. Undertaking the project only for Segments 2 and 3 was found not to be economically justified in the 1972 study. However, in conjunction with a 12 foot channel on Segment 5, Illinois Waterway, the increased channel depth was found to be economically justified and could increase capacity by up to 37.5%.

The study "Evaluation of Operational Improvements at Locks and Dam No. 26, Mississippi River,"[14] addressed several minor improvements including: improvement of lock equipment, provision for hiring additional lock staff and greater use of the auxiliary chamber. Greater use of the auxiliary chamber was to be achieved through scheduling procedures. The study concluded that each of the additional improvements noted will, at best, provide only a few minutes of reduction in tow processing time." Subsequent evaluation indicates that by improving the lock entries and by improving chambering time to provide normal entry speeds, chambering times would allow only about a five percent increase in capacity.

Lock Replacement Alternatives: Rather clearly, the traffic levels on Segment 2 that will materialize are dependent on the type of improvements made at other locations. However, it must be noted that the potential capacities without structural improvements of the segments above and below Segment 2 exceed the capacity of the authorized structure at Locks and Dam No. 26. Thus, while the increase of lock sizes of this segment is not independent of decisions made at other facilities, it would appear that independent of these decisions, sufficient year 2000 demand will materialize to require additional capacity of this segment.

Projected traffic levels exceed the estimated capacity of the authorized structure at Locks and Dam No. 26. The rather obvious alternatives for additional locks would be a recreational lock, one 600'x110' lock or one 1200'x110' lock. The addition of a recreation lock would provide a negligible increase in capacity.

Table III-23 presents the Locks and Dam No. 26 practical capacity and the associated costs for various levels of improvement. The capacity of the existing 600'x 110' lock is shown as 64,000,000 tons annually as the practical limit (90% of theoretical maximum) adjusted for the seasonality effect and including all of the nonstructural improvements mentioned. The other capacities do not include non-structural policy improvements. The costs for the 1200'x110' lock and for the 1200'x110' plus 600'x110' lock were taken from the 1978 Locks and Dam No. 26 Design Memorandum and updated to 1977 levels. Total project costs are about 50% higher.

To meet any of the projected year 2000 demands addition of at least one 600'x110' lock is necessary. This will only meet the low demand and would require an additional expenditure of about $78,000,000. Addition of a second 1200'x110' would allow the expected year 2000 demand to be met, but is still insufficient for the high demand. This structure would require an additional expenditure of about $146,000,000.

Table III-23 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

Table III-23

Potential Improvements to the Lower Upper Mississippi in Segment 2 to Increase Capacity

| | Improvement | Minimum System Capacity $(x10^6)$ | Cost $(x10^6)$ | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None - Present 600'x 110' lock using 4-up/4-down policy | 64 | $ 0 | |
| 2. | Provide recreational lock | 65 | $ 2 | |
| 3. | Provide authorized 1200'x110' lock L/D 26 | 77 | $146 | 1 |
| 4. | Provide 1200'x110' lock and a 600'x110' additional lock L/D 26 | 120 | $224 | 2 |
| 5. | Provide 1200'x110' additional lock L/D 26 | 154 | $292 | 2 |

2. Middle Mississippi River. The segment includes the Mississippi River and tributaries between its confluence with the Missouri River and its confluence with the Ohio River. The only navigable tributary is the Kaskashia River, which is controlled by a lock and dam and is not expected to experience capacity problems. The remainder of this segment is lock-free south of St. Louis, with Locks and Dam No. 27 located in the northern portion of the segment, the only lock in the segment.

Non-Structural/Alternatives: Like the authorized structure for Segment 2 the lock size at Locks and Dam 27 on Segment 3 limits the effectiveness of non-structural policy measures. While some increases in capacity might be possible, the presence of two large locks and their location on a canal make most of the non-structural and minor improvement alternatives superflous.

Channel Improvements: The channel in this segment is generally quite adequate for navigation and well maintained. Some low-water problems have occurred but these have mostly effected access to the channel rather than the channel itself. Channel depth and bend radii present no navigation problems.

As mentioned for Segment 2, the evaluation of a 12 foot channel was undertaken in the 1972 "Mississippi River - Illinois Waterway 12 Foot Channel Study"[15] in combination with Segment 2. The project as evaluated assumed that a 12 foot channel was already in existence in Segment 2 and that twin 1200 foot locks at Locks 25 were operational. The project included regulation works and dredging below Locks 27 as well as widening to 400 feet. The total cost was presented as $405,387,000 and annual harges were presented as $24,604,000 in the 1972 study. This would be approximately $740,000,000 and $45,000,000 in 1979 dollars. The capacity of the segment could increase by up to 37.5%.

Lock Replacement Alternatives: Projected demand for this segment will exceed the capacity of the segment. Non-structural alternatives offer little hope of significantly increasing capacity. Similarly, the low percentage of recreational lockages, make the addition of a recreational lock of little use. The only viable option is the replacement of the existing 600'x110' lock with an additional 1200'x110' at a cost of about $153,000,000.

Table III-24 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

3. Baton Rouge - Morgan City Bypass. This segment is the Port Allen-Morgan City Bypass, connecting the Mississippi River at Baton Rouge with the GIWW at Morgan City, Louisiana. Tow locks are present on this segment. Port Allen lock has a 1198'x84' chamber and Bayou Sorrell lock at 760'x56' chamber.

## Table III-24

## Potential Improvements to the Middle Mississippi River in Region 2 To Increase Capacity

| Improvement | Minimum System Capacity $(x10^6)$ | Cost $(x10^6)$ | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 120 | \$ 0 | |
| 2. Provide recreation lock | 124 | \$ 2 | |
| 3. Provide 2nd 1200'x110' lock | 154 | \$153 | 1 |

### (d) Reporting Region 4 - Baton Rouge to Gulf

Non-Structural Measures: Port Allen lock is currently using a N-up/N-down policy. Analysis of available data reveals that an increase in the present percentage of multi-vessel lockages could increase capacity of Port Allen by about 10%. Measures to reduce approach and entry times could increase capacity at Port Allen by an additional 15%.

Channel Improvements: Channel dimensions on this segment restrict tow size to five barges, depth is adequate for 9' draft and bend radii sufficient for navigation purposes. Without additional channel width, utilization of the existing locks may be hindered due to restriction on tow size.

Lock Replacement Alternatives: Bayou Sorrell will not be sufficient to meet projected demands during all portions of the year although it is open-pass much of the year. Increasing the size of Bayou Sorrell Lock so that it is consistent with Port Allen Lock is adequate to meet demand if channel restrictions do not present any problem. It should be noted that due to the number of petroleum barges, and generally the large variation in tow and barge sizes utilizing this segment, a lock width apparently exceeding channel width may be reasonable to allow for partial chamber packing resulting in better utilization of the lock.

## Table III-25

## Possible Improvements to Baton Rouge-Morgan City Bypass in Region 4 to Increase Capacity

| | Improvement | Minimum System Capacity $(x10^6)$ | Cost $(x10^6)$ | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 22 @ Bayou Sorrell | $ 0 | |
| 2. | Provide 1200'x84' lock at BayouSorrell | 29 @ Port Allen | $92 | 1 |
| 3. | Increase % of Multivessel Lockages | 32 @ Port Allen | $92 | 1 |
| 4. | Improve Approach and Entry in Additiion to (3) | 37 @ Port Allen | $92 | 1 |

Table III-25 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

### (e) Reporting Region - Illinois River

Segment 9 represents the Illinois Waterway. There are currently seven locks on the waterway. Some of these locks are experiencing increasing delays. "Duplicate locks", (size 1200'x110') on the Illinois Waterway were authorized in the River and Harbor Act of 23 October 1962, although construction has not yet started on this project.

Non-Structural Alternatives: According to the NWS Inventory of Physical Characteristics, Marseilles Lock is reported to have mitre gate machinery that is worn from use while Lockport, Brandon Road, Dresden Island and Starved Rock Locks are reported to have operating machinery. Improvements could, conceivably, increase lockage times.

While congestion has not been severe on this segment, some moderate non-structural measures have been undertaken and shown to be effective. The analysis performed in the Duplicate Locks GDM Phase I prepared by the United States Army Corps of Engineers also indicated non-structural alternatives to be effective. In particular, the GDM considered installing automated trash rakes at Brandon Road and Lockport, installation of bubbler systems at Marseilles and Starved Rock, an auxiliary discharge at Brandon Road, preventing illegal fleeting at Brandon Road and approach improvements at all locks to affect enforcement of tow rearrangement outside of the chamber. The report stated that at Brandon Roads Lock, the installation of automated trash rakes could "reduce filling time by well over 50%." The report concluded that if all of the stated improvements were implemented, capacity on the Illinois Waterway would be as follows:

| | |
|---|---|
| Lockport | 30 million tons |
| Brandon Roads | 30 million tons |
| Dresden Island | 42 million tons |
| Marseilles | 40 million tons |
| Starved Rock | 45 million tons |
| Peoria | 56 million tons |
| La Grange | 60 million tons |

To date, no non-structural improvements have been implemented at Marseilles, the lock which is constraining, and has a present capacity of 26 million tons. If the improvements suggested in the report were fully implemented, Lockport and Brandon Road Locks would likely become the most constraining locks on the Illinois Waterways, In addition, the analysis undertaken in this report indicates that provision of switchboats or a traveling kevil would increase capacity on the waterway due to the present high percentage of double and setover lockages.

Channel Improvements: South of Lockport Lock, the channel is generally adequate and well maintained. Although authorized channel dimensions were not completely implemented and some problems are present due to bend radii, bridges, and the total width of the channelized section, 15 barge tows can navigate this segment. North of Lockport the channel is smaller, ranging from 160 feet to 225 feet. This does restrict tow size in the area, although proposals to widen the channel are currently being held in abeyance pending the disposition of the duplicate locks proposal.

The evaluation of a 12 foot channel was undertaken in the 1972 "Mississippi River-Illinois Waterway Study."[16] The project included dredging of the channel bed to achieve the additional depth. The total cost of the project was presented as $114,203,000 and $9,390,000 in annual charges. This would be about $210,000,000 and $17,000,000 in 1979 dollars. Duplicate Locks throughout the waterway were also assumed to be operational. In conjunction with increases in depth in Segments 2 and 3 increases in capacity of up to 37.5 percent could be achieved. The 12 foot channel was found to be justified in 1972 study, however, implementation is currently prohibited by PL 52-502.

Lock Replacement Alternatives: Current capacity on the Illinois Waterway is insufficient to meet any of the projected year 2000 demands.

Provision of 1200' x110' locks with the elimination of Brandon Road Lock (as proposed in the GDM) would increase capacity for the segment to about 77,000,000 tons. The other possibilities are the addition of a 1200'x110' lock with a 600'x110' lock or the construction of twin 1200'x 110' locks. The cost of providing 1200'x110' locks was taken from the 1975 GDM and updated to 1977 dollars. The cost for both the locks and the total project is shown.

Table III-26 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

### (f) Reporting Region 7 - Ohio River

1. Upper Ohio River. This segment includes the Ohio River between Pittsburgh, Pennsylvania and the Kanawha River, plus the Muskingum River. Nine locks are present on this segment, with a large divergence in size.

## Table III-26

## Potential Improvements to Illinois Waterway in Region 5 To Increase Capacity

| | Improvement | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 26 at Marseilles | 0 | |
| 2. | Implement improvements according to Duplicate Locks GDM for four upper locks | 30 at Lockport, Brandon Rd. | up to $20 | |
| 3. | Provision of recreation locks at Lockport and Brandon Rd. in addition to (2) | 35 at Lockport, Brandon Rd. | $4 | |
| 4. | Provide 1200'x 110' locks, eliminate Brandon Rd. Lock | 77 at all locks | $370 locks only ($751 total project cost including locks) | 6 |
| 5. | Provide 1200'x 110' with new 600'x110' locks | 120 at all locks | $370 only | 6 |
| 6. | Provide 1200'x 110' locks with new 600'x110' locks | 120 at all locks | $552 | 12 |
| 7. | Provide two - 1200'x100' locks throughout segment | 154 at all locks | $740 | 12 |

Non-Structural Measures: On the western portion of this segment, six locks have main chamber sizes of 1200'x 110' with normal lockage times and no auxiliary chamber interference. At Emsworth Lock, representive of the three locks in the segment with 600'x110' main chambers (i.e., Dashields, Montgomery and Emsworth Locks), measures to reduce chamber interference could gain as much as 40% increased utilization of the auxiliary chamber.

Non-structural policy measures have little potential for increasing capacity on this segment. Only at Emsworth, Dashields, and Montgomery Locks are they of significant value. Implementation of a complete Ready-to-Serve lock operating policy would increase capacity about 20% at Emsworth. At the 1200'x110' locks non-structural policy measures are generally ineffective.

Channel Improvements: The channel on this segment of the river is generally adequate for navigation and will allow for passage of 15 barge tows. The combination of width and bend radii is more than adequate within this segment to allow for unimpeded navigation.

Lock Replacement Alternatives: Existing capacity on this segment will be insufficient to meet projected demands. Non-structural alternatives or construction of a recreation lock would have insignificant effects on capacity.

The first possible structural improvement would be to provide 1200'x110' locks at the upper three locks on this segment, increasing capacity to 77,000,000 tons. Keeping the 600'x110' locks at those sites would increase capacity to 120,000,000 tons, which is sufficient to meet the low demand. The last option is to provide twin 1200'x 110' locks throughout the segment increasing capacity to 154,000,000 tons.

The locks currently having 1200'x110' and 600'x 110' chambers have experienced some interference to traffic between the two locks limiting capacity to 104,000,000 tons. It is presumed that placement of an additional or replacement lock can be accomplished to eliminate this interference so that capacity will increase to 120,000,000 and 154,000,000 tons for the last two alternatives considered.

Table III-27 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

2. Middle Ohio River. This segment includes the Ohio River between the Kanawha and Kentucky Rivers - plus the Big Sandy River. Four locks are included in this

segment. Three have 1200'x110' and 600'x110' chambers. Gallipolis has 600'x110' and 360'x110' chambers and is currently under study for replacement.

Table III-27

Potential Improvement to Upper Ohio River in Region 7 to Increase Capacity

| Improvement | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 37 at Emsworth | 0 | |
| 2. Implement Ready-to-Serve policy | 42 at Emsworth | \$2-3 per yr. | |
| 3. Reduce chamber interaction at Emsworth in addition to (2) | 45 at Emsworth | \$0.5-5 | |
| 4. Provide 1200'x 110' locks at upper three locks | 77 at Emsworth | \$143 | 3 |
| 5. Provide Improvement 4 keeping existing 600'x 110'locks | 120 at Emsworth Dashields and Montgomery<br>104 at all other locks | \$143 | 3 |
| 6. Provide new 1200' x110' and 600'x 100' locks at Emsworth, Dashields and Montgomery | 120 at Emsworth, Dashields and Montgomery<br>104 at all other locks | \$173 | 6 |
| 7. Provide two - 1200'x110' locks throughout. | 154 at all locks | \$907 | 12 |

According to the report, "Capacity Studies of Gallipolis Locks," the following alternatives were recommended for further study as the most likely measures to increase capacity at Gallipolis Locks:

(a) Selected operating policies for the existing Gallipolis lockage facilities including 1-up/1-down and FIFO unrestricted with increased usage of the auxiliary chamber.

(b) Switchboat operations in the upper pool, as in (b) above, plus an extended landward quide wall in the lower pool to be used by tows to recouple after lockage without delaying turnback of the lock.

(c) Switchboat operations in the upper pool, as in (b) above, plus either switchboat operations or an extended center guard wall in the lower pool.

(d) FIFO Ready-to-Serve operating policy, which also would require switchboats and mooring facilities.

As part of the study, a N-up/N-down operating policy was simulated for existing conditions and for switchboat operations and was not found beneficial. This is because use of the procedure blocks access to the auxiliary chamber. Use of a N-up/N-down policy at Markland, the other representative lock in the segment, would not be helpful.

A Ready-to-Serve policy would be effective only at Gallipolis Locks. At Gallipolis locks this was the most effective measure studied and could increase capacity approximately 20%.

Channel Improvements: Like the Upper Ohio River, channel conditions are quite adequate for navigation and it is not envisioned that channel improvements can increase the capacity of the segment.

"Technical Report H-78-6, Capacity Studies of Gallipolis Locks, Ohio River, West Virginia,"[17] May 1978, considered a number of nonstructural policy options and minor improvements. The study concluded that considerable capacity increases could be attributed to several nonstructural policy options. However, of the minor improvements suggested, the study concluded the following:

(a) that establishing a rule requiring tows to stay sufficiently clear of lock filling and emptying system intakes and outlets so that chamber filling and emptying time could be reduced to a minimum would provide only a "small" increase in capacity.

(b) that keeping the approaches, particularly the lower approaches, at a depth that would allow the most efficient entry of tows into the chambers would provide a "negligible" increase in capacity.

(c) that substantially greater use of the auxiliary chamber could be achieved through the use of scheduling procedures because at the present time use of the auxiliary chamber is low.

The report further concluded that by extending the downstream center wall to a length of about 1500 feet and simultaneously using switchboat operations in the upper pool, chamber interference could be reduced to a minimum. This alternative would disrupt traffic during construction for about seven months according to the district. The increase gained by this alternative alone is on the order of 10%. The total increase, including a Ready-to-Serve policy, is on the order of 30%.

Lock Replacement Alternatives: Projected year 2000 demands exceed the current capacity of this segment. Nonstructural measures will increase capacity, but there will still be a significant short-fall between capacity and demand. Recreation lockages are minimal, so that a recreation lock will not affect capacity.

The first structural alternative to increase capacity would be the provision of a 1200'x 110' lock at Gallipolis, with elimination of the 360'x110' lock. This would increase capacity to 120,000,000 tons although due to chamber interference at other sites on the segment, capacity would only reach 104,000,000 tons. It is presumed that this interference could be eliminated with only minor structural measures, although it is unclear how bad this interference would be at high levels of utilization. The next alternative would be construction of twin 1200'x 110' locks which would meet the demands on the system.

Table III-28 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

Table III-28

Potential Improvements to Middle Ohio River in Region 7 to Increase Capacity

| | Improvement | Minimum System Capacity ($\times 10^6$) | Cost ($\times 10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 49 at Gallipolis | 0 | |
| 2. | Implement ready-to-serve policy | 58 at Gallipolis | \$2-3 per year | |
| 3. | Reduce chamber interference in addition to (2) | 65 at Gallipolis | \$2-3 per year | |
| 4. | Provide additional 110' lock at Gallipolis maintaining existing chamber 600'x110' | 120 at Gallipolis<br>104 at all other locks | \$53 | 1 |
| 5. | Provide two 1200' locks throughout | 154 | 283 | 5 |

3. Lower Ohio River-Three. This segment includes the Ohio River between the Kentucky and Green Rivers. Three locks are present on this segment, all having 1200'x 110' and 600'x110' chambers.

Nonstructural Measures: McAlpine and Cannalton Locks have slightly lower capacities than Newburgh Lock.

A 15% increase in capacity may be possible in the auxiliary chamber of McAlpine Lock if the filling/emptying system can be improved. About a 15% increase in capacity in the auxiliary chamber of McAlpine Lock might also be possible if chamber interference is eliminated. Due to the chamber sizes, many of the nonstructural policy measures are not applicable to this segment. However, implementation of a 4-up/4-down lockage policy would increase capacity about five percent at McAlpine and Cannelton.

Channel Improvements: The channel width and bend radii are sufficient for unimpeded navigation. It is not envisioned that capacity on the segment could be increased through channel improvement.

Lock Replacement Alternatives: Construction of a recreation lock at all locks and implementation of improvement measures will increase segment capacity to $124,000,000 tons annually. Construction of twin 1200'x 110' locks will increase capacity to about 154,000,000, assuming there is no interference between chambers, at a cost of about $175,000,000.

Table III-29 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

4. Lower Ohio River-Two. This segment includes the Ohio River between the Green and Tennessee Rivers. The segment currently contains three locks, although two are being replaced by Smithland Locks and Dam which has twin 1200'x110' chambers. The other lock, Uniontown, has 1200'x110' and 600'x110' chambers. Only these two locks are considered as part of the navigation system.

Nonstructural Measures: An N-up/N-down policy would be effective in increasing the capacity of Uniontown Lock by about 10%.

Channel Improvements: The channel width and bend radii are sufficient for unimpeded navigation. It is not envisioned that capacity on the segment could be increased through channel improvements.

Lock Replacement Alternatives: Given current lock sizes, the only lock replacement alternative is to provide twin 1200'x110' locks at Uniontown. This will expand capacity to 154,000,000 which will approximately meet all demands projected.

## Table III-29

### Potential Improvements to the Lower Ohio River to Increase Capacity

| Improvements | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 104 at McAlpine | 0 | |
| 2. Implement 4-up/4-down lock policy | 109 at McAlpine | 0 | |
| 3. Eliminate chamber interference | 112 at McAlpine | 0 | |
| 4. Improve auxiliary chamber filling system | 115 at McApline | $0.5 | |
| 5. Provide recreation locks | 124 at all locks | $6 | |
| 6. Provide two - 1200'x110' throughout | 154 at all locks | $175 | 3 |

Table III-30 presents the minimum system practical improvements to increase segment capacity.

5. Lower Ohio River-One. This segment includes the Ohio River from its confluence with the Mississippi River and its junction with the Tennessee River. Two locks are present on this segment, both being open-pass part of the year. Current studies are evaluating the replacement of these two lock sites with one dam and dual 1200'x110' locks removing both dams and providing open river conditions all year and adding locks and dams at the existing sites.

Nonstructural Measures: During those portions of the year when this segment is open-pass, nonstructural measures are clearly irrelevant. At other times of the year, nonstructural policy measures are only effective at Locks and Dam No. 53 where an N-up/N-down or a lock policy would increase capacity by about 10%.

## Table III-30

## Potential Improvements to the Lower Ohio River Two to Increase Capacity

| | Improvement | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 104 at Uniontown | $0 | |
| 2. | N-up/N-down policy at Uniontown | 114 at Uniontown | $0 | |
| 3. | Provide two 1200'x110' locks at Uniontown | 154 at Uniontown and Smithland locks | $52 | 1 |

Channel improvements: The channel is quite adequate for navigation purposes and it is not believed that additional channel improvements will significantly increase capacity.

Lock Replacement Alternatives: Although current studies are considering replacing the locks on this segment with a single lock and dam , insufficient information on this alternative was available to estimate costs. For purposes on this analysis, it is assumed that construction alternatives will retain the present two sites. Of course, actual selection of construction alternatives for this segment will be undertaken during the feasibility study and appropriate trade-offs will be considered. Capacity for these structures ignores open-pass conditions, essentially reflecting only those months when capacity can be reached and delay problems encountered on this segment.

Nonstructural measures will increase capacity somewhat. In addition, a recreation lock at Lock and Dam 52 would increase its capacity, but would do little to improve segment capacity since it is larger than lock and Dam 53. The first construction improvement would be to provide a new 1200'x110' lock at Lock and Dam 53. This improvement, shown as alternative 3 below, is under construction and expected to be completed this year. The next two alternatives represent addition of a 1200'x110' lock at Lock and Dam 53, with retention or replacement of the existing 600'x110' lock. The last alternative would place dual 1200'x110' structures at both locations on this segment.

Table III-31 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

6. Monongahela River. This segment consists of the Monongahela River. Nine locks of various sizes are present on this river. No navigable tributaries are present in this segment.

Nonstructural Alternatives: Implementation of nonstructural alternatives have rather limited potential for increasing capacity of this segment. An N-up/N-down policy is not helpful in this segment, although a Ready-to-Serve policy would increase capacity at Locks 2 and 7. This conclusion seems to be consistent with the "Final Environmental Statement on the Operation and Maintenance of the Navigation System"[18] for the Monongahela River prepared in 1975 by Pittsburgh District, United States Army Corps of Engineers. It is stated in the report that minor modifications in the structures and their operation have already been implemented as a result of previous efficiency studies and that further increases in efficiency will require major modifications to the facilities.

Channel Improvements: Below Lock and Dam No. 4 the channel is quite adequate for navigation and will allow passage of 16 barge tows. Above Lock and Dam No. 4 the channel is more restrictive and the bend radii and bridges limit tow sizes currently observed on the lower portion of this segment. In the extreme upper portions of this segment, it is likely that channel widening would be necessary for larger tows to use this portion of the segment. However, due to the nature of the channel banks, the cost of channel improvements in this segment are likely to be prohibitive and do not appear necessary to accommodate currently observed tow sizes and traffic patterns.

Lock Replacement Alternatives: Implementation of nonstructural alternatives have a negligible impact on the capacity of the segment. Recreation lockages are a small percent of lockages of this segment, so that construction of recreation locks would not significantly effect capacity. The "Final Environmental Statement," cited earlier, also reached this conclusion.

## Table III-31

## Potential Improvements to the Lower Ohio River One in Region 5 to Increase Capacity

| | Improvement | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 34 at L/D 53 | None | |
| 2. | Implement N-up/ N-down policy at L/D 53 | 38 at L/D 53 | Minimal | |
| 3. | Provide 1200'x 110' lock at L/D 53 | 77 at L/D 53 | $77 | 1 |
| 4. | Provide 1200'x 110' lock, keeping existing 600' x110' lock at L/D 53 | 120 at L/D 53 | $77 | 1 |
| 5. | Provide new 1200'x110' and 600'x110' locks at L/D 53 | 120 at both locks | $108 | 2 |
| 6. | Provide dual 1200'x110' locks throughout | 154 at both | $222 | 4 |

Due to the rather non-standard lock sizes on this segment, the possible replacement alternatives are numerous. For purposes of this analysis, the replacement alternatives have been limited to lock sizes already in place on the segment which adequately covers reasonable options. The sequence of possible alternatives is based on increasing the capacity of the smallest locks on the segment to provide for some consistency over the segment.

The first improvement would be to provide 720'x 84' chambers at Locks No. 7 and 8, currently the smallest locks in the segment. This option has been studied and was recommended for implementation, with provision of a second lock of the same dimensions when future traffic levels exhibit the need for a second lock. Maxwell Locks, immediately below Lock and Dam 7 has two 720'x84' chamber size. Morgantown Lock, next above Lock and Dam 8 has a 600'x84' chamber size. Despite Maxwell Locks have considerably larger capacity under present conditions. This further supports the selection of 720'x84' locks at Locks and Dam No. 7 and 8, however, still leaves capacity of the system below year 2000 demand levels.

The next two alternatives would provide a 720'x 84' lock at Locks 4, 7 and 8 and a 720'x110' lock at Lock 3, with or without keeping the existing 360'x56' locks at all four sites. Other alternatives consider maintaining the existing main chambers as auxiliary chambers.

Continuing this process, one reaches the point where dual 720'x84' (Locks 4, 7 and 8) or dual 720'x110' locks (Locks 2 and 3) are necessary to accommodate any thing approaching year 2000 demand levels. This would increase capacity to 88,000,000 tons towards the mouth of the river, with somewhat lower levels of capacity as one moves upstream. Total cost of these improvements would be about $207,000,000. One other possibility should be noted. Replacement of some of these structures would be at the existing dam site, although in at least one case the replacement structure could be downstream necessitating a new dam and a corresponding increase in cost.

The practical capacity of most of the dual locks in this segment under present conditions is low because of interference between chambers. The capacity estimates presented for replacement locks assume that there would be no loss of capacity due to interference between chambers.

Table III-32 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

7. Kanawha River. This segment is the navigable portion of the Kanawha River. Three locks and dam sites are present on this segment. All three sites have twin 360'x56' locks.

Nonstructural Measures: Given the small lock sizes nonstructural policy mesures are appropriate for this segment.

Due to the high perventage of tows requiring three or more cuts at Winfield Lock, implementation of a Ready-to-Serve policy would decrease the extra time for multi-cut lockages and also decrease approach times. The savings could increase capacity by between 20 and 40%.

Four operating policies were investigated for Winfield Lock in W.E.S. Miscellaneous Paper H-77-1 "Capacity Studies of Winfield Locks Kanawha River, West Virginia",[19] February 1977.

Table III-32

Potential Improvements to the Monongahela River in Region 7 to Increase Capacity

| Improvement | Minimum System Capacity $(x10^6)$ | Cost $(x10^6)$ | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 16 at Locks 7 & 8<br>40 at Locks 3 & 4<br>52 at Lock | 0 | |
| 2. Implement Ready-to-Serve policy at L/D 7 & 8 | 18 at Locks 7 & 8 | $4-6 per yr. | |
| 3. Provide 720'x84' at Locks 7 & 8 | 43 at Locks 7 & 8<br>40 at Locks 3 & 4<br>52 at Lock 2 | $43 | 2 |
| 4. Provide 720'x84' at Lock 4, 720' x110' at Lock 3 & 720'x84' at Locks 7 & 8, keeping 360'x56' at locks 3, 4, 7 and 8 | 60 at Locks 4, 7 & 8 | $83 | 4 |
| 5. Provide 720'x84' at Lock 4, 720'x 110' at Locks 2 & 3 and 720'x84' Locks 7 & 8, keeping 720'x56' at Locks 3 & 4, 360'x56' at Locks 7 & 8, and 720'x110' locks at L/D2 | 60 at Locks 7 & 8<br>66 at Lock 4<br>88 at Lock 2<br>67 at Lock 3 | $106 | 5 |

## Table III-32 (Continued)

## Potential Improvements to the Monongahela River in Region 7 to Increase Capacity

| | Improvement | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 6. | Provide 720'x84' at Lock 4, 720'x 110' at Locks 2 & 3, keeping existing 720'x 56' and 720'x 110' dual 720'x 84' at Locks 7 & 8 | 86 at Locks 7 & 8<br>66 at Lock 4<br>67 at Lock 3<br>88 at Lock 2 | $140 | 7 |
| 7. | Provide dual 720'x84' at Lock 4, dual 720'x 110' at Lock 3, dual 720'x84' at Locks 7 & 8 and a 720'x110' at Lock 2, keeping existing 720'x 110' | 86 at Locks 4, 7 & 8<br>88 at Locks 2 & 3 | $173 | 9 |

(a) First In, First Out Unrestricted.

(b) First In, First Out Unrestricted with a 10 percent reduction in lockage component times as a result of improved operating efficiency.

(c) First In, First Out with a Ready-to-Serve policy.

(d) 3-up/3-down.

Alternative (b) and (c) were found to increase annual tonnage 95 percent utilization by seven and 42 percent respectively over alternative (a). Alternative (d) was found to increase capacity but at the expense of high delays. Implementation of a Ready-to-Serve policy was not considered feasible because of the high cost of the great number of switchboats required. The 10% reduction in lockage component times in alternative (b) was to be the result of more efficient locking operations, by whatever means this might be accomplished." Currently, filling/emptying times are normal and approach, entry and exit speeds are normal. (Except for the entry to the main chamber where increased speed could provide a much less than five percent increase in capacity).

Channel Improvements: Generally the channel width and bend radii are sufficient for navigation purposes. Nine barge tows can be accommodated, which is sufficient, with appropriately sized locks, to accommodate year 2000 high demands.

Lock Replacement Alternatives: Demands are projected to exceed the current capacity of the system. A recreational lock would have no effect and nonstructural measures are not sufficient to expand capacity to meet demands. The "Capacity Studies of Winfield Lock" suggested further studies of 600'x110' and 800'x110' locks. Provision of a 600' x110' or 800'x110' lock would expand capacity to meet the low and expected demands respectively. Either of these options could be combined with retention of 1-360'x56' lock. The 800'x110' and 360'x56' option could provide sufficient capacity to meet the projected year 2000 high demand. Also, 2-600'x110' locks would exceed the high demand.

Table III-33 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

8. Green River. This segment includes the Green River. Three locks are present on this segment and all locks have chambers 600'x84'. Lock and Dam 3 is very near the headwater and not expected to reach capacity. Therefore, only Locks and Dams 1 and 2 are considered.

Non-Structural Measures: Due to the physical lock characteristics and two characteristics, nonstructural policy measures are not effective in increasing capacity of this segment.

Channel Improvements: The characteristics of the channel are sufficient for navigation purposes. The channel can accommodate tows consisting of four jumbo barges. Although generally smaller than other channel

## Table III-33

### Possible Improvements to the Kanawha River in Region 7 to Increase Capacity

| | Improvement | Minimum System Capacity ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 20 at Winfield | $0.5-5 | |
| 2. | Minor improvement resulting in 10% reduction in lockage times | 22 at Winfield | $0.5-5 | |
| 3. | First in/First out Ready-to-Serve | 28 at Winfield | $2-3 per year | |
| 4. | Provide 600'x110' locks retaining 1-360'x56' lock | 40 at all locks | $77 | 3 |
| 5. | Provide 800'x110' locks throughout retaining 1-360' x56' lock | 48 at all locks | $92 | 3 |
| 6. | Provide 2-600'x 110' locks throughout | 60 at all locks | $138 | 6 |

widths in the Ohio River Valley, it is sufficiently wide for the locks currently on the River. Increasing of channel dimensions would be required to accommodate tows larger than those currently on the River.

Lock Replacement Alternatives: Projected demands exceed current capacity of this segment. Although a smaller additional lock would suffice, the most reasonable lock replacement alternaive is an additional identical chamber, to meet the high demand. This would increase capacity to about 110,000,000 tons.

Table III-34 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

## Table III-34

## Possible Improvements to the Green River in Region 7 to Increase Capacity

| | Improvement | Minimum System Cap. ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 55 at L/D 1 | 0 | |
| 2. | Provide new 600' x 84' lock, keep old 600'x84' lock | 110 at all | \$33 | 2 |
| 3. | Provide new dual 600'x84'locks | 110 at all locks | \$60 | 4 |

### (g) Reporting Region 8 - Tennessee River

1. Lower Tennessee River. This segment includes the Tennessee River from the mouth of its junction with the Tennessee-Tombigbee Waterway. Two locks are present on this segment, both having 600'x110' chambers.

Non-Structural Measures: A Ready-to-Serve policy would increase capacity at Kentucky Lock by over 30%. A N-up/N-down policy would be ineffective.

Channel Improvements: Channel conditions on this segment are generally adequate for navigation purposes. Accommodation of 15 barge tows is possible.

Lock Replacement Alternatives: Projected year 2000 traffic demands exceed the capacity of this segment. Both construction of recreation locks and implementation of a Ready-to-Serve lockage policy will increase capacity, although not sufficiently to meet projected demand.

Provision of an additional 600' x110' lock at each site will increase capacity to 60,000,000 tons which will meet year 2000 low and expected demand. Provision of 1-1200'x110' will provide adequate capacity for this segment at all levels of demand.

Table III-35 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

Table 111-35

Possible Improvements to Lower Tennessee River in Region 8 to Increase Capacity

| Improvement | Minimum System Cap. ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 30 at Kentucky | | |
| 2. Implement Ready-to-Serve Policy at Kentucky | 40 at Kentucky | \$2-3 per yr. | |
| 3. Provide recreational lock | 43 at Kentucky | \$ 2 | |
| 4. Provide new additional 600'x110' locks | 60 at both locks | \$ 81 | 2 |
| 5. Provide new 1200'x110' locks | 77 at both locks | \$158 | 2 |

### (h) Reporting Region 10 - Gulf West Coast

1. Gulf Intercoastal Waterway One. This segment contains the Gulf Intercoastal Waterway from New Orleans, La. to the Calcasieu River. Five locks are present on this segment, all of different dimensions. Several are saltwater intrusion locks and several are partially open-pass locks. One of the locks, Vermillion, is currently authorized and funded for replacement with a 1200' x110' chamber.

Non-Structural Measures: Although a N-up/N-down policy is currently being utilized at Calcasieu and Vermillion Locks, data were unavailable to assess its effectiveness. The physical characteristics of the lock would tend to indicate that this is an effective measure during some periods. Increasing the percentage of multivessel lockages at Calcasieu Lock could increase capacity by nearly 20%.

Channel Improvements: Channel dimensions on this segment restrict tow size to five barges, with only one barge wide, depth is adequate for 9' draft and bend radii generally sufficient for this tow size. Possible widening of the channel is being studied with dimensions recommended for evaluation ranging up to 300' width and 16' depth. These improvements would tend to increase the average load per barge and average tow size. The channel restrictions also probably limit the effective use of the existing locks on the system as multivessel lockages are common.

The River and Harbor Act of October 1962 authorized deepening and widening of the GIWW in Segment 28 and some channel relocations, with local interest to provide: all lands, easements, and rights-of-way required for construction and subsequent maintenance; accomplish all relocations of pipelines, cables, and other utilities; and to bear 42% of the construction cost in connection with the Houma-Louisiana bypass. To this date local interests have been unwilling to provide those items and have expressed at public meetings that the benefits of this proposal are national so that costs should not be borne by local interests. None of the 1962 authorized improvements listed below have been implemented.

The authorized enlargement of the GIWW provides for:

(a) a channel 16 x 150 feet through the reach between the Mississippi and Atchafalaya Rivers.

(b) a channel 16 x 150 feet through the Algiers Alternate Canal.

(c) a channel 16 x 150 feet through the bypass route around Houma.

(d) a channel 16 x 200 feet through the reach from the Atchafalaya River to the Sabine River.

Lock Replacement Alternatives: Current capacity on this segment is insufficient to meet projected demands. Possible replacement alternatives do not consider Harvey Lock, but combine it with Algiers Lock as they are simply alternative routes to the same areas. It is believed that locks within this segment should be sized consistently. Meeting projected demands within this segment will require dual 1200' x 110' throughout the segment. However, effective utilization of these lock sizes may require improvements in the channel. As with the Baton Rouge-Morgan City bypass it should be noted that the large number of petroleum barges and the variation in tow and barge sizes on this segment tend to a lock width that at first appearance would seem to exceed possible restrictions of the channel width.

Table III-36 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

### (i) Reporting Region 11 - Gulf Coast East

1. Gulf Intercoastal Waterway East One. This segment includes the Gulf Intercoastal Waterway east of New Orleans, Louisiana to the mouth of the Pearl River. Lake Pontchartrain and Michoud Canal are included in this segment. Only one lock on the Industrial Canal with chamber 640'x75' and 31' depth on sill is present on this segment and it is currently under study for replacement.

Non-Structural Measures: Elimination of knockouts and traveling Kevils would increase capacity by about five percent. An N-up/N-down policy is currently in use. The head differential at the lock, the location of the lock between river and the Industrial Canal and the presence of bridges on the canal, make lockage policies quite important at this lock.

Channel Improvements: Although the physical dimension of the channel restrict tow size, there are several other features of the channel that are at least important in determining tow size. One is the presence of bridges on the canal. The other is the general navigation conditions east of this segment which make larger tows difficult to control during certain times of the year.

## Table III-36

## Possible Improvements to GIWW West One in Region 10 to Increase Capacity

| | Improvement | Minimum System Cap. ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 36 @ Algiers/ Harvey Comb. | 0 | |
| 2. | Provide 1000'x 75' lock at Algiers | 44 @ Vermilion | $ 67 | 1 |
| 3. | Provide 1200'x 75' lock at Vermilion with improvement2 | 48 @ Vermilion<br>49 @ Algiers/ Harvey Comb. | $ 75 | 2 |
| 4. | Provide 1200'x 110 locks throughout except Harvey | 77 @ all locks | $185 | 4 |
| 5. | Provide 1200'x 75' with existing chambers and dual 1200'x75' locks at Algiers (No improvement Harvey) | 86 @ Vermilion | $220 | 5 |
| 6. | Provide 1200'x110' locks throughout with existing chambers plus 2-1200'x110' locks at Algiers (No improvement Harvey) | 125 @ Vermilion | $278 | 5 |

Widening the channel could possibly allow larger tows on this segment. The major problem in widening the channel is the relocation of industry on the Industrial Canal. This is considered in the replacement study as part of the alternative for considering a deeper ship lock at this site. Channel depth is quite adequate for shallow draft navigation on this segment.

Lock Replacement Alternatives: Delays at the existing lock are significant and a replacement study is currently being undertaken. Only shallow draft locks are considered, although the existing lock will accommodate deep draft navigation.

Projected demand exceeds the current capacity of the system. Provision of a second 640'x75' chamber would only meet the low demand. Expected and high demands could be met with the addition of a 1200' x75' lock. This would also allow the retention of current deep draft navigation capabilities since the existing lock has a sill depth of 31 feet. However, it should be noted that both the width and depth of the existing lock are constraints on the capabilities of this lock to accommodate all ocean vessels that might desire to utilize this lock.

Table III-37 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

### (j) Reporting Region 12 - Tombigbee, Alambama, Coosa, Black Warrior River

1. Black Warrior and Tombigbee River. This segment includes the Black Warrior River. Six locks are on this segment, five of which have 600' x110' chambers. The sixth, Oliver Lock and Dam, has a 460' x95' chamber.

Non-Structural Measures: Generally non-structural policy measures are of little use for increasing the capacity of this segment. An N-up/N-down policy is not effective. A ready-to-serve policy would slightly increase capacity at Oliver Lock and Dam

Channel Improvements: Generally the channel is a restriction on navigation on this segment. Neither the

## Table III-37

## Possible Improvements to GIWW East One in Region 11 to Increase Capacity

| Improvement | Minimum System Cap. $(x10^6)$ | Cost $(x10^6)$ | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 26 | 0 | |
| 2. Elimination of knockouts and a traveling kevil | 27 | \$2-3 per yr. | |
| 3. Provide second 640'x75'chamber (12' Draft) | 52 | \$21 | 1 |
| 4. Provide 1200x75' chamber (12' Draft) | 48 | \$32 | 1 |
| 5. Provide 1200'x75' chamber with existing 640'x 75' (12' Draft) | 74 | \$32 | 1 |
| 6. Provide 1200'x 110' chamber Draft) | 77 | \$35 | 1 |

width or bend radii are sufficient to allow for full utilization of lock size over the length of the river. Additional width and some channel straightening would be required on this segment to accommodate larger tows than presently use the waterway.

Lock Replacement Alternatives: Projected demand exceeds the existing capacity of this segment. Recreation locks would do little to increase capacity, although nonstructural measures provide some small increases. Provision of a new 600' x110' lock at Oliver would increase capacity to 31,000,000 over the segment. Provision of an additional 600'x110' lock and retaining the existing lock at each site will increase capacity to 57,000,000. Dual 600'x110' locks at each site will increase capacity to 60,000,000 tons annually.

Table III-38 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

### Table III-38

### Possible Improvements to Black Warrior and Tombigbee River in Region 12 to Increase Capacity

| | Improvement | Minimum System ap. ($x10^6$) | Cost ($x10^6$) | No. of Locks Replaced |
|---|---|---|---|---|
| 1. | None | 27 @ Oliver | 0 | |
| 2. | Provide 600'x110' at Oliver | 31 @ Oliver | $ 27 | 1 |
| 3. | Provide dual 600'x110' locks throughout using existing 600'x 110' locks | 60 @ all locks | $204 | 7 |

2. Tennessee-Tombigbee Waterway. This segment is the Tennessee-Tombigbee Waterway currently under construction. No traffic projections have been estimated for this segment due to lack of information on traffic distribution patterns and the start up date of the waterway. This waterway provides an alternative route to the eastern Gulf Coast from upper river ports. Since the current routing via the Lower Mississippi River is not constrained locks it is not expected that significant capacity problems will be experienced on this segment.

### (k) Reporting Region 18 - Snake Waterway/ Willamette River

This segment includes the Columbia-Snake Waterway between Lewiston, Idaho and Bonneville Lock and Dam. Eight locks are present on this segment. All, except Bonneville, have 675'x86' chambers. Bonneville has a 500'x76' chamber,though recent study was completed to modify and enlarge this lock.

Non-Structural Measures: The "Feasibility Study"[20] for Bonneville Locks, 14 September 1978, evaluated the use of switchboats s a means of increasing lock capacity. The study concluded that the use of a full-time switchboat is considered the most probable future or base condition for the purpose of evaluating alternatives. The use of switchboats was found to be eonomically justified for the mid to late 1980s to increase lock capacity to 12.9 million tons per year.

A series of model tests were conducted under review of towboat operators to straighten the upstream approach to Bonneville Lock and reduce channel velocities, thus eliminating hazardous conditions. The model tests, as interpreted by the operators, indicated that the channel conditions could not be improved appreciably. Also, according to the "Feasibility Study" moving the moorage area closer to the lock is not judged feasible as moored tows would be in the path of, or a hazard to, tows moving directly in and out of the lock. An N-up/N-down policy is currently in use at Bonneville, but insufficient data are available to determine its effects.

Channel Improvements: Generally the channel in this segment is adequate for navigation needs and for the lock system present on the segment.

Lock Replacement Alternatives: A recreational lock would increase capacity by about five percent. The first possible aternative is clearly to replace Bonneville Lock with a lock sized consistently with the remainder of the system. Replacement of the existing lock with a 675'x86' lock will increase capacity of the segment to 27,000,000 which is quite adequate for the year 2000 it is not considered feasible to maintain the existing lock at Bonneville while installing a replacement lock. This is because a new lock at the same site would have to use the same approach chamber as the existing lock.

Table III-39 presents the minimum system practical capacity and the associated costs for various levels of improvements to increase segment capacity.

## Table III-39

## Possible Improvements to Upper Columbia-Snake Waterway in Region 18 to Increase Capacity

| Improvement | Minimum System Cap. $(x10^6)$ | Cost $(x10^6)$ | No. of Locks Replaced |
|---|---|---|---|
| 1. None | 9 @ Bonneville | 0 | |
| 2. Ready-to-serve | 13 @ Bonneville | \$2-3 | |
| 3. Provide Recreational Lock | 14 @ Bonneville | \$2 | |
| 4. Provide 675'x86 lock at Bonneville | 27 @ all locks | \$43 | 1 |

## IV - CHANNEL MAINTENANCE

Waterway channel dimensions are authorized by the Congress. The authorized dimensions, however, once provided by a new work project, are subject to the deteriorating natural forces of river hydrology. In order to combat channel deterioration and the reduction of channel dimensions, the Army Corps of Engineers conducts an extensive channel maintenance program. Because the hydrology and morphology of every waterway is unique, the maintenance program undertaken on each waterway is specific to that waterway. In particular, it can be stated that basically different hydrological conditions exist for each major type of waterway, channelized river (with locks and dams), free-flowing rivers, canals, intracoastal waterways, lakes and coastal ports or deep draft channels.

For these reasons, it is not possible to compare or evaluate channel maintenance programs strictly from the standpoint of relative cost of relative volume of work. For example, over the last three to five years, an average annual volume of 1,701,500 cubic yards of dredged material were removed from the Apalachicola River at an average cost of $0.75 per cubic yard. This corresponds to an average annual cost of $4,509 per mile of waterway and 6,012 cubic yards dredged annually per mile of waterway. On the other hand, over the last three to five years, an average annual volume of 71,000 cubic yards of dredged material were removed from the Monongahela River at an average cost of $2.97 per cubic yard. This, however, only corresponds to an average annual cost of $1,636 per mile of waterway and 550 cubic yards dredged annually per mile of waterway. Yet, the likelihood of encountering depths less than authorized on the Apalachicola River is much greater than on the Monongahela River.

It is important, however, to be able to compare the relative effectiveness of channel maintenance programs for planning purposes, particularly to be able to identify the effects of the various NWS Scenarios.

The measure that is used to evaluate the relative effectiveness of channel maintenance programs is the reliability of authorized channel dimensions: the depth, width and radii of bends. The reliability of the present maintenance program, in terms of costs, volumes dredged and facilities provided, to maintain authorized dimensions was examined. The term "reliability" refers to the percent of time controlling dimensions equal or exceed authorized dimensions.

While the decision to provide a certain magnitude and reliability of authorized depth is an economic, institutional and policy question, it is necessary to establish the current level of maintenance and the results achieved. The first subsections of this section address current maintenance programs. Efforts are then made to correlate the level of maintenance, its cost and effectiveness to potential future modifications and requirements in the final subsections.

The components of a waterway maintenance program can include dredging, river training and flow regulation. The determination of maintenance needs, specifically as a result of changed conditions, requires a great deal of experience on the waterway in question and detailed project level evaluation in order to reliably provide authorized dimensions at a minimum cost. This is due to the lack of available general evaluation measures and the great difficulty in determining the level of maintenance efforts required because of the complexity of the hydrological phenomena which define the need for maintenance. Therefore, because of the lack of generalized studies, the basis for the analyses presented herein is available Corps project reports, operations records, and the expertise of Corps operational staff.

In general, as the stability of waterway hydrology is enhanced, the severity of natural forces is reduced and the difficulty of maintaining the authorized dimensions reduced. The provision of locks and dams on a waterway and provision of flood storage capacity, which can be used for flow augmentation, provide flow regulation to enhance stability and reduce dredging requirements. River training works also increase the stability of the river by stabilizing its morphology. Dredging, on the other hand, does not require the high capital investment associated with flow regulation and river training works. The selection of an optimum maintenance program requires an assessment of the effectiveness of all three components. Usually, some combination of the three components is required.

## METHODOLOGY

This section naturally begins with the presentation of authorized and controlling depths on the waterway system.

The present maintenance program for each segment is then described so that areas of insufficient maintenance can be identified. In order to understand the nature and severity of the deficit, the relationship between river hydrology, morphology and the current level of maintenance is examined. A general discussion of these relationships is provided in the first section for the benefit of the reader. Available evaluations were gathered. This process included both an extensive literature survey and interviews with Corps expert personnel from nearly all district and division offices.

An evaluation was first made to determine which segments were experiencing difficulties in maintaining sufficient dimensions with their current maintenance program.

For those segments having maintenance programs which are sufficient to maintain authorized depths with nearly 100% reliability, the current maintenance program and level of maintenance are outlined.

Segments which have maintenance programs which are insufficient to maintain authorized depths with the desired reliability are examined using available information in order to determine the nature and severity of the deficit.

The maintenance programs for inland channels and coastal ports are examined separately because of principal differences between the two, including different physical features (hydrology and morphology), different types of maintenance (different types of dredges and methods of dredging) and different structures of available operational data. For example, the critical periods for maintenance on inland waterways are clearly seasonal in nature while in coastal channels they are associated more with the random occurrence of major storms. Possibly related to this fact is that it was possible to determine the reliability of channel maintenance in inland channels from available information, whereas it was impossible to find any consistent records from which to address the reliability of the maintenance of coastal ports. (In addition, the scope of the NWS only allows the review of coastal port maintenance based on existing studies.)

As the major component of channel maintenance, the current dredging fleet is examined with respect to its ability to adequately maintain the waterways in light of current requirements and constraints. A cost model is provided to aid in the evaluation of dredging costs in relation to possible future constraints or requirements.

Finally, in order to facilitate the selection of alternative maintenance programs to be proposed in response to potential future modifications, alternative channel maintenance programs, which have been proposed in prior studies, are presented in the final parts of this section. As previously mentioned, the absence of any commonly accepted generalized methods of defining maintenance needs for modified conditions made the compilation of existing project report results the only possible way to quantify options. It is not the intention of this report to consider the feasibility of the alternative programs presented, but rather to establish a basis on which to evaluate the relative cost and effect of alternative programs to be proposed in later work.

## CHANNEL MAINTENANCE PROGRAMS, AUTHORIZED DEPTH AND THE RELIABILITY OF AUTHORIZED DEPTH

The purpose of this section is to present authorized channel dimensions and to delineate existing deficiencies in the maintenance of authorized channel dimensions. To set the stage for detailed analyses, a review is provided of the relationships between the reliability of authorized depth and hydrologic conditions and dredging/river training efforts. An integral part of this analysis is the evaluation of controlling depths maintained and a comparison of depth duration, hydrological events, and required maintenance dredging. A summary of ongoing maintenance programs, including the use of training works, advanced dredging and routine maintenance dredging, is presented by analytical segments. The major parameters which affect channel maintenance are considered. Those parameters of particular interest include depth and flow duration data, other hydrological data, maintenance dredging programs, and channel improvements including training structures. When available for a given segment, the above data are correlated in order to determine their interrelationships and to establish, where possible, common denominators which may be applicable to reoccurring channel dimension deficiencies.

### (a) River Hydrology, Morphology and Channel Maintenance

Rivers in their natural state are dynamic entities, constantly changing and difficult to predict.

Rainfall and/or snow-melt runoff in the upper reaches of a watershed produce continual fluctuations in river discharge and stage height. These fluctuations, in turn, directly affect sediment transport which, in conjunction with wave action and freeze-thaw conditions, create navigational hazards by rearranging the physical configuration and dimensions of navigable channels.

The perpetuation of a dependable navigation channel requires the establishment and maintenance of a stable alignment which conforms to authorized or project dimensions and in which a minimum amount of shoaling occurs. In order to maintain a stable channel alignment, training works can be constructed to prevent bank erosion and caving, limit meandering, and constrict the main channel thereby concentrating flows and deepening the navigable portion of the river. The channel improvement features may take the form of revetments to protect the river bank from erosion, contraction dikes to reduce the width and, consequently, increase the depth of the channel, and foreshore protection to protect the area between river and levees.

While training works aid in the maintenance of project depths, rapid and excessive fluctuations in flows may still result in shoaling. Accordingly, periodic maintenance dredging is required to effectuate a navigable depth throughout the year. As defined, maintenance dredging is limited almost entirely to keeping channels open to traffic during declining or low-river stages.

In certain high shoal areas where frequent or continuous dredging is required, overdepth dredging is usually practiced to maintain authorized project depths. In other areas, advance maintenance dredging may be advantageous to reduce dredging frequency (and additional associated mobilization costs) or to take advantage of the operating efficiency of dredging equipment with a capacity greater than that required to maintain project depths.

1. River Stability. The stablility of a river is a qualitative parameter which defines its ability to maintain its morphological features. These features include maximum and mean width, maximum and mean depth, mean and local slope, straightness, bank slope and cross-sectional area. By this definition, a stable river is one which little sedimentation or scour occurs. These are the factors which act to change the river morphology. Unstable rivers are subject to meandering and actively changing sandbars as a result of sedimentation and scour. On stable rivers, there is an explicit relationship between water level and depth. On unstable rivers, this relationship does not exist and nearly the same depths occur during peak floods as during extreme low-flows.

Rivers which have beds and banks composed of coarse grained materials coupled with shallow slopes and narrow widths, with respect to the range of discharges experienced, tend to be stable. The relative stability of a river can be determined based on a method suggested in the paper "Optimum Dredged Depth in Inland Waterways,[21] by Dr. A. Hochstein, 1975. Using this method, relative stability can be established using stability parameters which quantify relationships between river characteristics and comparing these relationships to other rivers of known stability and of similar size and hydrology.

The stability parameters P1 and P2 are defined below.

$$P_1 = \frac{1{,}000\ d_g}{JW}$$

$$P_2 = \frac{Q^{0.5}}{J^{0.2}\ W}$$

$d_g$ = average grain diameter, $d_{50}$ in meters

J = water level gradient at high water

W = width of river water surface at high water in meters

Q = average discharge in cubic meters per second

Table IV-1 presented by Hochstein summarizes the range of stability parameters which typify large, free flowing rivers.

Table IV-1

Classification of River Stability

| Classification of River Stability | Indicators of Riverbed Stability | |
|---|---|---|
| | $P_1$ | $P_2$ |
| Very Unstable | 0.15 | 0.1 |
| Unstable | 0.15 - 0.6 | 0.1 - 0.4 |
| Semistable | 0.6 - 2.0 | 0.4 - 0.8 |
| Stable | 2.0 - 3.5 | 0.8 - 1.2 |
| Very Stable | 3.5 | 1.2 |

2. Factors Affecting the Occurrence and Duration of Controlling Depth. Sediment movement, both suspended and bed load, on a free flowing river primarily occurs during the high flow period. During this period, much of the bed sediments which were deposited in the previous season are remobilized and redistributed, and great quantities of new sediments enter the river during high flows, sandbars are built up and deeper reaches experience a scouring effect, thereby supplying additional load to the river and crossings. However, due to high water levels, channel depths are generally great enough to allow barges to be fully loaded, often beyond the draft at authorized depth. As the high flows begin to recede, flow velocities decrease in deeper reaches and increase at sandbars due to the local backwater effect. As a result, the sandbars are subjected to erosive forces and bed load is shifted to deeper portions of the channel. If the flows recede very rapidly, then the natural scouring effect of the river cannot significantly affect sediment deposition. Therefore, the more rapidly flows recede the more likely the ocurrence of shoals with controlling depths less than authorized. If, on the other hand, the high flows recede more gradually such that flows which occur at or near full bank stage can be maintained for a relatively long period of time, these velocities can often scour the channel enough to maintain authorized depths. An example of this phenomenon can be observed on the Arkansas River. After the flood of 1973, flows receded very rapidly. As a result, authorized depth could not be maintained, without dredging. In following years, a plan was enacted whereby flood waters are stored and subsequently released at a rate that will maintain flows near full bank stages for long periods in order to aid and prolong the scouring process. This is referred to as a "navigation taper." The result has been that authorized depth has been maintained with increased reliability in recent years. The effect is the same, though less pronounced, on most other rivers.

Put into more general terms, because of development within the drainage basin (primarily dedicated to providing conservation storage for irrigation and the storage of flood waters to provide flood protection for downstream shore-based interests) not only is the probability of extreme flows changed, but several of the hydrological parameters which determine the maintenance requirements of the river are altered. For example:

(a) the magnitudes of low flows are increased due to flow regulation or decreased due to water consumption, and the duration of lowflows are reduced.

(b) the magnitudes of high flows are, in most cases, reduced and the duration of high flows are also reduced.

(c) the duration of intermediate flows is generally increased.

(d) the rate of recession of high flow transition to low flow is reduced.

These relationships are shown schematically on Figure IV-A. Since depth generally increases with flow, as the duration of low flows decrease, the probability of encountering adequate depths increases. At high flows, when the sediment carrying capacity of the river is greatest, not only is the magnitude of flows reduced, reducing the amount of sediment that can be carried, but dams in the upper basin trap the larger sediments which would normally become part of the bed load of the river causing shoals. Most importantly, as evidenced on the Arkansas and Missouri Rivers, when the rate of flood recession is decreased, increasing the duration of intermediate flows, the time when the river can scour its own bed is increased. All of these factors act to decrease the maintenance dredging requirements for the maintenance of authorized depth at a given level of reliability.

Properly constructed training works act in much the same way. Training works constrict the channel such that higher scour velocities are maintained in the channel in areas of sediment accumulation.

Thus, the following parameters can be isolated as factors which determine controlling depths and the length of time controlling depths are less than authorized.

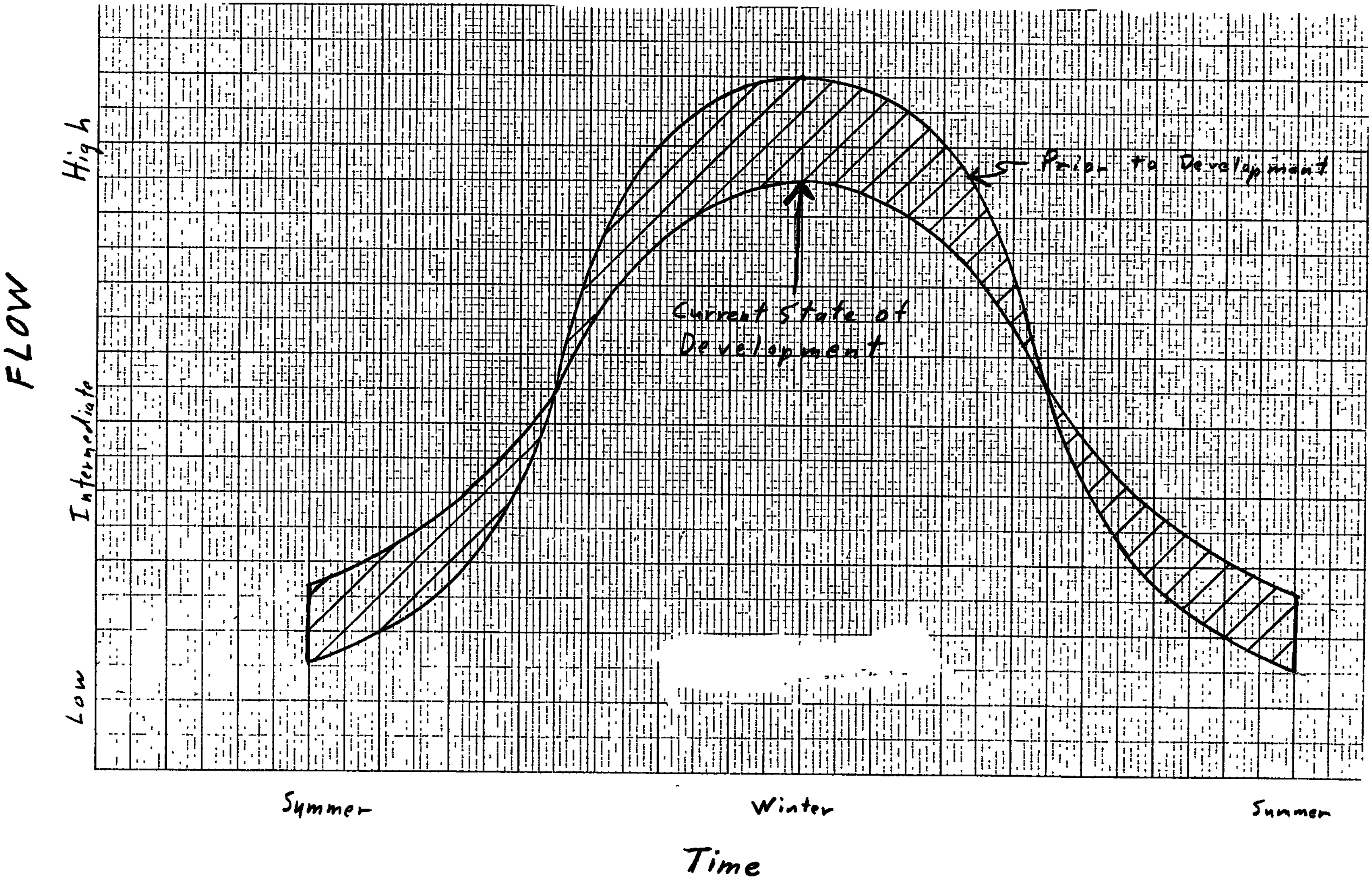
(a) the rate of high flow recession.

(b) the peak flow during the high flow period.

(c) the duration of the high flow period.

## Figure IV-A

### Generalized Curve- Flow Related to State of Development



(d) the duration of the low flow period.

(e) the level of flow during the low flow period.

To date, no specific relationships have been proposed which can quantitatively relate all of these parameters to controlling depths and the required volume of dredging.

3. Determination of the Reliability of Authorized Depth Maintenance. On most rivers, the relationhip between stage and flow is relatively well defined and readily available. Of course, the correlation is constantly changing again, the rate of change depends on the general stability of the riverbed) due to morphological and hydrological changes which are constantly occurring over time. However, these changes can usually be detected and recorded. This allows the location of the water surface at any site to be rapidly determined based on low measured at a few sites. The location of the riverbed, however, cannot be clearly defined and it is the relationship between the riverbed and the water surface, in other words, water depth, which is of the utmost importance for navigation purposes. In particular, the minimum channel depth (or controlling depth) along a waterway reach determines the maximum draft tow which can navigate the reach. The tow operator's ability to predict the controlling depth, which is a function of several complex hydrological parameters as well as dredging and river training activity, determines the draft to which he can load the tow.

The controlling depth can be measured directly by periodic longitudinal surveys of the navigation channel. The accuracy of the information depends on the frequency of the survey, which must be very frequent on rivers with rapidly fluctuating flows and bed elevations and less frequent on more stable rivers.

Stable rivers generally exhibit a good correlation between flow and controlling depth. As a result, the duration of controlling depth can be obtained using the flow duration curve. If the low water reference plane is located at the stage corresponding to a flow occurring 95% of the time, then assuming maintenance works are adequate, depths should be greater than authorized about 95% of the time.

On the other hand, on unstable rivers, there is generally no simple relationship between flow and controlling depth. For example, if peak flood flows are high, the duration of high flows long, and the rate of recession rapid, then sandbar buildup will be high, the duration of flows at a level to cause scour will be small, and lower water depths will be experienced at higher flows. If peak flood flows are low, the duration of high flows short, and the rate of recession gradual, then the river may have time to scour its bed and authorized depth can be attained at nearly any flow depending on the intensity of the hydrological parameters. It is more of the case, however that the three parameters have differing intensities.

Accurate measurements of controlling depths have only been collected during recent years, if at all. Because of the highly varying hydrology on most rivers, a very long period maintenance from the positive effect of scour even in a relatively stable hydrological year.

Over periods of more limited record (5-10 years) flow and measured controlling depths can be related according to the probability of their simultaneous occurrence. The probability of a given flow occurring can be correlated with the probability of a certain controlling depth at that flow in order to obtain a controlling depth-duration relationship. It is more logical, when evaluating an unstable river, to determine the reliability of maintenance operations by analyzing the duration of controlling depth in this manner rather than by the duration of low-flows. These relationships are discussed in more specific terms in following sections dealing with Segments 3, 4, 5 and 6 on the Mississippi River.

4. Relationship Between the Reliability of Authorized Depth and Dredging Maintenance Requirements. These rivers may be dredged throughout the year, except at the high water stage, and dredging operations can sometimes remove a greater volume in one year and thus create a reserve that may avoid the need for dredging in the subsequent year.

In unstable rivers, with intensive riverbed processes, even a small increase of channel depth relative to the natural depth of river, the degree of siltation depends on the amount of depth relative to natural depth, and an increase in depth causes a higher increase in siltation rate.

Annual dredging requirements on an unstable river can vary greatly, as the intensity of dredging required to maintain authorized depths depends heavily on all of the highly variable parameters discussed above. For most rivers, it has been established that for navigation purposes, dredging operations should be sufficient when combined with river training and flow regulation to provide depths equal to or greater than authorized with a probability of about 95% over long periods of time. Because of the complexity of most hydrographs on unstable rivers, a great deal of time is generally required to determine the effectiveness of a dredging operation in terms of controlling depth duration.

Once a depth duration relationship is achieved, however, determining the maintenance dredging requirements necessary to increase (or decrease) the reliability of authorized depth, or accommodate an increase in authorized depth, is even more difficult than determining the initial dredging requirements.

There is no known or commonly accepted method of estimating channel dredging requirements other than by extrapolating historical trends and detailed design level studies based on hydrographic survey. As a result, it is very difficult to analyze the effects of future waterway modifications on dredging requirements for purposes of the NWS. For the waterways where the above type of detailed study has been performed, the results of the analysis are presented in the section entitled "Alternatives for Channel Improvements." For other waterways, a second method is used.

The second method can provide only a very rough indication of the level of magnitude of maintenance dredging which may be expected as a result of increasing depth. This method is presented for use here in the absence of other general evaluation measures. The general relationship between maintenance dredging requirements (volumes) and depth maintained takes the form discussed in Hochstein's "Optimum Dredging Depth in Inland Waterways"[22]:

$$\left(\frac{D_2}{D_1}\right)^m = \left(\frac{V_1}{V_2}\right)$$

$D_1$ = present depth maintained x% of the time
$D_2$ = projected depth maintained x% of the time
$V_1$ = volume of dredging required at present depth $D_1$
$V_2$ = volume of dredging required at projected depth $D_2$
m = a variable which usually ranges between 3 and 5 and can be roughly related to river stability (3 = very stable, 5 = very unstable)
x = constant value for $D_1$ and $D_2$ obtained from the depth duration curve.

As the formula shows, minor increases in depth can cause major increases in dredging volumes. This is due to the appearance of more and longer shoaling areas and a higher rate of siltation as the depth maintained increases.

It should be noted that a physical limitation to the depth to which a river can be dredged exists. In the event that dredging causes a change in the river form, wherein the lowering of the water level in the river will be followed by a corresponding lowering of the water level in the channels and the upper part of the river, then increased dredging will not result in increased depth. Thus, dredging becomes physically impractical if the cross-sectional area of the channel equals a substantial portion of the cross-sectional area of the river, because the water level will fall nearly as fast as the river bottom is lowered.

### (b) Authorized Channel Dimensions by NWS Segments and the Identification of Segments Having Deficient Dimensions

A review of authorized and controlling channel dimensions was performed for each of the Reporting Regions in the NWS. Within certain reaches, sub-segments are presented to accommodate the wide range of channel dimensions between tributary and mainstream portions of the same segment. The results of the above review are tabulated for inland waterways in Table IV-2 and for coastal waterways in the section entitled "Current Maintenance Programs and Authorized Depth in Approaches to Coastal Ports."

During interviews with various Corps District experts, it became clear that no uniform definition with respect to authorized depth is followed. Some districts equate the authorized depth with actual depth while other districts consider the authorized depth to be the maximum vessel draft.

As indicated, there appears to be two dissociated situations in which variations from the authorized dimensions may exist. The first type of variation applies to segments in which one or more of the controlling channel dimensions are frequently or always less than the authorized dimensions. These variations are noted as "Dimension Deficiencies" in the far-right hand column of Table IV-2. The second type of variation noted occurs when the design discharge (equatable to SLW) is maintained less than 95% of the time, percentages lower than the accepted norm may indicate a maintenance deficiency. Depth duration curves were utilized to relate the reliability of channel depths to flow duration for pertinent inland waterways.

Table IV-3 indicates those inland segments which exhibit some form of channel dimension deficiency and a brief description of the problem.

### (c) Current Channel Maintenance Programs and the Reliability of Authorized Depth by NWS Segment

A summary of dredging quantities and costs and types of dredging and dredge material disposal are summarized in Table IV-4. Most of the information contained in this summary has been extracted for the National Waterway Inventory. This document contains many discrepancies,

# Table IV-2

## Waterways Dimensions
## (Inland Waterways

| Rep. Reg. | Seg. Name | (1) Auth. Width | Cont Width | (1) Auth. Depth | Cont. Depth | (2) Design Discharge | % of Time D.D. Maintd. | Dimension Deficiencies |
|---|---|---|---|---|---|---|---|---|
| 1 | U. Mississippi R. St. Anthony Lock to Lock 10 | 200-300 | 200-300 | 9 | 9 | 1,300 | UA | |
| | Lock 11 & pool to Illinois R. | 400-200 | - -200 | 9 | 9 | 13,200 | 99 | |
| 2 | Lower U. Mississippi R | 200 | 200 | 9 | 9 | 30,000 | 98 | |
| 2 | Mid. Mississippi R. | 300 | 300 | 9 | 9 | 54,000 | 98.5 | |
| | Kaskaskia R. | 225 | 225 | 9 | 9 | -- | 100 | |
| 3 | Lower Mid Mississippi R. | 300 | 300 | 12 | 9 | 147,000 | 97 | D |
| 3 | U. Lower Mississippi R. | 300 | 300 | 12 | 12 | 150,000 | 100 | |
| | Yazoo R. | 100 | 75 | 9' | - | 3,000 | UA | W/D |
| 3 | Lower Mississippi R. | 300 | 300 | 12 | 9 | 180,000 | 100 | D |
| 4 | Mississippi R., Baton Rouge - N.O. | 500 | 500 | 40 | 40 | 185,000 | 100 | |
| 4 | Mississippi R., N.O. - MRGO | 500 | 500 | 36 | 36 | UA | -- | |
| | N.O. - Harvey Cnl. | 125 | 125 | 12 | 12 | UA | -- | |
| | N.O. - Michould Cnl. | 250 | 250 | 36 | 36 | UA | -- | |
| 4 | Ouachita, Black & Red Rvrs. | 100 | 100 | 6.5 - 9 | 6.5 | 500 | 100 | D |
| 4 | Old & Atchafalaya Rvrs. | 125 | 125 | 12 | 12 | 105,000 | 94.4 | |
| | Morgan City - Gulf | 200 | 200 | 20 | 20 | -- | -- | |
| 4 | Baton Rouge - Morgan City Bypass | 125 | 125 | 12 | 12 | UA | -- | |
| 5 | Illinois W/W | 300 | 110 | 9 | 8 | 10,750 | 65 | W/D |
| | Chicago S.S.C. | 225 | 160 | 9 | 9 | 5,455 | 90 | W |

# Table IV-2 (Continued)

## Waterways Dimensions (Inland Waterways)

| Rep. Reg. | Seg. Name | (1) Auth. Width | Cont. Width | (1) Auth. Depth | Cont. Depth | (2) Design Discharge | % of Time D.D Maintd. | Dimension Deficiencies |
|---|---|---|---|---|---|---|---|---|
| 6 | Missouri R. | 300 | 250 | 9 | 8.5 | 29,000-35,000 (4) | 58 | D |
| 7 | U. Ohio R. | 500 | 300 | 9 | 9 | 3,320 | 100 | W |
| | Muskingum R. | 100 | 100 | 4 | 4 | UA | -- | |
| 7 | Mid. Ohio R. | 500 | 300 | 9 | 9 | 9,000 | 95 | W |
| 7 | Lower Ohio R. (3) | 300 | 241 | 9 | 9 | 9,700 | 95 | W |
| 7 | Lower Ohio R. (2) | 300 | 300 | 9 | 9 | 15,000 | 95 | |
| 7 | Lower Ohio R. (1) | 300 | 300 | 9 | 9 | 21,500 | 95 | |
| 7 | Monongahela R. | 250 | 250 | 9 | 9 | 310 | 100 | |
| 7 | Allegheny R. | 250 | 250 | 9 | 9 | 2,240 | 100 | |
| 7 | Kanawha R. | 300 | 300 | 9 | 9 | -- | -- | |
| 7 | Kentucky R. | 75 | 75 | 6 | 6 | 200 | 95 | |
| 7 | Green R. | 200 | 90 | 5 | 5 | UA | -- | W |
| 7 | Cumberland R. | UA | 100 | 9 | 7 | 9,000 | 100 | D |
| 8 | U. Tennessee R. | UA | 150 | 9 | 8 | UA | -- | D |
| 8 | Lower Tennessee R. | UA | 250 | 9 | 11 | 13,000 | 100 | |
| 9 | Arkansas & Verdigris Rvrs. | 250 | 250 | 9 | 9 | 4,000 | 100 | |
| | White & Black Rvrs | -- | 125 | -- | 5 | 9,600 | 95 | |
| 10 | GIWW West One/Trib. | 40 | 40 | 5 | 5 | UA | -- | |
| 10 | GIWW West Two/Trib. | 125 | 125 | 12 | 12 | UA | -- | |
| 10 | GIWW West Three/Trib | 25-700 | 25-700 | 12 | 12 | UA | -- | |
| 10 | Houston Ship Cnl. | 1,125 | 1,125 | 40 | 40 | UA | -- | |
| 11 | GIWW East One/Trib. | 150 | 150 | 12 | 12 | UA | -- | |
| 11 | GIWW East Two/Trib. | 125 | 125 | 12 | 3 | UA | -- | D |

# Table IV-2 (Continued)

## Waterways Dimensions (Inland Waterways)

| Rep. Reg. | Seg Name | (1) Auth. Width | Cont. Width | (1) Auth. Depth | Cont Depth | (2) Design Discharge | % of Time D D Maintd | Dimension Deficiencies |
|---|---|---|---|---|---|---|---|---|
| 11 | Apalachicola, Chattahochee, Flint Rvrs. | 100 | 100 | 9 | 9 | 9,200 | 83 | |
| 12 | Black Warrior, Tombigbee Rvrs. | 200 | 200 | 9 | 9 | 1,600 | 95 | |
| 12 | Alabama, Coosa Rvrs. | 150 | 150 | 9 | 9 | 8,600 | 94.5 | |
| 12 | Tenn. - Tombigbee W/W | 300 | UA | 9 | UA | UA | -- | |
| 13 | Florida/Georgia Coast | | | | | | | |
| | AIWW - Florida | 90-150 | 85 | 7- 12 | 4 | -- | -- | W/D |
| | AIWW - Georgia | 90 | 90 | 12 | 9 | -- | -- | D |
| 13 | Carolinas Coast | | | | | | | |
| | AIWW - S.C. | 90 | 90 | 12 | 12 | -- | -- | |
| | AIWW - N.C. | 90 | 90 | 12 | 10 | -- | -- | D |
| 15 | U. Atlantic | | | | | | | |
| | Cape Cod Cnl. | 450 | 450 | 32 | 32 | -- | -- | |
| | Blynman Cnl. | 200 | 100 | 8 | 4 | -- | -- | W/D |
| 16 | N.Y. Waterways Barge Cnl. | 104 | 104 | 14 | 14 | -- | -- | |
| 18 | U. Columbia-Snake W/W | 250 | 250 | 14 | 14 | -- | -- | |
| 18 | Lower Columbia-Snake W/W | 250-600 | 250-600 | 14-40 | 11-40 | -- | -- | D |
| | Willamette R. | 150 | 150 | 5-8 | 3-8 | -- | -- | D |

UA - Unavailable
(-) - Does not apply
W/D - Indicates maintenance deficiency for width (W) and depth (D)
(1) - Authorized widths and depths within analytical segments may vary due to diversified morphology of main stream and tributaries
(2) - Design discharge selected on basis of lowest LWRP with main stream of each analytical segment
(3) - More than 30 subsegments with channel dimension deficiencies
(4) - Navigational channel dimensions varies according to releases from upstream controlling structures
(5) - Per MRD. River is closed to navigation for four months during winter.

# Table IV-2 (Continued)

## Waterway Dimensions
## (Coastal Channels, Harbors/Great Lakes)

| Rep. Reg. | Seg. Name | (1) Auth. Width | Cont. Width | (1) Auth. Depth | Cont. Depth | (2) Design Discharge | % of Time D.D. Maintd | Dimension Deficiencies |
|---|---|---|---|---|---|---|---|---|
| 10 | GIWW West Two/Trib. | | | | | | | |
| | Channels & Harbors | 100-1,125 | 100-1,125 | 6-47 | 6-40 | UA | -- | D |
| 10 | GIWW West Three/Trib. | | | | | | | |
| | Channels & Harbors | 100-700 | 100-700 | 12-45 | 12-45 | UA | -- | |
| 11 | GIWW East One/Trib. | | | | | | | |
| | Channels & Harbors | 60-350 | 60-350 | 3-38 | 3-38 | UA | -- | |
| 11 | GIWW East Two/Trib. | | | | | | | |
| | Channels & Harbors | 15- 30 | 15- 30 | 3-32 | 3-32 | UA | -- | |
| 11 | Florida Gulf Coast | | | | | | | |
| | Caloosahatchee R. to Anclote<br>Anclote to St. Marks | 100 | UA | 12 | 9 | -- | | |
| 12 | Black Warrior, Tombigbee Rvrs. | | | | | | | |
| | Mobile Harbor | 400 | 400 | 40 | 40 | UA | -- | |
| 13 | Florida/Georgia Coast | | | | | | | |
| | Hrbrs. - Georgia | 200-600 | 200-600 | 27-40 | 11-40 | -- | -- | D |
| | Hrbrs. - Florida | UA | UA | UA | UA | -- | -- | |
| 13 | Carolinas Coast | | | | | | | |
| | Channels & Harbors - S.C. | 250-2,200 | 250-2,000 | 10-35 | 10-35 | -- | -- | |
| | Channels & Harbors - N.C.(3) | 100-850 | 80-850 | 12-42 | 12-42 | -- | -- | W/D |
| 14 | Cheasapeake/Delaware Bays | 40-1,500 | 40-1,500 | 5-45 | 2-40 | -- | -- | D |
| 14 | N.J. & N.Y. Coast | 75-3,000 | 60-3,000 | 8-45 | 8-45 | -- | -- | W |
| 16 | N.Y. Waterways | | | | | | | |
| | Lake Champlain | 40-800 | 40-800 | 5-12 | 4-12 | -- | -- | D |

# Table IV-2 (Continued)

## Waterways Dimensions
## (Coastal Channels, Harbors/Great Lakes)

| Rep. Reg. | Seg. Name | (1) Auth Width | Cont. Width | (1) Auth. Depth | Cont Depth | (2) Design Discharge | % of Time D. D. Maintd. | Dimension Deficiencies |
|---|---|---|---|---|---|---|---|---|
| 16 | Lake Ontario/St. Lawrence | 80 | 80 | 27 | 27 | -- | -- | |
| 16 | Lake Erie | 200-300 | 200-300 | 12-21 | 11-21 | -- | -- | D |
| 16 | Lake Huron | -- | -- | -- | -- | -- | -- | |
| 16 | Lake Michigan | -- | -- | -- | -- | -- | -- | |
| 16 | Lake Superior | 245-1,000 | 245-1,000 | 12-38 | 12-29 | -- | -- | D |
| 17 | Puget Sound | 100-150 | 100-150 | 8-30 | 10-26 | -- | -- | D |
| 17 | Oregon/Washington Coast | 50-150 | 50-150 | 4-10 | 3-7 | -- | -- | D |
| 19 | Northern California | 60-600 | 60-600 | 30-45 | 30-32 | -- | -- | D |
| 19 | San Francisco Bay Area | 100-2000 | 100-2000 | 30-55 | 22-50 | -- | -- | D |
| 19 | Central/South California | 150-200 | 150-200 | 15 | 10-13 | -- | -- | D |
| 20 | Southeast Alaska | -- | -- | -- | -- | -- | -- | |
| 20 | South Central Alaskan Coast | -- | -- | -- | -- | -- | -- | |
| 20 | West/No. Alaskan Coasts | -- | -- | -- | -- | -- | -- | |
| 21 | Western Pacific | -- | -- | -- | -- | -- | -- | |
| 22 | Caribbean | -- | -- | -- | -- | -- | -- | |

UA - Unavailable
(-) - Does not apply
W/D - Indicates maintenance deficiency for width (W) and depth (D)
(1) - Authorized widths and depths within analytical segments may vary due to diversified morphology of main stream and tributaries
(3) - More than 30 subsegments with channel dimension deficiencies

# Table IV-3

## Deficient Segments

| Rep. Reg. | Seg. Name | Def. Dimension | Remarks |
|---|---|---|---|
| 1 | U. Mississippi R. | D | Increased number of groundings due to insufficient depth maintenance and low water. |
| 2 | Lower U. Mississippi R. | D | Increased number of groundings since 1975 apparently due to low water |
| 3 | Lower M. Mississippi R. | D | 12' depth authorized is to be attained through stabilization program which is not yet complete. Authorized depth maintained at present is 9'. |
| 3 | Yazoo R. | W/D | The project which was to improve the river to meet the authorized dimensions of 9'x100' is currently being evaluated. |
| 3 | Lower Mississippi R. | D | Same as Segment 3 above Stabilization program not yet completed |
| 4 | Ouachita, Black R. | D | Project to establish the authorized 9' depth is complete from mouth of Black R. to Louisiana/Arkansas Border. Estimated date of project completion to Camden, Ark. is 1984. |
| 5 | Illinois Waterway | W/D | Original construction dimensions were less than the 9'x300' subsequently authorized and currently, the controlling width and radii, specifically navigable width of bridge spans, are considerably less than authorized and may be as narrow as 110'. |
| 5 | Chicago SSC | W | Bridge constriction limits channel width to 160'. |
| 6 | Missouri R. | W/D | Controlling dimensions below Boonville, Mo. only 6.5' x 250' due to possible need for additional training structures. Navigation shut down during winter and when multi-purpose storage above Sioux City insufficient to maintain minimum design flow |
| 7 | U. Ohio R. | W | Authorized width should be 300' with appropriate widening at bends. |
| 7 | M. Ohio R. | W | |

# Table IV-3 (Continued)

## Deficient Segments

| Rep. Reg. | Seg. Name | Def. Dimension | Remarks |
|---|---|---|---|
| 7 | Lower Ohio R. | W | Same as Upper Ohio except bridge on Portland Canal at Louisville, Ky. restricts channel width to 241'. |
| 7 | Green R. | W | Headwater constricted to 90' width by bedrock topography. Existing traffic does not warrant improvement. |
| 7 | Cumberland R. | D | Eleven mile reach of river near Old Hickory Lock has bedrock riverbed which limits depth to 7' at low water stage. |
| 8 | U. Tennessee R. | D | Controlling depth of 8' in headwater less than authorized. Limited traffic does not warrent channel improvement at this time. |
| 9 | White R. | D | Shoaling is frequent problem with low depth reliability due to limited maintenance funding and periodic low flows. |
| 9 | Red R. | D | Project to establish the authorized 9' depth under implementation. |
| 11 | GIWW East/One<br>Carrabelle to Apal. Bay | D | Shoaling limits controlling depth to less than authorized. |
| 11 | Apalachicola R. | D | Low releases from upstream reservoirs occasionally limit controlling depths to less than 9' authorized. |
| 12 | Alabama R. | D | Shoaling and low flows limit controlling depth to less than authorized. |
| 16 | Lake Erie | D | Shoaling and seiches affect controlling depths. |
| 16 | Lake Superior | D | Shoaling and seiches affect controlling depths. |
| 18 | Upper Columbia | D | Controlling depth conforms with navigational depth over lock sills. |
|  | Willamette | D | Low water stages controlled by upstream releases. Declining use limits flow requirements. |

# Table IV-4

## Summary of Dredging by Analytical Segment

| Reporting Region | Segment Name | Ave. Annual Vol. Latest 3-5 yrs.(1) CY X $10^2$ | Ave Annual Cost Latest 3-5 yrs. \$ X $10^3$ | Ave. Cost \$/Cu. Yd. | Length of Seg.-ment (1) Miles | Ave. Cost Mile | Ave. Vol Per Mile Cubic | Type of Waterway | Types Dredging | Types Disposal | Dredging Equipment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | COL | Private |
| 1 | Up. Miss. River | 27291 | 2737 | 1.00 | 673 | 4067 | 4055 | C | C,D.T | B,C,O,Z | 2T,2T | 1D |
| 2 | Lower Up Miss R. | 0 | 0 | - | 22.6 | 0 | 0 | C | - | - | - | - |
| 2 | Mid. Miss. River | 60386 | 3163 | 0.52 | 267 | 11846 | 22616 | | T,U | O | 1T, 1U | 16D,1B |
| 3 | Lower Mid. Miss. R. | 220000 | 5790 | 0.26 | 356 | 16264 | 61798 | F | T,U | Z | 3U | 3D |
| 3 | Upper L. Miss. River | 109211 | 2534 | 0.23 | 426 | 5948 | 25636 | F | U | O | 1U,1T | TD |
| 3 | L. Miss. Old R.-B.R. | 14805 | 889 | 0.60 | 69 | 12884 | 21457 | F | T,U | O | - | - |
| 4 | Miss. R.B.R. To N.O. | 58446 | 1999 | 0.34 | 127 | 15740 | 46070 | S | C,E | O | - | 19D,1B |
| 4 | Miss. R.-N O.-Gulf | 475897 | 20608 | 0.43 | 202 | 102020 | 235593 | S | H,T,U,Z | A,O,P,Z | 1H | 26D,10B |
| 5 | Illinois W/W | 25124 | 1711 | 0.68 | 349 | 4903 | 7199 | | T,Z | O | 1T | 3D |
| 6 | Missouri River | 48484 | 4017 | 0.83 | 621 | 6469 | 7807 | F | U | O | 1T,1U | |
| 7 | Upper Ohio River | 1908 | 488 | 2.56 | 359 | 1359 | 531 | C | C,T | C,Z | | 3D,2B |
| 7 | Mid. Ohio River | 7275 | 862 | 1.18 | 288 | 2993 | 2433 | C | C,T | O,Z | - | - |
| 7 | L. Ohio River III | 4666 | 396 | 0.85 | 238 | 1664 | 1961 | C | T | O | - | 3D |
| 7 | L. Ohio River II | 9660 | 1090 | 1.13 | 151 | 7218 | 6397 | C | T | O | - | 1D |
| 7 | L. Ohio River I | 20 | 2 | 1.00 | 46 | 43 | 43 | C | T | O | - | - |
| 7 | Monongahela R. | 710 | 211 | 2.97 | 129 | 1636 | 500 | C | C | C | - | - |
| 7 | Allegheny R. | 400 | 111 | 2.78 | 72 | 1541 | 568 | C | C | C | - | - |

(1) Source: Inventory of Waterway Physical Characteristics
(2) 1978 Costs

# Table IV-4 (Continued)

## Summary of Dredging By Analytical Segment

| Reporting Region | Segment Name | Ave. Annual Vo. Latest 3-5 yrs.(1) CY X $10^2$ | Ave Annual Cost Latest 3-5 yrs. $\$$ X $10^3$ (2) | Ave. Cost $/Cu.Yd. | Length of Seg.- ment (1) Miles | Ave. Cost Mile | Ave. Vol. Per Mile Cubic | Type of Waterway | Types Dredging | Types Disposal | Dredging COE | Equipment Private |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Kanawha R | 110 | 200 | 18.18 | 91 | 2198 | 121 | C | C,T | Z | | |
| 7 | Kentucky R. | 1100 | 119 | 1.08 | 255 | 467 | 431 | C | C | O | | |
| 7 | Green R | 750 | 97 | 1.29 | 212 | 458 | 354 | C | C | O | | |
| 7 | Cumberland R. | 892 | 181 | 2.03 | 381 | 475 | 234 | C | C,T | O,C | | 2D |
| 8 | U.Tenn & Clinch Rivers | 0 | 0 | - | 499 | 0 | 0 | C | - | - | | |
| 8 | L. Tenn. R.-Ohio River | 300 | 52 | 1.73 | 215 | 242 | 140 | C | - | 10 | | |
| 9 | Ark. Verd. Wht. & Blk. Rivers | 32942 | 2420 | 0 78 | 701 | 3447 | 4686 | C,F | T | B,C | | |
| 9 | Quachita-Blk & Red Red | 24493 | 1271 | 0.50 | 566 | 2246 | 4328 | C,F | T | C,O | | |
| 9 | Old & Atch. | 52219 | 1410 | 0.27 | 168 | 8392 | 31081 | C | T,Z | C,O,Z | | |
| 9 | B. Rge. Morg City By-pass | 6350 | 295 | 0.46 | 64 | 4909 | 9922 | C | T | C,O | | |
| 10 | GIWW-West I & Tribs | 41567 | 2914 | 0.70 | 489 | 5959 | 8500 | I,S | C,H,T | C,O,P,Z | | 4D,2B |
| 10 | GIWW W. II & Tribs | 430132 | 13497 | 0.31 | 698 | 19337 | 61623 | I,S | H,T | C,O,P,Z | | |
| 10 | GIWW W. III & Tribs | 50575 | 5390 | 1.07 | 260 | 20731 | 19452 | I,S | H,T,Z | C,O,P,Z | | 5D |
| 10 | Houston Ship Canal | 87460 | 4679 | 0.53 | 175 | 26731 | 49977 | C | H,T,Z | C,O,P,Z, | 1H | 10D,6B |
| 11 | GIWW E I & Tribs | 45078 | 2381 | 0.50 | 539 | 4417 | 8474 | I,C,S | H,T | C,O | 2T | 21D,1B |
| 11 | GIWW E II | 17304 | 1300 | 0.75 | 467 | 2784 | 3705 | I,C, | H,T,Z, | C,O,Z | | 1D |
| 11 | Florida Gulf Coast | 16580 | 3358 | 2.03 | 614 | 5487 | 2700 | I,C,S | H,P,Z | C,O,Z | | 17D |

(1) Source: Inventory of Waterway Physical Characteristics
(2) 1978 Costs

# Table IV-4 (Continued)

## Summary of Dredging by Analytical Segment

| Reporting Region | Segment Name | Ave. Annual Vol. Latest 3-5 yrs.(1) CY X $10^2$ | Ave. Annual Cost Latest 3-5 yrs. \$ X $10^3$(2) | Ave Cost S/Cu.Yd. | Length of Seg.-ment (1) Miles | Ave. Cost Mile | Ave Vol. Per Mile Cubic | Type of Waterway | Types Dredging | Types Disposal | Dredging COE | Equipment Private |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | Blk. Warrior & Tomb. | 63843 | 3289 | 0.52 | 452 | 7277 | 14125 | C | H,T,Z | B,C,H,Z | - | - |
| 12 | Ala Coosa River | 16344 | 631 | 0.39 | 798 | 791 | 2048 | C | T | O | - | - |
| 12 | Tenn. Tom W/W | - | - | - | 314 | - | - | C | - | - | - | - |
| 11 | Apal Chat. Flint | 17015 | 1276 | 0.75 | 283 | 4509 | 6012 | C | T | C,O | - | - |
| 13 | Fla. Ga. Coast | 119795 | 9814 | 0.82 | 1956 | 5017 | 6124 | I,E,F | H,T,Z | B,C,P,Z | 2H | 25D,2B |
| 13 | Carolina Coast | 167628 | 15746 | 0.94 | 1434 | 10987 | 11690 | I,C,E,F | H,S,T,Z | B,C,H,O,P,Z | 25ISP | 16D,5B |
| 14 | Chesap. & Del Bays | 58937 | 11894 | 2.02 | 1437 | 8277 | 4101 | I,S,E,F | C,H,O,R,S,<br>T,Z | B,C,H,O,P,Z | 3H,IS | 33D,15B |
| 14 | N.Y. N.J Coast | 57689 | 11892 | 2.06 | 778 | 15285 | 7415 | I,S,E,F | C,H,O,S,Z | B,O,P,Z | - | 19D,6B |
| 16 | N.Y State W | 12291 | 15530 | 8.05 | 781 | 18885 | 2170 | C,A | C,H,T,Z | C,P,Z | - | 1D |
| 15 | U. Atlantic | 8221 | 2507 | 3.05 | - | - | - | S,D,F | C,H,S,T,Z | B,C,O,P,Z | - | 11D,14B |
| 16 | L. Ont St. Lawr. Sea. | 4263 | 515 | 1.21 | - | - | - | L,E,S | C,H | O,Z | - | 1D,2B |
| 16 | L. Erie | 42971 | 5902 | 1.38 | - | - | - | L,E,S | C,H | C,O,Z. | 3H | 6D,10B |
| 16 | L. Huron | 7164 | 5431 | 7.58 | - | - | - | L,E,S | C,H,I,T,Z | B,C,O,Z | 1H | 16D,21B |
| 16 | L. Michigan | 13443 | 2778 | 2.07 | - | - | | L,D,S | C,H,T,Z | B,C,O,Z | - | 2D,27B |
| 16 | L. Superior | 2308 | 556 | 2.41 | - | | - | L | C,H,T,Z | C,Z | - | 7D,3B |
| 17 | Puget Sound | 6040 | 755 | 1.25 | - | - | - | | C,P | C,O | - | 3D,7B |
| 18 | U. Col-Snake W/W | 0 | 0 | - | 315 | 0 | 0 | D | - | - | - | 7D,1B |

(1) Source: Inventory of Waterway Physical Characteristics
(2) 1978 Costs

# Table IV-4 (Continued)

## Summary of Dredging by Analytical Segment

| Reporting Region | Segment Name | Ave. Annual Vol. Latest 3-5 yrs.(1) CY X $10^2$ | Ave. Annual Cost Latest 3-5 yrs. \$ X $10^3$(2) | Ave. Cost \$/Cu.Yd. | Length of Seg.-ment(1) Miles | Ave. Cost Mile | Ave Vol. Per Mile Cubic | Type of Waterway | Types Dredging | Types Disposal | Dredging COE | Equipment Private |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | L. Col.-Snake W/W | 199915 | 7548 | 0 38 | 150 | 50320 | 133270 | P,L,E,S | D,H,P | B,O,P | 3H,1T | 70,1B |
| 18 | Oregon Wash Coast | 61902 | 4978 | 0 81 | 167 | 29800 | 37007 | F,S | C,D,H,T,Z | B,O,P | - | 4D,1B |
| 19 | Northern Calif | 4789 | 600 | 1.26 | 2 | 300000 | 237400 | - | C,H,Z | C,P,Z | - | - |
| 19 | San Fco. Bay Area | 59439 | 9686 | 1.63 | 559 | 173266 | 106331 | S | C,H,T,Z | C,O,P,Z | - | 3D,3R |
| 19 | Central S Calif. | 101063 | 18362 | 1.82 | - | - | - | - | 1,Z | B,O,P | - | 3D,3B |
| 20 | S.E. Alaska | 0 | 0 | 0 | 0 | 0 | 0 | - | C | C | - | 1D,7B |
| 20 | S. Central Alsk. Coast | 825 | 247 | 2.99 | - | - | - | - | C | O | 2T | - |
| 20 | W & N Coast of Alask | 110 | 50 | 4 55 | - | - | - | - | C | C | - | - |
| 21 | W. Pacific Incl. H I Guam Latin Am | 1518 | 206 | 1.36 | - | - | - | - | C,D,H,P | C,P | - | 1B |
| 22 | Carribean Incl. P R | 2050 | 289 | 1.41 | - | - | - | - | C,H | O | - | 5O,2B |
| Totals | | 2909108 | 303817 | 1 04 | - | - | - | - | - | - | - | - |
| | U Miss-St. Paul Dist. | 5682 | 1522 | 2.68 | 278 | 5475 | 2044 | C | O,T | B,C,O,Z | 2T,1I | 1D |
| | U. Miss-Rock Is Dist. | 6203 | 2143 | 0.68 | 318 | 2147 | 2143 | C | T,D | B,O,Z | - | - |
| | U. Miss-St Louis Dist. | 14355 | 17506 | 0.52 | 82 | 9085 | 17500 | C | T | O | - | - |

(1) Source: Inventory of Waterway Physical Characteristics
(2) 1978 Costs

## Table IV-4 (cont'd)

## Summary of Dredging by Analytical Segment

KEY

### Type of Dredging or Dredge (COE)

D - Dragline
I - Dipper
L - Ladder
U - Dustpan
C - Clamshell
O - Orange Peel
H - Hopper
P - Plain Suction
T - Cutterhead
S - Side Casting
Z - Other

### Type of Disposal

A - Agitation
B - Beach Nourishment
C - Confined
M - Marsh
O - Open Water
P - Ocean
Z - Other

### Type of Dredge (Private)

D - Dredge
B - Barge

### Type of Waterway

C - Channelized
F - Free Flowing River
S - Seaway (Doep Draft)
CA - Canal
I - Intracoastal Waterway
L - Lake

particularly with regard to reportings by different districts. For example, it is not clear whether quantities are measured (total volume dredged) or credited (within the authorized prism). Some districts have reported the length of every authorized channel, including minor approach channels, whereas others have only reported main channels and other canals, but not river channels. Some districts have divided quantities dredged by different types of dredges, others have combined them and defined them as "other" types of dredging. The term "confined" disposal obviously caused some confusion with regard to upland disposal as some districts show upland disposal as "confined" whereas others show it as "other." Nevertheless, this table does give a reasonable indication of the current level of maintenance dredging on different river segments.

Segments or parts of segments which are not included in this section are included in the section entitled "Channel Maintenance Programs and Authorized Depth in Approaches to Coastal Ports." Only segments having authorized inland waterways are included.

1. Reporting Region 1 - Upper Mississippi River. The Upper Mississippi River is maintained and regulated by the St. Paul, Rock Island and St. Louis District offices of the Corps. While the use of groins or dikes has been very limited due to lock and dam construction, the St. Paul District is currently reevaluating their applications to comply with reduced dredging mandates. In this respect, the University of Minnesota conducted a study to evaluate the influence of submerged groins on the bed regions of alluvial channels. However, the concept is presently untested in the prototype.

No dikes have been built in the Rock Island District since 1948. Navigation channel dikes built in the late 1800's and early 1900's are now under six to eight feet of water. Jacks and jetties are now being used to reduce bank erosion on small streams, a primary concern in this district.

Normally, critical sites from Winona, Minnesota, upstream to Minneapolis, Minnesota, are dredged by the 20" cutterhead dredger in May and June. During June, July and August, the dredge works in the Rock Island District but

## Table IV-5

## Cost per Cubic Yard and Cost per Mile of Waterway for Dredging in the Upper Mississippi River

| Waterway | Corps District | Main Bordering States | Predominant Means of Dredge Mat'l. Disposal | Severity of Environmental Constraints | Dredging[2] Vol. per Mile of W/W cu. yd. | Average[2] Cost/ cu. yd. $ | Average[2] Cost per Mile $ |
|---|---|---|---|---|---|---|---|
| U. Mississippi | St. Paul | Minnesota/ Wisconsin | Upland | Severe | 2,044 | 2,68 | 5,475 |
| U. Mississippi | Rock Island | Iowa/ Illinois | Beach[3] Nourishment | Moderately Severe | 2,143 | 0.68 | 2,142 |
| U. Mississippi[1] | St. Louis | Illinois/ Missouri | Open Water | Less Severe | 17,506 | 0.52 | 9,085 |

NOTE:

[1] Above confluence with Illinois Waterway.

[2] Data based on National Waterways Inventory.

[3] This determination, as well as cost, is based on the analysis of the inventory of physical characteristics. Since the time of taking the inventory, land disposal has become the predominant means of dredged material disposal.

returns to the St. Paul District in October and dredges any sites that have shoaled during the navigation season. The dredge Hauser dredges in the Minneapolis-St. Paul, Minnesota area from May through September and performs structural maintenance and miscellaneous dredging thereafter. All dredging normally ends by the end of November due to bad weather. The 20" dredge St. Genevieve dredges the lower four pools of the region above the confluence with the Missouri River and accounts for about 50% of the total volume dredged.

The headwater states of Minnesota and Wisconsin on the Upper Mississippi have been applying increasingly severe environmental constraints to dredging operations in the waterway. As a result, disposal of the dredged material has been to upland confined sites. Further down, in Iowa, beach creation is favored, and still further down, between Missouri and Illinois, open water disposal is used. This has apparently produced significant variations in dredging costs between regions, as shown in Table IV-5.

The Upper Mississippi has been subject to the most comprehensive environmental study of any segments under the Great River Environmental Action Team (GREAT) Program. It is divided into GREAT I, covering the St. Paul District, GREAT II, for the Rock Island District and GREAT III, for the St. Louis District. The GREAT I studies are well advanced whereas GREAT II and III are still at the formulation stage.

Under the GREAT Program, each dredging site was evaluated, and based on the frequency of dredging and other parameters, the dredging depth was determined. Between 1975-1978, 23%, 53% and 24% of the dredging, based on volume, was accomplished to 13, 12 and 11 feet depths respectively. This resulted in an overall reduction of 940,350 cubic yards or 23.7% of the main channel maintenance based on initial dredging requirements at each site.

The dredging frequency increased by 77.1% at 15 sites with a corresponding dredging quantity decrease of 19.6%. At these sites, dredging would be required three out of four years for reduced depth dredging versus dredging two out of five years for 13 feet dredging. A dredging equipment analysis indicates that this is economically viable with existing equipment.

At 18 other sites, frequency decreased 9.9% with a dredging quantity decrease of 67.5%. At these sites, there was a very significant decrease in dredging quantity without any corresponding increase in dredging effort or cost.

Records during the period of reduced depth dredging did not indicate an increase in the number of channel closures though there is a greater risk, particularly with an 11 feet dredging depth.

A preliminary conclusion of the GREAT I study, based on cutterhead dredge production rates, was that the cost of dredging to 12 feet with a cutterhead dredge is the same as the cost of dredging to 11 feet. This is because the cutterhead can move faster when taking a shallower cut. The cost considered here is proportional to the number of hours required to dredge a given area to a minimum of an 11 feet depth. Since the production in cubic yards per hour of cutterheads dredging to 13 feet is less than that of those dredging to 11 or 12 feet, the GREAT I study concluded that dredging frequency could increase 22% with no increase in total cost if cutterheads were used to dredge to 11 or 12 feet rather than 13 feet. Similarly, dredging frequency with clamshell dredges could increase 28% with 12 feet dredging and 52% with 11 feet dredging without increasing the total dredging cost compared to 13 feet dredging.

In cooperation with GREAT, the St. Paul District made many changes in their dredging program. Beginning with the 1975 dredging season, they decided to assume much higher risks in maintaining the integrity of the navigation channel than ever before.

(a) Many questionable sites, hich would normally of channel closure, were not dredged.

(b) Detailed survey sheets were sent to the United States Coast Guard for aids to navigation adjustment to affect using all available natural channel alignment.

(c) Research is being conducted at several sites to determine if the channel will seek a new alignment that might require less maintenance.

(d) Research is being conducted in the area of reduced over-dredge depth, i.e., two feet rather than four feet annual dredging requirement volume to reduce the environmental impact of material placement.

Historically, the Upper Mississippi River Nine Feet Channel Project has been dredged to a standard total depth, including overdepth, of 13 feet Experience has proven a channel with a minimum depth of 10 feet can close within days during stable flow conditions when utilized by motor vessels and tows drawing nine feet or less. Therefore, an 11 foot channel is considered essential to retain a stable condition and the additional two feet of depth was considered as advance maintenance dredging and tolerance for dredging equipment.

The total annual volume dredged during the past three to five years is 2,729 cubic yards in the Upper Mississippi at an average cost of $1.00 per cubic yard and $4,067 per mile. A breakdown, by districts, is provided in Table IV-5.

During 1975, 1976 and 1977, the St. Paul District hedged 706,207 cubic yards, 645,544 cubic yards and 182,303 cubic yards,respectively. Since the average annual dredging during the 1968-1977 period was 1.4 million cubic yards, the dredging requirements for the 1975-1977 period must be considered extremely low, due primarily to low-flow spring floods. With a few exceptions, where the initial trend indicates an increased frequency of dredging, the reduced dredging program has proven effective in reducing the volume of dredging. However, the overall success of the program must also be evaluated in terms of navigation reliability. This will be possible only when sufficient hydrological and morphological data are collected to provide a statistically significant evaluation under low-flow conditions.

In the Rock Island District, records indicate that the volume of material dredged between 1941 and 1976 ranged from 405,000 to more than 2,055,000 cubic yards per year with a mean of 1,211,000 cubic yards per year. Due to the new controls described above, dredged volumes have dropped to approximately 207,000 cubic yards in 1976, 72,000 cubic yards in 1977 and 68,500 cubic yards in 1978. The NWS Inventory indicates that during this period of time, the authorized channel dimensions were still maintained despite the radical reduction in dredging quantities. However, information obtained from GREAT I indicates an increase in the number of groundings occurred during the same period of time. It would appear that grounding phenomena are a response to a combination of unusually low-flows in dry seasons and decreased channel maintenance dredging. Furthermore, it has been suggested by District personnel that unusually low flood stages, and consequently less intensive shoaling during the last few years have mitigated the effects of reduced maintenance dredging. If such is the case, a return to more normal hydrologic circumstances could result in more severe navigation problems on this segment of the river.

As previously discussed, the primary methods of disposal currently used are upland disposal in the St. Paul District, beach nourishment (or beach creation) in the Rock Island District, and open water disposal in the St. Louis District. However, current disposal methods used by RID are trending toward upland disposal and away from traditional beach nourishment. Upland disposal removes the material from the river's environment, thus avoiding environmental impact there. However, it requires costly and energy consuming transport of dredged material over relatively long distances, and the provision of suitable sites, and it may present a problem in meeting water quality standards for the effluent.

Beach nourishment, which essentially is the creation and maintenance of recreation beaches, may be classified as a beneficial use of dredged material. The State of Iowa has favored this type of disposal. No substantial environmental problems are identified in the literature, but there is insufficient experience to determine that this will be an environmentally satisfactory method of disposal in the long-term.

A number of alternative potential disposal options are under investigation under the GREAT I and II programs. These include fill for development purposes and road construction, fine aggregate for asphalt and concrete and ice control in winter. Insofar as many of these uses are substitutes for materials from commercial sand and gravel operations, there is an institutional problem in placing the Corps of Engineers in competition with private industry. Furthermore, the point of use may be too far from the dredging site for the economic transport of dredged material, and as the timing of demand will not be in phase with the availability of material, storage areas will be required having the same impacts as disposal sites (GREAT I, 1979a).

2. Reporting Region 2 - Lower Upper Mississippi River. The Lower Upper Mississippi River, maintained by the St. Louis District office, represents a transition from the heavily regulated and canalized Upper Mississippi to the free-flowing Middle and Lower reaches of the river.

In the canalized reach of the District, the forebay and exit areas to the locks are dredged every three or four years as determined by periodic survey. The most common reoccurring maintenance problem in this portion of the river appears to be the control of winter icing at the locks, which is discussed in Section VI.

Dredging on the open portion of the river is performed by a dustpan dredge approximately seven months a year. In general, three feet of overdepth dredging is performed to insure a nine feet minimum channel throughout the year without redredging. No empirical methods are used for predicting shoaling areas or rates. Rather, historical records of shoaling areas are evaluated for determining the applicability of advance maintenance dredging.

Some fluctuation of low-stage water levels may occur due to flow regulation in the upstream Rock Island District. Dredging volumes for the period from 1971 to 1975 ranged from 2,200,000 cubic yards/year to 7,750,000 cubic yards/year with an average of 4,800,000 cubic yards/year.

While the authorized depth for this segment of the river is nine feet, the controlling depth maintained is usually 12 feet or greater. Analysis of the reliability of authorized depth maintenance from January 1971 through December 1978 indicates that the nine feet authorized depth was maintained 100% of the time during that period with the exception of the 1976 drought when extremely low-flows created depth maintenance problems here and along the entire Mississippi River. Flow-duration curves for the St. Louis Gage indicate the existing Low Water Reference Plane of -3.5 is maintained about 93% of the time. This does not indicate, however, that the controlling depth falls below the authorized depth 7% of the time since the District is charged with the responsibility of maintaining the minimum nine feet depth irrespective of low-water stages of the river.

However, the LWRP in this segment still has an unacceptable duration. The reliability of the reference flow should be on the order of 97-99% for the main flow of the Mississippi River. In practice, this means that the District has not clearly defined the water flow level that should be considered the extreme drought during which time the Corps is unable to maintain authorized depth.

Generally, the Corps capability to maintain the authorized depth should be related to the LWRP. However, in practice, the success of channel maintenance depends on a combination of factors, as previously described. For example, a rapid recess·of water levels in 1976 created depth deficiencies at flow levels (100,000-60,000 cfs) substantially higher than the flow at the LWRP (about 50,000 cfs). Conversely, between October 1976 and February 1977, the District was able to maintain authorized depths by increased dredging despite the fact that the low flow (about 40,000 cfs) was substantially below the water reference flow.

The flow duration curves show that, historically, the LWRP had the required duration (water flow equal to or higher than 50,000 cfs 98% of the time). However, due to river basin development and run-off regulation, the water flow has been reduced during the more recent time period. Accordingly, the low water reference plane should be adjusted to a lower level.

Analysis of the monthly dredging quantities for the St. Louis District correlated with monthly high and low flows indicates that maintenance of 12 feet channels does not appear possible when the discharge falls below 100,000 cfs or when unusually high flows combine with rapid flood recession to accentuate shoaling conditions. This latter condition was observed following the 1973 flood and again in 1975 when only extensive dredging and higher than normal low stages made it possible to maintain authorized channel dimensions.

3. Reporting Segments 3 & 4 - Lower Mississippi River and Baton Rouge to Gulf. These segments include the Lower Mississippi from Cairo, Illinois to Baton Rouge, Louisiana; the Mississippi River from Baton Rouge to the

Gulf, including the Port of New Orleans and the Mississippi River Gulf Outlet; the Ouachita-Black and Red Rivers; the Old and Atchafalaya Rivers and the Baton Rouge-Morgan Cist Bypass.

Dredging requirements on the Lower Mississippi River have been directly affected by the construction of river stabilization works. Begun in 1928 as part of the Mississippi River and Tributaries Project (MR & T), the benefits of the channel improvement program are documented by the gradual reduction in the number of locations requiring maintenance dredging,as seen on Table IV-6.

Table IV-6

Number of Dreding Locations in Districts on Mississippi River, Cairo to Baton Rouge

| Range, Mile<br>Length, Mile | Memphis<br>943.8-599.4<br>354.4 mi. | Vicksburg<br>599.4-322.5<br>276.9 mi. | New Orleans<br>322.5-234.0<br>88.5 mi. |
|---|---|---|---|
| 1966 | 45 | 28 | 1 |
| 1971 | 32 | 12 | 1 |
| 1976 | 12 | 4 | 2 (long slow fall) |
| 1978 | 14* | 4 + 1 | 0 |

*Redredged eight of these locations.

A comparison of the volume of material dredged from 1971 through 1975 and the average for the last three years as presented in the Corps of Engineers Inventory is presented in Table IV-7. As indicated, the volume of material dredged has remained relatively uniform despite the reduction in the number of dredging locations. The overall effect of the training structure stabilization of the navigation channel, design criteria may vary somewhat in different districts to accommodate specific problems unique to the river's configuration within each District. For example, the Memphis District is responsible for a reach which is 355 miles long and as much as two miles wide with a meander belt of 30 to 50 miles wide. The minimum and maximum discharge is 78,000 and 2,020,000 cfs respectively. With these conditions, the wide natural

Table IV-7

Dredging Volumes
Cairo to New Orleans
(1,000 c.y.)

| | Memphis | Vicksburg | New Orleans | Total |
|---|---|---|---|---|
| 1971 | 28,528 | 4,569 | 7,754 | 40,851 |
| 1972 | 28,641 | 7,029 | 8,448 | 44,118 |
| 1973 | 31,209 | 8,834 | 14,677 | 54,720 |
| 1974 | 38,149 | 11,262 | 16,931 | 66,342 |
| 1975 | 18,939 | 7,547 | 7,203 | 33,689 |
| 5 Year average | 29,093 | 7,848 | 11,003 | 47,944 |
| Inventory average* | 22,000 | 10,921 | 7,329 | 40,250 |

* From COE Inventory latest three to five years of record through, and including 1977.

channel has to be contracted and the middle bars eliminated to maintain an adequate navigation channel and enlarge the flood capacity of the river. This is accomplished by designing to the stabilization line which maintains a contracted channel width of 2,500 to 3,000 feet.

The 12 foot depth which has been authorized for the Lower Mississippi River is to be attained upon completion of the ongoing stabilization program. Although dreding procedures are presently directed towards the maintenance of a minimum depth of nine feet, the 12 foot channel has been maintained an average of 70% of the time from 1960 through 1978 although, with the exclusion of the drought years 1976 and 1977, the average reliability improves to 82% for the years 1967 through 1978.

Above Baton Rouge, the main channel is entirely dredged by dustpan dredges which were, until recently, entirely Corps owned. The average depth of cut is generally high, 8.9 feet. Disposal is entirely open water alongside the channel. The dustpan dredge is well adapted for this type of operation. However, if one considers the improbable scenario of environmental constraints being placed to preclude open water disposal and/or require long distance transport, the whole issue of river maintenance becomes problematic. Dustpan dredges are not adaptable, and thus new technologies would be needed. Below Baton Rouge, where there is a 40 foot channel for ocean going ships, the river is dredged using dustpans, cutterhead and hopper dredges. By volume 11%, 42% and 47% is done by each type respectively. The hoppers are particularly used in the passes to the Gulf of Mexico at the mouth of the river. A portion of the dredged material is disposed of in confined sites along the shoreline in the passes, but most material is disposed of in open water alongside the cut or in deep water in the Gulf.

Experience gained from previous dredging projects is used to determine whether advance maintenance would be advantageous. Reconnaissance surveys are also used to provide information on the shoaling rates of various reaches of waterway. Before-dredging and after-dredging surveys are made for purposes of payment but are not used to determine shoaling rates.

The duration of minimum controlling depths for segments of the Lower Mississippi River from Cairo, Illinois to Baton Rouge, Louisiana are presented on Table IV-8. As indicated, the reliability of depth maintenance dropped significantly in 1976, particularly in the Greenville to Helena segment. This decrease continued in 1977 with the most impact occurring in the Vicksburg to Helena and Memphis to Cairo segments. While the reliability of depth maintenance improved in 1978, the segment between Greenville and Helena still exhibited a greater difficulty in maintaining authorized depths.

Records of hydrological conditions were available for the Lower Mississippi River from Cairo to New Orleans. These records were analyzed and correlated with dredging records, and minimum controlling depths for the period of record.

Dredging projects generally begin in the spring each year while flows are still receding, and reach a peak during the low summer stages of the river and continue as late as December. The first indications of channel depth problems occur while the river is still well above the design discharge for this segment of waterway. At no time during the period of record analyzed did the discharge fall below 190,000 cfs, a value somewhat higher than the 150,000 cfs design discharge.

Although a precise correlation of the data is not possible, several trends were noted. The channel bed appears more sensitive to rapid decreases in low water stages than to the magnitude of peak flows. A clear example of this may be seen in the 1974 record where each of three declining limbs of the hydrograph is mirrored by a subsequent channel problem. Similar circumstance are noted in 1971 and 1972 hen early decreases on the low stage hydrograph resulted in minor channel problems as early as April. While yearly dredging quantities did not necessarily coincide with the magnitude of peak flows or the rapidity of the declining stages, tne monthly dredge volumes were roughly correlatable with the shape of the preceding spring hydrograph again indicating a stream bed response, in the form of material movement, to fluctuations in river stages.

As indicated on Table IV-8, 1976 was a year during which relatively severe channel maintenance problems occurred. A review of the data indicates that the problems were due, for the most part, to unusually low water stages during the latter half of the year.

According to discharge duration curves on the Lower Mississippi, the duration of LWRP is about 97% and appears to be adequate.

The Red and Ouachita-Black Rivers are maintained and regulated by the Vicksburg and New Orleans Districts of the Lower Mississippi Valley Division. The authorized nine foot navigation project on the Ouachita-Black Rivers is under construction with completion expected in the early 1980's. The project includes the construction of four new locks, new dams and channel realignment. Two of the locks, the Columbia and Jonesville, are in operation, the Felsenthal Lock is under construction, and the design for the Colion Lock and Dam is in progress.

A nine foot navigable channel is under construction on the Red River in order to improve the navigable channel between the Mississippi River and the first Lock and Dam. General Design Memoranda have been prepared for Locks and Dam 1 to 3 and detailed Design Memoranda are available for Locks and Dams 1 and 2.

# Table IV-8

## Duration Controlling Depths Lower Mississippi River

| River Section | % of Time | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
|---|---|---|---|---|---|---|---|---|---|
| Bat. Rouge | <10' | - | - | - | - | - | 2.2 | - | - |
| to | 10'-12' | - | - | - | - | 2.2 | 12.0 | - | - |
| Natchez | 12'+ | 100 | 100 | 100 | 100 | 97.8 | 85.8 | 100 | 100 |
| Bat. Rouge | <10' | - | - | - | - | - | 2.2 | - | - |
| to | 10'-12' | - | - | - | - | 2.2 | 12.0 | 3.8 | 5.8 |
| Vicksburg | 12'+ | 100 | 100 | 100 | 100 | 97.8 | 85.8 | 96.2 | 94.2 |
| Bat. Rouge | <10' | - | - | - | - | - | 2.2 | 3.8 | - |
| to | 10'-12' | 5.5 | 1.2 | 6.6 | 6.3 | 3.6 | 12.0 | 24.1 | 6.3 |
| Greenville | 12'+ | 94.5 | 98.8 | 93.4 | 93.7 | 96.4 | 85.8 | 72.1 | 93.7 |
| Bat. Rouge | <10' | 2.7 | - | 7.9 | - | - | 29.0 | 6.6 | - |
| to | 10'-12' | 12.9 | 5.5 | 15.9 | 6.3 | 4.4 | 7.1 | 31.5 | 16.4 |
| Helena | 12'+ | 84.4 | 94.5 | 76.2 | 93.7 | 95.6 | 63.9 | 61.9 | 83.6 |
| Bat. Rouge | <10' | 3.0 | 5.8 | 9.9 | 1.9 | 3.8 | 30.4 | 10.7 | 3.3 |
| to | 10'-12' | 20.0 | 15.3 | 14.0 | 5.5 | 8.8 | 8.2 | 32.1 | 18.4 |
| Memphis | 12'+ | 77.0 | 78.9 | 76.1 | 92.6 | 87.4 | 61.4 | 57.2 | 78.3 |
| Bat. Rouge | <10' | 6.6 | 13.4 | 10.4 | 11.0 | 7.7 | 33.2 | 20.5 | 3.3 |
| to | 10'-12' | 20.0 | 10.7 | 13.4 | 6.8 | 11.2 | 11.5 | 33.7 | 18.1 |
| Cairo | 12'+ | 73.4 | 75.9 | 76.2 | 82.2 | 81.1 | 55.3 | 45.8 | 78.6 |

The design, which is being performed by the New Orleans District, is such that the waterway would have little or no maintenance dredging requirements after construction. This will be accomplished through the use of locks and training structures.

Design discharge of the Red River at Alexandria, Louisiana is 4,000 cfs. This flow has a historical reliability of 87%. However, the flow-duration curve depicted is for the period from 1929-1969 and current maintenance programs, including dredging and training projects, are reported to have increased the reliability of authorized depth durations to 95%.

Design discharge of the Ouachita-Black River system between the Jonesville Lock and Dam and Lock and Dam No .6 is between 500 and 1,000 cfs. The minimum discharge has a theoretical reliability of nearly 100%.

The Ouachita River is considered to be a "gift of Nature" in that it is relatively sediment free and requires very little dredging even without training work. However, the mean annual dredging volumes over the last five years for the other waterways within this analytical segment were approximately 2,500,000 cubic yards.

The Yazoo River is authorized for a nine feet depth but was not constructed. The present project is a clearing and snagging project with no depth specified.

4. Reporting Region 5: Illinois Waterway. The Illinois Waterway is maintained jointly by the Chicago District upstream of La Grange) and St. Louis District (downstream of La Grange to the Mississippi River).

The general principles of channel maintenance employed by the St. Louis District have been described for Reporting Region 2.

There are few maintenance dredging problems on the Illinois River in terms of maintaining authorized depth. Since the Corps holds no riparian rights on the river, it owns no potential land disposal areas. Currently, the Corps waits until flows stabilize so individual shoals can be ."seen" before dredging. Dredging is performed by the Corps dredges William A. Thompson and St.

Genevieve. About 50% of the dredged volume on the Illinois waterway is dredged by the St. Genevieve in the lower 80 miles of the river.

The need for dredging in specific areas is determined by several reconnaissance techniques. Sweeping operations are conducted using a bar lowered to project-depth for location of shoaled areas. In reaches considered annual problem areas, sweeping is conducted using a crane. Sonic sounding is undertaken during periods when dredging is ceased for the purpose of locating deposits. Hydrographic surveys are conducted in the La Grange and Peoria pools using a graduated pole. Often, information received from towboat operators will indicate problem areas.

Dredging generally begins on the lower end of the waterway in the early spring. Overdepth dredging of 1.5 to three feet is usually performed in order to maintain the nine feet minimum depth without redredging in the same season. Dredged volumes average about 2,500,000 cubic yards a year for this segment.

Although maintenance dredging may be necessary at any point in the waterway, the experiences of the Corps field offices over the last 10 years indicate certain types of areas where shoaling is most common. These are bends in the river, downstream of locks, tributary confluences, and some miscellaneous areas where the velocity of the water is retarded. According to the NWS Inventory, controlling depths of eight feet occur within the La Grange Pool, the Peoria Pool, and the Starved Rock Pool. Depths of eight feet occur only in rare instances, however.

Additional procedures include annual snagging projects that are undertaken to clear the channel of debris, which is generally placed on unowned islands. Any vessels which sink in the waterway and present a hazard to navigation are removed.

During December, January and February, ice, although seldom a navigation problem, may be encountered in the lower river around Peoria.

During extremely high spring flows, the Coast Guard may order navigation to cease on the Illinois River to prevent levee overtopping and erosion. Navigation ceased for about one week in 1978 due to high water and in

1979, navigation was shut down from March 21 to April 27. Travel restrictions, such as daylight only and no-wake transit, were in effect until May 24.

Although stoppages of this nature do not occur every year, high-flow navigation restriction do seem to be persistent reoccurring problems.

5. Reporting Region 6: Missouri River. The Missouri River is maintained and regulated by the Omaha District from Sioux City to Rulo, Nebraska, and the Kansas City District from Rulo downstream to the Mississippi River. The authorized channel dimensions which are 9' x 300' for this navigation project, are maintained about 95% of the time during the navigation season. When the channel does shoal during the navigation season, the controlling dimensions rarely decrease to less than 8.5' x 250'. These channel constrictions occur only sporadically along straight flat reaches of the lower portion of the river and have a tendency to clear themselves within a few days.

The Missouri River is somewhat unique in that river flows are essentially controlled by upstream reservoir releases. Under present operating criteria, average flows, regulated to serve in excess of 31,000 cfs are either to make up for deficient inflow downstream or to reduce flood storage. The average Sioux City flow necessary to maintain the navigation service level is allowed to vary from 29,000 cfs up to 35,000 cfs, dependent upon system storage on March 15 and July 1 as indicated on Table IV-9.

Table IV-9

Missouri River Flow and Storage

| Date | CFS | System Storage 1,000 AF |
|---|---|---|
| March 15 | 35,000 | 56,150 or more |
| | 29,000 | 47,700 or less |
| July 1 | 35,000 | 59,000 or more |
| | 29,000 | 50,600 or less |

The length of the navigation season is established on the basis of total system storage at the end of the months March through June. Any required shortening of the season is made at the end of the season. In this manner, the season always opens on April 1 at the mouth of the Missouri River, but can be shortened to close before the eight-month, December 1 date. The effects of growing main stem water use upon navigation are reduction in rate of flow, a shortening of season, and finally the stopping of navigation releases.

Flow-duration curves prepared in 1954 for the 1960 level of development indicate 28,000 cfs were maintained 100% of the time during the navigation season and 30,000 cfs had a 74% recurrence reliability. Although the present degree of control has increased and 98% of the project is complete, the river occasionally shoals above the nine feet level even though the flow exceeds the Sioux City design discharge of 31,000 cfs. However, due to the fluctuating nature of the river bed, the shoals frequently degrade within a few days so the Corps does not attempt to mobilize dredge equipment immediately.

Rating curves for the river show that the river can have a range of stages at any flow due to the range of roughness the bed can experience. For this reason, controlling of authorized depth cannot be easily measured from water surface levels and it is assumed that authorized depth is being adequately maintained when flows are at full service levels or higher. However, there appears to be no correlation between the percent of "full service" flow maintained and the duration of controlling depths lower than authorized.

The intensive training works program on the Missouri has all but eliminated the need for maintenance dredging. While the construction of dikes serves two basic functions, erosion control and stabilization of the navigation channel, the latter function is the primary concern.

Dikes on the Missouri River are set 600 to 1,000 feet apart as dictated by the sinuosity of the channel. While early dikes were constructed of piling reinforced with stone, this form of construction has given way to stone dikes with pilings only used for mooring clumps. Recently, efforts have been made to reopen chute channels and maintain a water supply to oxbow lakes by disconnecting van dikes and sills from the banks. A minimum maintenance concept is being employed whereby in areas where no major damage is likely, limited revetment failure from natural causes will be permitted.

Dredging is used to maintain adequate channel depths or widths at river locations where the natural erosive character of the river, in combination with training structures, temporarily does not provide the desired navigation channel dimensions. In the 500 miles of river below St. Joseph, Missouri, 24 sites were dredged in 1974. However, dredging has not been necessary since 1976 nor has dredging been required above Rulo, Nebraska since 1965. The need for dredging is expected to diminish as the completed stabilization and navigation project continues in operation under current water conditions: that is, to 35,000 cubic feet per second discharge past Sioux City, Iowa. Navigation channel deposits which might require dredging cannot be predicted in advance; however, several kinds of areas are known to be more susceptible to sediment buildup than others. The susceptible areas include reaches downstream of tributary mouths, unusual channel alignments, and bridge crossings. Future dredging is expected to be performed either by government forces or by contract on an as-needed basis. Disposal of dredged material would normally take place in river areas between or behind the dikes or in the river itself. This practice destroys aquatic habitat and was objected to by agencies primarily concerned with fish and wildlife. Beginning in 1974, the dredge material was deposited in the main channel at two dredging sites on a trial basis. This method is being studied to determine the conditions under which it can be used without shoaling the downstream channel.

A survey boat is used to traverse the navigable channel on about a two week schedule in order to determine the precise location of the navigation channel for the district offices. The boat also communicates directly with tow operators and advises the Coast Guard as to channel buoy locations. At the beginning of each navigation season the Coast Guard surveys the river and places buoys.

A possible alternative to dredging on the lower river would be to add another reconnaissance crew since it is felt that most groundings occur because pilots are unable to determine the precise location of the deepest water due to rapid shifts in channel cross sections.

6. Reporting Region 7 & 8: Ohio and Tennessee Rivers. Analytical Segments 11 - 23 represent the Ohio River and all of its tributaries maintained and regulated under the auspices of the Ohio River Division in Cincinnati, Ohio. All of the segments are canalized and have similar types of maintenance requirements as a result of their outward uniformity. However, the various Districts within the Division perform their operations as dictated by the specific reaches of waterway for which they are responsible.

In general, advance maintenance dredging is felt to be of little value beyond one season. Accordingly, projects are only dredged to an overdepth sufficient to avoid redredging again later in the same season. Within the Louisville District on the Ohio River, soundings are normally made about once a year for their projects with the exception of critical bars and lock approaches where three line soundings are made three to five times each low-water season.

All dredging on the Ohio River is performed by contractors. The river was shut down to navigation for 10 days in 1978 due to shoaling between the Cumberland and Tennessee Rivers. A contributing factor to the lengthy closing was the time required to mobilize contractor dredges. The availability of equipment is such that if normal maintenance dredging is deferred for one year, there is insufficient capacity to perform the total required dredging the following year.

During the low-flow season on the Ohio River, the Coast Guard will pull in its buoys to form a narrower channel so that each tow will have to follow the same alignment, thus helping to keep the channel scoured to adequate depths by continuous passages.

Average annual dredging volumes for the Analysis Segments within Reporting Region 7 & 8 for the last five years of record were shown on Table IV-4.

Dredging requirements in these completely canalized waterways are obviously incomparable with dredging quantities in open-flow waterways. However, as it was shown above, this fact does not reduce the importance of adequate dredging. The most common dredging sites are approach channels to locks and the downstream portions of the Ohio River tributaries. The bulk of dredging is done with cutterhead dredges; however, clamshell dredges are used quite extensively on the smaller shoals.

7. Reporting Region 9: The Arkansas Verdigris, White & Black Rivers. The Arkansas, Verdigris, White and Black Rivers are maintained by the Tulsa and Little Rock Districts of the Southwestern Division and the Vicksburg and Memphis Districts of the Lower Mississippi Valley Division. Training works and control structures on the Arkansas River are quite effective in maintaining authorized channel dimensions. The Arkansas River has a 250 foot navigable channel, which was developed using bank protection works, cutoffs, pilot channels, dikes, and dredging. The Verdigris River has a 150 foot wide channel, which is maintained by cutoff, river widening, and dredging. Although there are no provisions for bank protection on the Verdigris River, no major bank problems have occurred to date.

Dikes in the District are stone or stone-filled piles with a "turn-out" on each that helps reduce excessive parallel flow along the face of the dike. Frequently, stone dikes are used for channel training as an artificial bankline. Due to the design of the controlling structures, the Arkansas system requires virtually no flow to maintain authorized depth. However, when dredging is required, it is most intensive during declining stages on the river.

It has been determined that advance maintenance of three feet or less is advantageous because it eliminates redredging or shoals that are caused by minor rises and shifting currents. It is not practical to perform deeper advance maintenance dredging because the waterway carries a heavy sand sediment load during high river stages. Where there is a shoaling tendency, this sediment load is more than enough to fill any reasonable channel depth that may be dredged for advance maintenance and to reform the shoal during the course of a routine river rise.

Although there are no one-way reaches on the Arkansas River, maintenance dredging is more often required to maintain the 250 feet width rather than depth. The Verdigris River is, as mentioned above, maintained 150 feet wide (except at bridges, where it is 250 feet wide) although authorized for 250 feet. If traffic levels increase significantly, the District will attempt to widen the channel to authorized width. At the present time, passing zones are located every two or three miles to allow the passages of two-way traffic.

The water control plan for the Arkansas River Basin contains a fixture known as a "navigation taper". When a large volume of water comes down the Arkansas River due to a sudden upstream release or storm in uncontrolled portions of the basin, sediment is deposited in the lower channel. In order to combat this and reduce dredging requirements, the lower 15% of the flood waters are released at a rate which is optimum for maintaining the channels (20,000 to 40,000 cfs, and reservoir releases are coordinated so that the flow from one reservoir immediately follows the flow from the previous reservoir and maintains an overall uniform flow in the lower channels. This provides the flows which may be necessary to maintain navigation until dredging restores the navigation channel to the design dimensions. Table IV-10 depicts annual dredging quantities and flows for the last seven years of record.

Table IV-10

Arkansas River
Maintenance Dredging
(Million Cu. Yds.)

| Year | Tulsa District | Little Rock District | Total | Annual Flow @ Van Buren, AR (Million Ac-Ft) |
|---|---|---|---|---|
| 1972 | 1.7 | 2.4 | 4.1 | 14.1 |
| 1973 | 1.1 | 3.5 | 4.6 | 61.1 |
| 1974 | 3.7 | 3.6 | 7.3 | 44.4 |
| 1975 | 0.7 | 1.4 | 2.1 | 33.9 |
| 1976 | 0.5 | 1.9 | 2.4 | 14.3 |
| 1977 | 0.4 | 1.7 | 2.1 | 15.1 |
| 1978 | 0.2 | 1.2 | 1.4 | 16.6 |

Maintenance dredging to maintain navigable depths amounted to approximately 1.4 million cubic yards in 1978. This was a decrease of about 0.7 million cubic yards from the 1977 dredging requirements. Some of the pools were held above the normal elevation to maintain navigation while the channel was bineg dredged.

Regulation structures on the Arkansas River have improved the flow duration reliability for discharges lower than 30,000 cfs.

The White River is authorized for the following channel dimensions:

(a) South to Mile 10 - 300' wide x 9' deep.

(b) Mile 10 to Augusta - 125' wide x 5' deep.

(c) Augusta to Newport - 100' wide x 4.5 deep.

The existing channel dimensions do not allow full use of navigation depths of connecting waterways such as the Mississsippi and Arkansas Rivers, and barge capacity is significantly and adversely affected by narrow channel widts and shallow and unreliable minimum depths. The lack of dependable channel depths causes navigation on the White River to be reduced in years of low flow to extremely shallow draft shipments between mid-August and mid-August and early November.

Design discharge on the White River is 9,650 cfs at Clarendon, Arkansas. This flow is maintained 95% of the time.

Table IV-11 shows depth availability on the White River by month and the yearly depth duration. There are many locations where shoaling caused by river crossings and excessively wide river reaches presents serious obstacles to navigation. The problem of unreliable depth is further complicated by the crooked alignment of the White River. Bend radii as small as 500 feet are common and tows frequently have to hit the bank and reverse many times in order to navigate the sharper bend.

Although the Black River was authorized for navigation improvement in the late 1800s, tonnage declined to zero in 1948 and the project was declared inactive due to the lack of traffic.

8. Reporting Regions Segments 10 & 11: GIWW East and West (Tributaries), Florida Gulf Coast, and Houston Ship Canal. These segments comprise the entire Gulf Intracoastal Waterway, harbors, and tributaries from

## Table IV-11

### White River
### Average Number of Days Certain Water Depths Unavailable

| Month | 9' | 8' | 7' | 6' | 5'[1] |
|---|---|---|---|---|---|
| January | 4 | 3 | 2 | 2 | - |
| February | 2 | 1 | 1 | 1 | - |
| March | 1 | - | - | - | - |
| April | 1 | - | - | - | - |
| May | 2 | 1 | 1 | - | - |
| June | 4 | 2 | 1 | 1 | - |
| July | 9 | 4 | 2 | 1 | - |
| August | 12 | 7 | 4 | 2 | - |
| September | 17 | 11 | 6 | 4 | - |
| October | 16 | 9 | 6 | 4 | - |
| November | 12 | 9 | 6 | 4 | - |
| December | 8 | 5 | 2 | 1 | - |
| TOTAL | 88 | 52 | 31 | 20 | - |
| % | 24 | 14 | 8 | 5 | - |

NOTE: [1] 107 project provides for minimum water depths of five feet in White River Navigation Channel up to Augusta. There are days when five-foot depth is not available in the reach from Augusta to Newport.

Brownville, Texas at the Mexican border to and including the Gulf Coast of Florida as far as Key West as well as the Apalachicola, Chattahoochee and Flint Rivers. These waterways are maintained and regulated by the Galveston District Office of the Southwestern Division, the New Orleans District Office of the Lower Mississippi Valley Division, and the Mobile and Jacksonville Districts of the South Atlantic Division. The authorized dimensions vary somewhat throughout the Gulf Coast, but the segments are characterized by very high dredging volumes and similar types of equipment and procedures.

The mean annual dredging volumes for each of the analytical segments along the Gulf Coast are depicted on Table IV-4. Both cutterhead and hopper dredges are extensively used, with the hopper dredges used in the deep draft coastal approaches. Disposal is in open water alongside the channel, ocean dumping, and confined sites. For the interior waterways, open water disposal is declining and the use of inland sites increasing.

One of the primary problems affecting the maintenance of authorized dimensions on the GIWW, and elsewhere, concerns cost sharing of improvements and maintenance by local interests. The act which authorized the channel dimensions of the various waterways stipulated that local interests provide all lands, easements and rights-of-way required for improvement and maintenance. This would include land and the cost of dikes to provide confined disposal areas. However, the policy has since been modified such that the Federal Government can now provide disposal areas in those instances where the original act did not specifically require diked disposal as a local item.

Local interests contend that most of the benefits derived from the improvement and maintenance of the waterways accrue to the nation which should bear the responsibility and cost of their upkeep. Accordingly, many improvement projects have never been implemented and maintenance dredging problems are increasing as environmental sanctions against open water dumping in harbors and inland waters are imposed.

Those channels authorized for improvements which have never been implemented include:

(a) a 16x150 foot channel through the reach between the Mississippi and Atchafalaya Rivers.

(b) a 16x150 foot channel through the Algiers Alternate Canal.

(c) a 16x150 foot channel through the bypass route around Houma.

(d) a 16x200 foot channel through the reach from the Atchafalaya River to the Sabine River.

(e) a 16x150 foot channel through the reach from the Sabine River to the Houston ship Channel.

(f) a 12x125 foot channel through the relocated channel in Matagorda Bay.

In addition, authorized maintenance programs, including a 12x125 foot channel through the existing Lydia Run Channel between Arkansas Bay and Arkansas Pass and the existing alignment through Houma, Louisiana have never been implemented nor has the 30x125 foot Lake Charles Deep Water Channel been maintained since completion of the Calcasieu Ship Channel.

A secondary affect resulting from the lack of channel improvement within some sectors of the GIWW is the caving and sloughing of banks in narrow channels. Local farmers assert that the loss of their farmland is due entirely to excessive prop-wash from the tows but since the Corps accepts no responsibility in these instances, the farmers have no recourse but to sue the tow owners for property damages.

The Apalachicola, Chattahoochee and Flint (ACF) are maintained by the Mobile District. Maintenance dredging is performed by contract and begins with the recession of spring flood waters. The District surveys the waterways and indentifies regions of critical shoaling which, typically, are frequent recurring problem areas. As a rule, the dredging program consists of an initial pass over the worst bars to insure continuing navigation. Once all the immediate problem areas have been corrected, the dredges return to perform regular maintenance dredging. The fact that contractors are currently performing the dredging on this segment is not necessarily the typical situation. However, a private contractor was recently selected to perform the dredging operation when he underbid the Corps "Cost + 25% " ceiling for the work.

A record of dredging volumes on the ACF for the five year period from 1973 through 1977 is presented on Table IV-12. Dredging quantities have increased significantly from 1973 to 1974 and remained at the higher level for the remainder of the period of record. During 1971, 1972 and 1974, the depth of cut of the 16" cutterhead dredge Guthrie, which operates on the ACF,aas well as the GIWW East was 3.2 feet.

## Table IV-12

## ACF Yearly Dredging Volumes

| Year | Gross Quantity (Cubic Yards) |
|---|---|
| 1973 | 983,702 |
| 1974 | 1,705,138 |
| 1975 | 1,725,189 |
| 1976 | 2,010,483 |
| 1977 | 1,790,097 |

A training work construction project completed in 1970 on the ACF did not prove to be as effective in eliminating the maintenance dredging as originally anticipated. However, there has been some improvement in depth duration reliability attributed to the dike construction and, in part, to advance maintenance dredging in reaches known to have persistent shoaling problems. Although 9,300 cfs were originally considered adequate to maintain a 9-foot channel depth, it has now been determined that a minimum flow release of 13,000 cfs from the Jim Woodruff Dam as well as maintenance dredging ue required to maintain the authorized depth. The present system, however, apparently lacks the storage capacity to provide a discharge of that magnitude throughout the entire low-water season.

The reliability of depth maintenance on the Apalachicola from 1962 through 1977 may be seen on Table IV-13. As indicated, the 9-foot authorized depth was maintained only 67% of the time during that period, although the last seven years of the record exhibit a considerable improvement in depth reliability. This is due, in part, to completion of the training structure project as well as an increase in the efficiency and intensity of the dredging program.

Flow data, representing the period from 1929 to 1978, indicate that the required 13,000 cfs discharge is maintained 67.5% of the time and 9,300 cfs is exceeded about 82% of the time. Historically, the 9,300 cfs referenced flow and original intensity levels of maintenance were insufficient to meet channel requirements. Increased maintenance efforts have brought the flow-duration and depth duration curves into agreement. A comparison of the depth reliability for the last seven years of record (82.7%) with the flow-duration curve affirms that, with

# Table IV-13

## Available Depths on Apalachicola River
## Percent Time Depth Available

| YEAR | ANNUAL RAINFALL(in) | 9 ft | 8.5 ft | 8.0 ft | 7.5 ft | 7.0 ft | 6.5 ft |
|---|---|---|---|---|---|---|---|
| 1962 | 44.97 | 44.4 | 44.4 | 46.5 | 46.5 | 65.4 | 100.0 |
| 1963 | 48.14 | 41.1 | 41.1 | 41.1 | 44.1 | 76.2 | 100.0 |
| 1964 | 70.11 | 89.0 | 89.0 | 89.0 | 100.0 | 100.0 | 100.0 |
| 1965 | 52.69 | 66.3 | 68.3 | 77.8 | 98.8 | 98.8 | 100.0 |
| 1966 | 59.13 | 73.1 | 73.1 | 73.1 | 100.0 | 100.0 | 100.0 |
| 1967 | 50.38 | 66.3 | 74.7 | 79.1 | 89.3 | 100.0 | 100.0 |
| 1968 | 39.02 | 27.1 | 27.1 | 33.3 | 74.9 | 80.0 | 100.0 |
| 1969 | 46.63 | 39.1 | 39.1 | 53.1 | 75.1 | 100.0 | 100.0 |
| 1970 | 50.32 | 50.7 | 56.2 | 80.6 | 100.0 | 100.0 | 100.0 |
| 62-70 | Average Depth | 55.2 | 57.0 | 63.7 | 81.0 | 91.2 | 100.0 |
| 1971 | 54.94 | 78.9 | 78.9 | 83.8 | 83.8 | 100.0 | 100.0 |
| 1972 | 51.77 | 71.5 | 71.5 | 82.7 | 87.7 | 100.0 | 100.0 |
| 1973 | 56.13 | 89.6 | 89.6 | 91.0 | 100.0 | 100.0 | 100.0 |
| 1974 | 51.92 | 67.7 | 67.7 | 79.7 | 100.0 | 100.0 | 100.0 |
| 1975 | 71.55 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1976 | 62.30 | 89.9 | 95.1 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1977 | 47.68 | 81.0 | 81.0 | 81.0 | 100.0 | 100.0 | 100.0 |
| 71-77 | Average Depth | 82.7 | 83.4 | 88.3 | 95.9 | 100.0 | 100.0 |
| ENTIRE PERIOD AVERAGE DEPTH | | 67.2 | 68.6 | 74.5 | 87.5 | 95.0 | 100.0 |

present maintenance dredging efforts, a minimum of 9,300 cfs is necessary to maintain the present degree of depth reliability. Should upstream storage conditions improve to the point where a 13,000 cfs minimum discharge could be maintained, a significant increase in the depth reliability would be realized, assuming the present intensity level of channel maintenance is sustained.

Comparison of monthly flow-duration curves indicate that the design discharge of 13,000 cfs is maintained about 95% of the time from January through May, dropping to approximately 60% from June through August and reaching a low of about 20-30% reliability in September, October and November before increasing to 65% in December.

9. Reporting Region 12: The Tennessee-Tombigbee, Black Warriors and Alabama Waterways. The Tennessee-Tombigbee Waterway, Black Warrior and Alabama Rivers form the head-waters of the Mobile River and are all maintained and regulated by the Mobile District of the South Atlantic Division. The major problems faced by the Mobile District are low water flows, especially on the Alabama River; bend constrictions; disposal of dredge material; shoaling; environmental permits; and the competition for water resources between navigation, fish and wildlife, and hydroelectric power.

The District has difficulty maintaining authorized depths on the Alabama River during low-flow periods and is studying alternative methods of maintaining depth, such as reservoirs. This latter practice is utilized occasionally to free grounded barges although the procedure is not officially authorized. Training works, in the form of stone dikes, ahve been constructed on the Alabama River. These have proven only marginally effective in stabilizing the river and reducing dredging requirements due to poor quality control during construction as well as the relatively flat gradient of the channel (0.1 feet/mile).

The Tennessee-Tombigbee Waterway project is still under construction with completion expected in 1986. The primary form maintenance anticipated on this waterway pertains to lock pairs. Similarly, the major maintenance problem on the Black Warrior concerns the locks which are generally closed for two weeks during the low-water season for repairs.

The Tennessee-Tombigbee Waterway is authorized for a 300 x 9 foot channel while the lower Tombigbee is now 200 x 9 feet which results in fleeting at Demopolis. Planning studies indicate that the authorized depth on the Tombigbee River is maintained close to 100% of the time.

There is some problem among the shippers with respect to the actual meaning of the authorized depth. While the nine foot authorization is the minimum controlling depth maintained, shippers relying heavily on overdepth dredging practices load their barges to the full nine feet draft and consequently encounter problems in shoal areas.

Most of the dredging is done with cutterhead dredges and a small percent with hopper dredges, the latter largely in the approach Mobile Harbor. Until recently, the cutterhead dredging was done with the Corps dredge, the 20" Collins. However, under the policy of the Industry Capability Program of allowing private industry to compete for work traditionally done by the Government plant, a number of contracts have been awarded to dredging contractors and the Collins, out of necessity, has been laid up. The average depth of cut for the Collins during 1971, 1972 and 1974 was 4.5 feet with most of the disposal to open water. Less than 10% of the disposal is to confined sites.

The inland dredging season begins when the spring floods recede, typically in early May. Since most of the dredging is performed by contractors, this creates some problems with respect the inability of the contractors to respond immediately to emergency shoaling situations. Typically the dredging season ends August, although it may continue into November.

As a matter of routine, the Corps surveys the waterways, identifies the most critically shoaled areas, and sends dredges to knock the tops off. Contrary to conditions on the Mississippi River, the worst locations are generally in the same place every year and revetments and training works are being considered in order to mitigate the annual deposition in these areas. This phenomenon can be explained by generally higher stability of these rivers.

On the Alabama River, a total of 19 sites are dredged annually with an average quantity of 900,000 cubic yards. On the Black Warrior-Tombigbee River System, an average of 20 sites is dredged annually with a total average quantity of 1,650,000 cubic yards. In the District, the total dredge volume remains pretty much the same from year to year, as indicated on Table IV-14.

It is the policy of the Corps to provide two feet of advance maintenance dredging on all maintenance dredging projects. Dredged spoils in the District are generally disposed of between the river banks.

Table IV-14

Maintenance Dredging, Black Warrior, Tombigbee, Alabama, Coosa Rivers

Black Warrior & Tombigbee River System

| Year | Gross Quantity (Cubic Yards) |
|---|---|
| 1973 | 1,842,385 |
| 1974 | 2,970,485 |
| 1975 | 2,548,120 |
| 1976 | 2,395,492 |
| 1977 | 2,008,155 |

The Alabama Coosa River System

| Year | Gross Quantity (Cubic Yards) |
|---|---|
| 1973 | 1,001,100 |
| 1974 | 1,851,686 |
| 1975 | 797,874 |
| 1976 | 2,026,684 |
| 1977 | 2,688,703 |

According to the flow-duration curve for the Alabama River at the Claiborne Lock anid Dam, the standard low water flow of 8,600 is exceeded about 97% of the time. This flow equates to a SLW stage of 9.2 feet. However, communication with the District indicates that the depth reliability on the Alabama River is somewhat less than the flow-duration curve might indicate due to shoaling conditions.

10. Reporting Regions 13-15: South Middle and North Atlantic Coast. These regions contain the Atlantic Intracoastal Waterway from Key West, Florida to Long Island Sound; the approaches to major harbors, including

those in the Chesapeake Bay and the Delaware River; and a number of navigable inland waterway systems, including the Hudson River. Proceeding in a northerly direction, these waterways are maintained by the Jacksonville District from Key West to Cumberland Sound, the Savannah District to Port Royal Sound, the Charleston District to the North Carolina/South Carolina boundary, the Wilmington District to the Virginia/North Carolina boundary, the Norfolk District to the Maryland/Virgina boundary, the Baltimore District to the Delaware/Maryland boundary, the Philadelphia District to, and including, the Manasquan Inlet in New Jersey, the New York District to the New York/Connecticut boundary, and the New England District/Division to the St. Croix River, Maine.

Approaches to major ports will be covered, as appropriate, in the section entitled "Current Maintenance Programs and Authorized Depth in Approaches to Coastal Ports".

As may be expected, authorized channel dimensions of the AIWW vary from district to district. Since this waterway is used primarily for recreational purposes, the maintenance of authorized dimensions is not particularly critical and, accordingly, receives less consideration than inland waterways with heavy commercial use.

The Office of Management and Budget (OMB) has promulgated maintenance funding criteria for projects authorized prior to 1968. These criteria include a minimum utilization of 100 million ton-miles per year and operation and maintenance costs not greater than .5 mills per ton-mile. Projects which do not meet these criteria are subject to a reevaluation by the appropriate District to justify continued maintenance expenditures. None of the AIWW projects in the South Atlantic Division passed the OMB criteria.

In the South Atlantic Division, the Savannah District maintains a 12x90 foot channel. Annual dredging requirements are about 1.5 million cubic yards and the spoils are disposed of in open waters. Future seasonal disposal constraints are anticipated due to fish spawning and lack of disposal sites where the waterway intersects harbors.

In the Wilmington District, most of the old projects dating from the 1880's through the 1920's are now recreational but the District no longer has the authority to maintain them.

No maintenance problems were identified in the Hudson River, exclusive of New York Harbor.

11. Reporting Region 18: Upper Columbia-Snake Waterway, Lower Columbia Snake Waterway/Willamette River. The authorized depth of the Columbia River is 40 feet from the mouth to Portland, 27 feet to the Dalles Lock and 14-feet to its confluence with, and including, the Snake River. However, the reach from Portland to the Bonneville Lock is maintained at 17 feet since most tow drafts in the upper reaches range from 14 to 16 feet.

The District utilizes only timber pile dikes to develop and maintain authorized channel dimensions on navigation channels on the Columbia River below Portland. The pilings have rock blankets on the stream and bank ends. The District does not construct dikes on the inside of a bank nor does it use stone dikes due to unfavorable past experience such as stream-end scouring and settlement.

Dredging begins in April or May and continues through December with the highest priority given to the entrance channel to the river. Training works at the mouth of the river have constricted several small channels into a single, 45 feet deep waterway. Maintenance dredging in the upper pools is on an irregular basis. Annual dredging schedules, including the identification of disposal sites to be utilized, are prepared for review and comment by state and federal agencies whose activities or areas of responsibility might be affected by the proposed dredging operations.

Hydraulic cutterhead pipeline dredges are currently used in this reach of the river.

Disposal of dredged material is accomplished by a variety of methods but the two most common methods utilized within the project area are upland disposal with berms and shoreline disposal. In-water disposal has also been used, but only infrequently.

Approximately 250,000 cubic yards of material are dredged annually from the upper reach of the river while about 9,000,000 cubic yards are removed from the channel between Bonneville and the mouth. Annual dredging in the

40 foot reach from Portland to the ocean is less than 4,000 cubic yards. About 5,000,000 cubic yards are dredged annually in the Columbia River delta.

Because of river training works, the same volume of annual maintenance dredging is required in the 40 foot deep reach from Portland to the ocean, as when the reach only had an authorized depth of 27 feet, to maintain the same reliability.

The design discharge for the Willamette River at Salem is estimated to be about 5,000 cfs which, when compared with the flow curve, indicates the authorized depth should be maintained 85% of the time. Since only the lower 50 miles of this waterway are utilized for commercial navigation, summer releases from the controlled upper reaches of the river are considered adequate.

The shoals between Vancouver and the Bonneville Dam generally require dredging on the average of once every five years. Airport Bar, Upper Vancouver Bar, and Government Island Bar shoals, however, require more frequent dredging. Airport Bar, which must be dredged annually, accounted for over 50% of the material dredged from the project area between 1970 and 1975. Table IV-15 lists the major dredge sites, as well as the frequency and volume of dredging operations.

Table IV-15

Maintenance Dredging Locations
Columbia/Snake Waterway

| Location | Frequency of Dredging | Date Last Dredged | Average When Dredged (c.y.) |
|---|---|---|---|
| Upper Vancouver | Every 3 years | Sept. 1975 | 113,000 |
| Entrance to Oregon Slough | Every 7 years | March 1970 | 164,000 |
| Airport Bar | Annually | Sept. 1975 | 152,000 |
| Gov't. Island Beach | Every 3 years | Sept. 1975 | 34,000 |
| Reed Island Bar | Every 5 years | Dec. 1972 | 68,000 |

The Columbia River, above the Bonneville Lock to and including the Snake River at Lewiston, Idaho is completely controlled. Project design for that segment guarantees that authorized depths are self-maintained 100% of the time. The lower reaches of the Columbia River are tidal with daily fluctuations ranging from 1 to 4-feet. Accordingly, it is difficult to make an accurate assessment of authorized depth maintenance. However, estimates by personnel in the Portland District place the reliability of authorized depth maintenance on the lower reaches of the river at about 80%. Discharges at the Columbia River are regulated. According to the flow duration curve at the Dalles, the minimum flow maintained 100% of the time is 70,000 cfs, and 100,000 cfs (approximate design discharge at Portland) is maintained 94% of the time. This suggests that the reliability of channel controlling dimensions is something lower than the design water flow.

### (d) Segments Experiencing Dimensional Deficiencies As A Result of Adverse Hydrological Conditions

The purpose of this section is to define locations and effects of adverse hydrological conditions during periods of low flow.

In the previous section, several waterways in the United States were identified as having either dimensional deficiencies or an insufficient probability of maintaining authorized depth during periods of adverse hydrological conditions such as extremely low flow, rapid water level fall or a combination of the two. These waterways are summarized in Table IV-16.

All of the segments shown are composed of free flowing waterways for at least a portion of their length. Other segments have been previously identified as having occasional insufficient depths; however, these waterways are controlled or channelized and controlling depths less than authorized have a very small probability of occurrence.

## Table IV -16

### Waterways Experiencing Problems in Authorized Depth Maintenance

| Reporting Region | River |
|---|---|
| 2 | Middle Mississippi |
| 3 | Lower Middle Mississippi |
| 3 | Upper Lower Mississippi |
| 3 | Lower Mississippi |
| 6 | Missouri |
| 11 | Apalachicola |

On waterways which are controlled by dams, the normal pattern of sedimentation and scour is disrupted. While sedimentation continues to occur, flow velocities are artificially reduced by the pools which are created by the dams. The result is that most siltation occurs in the pools near the lock and dam. Most maintenance dredging work, therefore, takes place in the approach to the locks.

In most pools, authorized depth is usually found in the upper reach of the pool with greater depths elsewhere. The riverbed in the upper reach is generally excavated and maintained at a depth equal to the authorized depth below the flat pool elevation. As long as water levels are not allowed to drop below the flat pool elevation, maintenance requirements are usually very low in the upper reach.

The following section will deal primarily with the free-flowing portion of the rivers listed in Table IV-16.

Table IV-17 presents the relative stability, as defined in the subsection entitled "River Hydrology, Morphology and Channel Maintenance," of the rivers listed in Table IV-16 as determined from the Indicators of Stability.

1. Reporting Region 3 - Lower Mississippi River. Authorized depth in the Lower Mississippi River is 12 feet, but the project has not yet been fully implemented, and as a result, depths are maintained at nine feet a considerable amount of time. Records of controlling depths from Cairo to Baton Rouge for the 19 years of

Table IV-17

Relative Stability of Selected Rivers

| Rivers | Classification |
|---|---|
| Middle Mississippi | Semistable |
| Lower Middle to Lower Mississippi | Unstable |
| Missouri | Stable* |
| Apalachicola | Stable |

NOTE: The Missouri River is now stable as a result of river training works.

record, 1960-1978, were obtained from the Vicksburg District. The records only indicate when controlled depths are less than 10 feet and less than 12 feet.

During the 19 year period of record, controlling depths greater than 10 feet were measured 88% of the time and controlling depths greater than 12 feet were measured 69% of the time in the 700 mile reach.

The Lower Mississippi River was determined to be unstable by use of relative stability parameters in the subsection entitled "River Hydrology, Morphology and Channel Maintenance." Further evidence of this can be seen by examining the relationship between discharge and controlling depth in this reach. Over this reach there are about 70 shoaling sites, and in any given year, only a few will be controlling. During the six year period investigated, controlling depths less than 10 feet were recorded at flows ranging from 120,000 to 600,000 cfs. Controlling depths greater than 12 feet have also been recorded at flows as low as 200,000 cfs. Because there is no direct relationship between flow and depth flow, depth relationships are presented in probabilistic terms. Curves of the minimum, maximum and most probable values recorded are indicated on the figure.

Figure IV-B shows a relationship drawn between discharge and the probability of occurrence of controlling depths on the Mississippi River between Cairo and Baton Rouge. The curves were developed based on daily values for discharge and controlling depth over the six year period from 1971 to 1976. The proper way to read the graph is as follows: "At a flow of 400,000 cfs, controlling depths greater than 10 feet were measured 90% of the

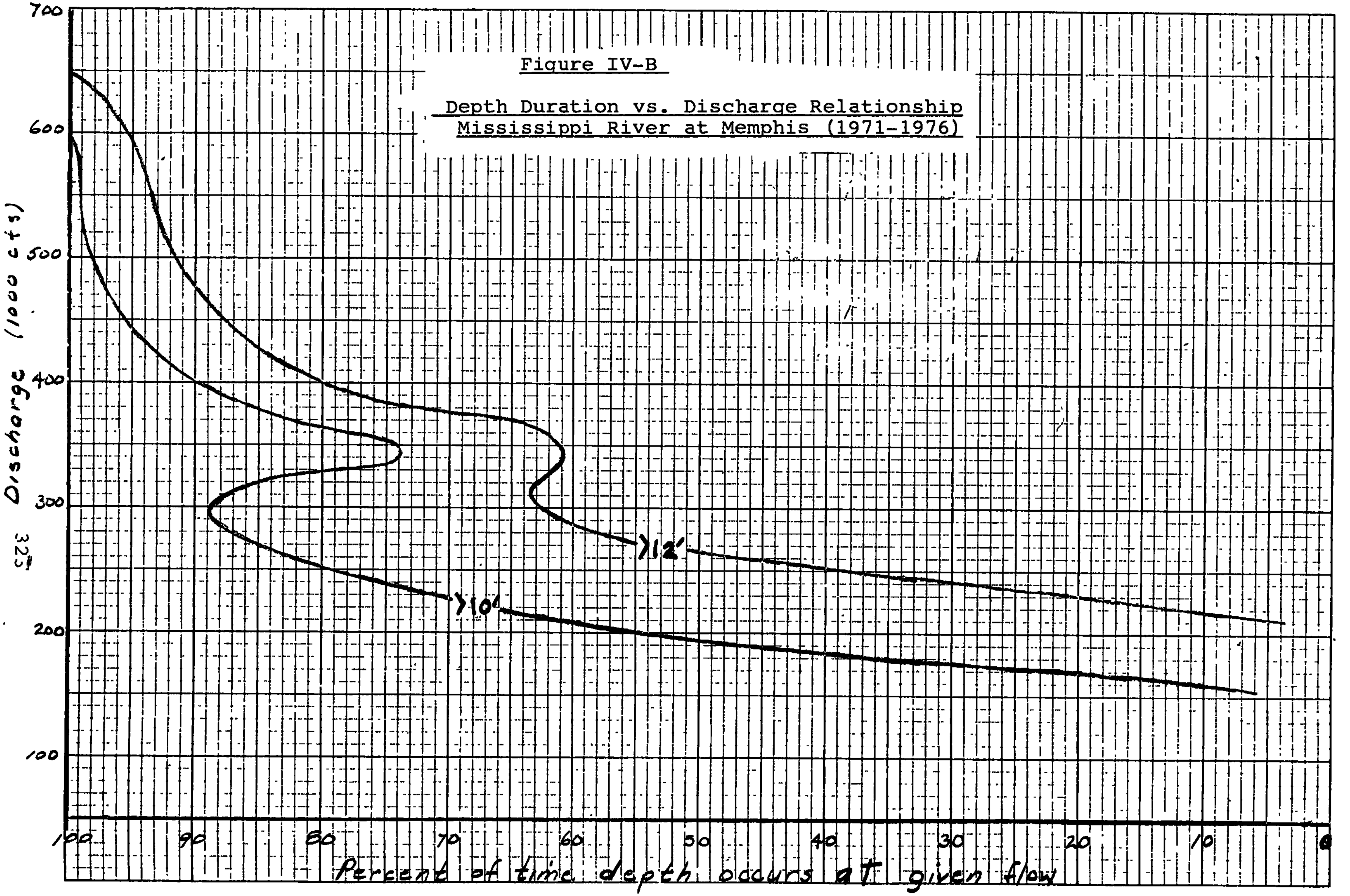


Figure IV-B

Depth Duration vs. Discharge Relationship
Mississippi River at Memphis (1971-1976)

time and controlling depths greater than 12 feet were measured 80% of the time." It should be noted that the curves are not smooth as one would expect if a direct correlation existed between flow and depth probability. In fact, depths of 10 feet or greater are maintained a higher percentage of the time at 300,000 cfs than at 350,000 cfs. This reflects the positive effect of channel maintenance. Controlling depths often drop to less than 10 feet even at intermediate to high flows; however, during the period of lowest flows, controlling depths greater than 10 feet were often maintained by a combination of dredging and natural scour. It was not possible to develop a depth-duration curve from the available information as only two depths, less than 10 feet and less than 12 feet were recorded.

The relationship shown in Figure IV-B is only a statistical representation of the six year period, 1971 to 1976. The controlling depth at any given flow is not a random variable but highly dependent upon hydrological occurrences during previous months and level of maintenance dredging and river training. The wide range of flows over which a given controlling depth can occur shows the importance of the other factors (rate of recession, peak flows, etc.) in determining sedimentation and scour rates.

Table IV-18 provides a compilation of several parameters which affect controlling depth as measured by the Memphis Gauge on the Mississippi River. For the period 1971 to 1976 values are shown for peak flood flow, rate of flood recession, mass volume of flood flow, time between peak flood flow and the attainment of 10 and 12 feet controlling depths and the flow when controlling depths of 10 and 12 feet were attained. While there are no simple relationships between the various parameters, generally, controlling depths of 10 and 12 feet occur at higher flows when the peak high flow, the duration high flow, and the rate of high flow recession are high. Conversely, controlling depths generally occur at lower flows when the peak high flow, the duration of high flow and the rate of high flow recession are low. A combination of some low parameters and some high parameters will provide controlling depths at intermediate flows. For example, in 1975 controlling depths of less than 10 feet were recorded when flows had receded to 433,000 cfs. This is an intermediate flow value and was recorded after a very high peak flood flow and a relatively gradual rate of recession.

# Table IV-18

## Flow Parameters
## Memphis Gauge (x1000 cfs)

| | DATE Flow at Depth <12' | DATE Flow at Depth <10' | DATE Peak | Recession Rate | Volume | Lag (Months) Peak to Loss of Depth | |
|---|---|---|---|---|---|---|---|
| 1971 | 6/26 - 358 | 7/05 - 297 | 3/09 - 1187 | 700 cfs/mnth. | $1.34\text{x}10^{12}$ cf | 3.6 | 3.9 |
| 1972 | 6/03 - 375 | 6/11 - 304 | 5/04 - 1153 | 1317 cfs/mnth. | $1.72\text{x}10^{12}$ cf | 1.0 | 1.25 |
| 1973 | 7/01 - 576 | 7/01 - 576 | 4/01 - 1633 | 707 cfs/mnth. | $3.38\text{x}10^{12}$ cf | 3.0 | 3.0 |
| 1974 | 5/01 - 635 | 5/02 - 614 | 2/07 - 1490 | 352 cfs/mnth. | $2.56\text{x}10^{12}$ cf | 2.8 | 2.8 |
| | 7/21 - 303 | 7/22 - 297 | 6/13 - 1100 | 245 cfs/mnth. | $3.07\text{x}10^{12}$ cf | 1.25 | 1.25 |
| 1975 | 7/10 - 484 | 7/13 - 433 | 4/06 - 1760 | 655 cfs/mnth. | $2.45\text{x}10^{12}$ cf | 4.1 | 4.2 |
| 1976 | 5/13 - 416<br>8/10 - 202 | 5/28 - 333<br>8/12 - 196<br>11/01 - 307 | 2/28 - 860 | 275 cfs/mnth. | $1.61\text{x}10^{12}$ cf | 2.5 | 3.0 |

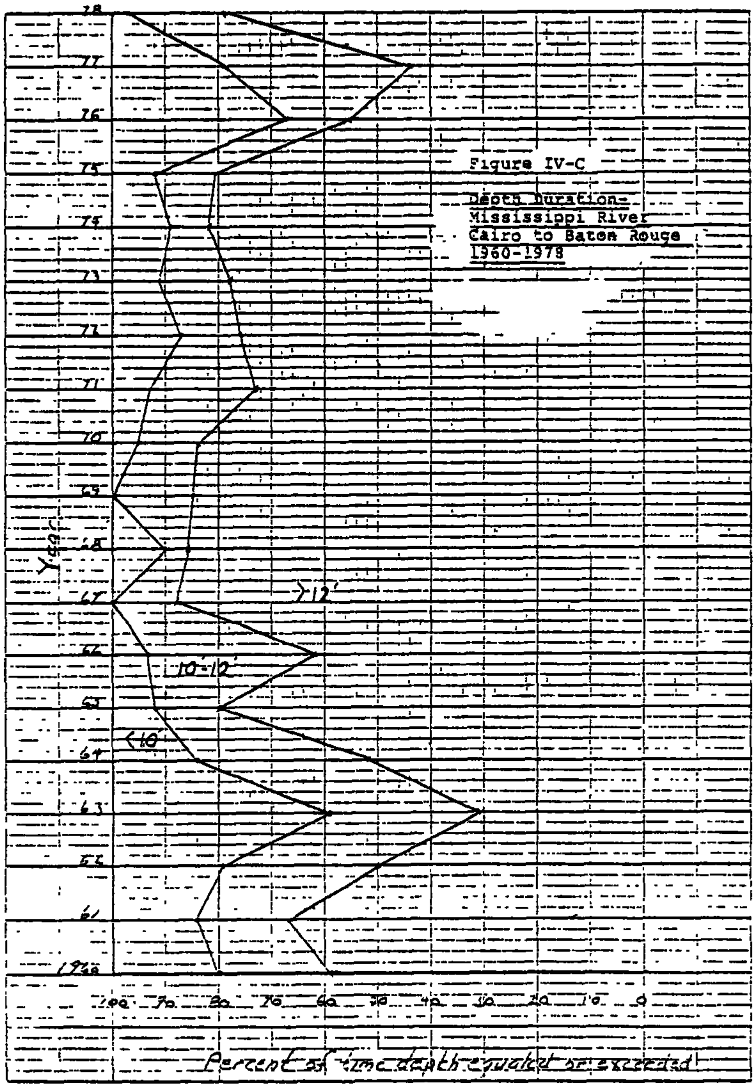
Figure IV-C is a graphical representation of the percentage of time controlling depths less than 10 feet and less than 12 feet that occurred during the 19 year period from 1960 to 1978 when controlling depths were measured directly and recorded. Over the 19 year period, controlling depths less than 10 feet were maintained 13% of the time and controlling depths less than 12 feet were maintained 31% of the time. Over the period 1971 to 1976, 1976 depths less than 10 and 12 feet were maintained 12% and 29% of the time, respectively, almost the same as the average during the longer period. However, according to the flow duration relationship, flows during the period 1971 to 1976 were significantly higher than historical flows measured from 1945 to 1970. If the probability of controlling depths occurring at flows recorded from 1971 to 1976 is combined with the probability of occurrence of historical flows, then over the period from 1947 to 1970 controlling depths less than 10 feet and 12 feet would have occurred 22% and 39% of the time, respectively, over the 25 year period.

Nonetheless, based on observation of the duration of controlling depths less than 10 and 12 feet measured directly over the 19 year period, it can be seen that, in general, controlling depths have been increasing. This is undoubtedly due to river training works completed during the 19 year period which reduced the number of shoaling sites requiring dredging. Because controlling depth is so sensitive to the extent of river training, only recently measured controlling depths can be considered as representative of present conditions.

Therefore, in order to determine the effectiveness of maintenance operations, a discharge versus depth probability relationship should be derived based on a few recent years of measured controlling depths and flows. Then, a flow duration relationship should be derived for the entire period of flow record and modified to reflect long-term flow pattern changes induced by basin development. The probability of occurrence of flows on the modified flow duration curve should then be combined with the probability of occurrence of controlling depths at those flows. This should show an accurate picture of how well current controlling depths are maintained with respect to long-term average hydrological conditions.

## Figure IV-C

## Depth Duration - Mississippi River
## Cairo to Baton Rouge
## 1960-1978



2. Reporting Region 2 - Lower Upper Mississippi. The Middle Mississippi River segment of Region 2 has an authorized depth of nine feet. Records of controlling depth in this reach are only available on a monthly basis from direct measurement for the period 1969 to 1978. Unfortunately, this only allows a rough relationship to be developed between monthly minimum controlling depths on the reach and the minimum discharge during the corresponding month as measured at the St. Louis Gauge. Daily data would have to be collected and compared to properly develop this relationship. As indicated, controlling depths less than 12 feet can occur over a wide range of flows. This supports the conclusion drawn above labeling this reach as semistable.

It was not found possible to develop a relationship between flow and depth probability because daily values of controlling depths were unavailable. However, it is felt that this relationship could be derived if a few years of daily or bi-weekly controlling depth records could be compiled. The results could then be compared with a long term flow-duration curve to obtain term duration relationship as for Reporting Region 3. There is good reason to suspect that a flow duration relationship similar to that found in Reporting Region 3 exists. In other words, controlling depths drop to less than 10 feet even at intermediate to high flows; however, during the period of lowest flows, controlling depths greater than 10 feet are maintained by a combination of dredging and natural scour. Thus, the period of time when flows are below the low water reference plan do not necessarily correspond to the period of time when authorized depths are not maintained. Figure IV-D shows a very approximate relationship between discharge and controlling depth, based on low monthly values over the period 1969 to 1978.

An approximate controlling depth-duration relationship is provided on Figure IV-E showing the approximate controlling depth-duration curve for the 10 year period.

Flow duration curves for the St. Louis Gauge show that during the more recent 27 year period, 1947 to 1974, flows have been somewhat lower than in the historical period, 1861 to 1974. The location of the low water reference plane (LWRP)is indicated.

# Figure IV-D

## Flow-Depth Relationship Mississippi River at St. Louis (1969-1978)

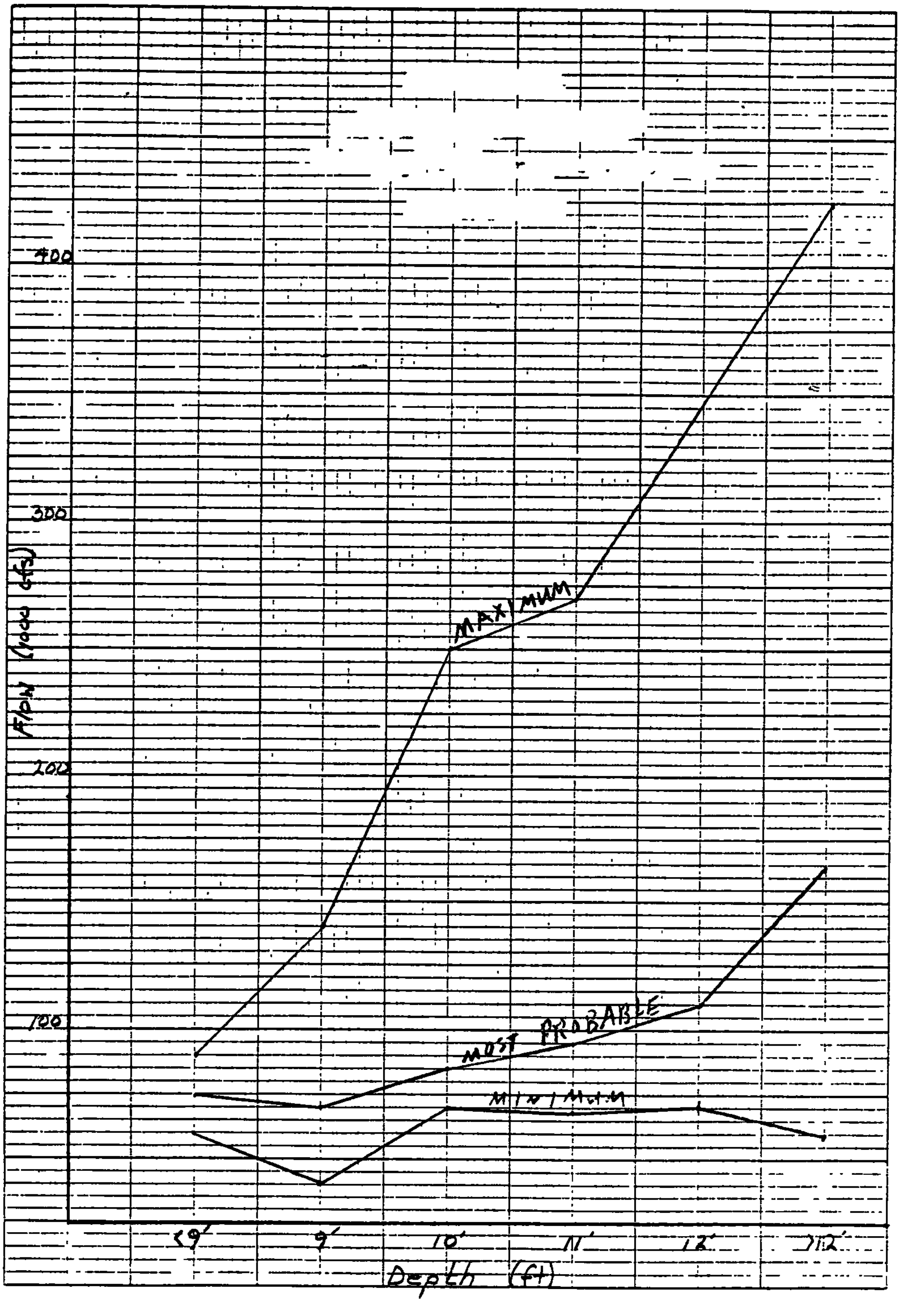
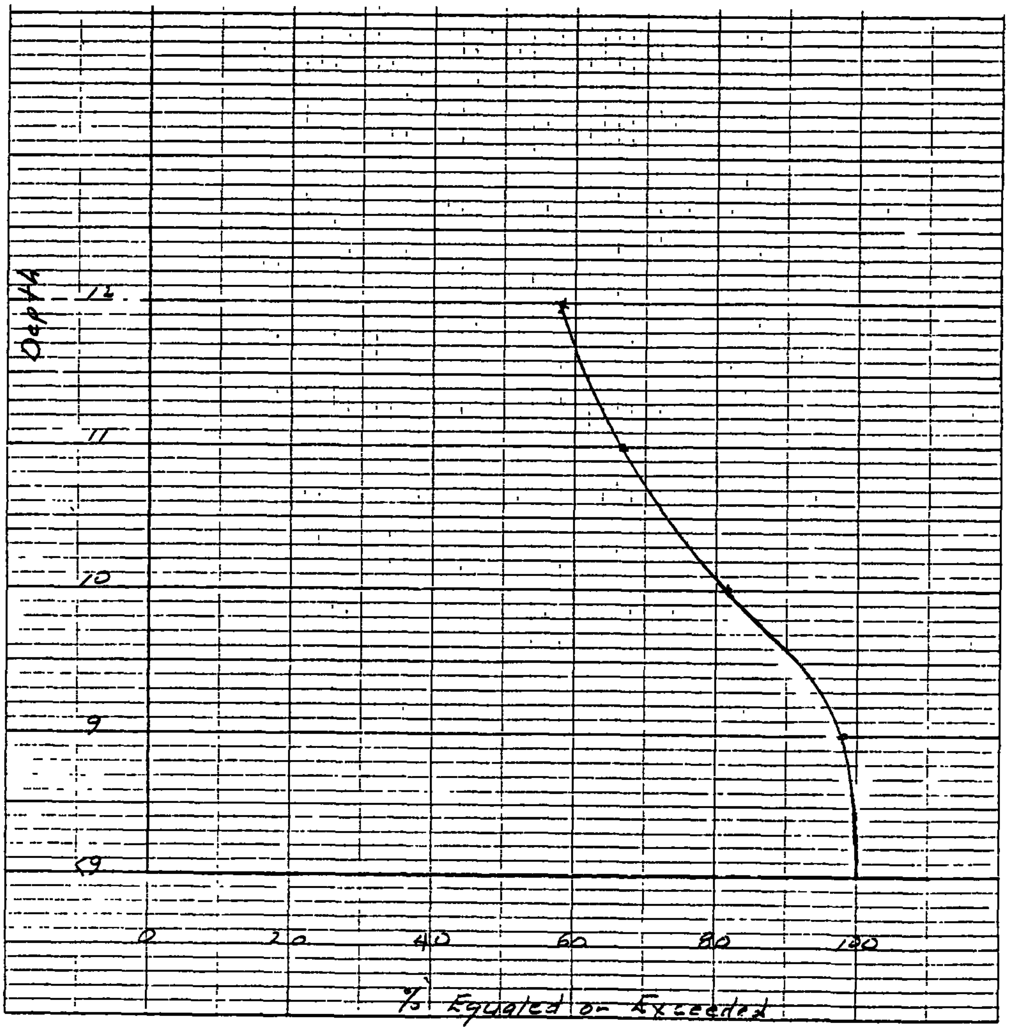


Figure IV-E

Depth Duration Mississippi River at St. Louis (1969-1978)



The low water reference plane is defined as the elevation at which the Corps attempt to maintain authorized depth 100% of the time. During the 10-year period 1969 to 1978, the controlling depth was less than authorized in 1970 and again in 1976 for a total duration of slightly over two months or about 2% of the time during the 10-year period. However, the period of time when depths were less than authorized only partly coincided with the period of time when water levels were below LWRP. Over the 114 years of record, flows have been great enough to maintain stages above the LWRP about 99% of the time. During the 28-year period ending in 1974, flows have only been great enough to maintain stages above the LWRP about 93% of the time. Thus, while the percentage of time that flows exceed the LWRP stage has been decreasing, the percentage of time that controlling depths have been maintained greater than authorized remains very high.

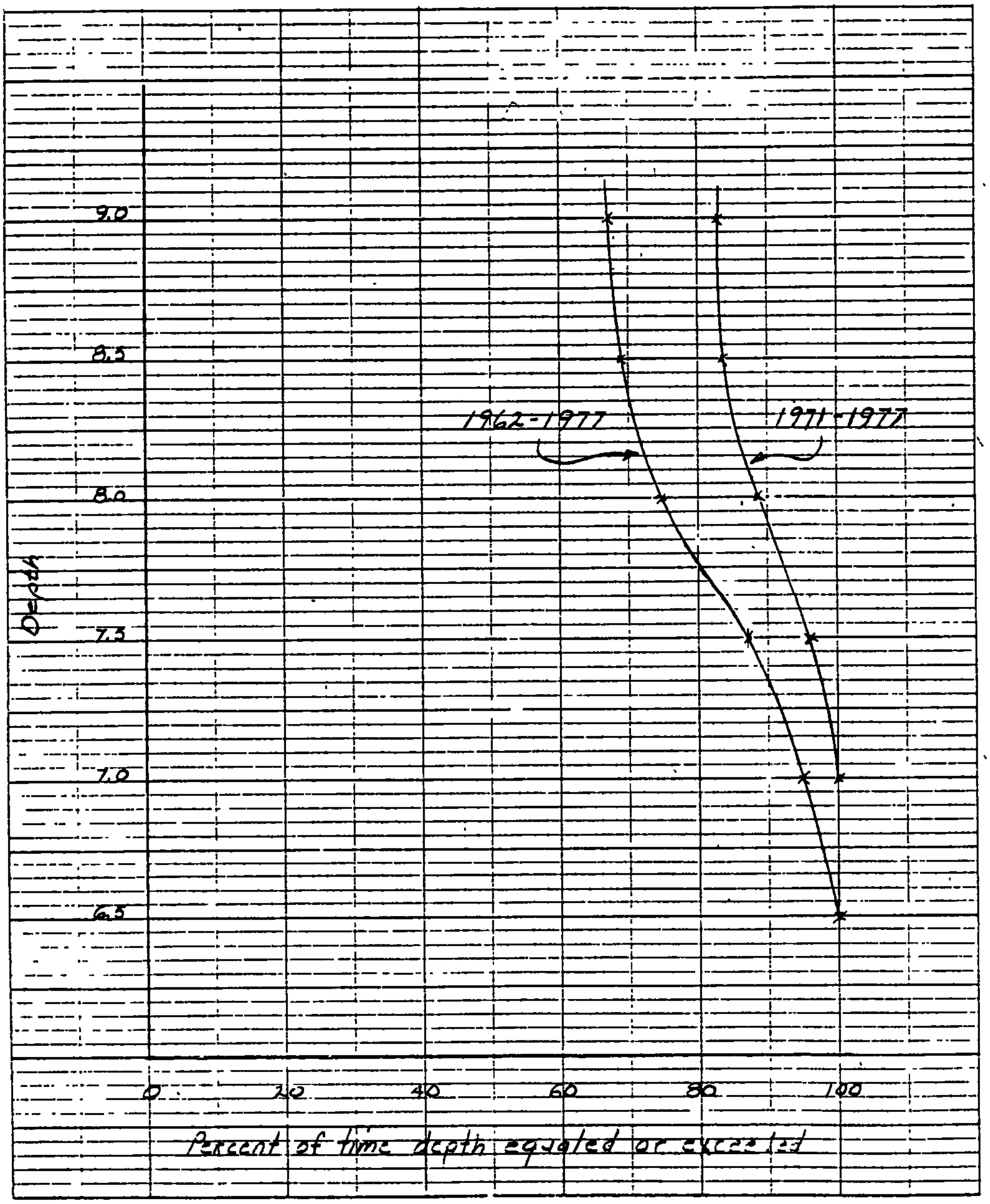
3. Reporting Region 11 - Gulf Coast East. Figure IV-F presents controlling depth-duration curves for the Apalachicola River. The authorized depth is nine feet. The duration of controlling depths from 1962 to 1977 were obtained directly from the report "Coordination Report on Navigational Improvements for Apalachicola River Below Jim Woodruff Dam, Florida."[23] As a result of the completion of training structures and an increase in the efficiency and intensity of the dredging program since 1971, the duration of controlling depths equal to or greater than authorized only occurred 83% of the time in the period 1971 to 1977.

There are no data available from which to derive a relationship between flow and controlling depths. However, based on the relative stability parameters of the section entitled "River Hydrology, Morphology and Channel Maintenance," the Apalachicola River is considered to be stable so that flows and controlling depths are likely to be directly related. If a direct relationship does exist, then the reliability of authorized depth can be expressed in terms of the occurrence of a design flow or low water reference plane.

4. Reporting Region 6 - Missouri River. On the Missouri River, flows are kept very regular throughout the navigation season by a series of upstream storage and regulation projects. Thus, rapid flow fluctuations in the flow region where major sedimentation or scour would occur

Figure IV-F

Depth Duration Apaloachiocola River



are avoided. The result is that a relatively stable channel is maintained on a river which would otherwise be unstable. Depths are maintained at or near authorized levels most of the time. Construction of training works to limit bank erosion and constrict channel dimensions has greatly reduced the need for other types of channel maintenance (dredging). No dredging has been performed on the Missouri River since 1976. Controlling depths less than authorized occur even at design flow, but only for very short periods of time before natural scour increases the depth.

5. Alternative Solutions to Diminish the Effects of Adverse Hydrological Conditions at Low Flow Stages. In order to determine the value to the towing industry of providing various depths, the concept of average usable depth is introduced. During much of the year, water depths can be greater than authorized, especially in channelized waterways, and during these periods, tows or vessels can load to greater drafts than at authorized depth. Usable depth of a waterway is limited to a value less than or equal to the maximum depth, $a_{max}$, and greater than or equal to the minimum depth, $a_{min}$, which the vessel can use, where $a_{max}$ is equal to the fully loaded draft of the largest type of vessels operated on the waterway plus the required clearance between the keel of the vessel and the river bottom, and $a_{min}$ is equal to the draft plus the required clearance between the keel of the vessel and the river bottom at the minimum controlling depth (depth maintained 95-98% of the time). The economics of loading to various drafts is evaluated in Section V. In general, however, the controlling depth-duration curve of a waterway can be used to evaluate the percentage of time that vessels can be operated at depths between $a_{max}$ and $a_{min}$. The average usable depth is equal to the average depth that the tow or vessel can use over a period of time.

The effect of adverse hydrological conditions is to decrease the average usable depth. In response to lesser depths, vessel operators will light load or accept an increased risk of loss. This notably increases costs, but also decreases waterway lock capacities and could result in reallocation of cargo to other transportation modes.

In order to diminish the effects of adverse hydrological conditions, sufficient capacity reserves must be provided. This includes both providing reserve lock capacity in order to pass similar volumes of traffic under both normal and adverse conditions and providing maintenance reserves to improve navigation conditions (increase usable depth) under adverse conditions. Both alternatives involve increased levels of investment and must be considered in light of their value as measures to decrease towing costs.

The basic methods for improving the navigation conditions of a waterway are dredging and training. An evaluation of present conditions (i.e., annual volume of dredging, state of river training, and the reliability of authorized depth as shown on the depth-duration curve) provides a measure of the effectiveness of the current maintenance program.

Increasing the annual dredging volume in order to increase depths or the reliability of depths maintained must be considered very carefully. On most inland waterways, dredging is very seasonal in nature. In addition, volumetric requirements vary greatly from one year to the next. Increasing the number of dredges available during adverse hydrological periods, such as the period of flood recession or prolonged low flows, increases the probability that fleet reserves will be available when required, but also decreases the overall utilization of the fleet when hydrological conditions are more favorable.

River training works act to directly reduce dredging requirements. Thus, the cost of training a river can be compared to the cost of maintaining a dredge fleet in order to evaluate the viability of replacing a dredging program with training dikes and revetments. In some cases it may not be technically possible to fully train the river so that limited dredging reserves must be maintained (Apalachicola, Arkansas and Missouri Rivers). In other cases, it may not be possible to achieve the desired depth without a very large reserve dredging capacity so that river training can be provided to achieve the increased depth with the current fleet (Lower Mississippi River).

The positive effect of flow regulation was previously discussed and should not be overlooked as a viable means of reducing dredging requirements. The value of this measure is dependent upon the storage capacity of the basin reservoirs that can be earmarked for augmenting or redistributing flows for navigation purposes. It is important to note that in certain situations, navigation doesn't need augmented flows at low water stage, but rather more gradual seasonal water fluctuations. The proper scheduling of water releases may considerably reduce channel maintenance works.

## CHANNEL MAINTENANCE PROGRAMS AND AUTHORIZED DEPTH IN APPROACHES TO COASTAL PORTS

There are many harbors, large and small, around the coast which depend on maintenance of their approach channels for their continued existence. Their actual condition depends on their rate of shoaling, federal funding available for dredging, the extent of environmental problems and the political climate in the area. The political climate is of considerable importance in that it determines the level of availability of local cost sharing funds and disposal sites for dredged material, the degree of importance of expressed environmental concerns and hence the application of environmental constraints, and the level of political pressure for the allocation of federal funds. To a large extent the political climate is largely determined by how important the harbor is perceived to be to the local economy.

In order to facilitate an evaluation of United States' coastal ports, convenience dictates grouping the various ports by location or, for our purposes, reporting regions. In this manner, regional maintenance similarities may be emphasized as well as geographical related distinctions between the different areas. The regions, which will be covered independently, are the Atlantic Coast, the Gulf Coast, the Pacific Coast and the Great Lakes.

Within each region are described the approaches of the most important ports, or port complexes, and the problems of maintaining them. The review includes the dredging methods used, dredging requirements, and ongoing maintenance programs. A generic review of channel maintenance is provided in the first subsection, entitled "General Description of Harbor Maintenance." Alternative programs to provide reliable approaches to coastal ports are addressed in the section entitled "Alternatives for Channel Improvement."

The objective of this task is to identify constraints to maintenance of coastal approach channels and review existing alternative maintenance programs. The findings of this task will be incorporated in the evaluation stage of the NWS to estimate the sufficiency of approach channels to coastal ports to ensure efficient access to inland waterways.

It was also the intent of the study team to describe the effectiveness of approach channel maintenance in terms of the reliability of the authorized channel dimensions provided. Channel reliability is understood to mean the percent of time (or number of days per year) that controlling dimensions are equal to, or greater than, the authorized dimensions. Unfortunately, data relating duration of controlling and authorized dimensions were not consistently available for review.

Segments or parts of segments not included in this section are included in the section entitled "Channel Maintenance Programs Authorized Depth and Reliability of Authorized Depth." Only segments containing the ten major United States coastal ports and Great Lakes are included.

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### (a) General Description of Harbor Maintenance

Channel improvements usually include attempts to maintain a channel of a certain width and depth in a fixed position, making initial as well as maintenance costs as small as possible. Extensive dredging or training work may be necessary to provide the authorized channel depth and width.

The estuary itself provides much of the material which deposits in certain areas. Wave action, shipping, and man-made changes can create turbulence or change current patterns with the result that material will be eroded from one portion of the estuary and deposited in another.

The marshes within an estuary can also supply a considerable amount of sediments to other parts of the estuary, although marshes are usually areas of accretion rather than erosion.

Sediments from the ocean (usually sand) can enter an estuary. This can be a major source of estuary shoaling in estuaries which exhibit a strong predominant upstream bottom flow near the entrance. Ocean sediments are continuously fed to the mouth of an estuary by littoral currents.

Improper dredging practices can account for large volumes of shoaling. When channels are dredged, flow pattern, quantity, and shoaling patterns change and the dredged channels may become sediment traps, or existing shoals may shift to another area upstream, downstream or both, becoming a greater problem than they were before dredging.

Historically, it was common practice when dredging estuaries to dump the dredged material in the entrance area or elsewhere in deeper holes. Experimentation has indicated that dredged material should not be put back in the estuary (unless economics dictate otherwise) but should, instead, be pumped ashore, placed in confined disposal areas or transported out to sea. Similarly, downstream dumping as well as agitation dredging are generally considered poor practice in estuarial maintenance.

Training of an estuary channel is a very delicate process and the possibility of errors by putting training walls in a wrong location or a wrong configuration at a wrong distance apart mav prove disastrous to channel stability. Spur groins of jetties from the side and properly aligned training walls may prove to be a great advantage. These require meticulous planning, including field and hydraulic model studies in addition to maintenance dredging operations and sediment traps to store unavoidable deposits.

1. Dredging. A description of dredging equipment is presented in this Section. In general, the equipment usually employed for harbor and coastal maintenance consists of hopper dredges, cutterhead dredges and other hydraulic dredges. There are several remedial measures and improvement works by which shoaling can be reduced in navigation channels in estuaries. Improvement in dredging methods, including the disposal of the dredged material, can affect large reductions in channel shoaling. The removal of dredged material from a channel may be accomplished utilizing one of the following methods depending on prevailing conditions in the estuary.

Pumping the material ashore with the ship's own pumps through a reclamation pipe. This is often the safest and least harmful way of depositing dredged material and at the same time reclaiming useful new land as well as maintaining current regulation. The disadvantages are long reclamation times and relatively high investments.

The overflow dredging method is predominantly used to dredge silt and, generally, only with outgoing tide. It is the quickest method of getting rid of sand banks with relatively loosely packed silt. As uncontrolled resettlement of the overflowing spoil in the ship channel must be expected, this method can only be used in areas with suitable currents and certain tidal phases. Its application therefore has gradually declined, but changed practices may cause a revival during the next decade by introducing continuous methods of agitation such as air lifts.

With the combined dumping/reclamation method, the spoil is dumped into a pit, which has been dredged previously, and is pumped up by a plain suction dredger. This dredger then pumps it ashore through a floating and fixed pipe. In this method, essential advantages of dumping (quick unloading) can be combined with those of reclaiming (final and useful depositing of the load).

The sump handling method has also been utilized. One dredge discharges its material into the hopper of another (usually old) dredge for rehandling and pumbing to shore, thereby reclaiming land.

The sidecasting method, particularly suitable for maintaining long navigation channels, is becoming popular. Initial development of this method involved equipping a vessel with a long boom extending 250 feet off the side through which the dredge pumped material directly rather than going through hoppers.

Another method of reducing channel shoaling (often in port entrance channel to reduce littoral drift) is through the use of sediment traps. Sediment traps are a means of inducing shoaling in a more favorable area than in which it would normally occur. The use of a sediment trap may be advantageous in shifting a natural shoal either into an area where a pipeline dredge can pump directly to a disposal area or into an area where dredging operations do not hinder shipping traffic.

2. Training Works. Training works particularly germane to coastal and harbor channel maintenance include jetties, breakwaters and dikes.

A jetty is generally defined as a structure extending into a body of water to direct and confine the stream or tidal flow to a selected channel or to prevent shoaling. Jetties are built at the river mouth or bay entrance to help deepen and stabilize a channel and thus facilitate navigation. One of the normal results of a jetty is to stop the littoral drift from passing the channel entrance by impounding the sand on the updrift side of the jetty.

Breakwaters are another kind of littoral barrier. These structures generally are utilized to protect shore areas, harbors, anchorages or basins from wave action. An offshore breakwater is also a littoral barrier, but through a different mechanism. Its effect is to drastically reduce wave action in its lee, thus reducing the generating forces of littoral currents. As a result, littoral material accumulates on the shore in the protected area. The shore on the updrift then builds up like the updrift of a jetty. As the shore advances toward the breakwater, the system becomes a more efficient littoral barrier. Eventually the shore can build all the way out to the breakwater.

Estuaries usually have more than one channel, and flow distribution in these channels may be very skewed with predominance for either ebb or flood flow. In nature this usually means a complex situation with respect to material transport by which the same sediment circulates in the estuary. Any improvement of one channel is likely to affect one or more other channels, either by producing more sediment transport due to increased flow or inversely by creating a trap for sediment so that the associated channels start to scour.

3. Common Maintenance Problems. Problems most commonly associated with coastal and harbor maintenance programs may range from naturally occurring forces to man-made complications to institutional restrictions. Ultimately, the end result associated with these problems is increased cost, either economical or environmental, or failure to maintain adequate or prescribed waterway dimensions.

A 1979 survey of 19 United States deepwater ports, Pilots Associations, Steamship Associations, United States Navy, United States Coast Guard and the Water Resources Council was conducted by the Ad Hoc Dredging Committee of the AAPA in order to determine what affect existing channel dimensions were having on waterborne traffic in the United States. Response to that survey indicates that a problem of substantial magnitude exists with respect to reduced channel dimensions. Findings suggest that while periodic emergency situations such as hurricanes can create extensive shoaling and extraordinary dredging requirements in some ports, the greatest navigational constraints and economic losses result from reduced channel dimensions. While these reductions were occasionally attributed to insufficient funding for channel maintenance as training work construction and repair, the primary causative agent appeared to be disposal obstructions ascribed to environmental regulations.

The effects of environmental legislation, regulations, and concerns have severely affected dredging operations necessary to deepen harbors and channels. In general, the Corps of Engineers will not authorize private dredging nor perform congressionally authorized dredging until objections of federal, state and local environmental agencies have been satisfied. In some instances, the dredged spoils must be transported to distant areas, or diked land-disposal areas have to be constructed. According to 1977 Corps of Engineers' studies, dredging costs can be increased by 200 to 1,000 % because of added transportation or dike construction costs.

The available alternatives to open dumping are either confining the dredged material behind dikes (and in some cases special treatment for the runoff water), or hauling spoil out to the deep ocean (100 fathoms). The costs of these procedures are staggering for some locations. Costs involve both acquisition of land for disposal areas (scarce and expensive in most developed port areas) and increased transportation (pumping through long pipelines or hauling in barges or hopper dredges) to new disposal sites.

As a result, dredging has become a much more expensive operation in many parts of the country. Projects are delayed while disposal areas are acquired, applications for permits are filed, and environmental impact statements prepared.

Since the enforcement of environmental regulations is in the hands of state agencies in non-federal waters, the effects vary from state to state. In areas where environmental concern is high, such as California (particularly the San Francisco Bay area), Florida, the Chesapeake Bay region, North Carolina, New England, and the Great Lakes, dredging has been affected the most. Conversely, on the Gulf Coast (save Florida), dredging is an accepted way of life, and there is great political pressure for economic development. Consequently, the effect of the disposal problem has not been as severe.

Other impediments which may adversely affect harbor and port maintenance activities may be site or region specific. For example, Great Lakes ports are entirely weather dependent. Icing on the lakes stops movement of ships, and water currents allow suspended particles in the water to settle. This results in the shoaling of all channels during the winter months.

The channels of the 55 ports authorized for maintenance on the Great Lakes must be dredged as rapidly as possible as soon as thawing permits.

As previously mentioned, ports on the Gulf Coast frequently experience extremely heavy shoaling, requiring emergency dredging, from hurricanes. Similar cataclysmic meteorological conditions may be experienced along the northeast coastal ports with the advent of winter storm conditions.

### (b) Atlantic Coast Ports (Reporting Regions 13, 14, 15)

Those Atlantic Coastal Ports considered to be of primary importance for the purpose of this evaluation include Boston Harbor, New York Harbor, the Delaware River Ports, Baltimore Harbor, and the Hampton Roads Ports.

The major problem confronting the North Atlantic range of ports in the development of channels and harbors is the accommodation of oil tankers and dry bulk carriers, since these vessels are undergoing the most rapid increases in overall size and draft. Existing channel depths in North Atlantic ports range up to 45 feet, but depths required in the year 2000 will range up to 80 feet or more. t all of the ports, channel depth will be controlled by the requirements for oil tankers. At Baltimore and Hampton Roads, the requirements for dry bulk cargo carriers will be equally significant. Where channel depths of 60 feet or more will be required, there is no case, except possibly the Port of Portland, Maine, where it will be feasible to improve the existing channels sufficiently; alternative solutions, therefore, will be required.

1. Boston Harbor - Reporting Region 15. Boston Harbor is located within an indentation of Massachusetts Bay and lies approximately 51 nautical miles northwest of the tip of Cape Cod. The section considered herein includes the entrance channels, the so-called Outer Harbor, and the main navigation channels, from naturally deep water within the Outer Harbor to and through the Inner Harbor and extending up the Chelsea River and Mystic Rivers.

The main project for Boston Harbor consists of three entrance channels, the principal one being 40' x 900' and 1100 feet with a lateral extension 35' x 600'. The other two entrances are respectively 30' x 1200' and 27' x 1000'. It also includes an anchorage 40' x 2700' x 6000' just within the entrance, thence a channel 40' x 600' and a lateral extension 35' x 600', with widening at bends, to Boston, East Boston, and Charleston, a distance of about six miles. Channels 35' in depth extend one and one-half miles up the Mystic River and nearly two miles up the Chelsea River. Other tributary channels within the Inner Harbor include the Reserved Channel, 35' x 430' for a distance of about one mile, and the Fort Point Channel, 23' x 175' for a distance of about three-quarters of a mile.

Boston Harbor is the only New England Port with container facilities. As most of the other New England ports, it is also important as a terminal for petroleum, specifically heating oil during the winter.

Boston Harbor has been in a state of flux as far as dredging operations go. In the past, there has been a mixture of maintenance dredging, improvement dredging, new dredging, and partial maintenance dredging. The Harbor has not been dredged in ten years, due to a lack of sediment. Two highway tunnels located in Boston Harbor restrict the maximum dredgable depth to 50 feet while a rapid transit tunnel at the same location restricts the hedgable depth to 40 feet.

The Boston Port Authority in response to a survey performed by the AAPA reported experiencing minor impacts on port operations and economy as a result of reduced channel dimensions, but is unable to quantify them.

The significant vessels which Boston could expect to have to accommodate in future years are shown below.

| Type of Vessel | Size | Draft (ft.) |
|---|---|---|
| Tankers | 70,000 dwt. | 40-45 |
| Dry Bulk Cargo | 25,000 dwt. | 35 max. |
| General Cargo | 25,000 dwt. | 35 max. |
| Passenger | 800 ft. long | 30-35 |
| Container | 25,000 dwt. | 35 max. |

Present channels will meet all requirements of significant vessels, except possibly tankers. These can be accommodated on high tides (9.5 feet tide) with berths locally deepened to permit working at low tides.

Should tanker requirements be underestimated, the possibility of offshore terminal facilities exists with adequate depth of water for substantially larger ships.

Operational safety would be enhanced by extending the present 40 feet depth to the full 1200 feet width of the channel.

2. New York Harbor - Reporting Region 14. The Port of New York is a geographic area within the States of New York and New Jersey, with its harbor boundaries established by the Port District. The District is a 1500 square mile area within a radius of about 25 miles in the distance from the Statue of Liberty. The harbor has a shoreline frontage of navigable water totaling 755 miles, of which 460 miles are in the State of New York and 295 miles are in the State of New Jersey. From the Atlantic Ocean, the inner harbor can be entered via Lower New York Bay, Long Island Sound or Raritan Bay. The Lower New York Bay entrance, served by Ambrose Channel and the alternate Bayside-Main Ship Channels, is the most common route for ocean vessels. New York Harbor is the largest single port in the United States with an annual trade of 185 million tons in 1977, and having the country's largest concentration of container facilities.

The Ambrose Channel and main ship channel is 45 feet deep and 2000 feet wide and serves Manhattan, Brooklyn and the New Jersey shore of the Hudson River as well as the major container facilities at Port Elizabeth and Port Newark, New Jersey; and the 35 feet deep by 600 feet wide New York and New Jersey Channels, running between Staten Island and New Jersey, serve the energy facilities of the Aurthur Kill.

Most of the dredging is in the New York/New Jersey area, which is heavily urban and lacking in suitable disposal sites. Traditionally, ocean dumping, pits, and harbor/upland containment were used.

Currently, the main approach channels are largely maintained by Corps trailing suction hopper dredges with dredged material dumped in the designated area in the

Bight. The total volumes of federal and non-federal dredging in New York Harbor varied between 8 million and 19.5 million cubic yards per year between 1970 and 1976, of which 76% on an average was federal work.

Annual shoaling in the channels and pier slips averages about 1,500,000 and 2,750,000 cubic yards, respectively. Heaviest shoaling occurs in the Weehawken-Edgewater channel and adjacent slips on the New Jersey side. Incomplete measurements indicate that a potential shoaling of 1,700,000 cubic yards annually may be attributed to sediments moving in suspension from headwater areas. Recirculation and redisposition of sediment by tidal flows are also considered to be major sources of shoaling. Sanitary sewage, storm drainage, and industrial and other wastes dumped into the Hudson River system constitute other significant sources of shoal material.

Extensive shoaling occurs in the federal navigation channels and in the privately owned pier slips along the lower section of the Hudson River, which serves the metropolitan New York City area.

Extensive shoal areas below 18 feet are common in the Lower Bay, and maximum depths at mean low water (mlw) outside of the channels seldom exceed 30 feet. In the Narrows, depths are much greater, ranging from 30 to 100 feet at mlw. In the Upper Bay, lateral shoals are present; however, at mlw the unmodified Hudson River channel is between 30 and 50 feet deep.

Although the controlling dimensions of the Ambrose Channel were 43' x 2000' in 1978, the National Dredging Study reports that they received no complaints with respect to federal channel maintenance efforts. However, concern has since been expressed that environmental constraints could prevent adequate maintenance. New York Harbor is subjected to the discharge of sewage, industrial effluents and urban runoff as well as industrial and maritime accidents which have contributed a wide range of contaminants to the waterway. As a result, the harbor bottom sediments contain concentrations of a variety of potentially toxic and hazardous substances. Dredged material, along with sewage sludge and chemical and industrial wastes have been dumped into the New York Bight, and together with pollutants from other sources have caused severe degradation of the marine environment resulting in pressure to stop ocean dumping. The study "Disposal of

Dredged Material Within the New York District"[24] was recently completed. It identified a number of feasible alternative options for dredged material disposal. Because it recommends that each option be evaluated on a project by project basis, it is not possible to indicate the impacts of these options on dredging costs.

Petroleum tankers pose the most serious present and future problem to the Port of New York, particularly on the New York and New Jersey Channels, as well as on the upper reaches of the East River. Oil product demand in the New York Metropolitan Region is anticipated to grow in the foreseeable future, so that a growth in product tanker traffic is likely.

The largest of the product carriers envisioned for operation in and out of East Coast ports in the next 30 years appears to be about 80,000 deadweight tons, with fully loaded drafts close to 45 feet. The Port of New York should be expected to be able to accommodate such vessels. To do so at any stage of tide, and without the need for cargo lightening at anchor, however, the Port's major ocean tanker channels would have to be about 50 feet deep at mlw.

Currently, large tankers ride Ambrose Channel on the high tide giving them a 50 feet deep passage and then lighter at a deep water anchorage in Upper New York Bay before proceeding down the 35 feet channel to their berth. It is estimated that feet feet of shoaling in Ambrose Channel would add $25 million a year to tanker operating costs by requiring the use of smaller vessels or preventing larger vessels from carrying their full load.

Another problem relates to the fact that the Port's prime containership waterway, the Kill van Kull and Newark Bay Channel that serve containership facilities in Newark, Elizabeth and Howland Hook on Staten Island, at their present depth of 35 feet at mlw will be unable to accommodate containerships or break-bulk general cargo vessels whose drafts have been predicted to reach 35 feet. Certain containerships on this waterway are already drawing close to 34 feet, and the SL-7 class operated by Sea-Land Service draws a constant draft of 33 feet. Combined with the petroleum product tanker traffic that uses this waterway, a deepening of this channel system to about 40 feet may be required. Containership economics do not permit vessel lightening at anchor or tidal delays as is the case with bulk cargo vessels. Thus, this channel depth problem may move toward critical proportions. Some widenings and easing of bends along this waterway may also be required because of the width and length of future containerships and tankers on this route.

According to the American Association of Port Authorities (AAPA), most of the Port's larger vessels by class and type are likely to be of the following general dimensions by the year 2000:

Passenger Ships: 625 to 800 feet long, about 90 feet wide and drawing between 27 and 29 feet of water, with certain older vessels still in operation during the next two decades to be somewhat larger.

Containerships: Ultimately, up to 950 to 1000 feet long, 105 to 115 feet wide, and drawing between 33 and 35 feet of water. It does not appear that LASH and SEABEE barge carrying ships will be a major factor in the total ocean traffic of the port.

General Cargo Break-bulk Vessels: Up to 700 feet in length, 90 feet or somewhat less in width and drawing 30 to 35 feet or less. Many such vessels will continue to be smaller.

Petroleum Tankers: Tankers, carrying both crude oil and refined products, from 25,000 to 45,000 deadweight tons, with lengths from 600 to 700 feet, widths from 85 to 100 feet, and drafts from 33 to 40 feet With the aid of cargo lightening operations and high tides, vessels up to 80,000 deadweight tons, and about 850 feet long and 120 feet wide are able to enter the existing harbor.

Dry Bulk Cargo Vessels: Up to 50,000 deadweight tons, 715 feet long, 125 feet wide, and drawing about 38 to 40 feet of water. Most will be much smaller.

Ocean Barges: No larger than the dry bulk cargo vessels described above.

With respect to categories of ship traffic other than tankers, the harbor seems to be adequate for foreseeable future needs. The Ambrose-Anchorage-Hudson River Channels are adequate for passenger ships, most of the containerships and break-bulk general cargo vessels. The Buttermilk, Bay Ridge, Red Hook and Lower East River Channels are adequate for dry bulk and breakbulk cargo vessels and containerships. New York Harbor Anchorages in Lower and Upper New York Bay should be reasonably adequate in sizes and numbers, though those located off the Stapleton-Rosebank section of Statan Island may require special attention and regulation to prevent large tankers at anchor from obstructing safe navigation on the adjacent Anchorage Channel. These waterway facilities should require no major improvements in the next 30 years for the traffic demand described above.

3. Delaware River Ports - Reporting Region 14. The ports of the Delaware River include facilities in the states of Delaware, New Jersey and Pennsylvania stretching along some 80 miles of its banks. The total tonnage carried by the river channel in 1968 was reported as 115 million tons. The largest port is Philadelphia, which in 1977 handled 50 million tons.

General cargo facilities are concentrated in three major locations - the waterfront of Philadelphia itself, Camden, New Jersey and Wilmington, Delaware. Associated with these general cargo ports are a whole complex of oil refineries, major steel mill and many other industries along the river which depend upon the import of raw materials in bulk for their operations. Some bulk exports, primarily coal and grain, move through the port at present.

There exists along both banks of the Delaware a series of major oil refineries, probably one of the largest concentrations of such facilities in the world. At least seven can be termed major refineries and there are a number of smaller installations which handle oil and oil products in varying amounts.

The ports are strung along a single channel with an authorized depth of 40 feet as far as a point 23 miles upstream of Philadelphia and 35 feet thereafter to Trenton. The 40 feet channel width is 800 feet to Philadelphia, 400 feet above Philadelphia. The 35 feet channel is 300 feet wide. The ship channel has many bends and in some cases, especially in the upper river, it is difficult for a large ship to negotiate.

The river below Trenton is influenced by semi-diurnal tides. The effect of upland discharge on tide state is most pronounced at Trenton, decreasing progressively downstream until, at Philadelphia and beyond, any significant influence disappears.

The 40 feet channel in the Delaware is an artificial channel maintained by dredging by the Corps of Engineers. Most of the dredging in the Philadelphia district is premaintenance dredging planned in advance and using the Corps' own dredges. The District has upland disposal sites available for 15-20 years, and a regional study is underway for long-term solutions.

Anchorages in the Delaware Bay are dredged on request, but this dredging is expected to become regular and planned.

Shoaling is not uniform in the authorized navigation channel, being heavy in some reaches while other reaches are subject to scour. The reach of channel downstream from the Schuylkill River to Wilmington, Delaware, experiences a high shoaling rate averaging 5,160,000 cubic yards annually. Within this 21 mile stretch, the highest average annual rate of 3,300,000 cubic yards annually occurs over six and one-half miles in the vicinity of the Pennsylvania-Delaware state boundary. These rates indicate 64% of the annual shoaling occurs in 31% of the total distance.

The National Dredging Study reports the main channel "never really" achieves the theoretical 40 feet projected depth. Mohr (1974) indicates that for many years the material dredged was dumped outside the channel or in rehandling basins to be rehandled and pumped ashore by pipeline dredges.[25]

The continuation of dredging and disposal methods in waterways containing a large percentage of fine bottom material resulted in a reduction in dredging efficiency accompanied by increasing costs because the material eventually became so fine and diluted that in some instances the bottom could not easily be defined. There existed a more or less gradual transition from muddy water to thick mud over a vertical distance of several feet.

Dredged material is now largely disposed of in confined areas. Since the dredging method has been changed to the use of sump rehandlers and diked disposal areas, total shoaling in the navigation channel has been reduced by about half, and it is now possible to maintain the full project depth. Furthermore, the large volume of fluff which was a result of recycling the fine material has been almost completely eliminated.

The Corps has adequate sites available to handle maintenance dredging downstream of Philadelphia for the next 15-20 years. However, there are problems in locating sites upstream of Philadelphia.

Over the years, it has been found that the controlling depth is often less than the 40 feet project authorization, although by using the tides, many 40 feet draft vessels go to Philadelphia and above. Almost constant maintenance is required by the Corps of Engineers and it has frequently been difficult to obtain sufficient funds to maintain the project depth. The immediate problem is the increasing difficulty of obtaining economically located disposal areas upstream of Philadelphia of the type now in use because of the scarcity of land area along both banks of the reach requiring maximum maintenance dredging, due to increasing commercial and industrial development.

An evaluation of the possibility of deepening the Delaware River Channel indicates that with modern technology, the channel can be deepened and conceivably can be maintained at its deeper depth. However, prohibitive costs and a lack of areas necessary for the disposal of dredge spoil from original channel deepening or extra maintenance make this solution impossible. In addition, the Delaware channel throughout most of its length is crossed by the underground acquifers which convey much of the ground water on which the Southern New Jersey area depends for its water supplies. Any deepening at all and particularly a major deepening would raise serious questions as to possible interference with this essential underground flow. Another factor is the salt-water wedge. The Upper Delaware is fortunate to be a fresh water port and many of the industries along both banks depend on that fact. Moreover, the water supply of the City of Philadelphia is drawn from the tidal stream where it is fresh. A major deepening would result in the movement of salt water further up the river with possible serious economic consequences for the whole region.

The 40 feet depth now available in the Delaware channel is completely inadequate for most of the bulk cargo movement of the future. As far as dry bulk (such as iron ore) is concerned, the forecast is that most of the vessels will have draft requirements of 45 to 50 feet and that combined ore-bulk-oil vessels, referred to as OBO vessels, which are becoming increasingly common, will require depths of 60 feet or more. Break bulk and container vessels in the general cargo trade will not require more than 30 to 35 feet of draft and will continue to be accommodated by the present channel.

4. Baltimore - Reporting Region 14. Baltimore is a major Eastern Seaboard port with an annual traffic volume of about 45 million tons, half of which is bulk cargo such as iron ore. Situated on the Patapsco River 12 miles from Chesapeake Bay, it is connected to the ocean both by Chesapeake Bay and the Chesapeake and Delaware (C & D) Canal. The former has a 42 feet deep x 800-1,000 feet wide channel, which is dredged for a total of 39 miles out of 175 miles to Cape Henry at the mouth of the bay. A project to bring this channel to the authorized depth of 50 feet would require dredging 51 miles of channel and is currently under design. The alternative route through the C & D Canal is only about 125 miles long but is limited by the 35 feet deep x 450 feet wide channel through the Canal.

The Corps of Engineers is responsible for the maintenance of about 100 projects in and around Chesapeake Bay. Although the main channel has authorized dimensions of 50 feet x 800 feet, dimensions reported in the NWS Inventory indicate the controlling depth was only 36 feet in some places as of 1978.

Shoaling of silty material occurs in the project channels from Chesapeake Bay into the harbor areas. Although the average rate of shoaling for sections of the project channel is not known, the greatest shoaling occurs in the Cutoff-Brewerton Angle and the Craighill-Cutoff Angle.

Annual maintenance dredging for Baltimore Harbor, the upper bay and Patapasco River approach channels, and the Chesapeake and Delaware connecting channel is approximately 500,000 cubic yards.

The major problem reported by the Baltimore District has been the lack of suitable dredged material disposal sites. Waterfront property on the periphery of Baltimore Harbor is highly industrialized, and large land areas for dumping are not available within economical distances of the channels to be dredged. Water areas adjacent to the shoreline are often not usable because of depths of water, and poor foundation conditions make the cost of necessary retaining dikes prohibitive. The State of Maryland is obligated to provide disposal sites under cost sharing requirements and is preparing a 20 year plan for this. Currently, they are making sites available for priority work.

The Port of Baltimore asserts its dredge disposal costs have increased 400% because of delays in obtaining federal and state permits. The port received congressional authorization to deepen its current shipping channel from 42 feet to 50 feet The port proposed to provide a dike land-disposal site for dredged materials on two nearby islands. However, an environmental group contested the project in federal court. In October 1978, the court held that the Corps had exceeded its authority in granting the permit and declared it invalid on the grounds that the project would adversely affect a fish habitat. In the meantime, the Port reports that reduced channel dimensions adversely impact port operations and the local economy. The estimated impact on operations is a loss of 2,300,000 tons of cargo with a value of $200 million and a 4.2% reduction of commerce in the area economy according to the AAPA report.

The following channels will be capable of accommodating tankers in the 80,000 to 150,000-deadweight ton category (providing their drafts are not greater than 50 feet), dry bulk cargo vessels up to 100,000 deadweight tons and maximum size containerships:

(a) Cape Henry Channel.

(b) York Spit Channel.

(c) Rappahannock Shoal Channel.

(d) Craighill Channel.

(e) Brewerton Channel.

(f) Fort McHenry Channel.

(g) Curtis Bay Channel.

(h) East Channel (control depth 49 feet)

Containerships having maximum dimensions of 850 feet in length, 120 feet in width and 35 feet in draft will be able to transit the C & D Canal, including the Brewerton Channel Eastern Extension and the connecting channels in the Chesapeake Bay between Back Creek and Brewerton Extension. However, none of the Baltimore channels are capable of accommodating 150,000-deadweight ton tankers whose drafts are greater than 50 feet. Such vessels could be accommodated if the following channels were dredged to a controlling depth of 55 feet:

(a) Rappahannock Shoal Channel.

(b) Cape Henry Channel.

(c) York Spit Channel.

(d) Craighill Channel.

(e) Brewerton Channel.

(f) Curtis Bay Channel.

(g) Fort McHenry Channel (up to the existing harbor tunnel crossing).

There is no physical constraint to deepening the above channels since the maximum ultimate depth which can be dredged over the Cape Henry tunnel and the proposed second Baltimore Harbor tunnel is 60 feet below mean low water. However, the maximum channel depth which could be realized over the existing Harbor Tunnel is 50 feet below mean low water. Therefore, such ships could not proceed beyond the Fort McHenry Anchorage.

It is assumed that it will take an additional 10 years after completion of the 50 feet project depth to go to 55 feet. The 55 feet project should be completed by the year 2000.

5. <u>The Hampton Roads Ports - Reporting Region 14</u>. The Port of Hampton Roads, including Norfolk and Newport News, is located about 30 miles west of the Chesapeake Bay Entrance. The Thimble Shoal Channel, which is the southernmost of two main entrance channels to the Bay is the principal means of entrance and departure for deep-draft ships calling at Hampton Roads. The current federal project in Thimble Shoal provides a channel 1,000 feet wide and 45 feet deep, with auxiliary channels 450 feet wide and 32 feet deep adjoining each side of the main channel. The main Hampton Roads Channel is 45 feet deep with widths of 1,500 feet and 800 feet from the Hampton Roads Bridge Tunnel to Lamberts Point, and 40 feet deep

with widths varying from 750 feet to 375 feet at the Norfolk and Western Railway Bridge.

The Hampton Roads Ports, which are the prime coal exporting ports of the United States, handled about 53 million tons of cargo in 1977.

The Norfolk District dredges approximately 3.8 million cubic yards of material annually employing seagoing hopper dredges, pipeline dredges and bucket and scow. The Port of Hampton Roads currently has a federally constructed and operated dredged materials disposal area of 2,500 acres on the flats in Hampton Roads adjacent to and north of Craney Island. The Craney Island disposal area is enclosed by riprap levees which hold material dredged by federal, state, municipal, and private intrests in the harbor area. The disposal area is designed to hold 100 million cubic yards of material and it is expected to be filled by 1981 or 1982. The availability of the Craney Island Spoils Disposal area has effectively lowered the cost of new channel construction and maintenance in Hampton Roads. An Army Corps of Engineers study project was authorized and funded by Congress to locate a replacement for, or an extension to, the present disposal area when it reaches capacity.

The Norfolk District has studied upland and estuarine disposal sites for its expected 270-280 million cubic yards of dredge spoil over the next fifty years and located a new 6,000 acre upland site which would involve transporting dredged material 10 miles. The site, which is currently wooded, would be covered to a depth of 27 feet.

However, the most recent disposal alternative entails raising the height of the Craney Island Spoil Disposal area as the most cost-effective disposal facility presently available.

Normal channel shoaling requires perpetual dredging operations and continued evaluation of disposal sites. Minor channel deficiencies have been noted in the NWS Inventory such that controlling depths may at times be slightly less than authorized. Silt screens have added some $50,000 to the cost of dredging at each site.

As indicated above in the physical descriptions of Hampton Roads Harbor channels, the project depth of channels is now 45 feet. With channels of this physical dimension, the large, dry bulk cargo carriers have been somewhat restricted in calling at the coal handling facilities of the Chesapeake and Ohio Railway in Newport News and the Norfolk and Western in Norfolk. However, vessels loaded to a mean draft of 45.5 feet have been able to successfully negotiate the channels utilizing the high tide. There are indications that vessels with capacities as great as 250,000 DWT are being forecasted for future Hampton Roads' coal traffic. Vessels with capacities of that magnitude would require a water depth of 55 feet in the channels. At that depth, oil tankers ranging up to 150,000 deadweight tons, the largest size expected, could be handled with no additional dredging.

### (c) Gulf Coast - Reporting Regions 4, 10, 11

Without exception, the major problem confronting all Gulf Ports is the need for enlarging existing deep water channels to accommodate fully loaded oil bulk ore (OBO) carriers and tankers. Other type vessels, including container ships, passenger ships, and conventional dry cargo vessels can operate fully loaded in a forty foot channel. LASH and SEABEE vessels require a slightly deeper channel. With one exception, all Gulf ports participating in this study have authorization for a forty foot project.

Future channel requirements vary from different Gulf ports depending on the type and size of vessels that each expects to use in the respective ports. It appears impractical, because of the vast geographical distances between participating ports (1,462 miles between Tampa and Corpus Christi measured along the coast line), to consider the Gulf ports grouped into a regional port complex such as might be feasible in other sections of the United States.

Those Gulf ports considered to be of primary importance for the purpose of this evaluation include Mobile, New Orleans/Baton Rouge, and Houston/Galveston.

1. Mobile Bay - Reporting Region 11. Mobile Bay, located in the southwestern part of Alabama on the Gulf of Mexico, is a roughly pear-shaped estuary 30 miles

long and varying in width from nine miles at its head to about 20 miles near its mouth, although the entrance to the Bay from the Gulf is only three miles wide.

The Port of Mobile, located at the head of Mobile Bay at the confluence of Mobile River, has an access via the Mobile Bay Ship Channel whose depth is 40' x 400' and 42' x 600' across the Entrance Bar.

The Alabama State Docks, an agency of the State of Alabama, is the port authority at Mobile and provides extensive and varied commodity handling facilities at dockside. In addition, there are several private operations providing general cargo and tank facilities within the river harbor. Upon completion of the Tennessee-Tombigbee Waterway (1986 estimated), Mobile and the Gulf of Mexico will have been linked to mid-America via a waterway system greatly enhancing the development potential of the port.

The Mobile District Office, Corps of Engineers, is responsible for the maintenance of 41.7 miles of bay and river channels as well as turning basins opposite the Alabama State Docks and Magazine Point and an anchorage area opposite the former site of the United States Quarantine Station at McDuffie (Sand Island).

While dredging in the past has been performed by the Corps' cutterhead dredge, it is reported that maintenance dredging of the approach channel was undertaken in 1977-1978 by a private contractor with a 24" cutterhead dredge.

The greatest rate of shoaling is experienced in the river channel, but dredging is required along the entire length of the project. Spoil from the river channel dredging is deposited on Blakely Island and dredging from the bay channel is spoiled along both sides of the channel.

Although the American Association of Port Authorities reports no adverse impact on port operations or the local economy due to reduced channel dimensions (implying that channels are maintained satisfactorily), some concern exists with respect to the rapid rate of shoaling in the channel and harbor areas in Mobile River and in the upper end of Mobile Bay as well as the disposal of spoil material removed from these areas. Due to the distance to the Gulf from the Mobile River and upper bay area, the cost of using a hopper dredge for excavation in those areas is prohibitive; therefore, use of a pipeline dredge is required. Land areas available for disposing of spoil removed from the river channel are rapidly being depleted. Throughout the length of bay channels, spoil from dredging operations is placed in parallel dumps on both sides about 2000 feet from the channel.

The Port of Mobile is specially geared to the handling of bulk cargoes, as evidenced by the massive volume of ores, coal and other dry cargoes now moving through the existing plant of the Alabama State Docks.

At its present depth of 40 feet, the Mobile Bay Channel presents a hindrance to the larger bulk carriers, dictating the need for a channel with a deeper draft than now exists. The greatest constraint to deepening the existing channel is the fact that a major section of the harbor, including the State Docks, is upstream of two tunnels, the oldest of which has a clearance of 47 feet. This effectively limits future deepening.

<u>2. New Orleans/Baton Rouge - Reporting Region 4</u>. The ports of Baton Rouge and New Orleans, located at the mouth of the Mississippi River system, are among the most important United States ports due to their pivotal position with respect to the inland waterway system and trans-shipment of commerce originating in the heartland of the country.

The port of New Orleans is located on both banks of the Mississippi River in the southeastern part of the State of Louisiana. The lower limit of the port is approximately 81 miles above Head of Passes which, in turn, is 20 miles from the Gulf via the Southwest Pass and 13 miles distant by way of the South Pass.

There are about 295 piers, wharves, and decks in the Port of New Orleans, including facilities to handle petroleum and other bulk liquid products, dry storage warehouses, cotton handling equipment, grain elevators, and other dry bulk facilities.

The Port of Baton Rouge is located on both banks of the Mississippi River and extends for about 240 miles from the southern terminus of the 12 feet channel and at the head of the deep draft channel of the Mississippi. There are about 52 piers, wharves, and docks in the Port of Baton Rouge area including dry storage warehouses, grain elevators, general cargo facilities, and tanks and equipment to store, receive or ship petroleum products.

Deep draft access to the ports is provided by the Mississippi River, through the South and Southwest Passes, and via the Mississippi River-Gulf Outlet (MRGO). The latter channel (MRGO) has a project depth of 36 feet, a bottom width of 500 feet and is connected to the Mississippi River by the Inner Harbor Navigation Canal (IHNC) within the port limits of New Orleans. This connection is 30 feet deep by 300 feet wide and includes a 75' x 640' lock. Access to the Gulf through the South Pass is via a 30' x 450' 13.1 mile long channel with a 30' x 600' bar channel (although a recent decision has been made to maintain the South Pass channel to a depth of only 17 feet). Southwest Pass has a 40' x 800' 20.1 mile long channel and a 40' x 600' bar channel. From the Head of Passes to the Port of New Orleans, there is a 40' x 1000' channel 86.7 miles long. Within the port there is a 40' x 500' channel within an authorized 35 feet deep by 1500 feet channel. From New Orleans to the upper limits of Baton Rouge, 129.6 miles, the channel has a project depth of 40 feet by a width of 500 feet.

Southwest Pass, the principal navigation channel between the Gulf of Mexico and the Mississippi River ports, is an example of a highly stratified estuary. There is a definite relation between amount of discharge and locus of shoaling in Southwest Pass. During times of high fresh water discharge, shoaling occurs in the jetty and bar channels; as discharge decrease, shoaling occurs at points farther upstream. This relation between shoaling and fresh water discharge exists because rapid deposition usually occurs at or near the tip of the salt water wedge, the location of which is controlled by the fresh water discharge.

Although other factors such as wind, waves and littoral currents influence the location and extent of shoal formation, these are less important and within the confines of the channel become virtually insignificant causes of sedimentation. Dredging is carried out on these channels using both Corps and private hopper, dustpan and cutterhead dredges. The proportion of dredging by each type is hopper, 47%; cutterhead, 42%, and dustpan, 11%. Dustpan dredges are not used in Southwest Pass.

Training works constructed in the Southwest Pass include low sills placed across non-navigable outlets to restrict low flows to the main channels. In addition to these jetties, dikes and inner bulkheads were constructed in an effort to reduce the amount of shoaling and, consequently, maintenance dredging required in this channel. However, heavy shoaling continued to be a serious maintenance problem prompting the construction of a channel model at the Waterways Experiment Station.

The model was tested using various configurations of both sides and bottom of the bar channel and various alignments of the jetties. The plan found most effective was construction of a curved realigned jetty channel and a new bar channel parallel to the existing bar channel. This configuration minimized the amount of fresh water discharge and reduced shoaling in the navigable part of the channel by 79%. However, due to the estimated high cost of removing existing structures in the project, no work as yet has been undertaken on realignment of the jetty channel or construction of a new bar channel.

There are various reports that channel authorized depths are not being maintained. The National Dredging Study reports that controlling depths at the Southwest Pass were less than 40 feet in 1970, 67% of the time; in 1971, 38%; in 1972, 0%; and in 1973, 95% of the time. The 1973 figure was high due to the floods that year. The AAPA reports that the Port of New Orleans, based on data provided by the New Orleans Steamship Association, estimated that in 1979 reduced channel dimensions resulted in a loss of 4,765, 737 tons of cargo with a value of $780,958,221 and lost benefits to the port and local economy of $172,006,609. Such losses have also occurred in prior years and are expected to continue.

The Associated Branch Pilots of New Orleans and Baton Rouge also report problems related to inadequate channel dimension,and seven groundings in 1977 and nine in 1978 were a direct result.

Shoaling, especially at times of high river stage, continues to pose a serious problem to the maintenance of the navigation channel in Southwest Pass.

Both of the ports`deep draft principal access routes (MRGO and SW Pass) will be inadequate for liquid and dry bulk carriers within the next decade. Significant vessels anticipated in the AAPA merchant ship size study for the year 2000 are listed on Table IV-19 together with comments as to planned services.

As of 1978, the MRGO carried only 2.7% of the traffic in the New Orleans area. However, there has been nearly a fivefold increase in volume since 1973 and more than doubling of its proportion of commerce since that time. The Port of New Orleans Master Plan for 1990 calls for moving elements of the Port away from the city to the Gulf Seaway. This move is expected to be gradual and will in effect return much of the river front for development for residential, commercial and recreational purposes. It will, of course, also increase the relative importance of MRGO.

At its 36 feet project depth, 500 feet wide, the MRGO will soon be limited by size developments even with standard cargo, passenger, combination break-bulk container and container vessels. Barge carriers of the LASH and SEABEE class are already limited to the Mississippi River and its expensively maintained passes. Dry bulk carriers are already limited to vessels capable of handling 20,000 tons by the present depth of the MRGO channel. Classes D through H are not now attainable within authorized project depths on either the Mississippi River or the MRGO.

The dimensions of the existing channel also further limit all vessels as to beam and speed as well as to loaded draft. The channel width will permit vessels only up to 76 feet in beam to pass safely using accepted criteria for bank and passing clearances. The existing channel also limits the draft of the vessel to approximately 32.5 feet with accepted allowances for trim, squat and bottom clearance. A typical containership having a 90 feet beam and 30 feet draft would be limited to a safe operating speed of approximately 7.5 knots by the existing channel.

3. <u>Houston/Galveston - Reporting Region 10</u>. The ports of Houston and Galveston are located, respectively, at the northern and southern ends of Galveston Bay on the Gulf Coast of Texas in the southeastern portion of the state.

## Table IV-19

## New Orleans Centerport
## Accommodation Plans for Significant Vessels

| | Class of Ships | Comments As To Planned Service |
|---|---|---|
| A. | STD. CARGO, PASSENGER & COMBINATION BREAK-BULK CONTAINER,<br>(700'x90' x 30-35') | Existing and currently facilities would be capable of accepting vessels of this class in sizes anticipated for 2000 A.D. This anticipates completion of currently authorized project for protective works on MR-GO and new ship lock. |
| B. | CONTAINER,<br>(950 x 110' x 30-35')<br>to<br>1000' x 115' x 35') | Location of container terminal in new CENTROPORT area instead of along Mississippi River anticipates new ship lock for access, to river as minimum. Effective operations would require approval of requested project for widening and deepening of MR-GO to handle drafts of fully loaded container-ships and economical operating speeds. |
| C. | BARGE-CARRIER,<br>(LASH, SEABEE, etc.)<br>864' x 107' x 37'<br>and<br>875' x 106' x 36' | Without approval of widening and deepening requested for MR-GO this class of vessel will be unable to operate "full and down" through either the MR-GO or Mississippi River SW Pass access to New Orleans. Imminence of frequent service by this class has required exception to CENTROPORT move to MR-GO from Mississippi River in case of initial phase of barge-carrier terminal construction. |

| CLASS OF SHIPS | COMMENTS AS TO PLANNED SERVICE |
|---|---|
| D. DRY BULK, (or OIL-BULK ORE) to 75,000 DWT.<br>715' x 95' x 35'<br>to<br>825' x 125' x 45' | Location of PUBLIC BULK TERMINAL on MR-GO anticipated earlier new ship lock construction than is current prospect. This plus delays in funding for MR-GO protective works to maintain project depth has hampered growth of utilization rate of this existing facility. Ship size expansion trends in this class already require widening and deepening of MR-GO as requested. |
| E. DRY BULK, (100,000 DWT.<br>820' x 125' x 45'<br>to<br>875' x 130' x 50') | Expansion forecasted for PUBLIC BULK TERMINAL by 2000 A.D. would be dependent on an even greater deepening and widening of MR-GO than the 50' x 750' project currently requested. Because MR-GO is so new and not yet occupied by industry, and because channel lies throughout in easily dredged earth, and because existing rights-of-way and already approved protective works would serve for deeper and wider channels as well, economic, physical, environmental and time constraints are minimized. There is probably no port area in the United States less constrained from expansion of channel capacity. Increasing the currently requested project for 50 feet depth beyond the 750 feet width may be a more economical way to provide for future depth and width increases. |

| | CLASS OF SHIPS | COMMENTS AS TO PLANNED SERVICE |
|---|---|---|
| F. | TANKERS COASTWISE, (72,000 to 80,000 DWT. 800' x 113' x 43 1/2') | Widening and deepening of MR-GO to 50' x 750' currently requested together with currently authorized projects will provide New Orleans and up-river petrochemical industries with channel capacity to accommodate 50-60% of all tankers in service for the year 2000. |
| G. | TANKERS, South America to Gulf & Atlanta United States Ports (80,000-150,000 DWT 800 x 120'x 45' to 1000' x 150' x 55' | Comments above relative to dry bulk carrier 100,000 DWT. and as to minimization to constraints in MR-GO to a greater depening and widening than the 50' x 750' project currently requested apply equally in this case. |
| H. | TANKERS, UNLIMITED (150,000-200,000 DWT. and larger 900' x 130' x 55' to 1100' x 170'x65' | The oil and natural gas producing areas served by New Orleans and the up-river deep water ports are unlikely to attract service by the 150,000 to 200,000 DWT. and larger tankers. These "jumbos" are expected to be developed primarily for haul of crude from overseas areas to fuel-scarce areas. In any case, offshore terminals would seem to be the most nearly economically feasible method of providing docking should the need develop. |

Galveston's principal waterfront facilities are along the northerly side of the eastern portion of Galveston Island and on the south side of Pelican Island. These islands are separated by the Galveston Channel. Deep-draft vessels enter the port through Galveston Harbor, which extends some 15 miles from deep water in the Gulf of Mexico through the pass formed by the jetties extending from Galveston Island and Bolivar Peninsula to the deepwater area known as Bolivar Roads. While Galveston Bay is only seven to nine feet deep, the Entrance and Outer Bar Channels are 42 feet deep and 800 feet wide. The Inner Bar and Bolivar Roads Channels are 40 feet deep and 800 feet wide. The Galveston Channel is maintained at a depth of 40 feet and width of 1,200 feet.

The project also provides for the maintenance of dual rubblemound jetties at the harbor entrance extending 35,900 feet and 25,907 feet respectively from Galveston Island (on the south) and Bolivar Peninsula (on the north) into the Gulf of Mexico.

In addition, the construction and maintenance of 13 groins along the Gulf Shore of Galveston and the maintenance of a 10 mile long concrete seawall are part of the existing federal project.

There are 49 piers, wharves, and docks in the vicinity of the port of Galveston.

The port of Houston is located about 50 miles north of the Gulf of Mexico on the Houston Ship Channel. The channel, which extends about 50 miles Inland from the Gulf of Mexico, is 40 feet deep and 400 feet wide for about three miles across Galveston Bay from Bolivar Roads into Buffalo Bayou. The project dimensions of the channel within Buffalo Bayou decrease to 40' x 300' for a distance of about 10 miles and 36' x 300' for another 11 miles to a turning basin 36 feet deep with a width varying from 400 to 1000 feet.

Houston is one of the main distribution points for the southwestern part of the United States Some of the principal commodities handled at the port are petroleum and petroleum products, sand and shell, fertilizer and fertilizer materials, steel mill products, grain, sulfur, clay and earths, and chemicals. There are 218 piers, wharves and docks in the vicinity of the port of Houston.

The transport of sediment in Galveston Bay is an extremely complicated phenomenon due to the numerous sources and the many factors that influence its movement.

Cutterheads are used to dredge the harbors, channels, end ship canal, with disposal of dredged material to confined sites and open water, whereas hopper dredges with ocean disposal are used in the bar channel.

The annual maintenance dredging in the reach from deep water in the Gulf of Mexico to Bolivar Roads (usually referred to as the entrance channel), in Galveston Channel and on the Houston Ship Channel, can be seen on Table IV-20.

Bay sediment transport and its effects on navigation channels have been a very troublesome problem of long standing. There are considered to be three primary sources of sediment entering Galveston Bay: river sediment, shoreline erosion, and littoral drifeet Of equal importance is the erosion and redistribution of channel dredging spoils that are deposited in the bay waters. Although serious shoaling problems exist in the Galveston Harbor Channel, the major problem is shoaling of the Houston Ship Channel.

## Table IV-20

### Dredging,Galveston/Houston Channels (Cubic Yards)

| Location | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1978 |
|---|---|---|---|---|---|---|---|
| Entrance Chnl. | 2,077,408 | 1,607,208 | 1,013,900 | * | * | * | * |
| Galveston Chnl. | 4,598,918 | 887,842 | 1,777,700 | 3,535,000 | 161,850 | 1,003,339 | 1,130,462 |
| Houston Ship Chnl. | * | * | * | 5,013,575 | 7,586,793 | 2,188,577 | 2,942,920 |

* Not available

The National Dredging Study reported that as of 1973, 80% of the dredged material from Houston Ship Canal was disposed of in 5,000 acres of Houston Port Authority owned marsh areas and upland areas near the project, in an environmentally acceptable way, but that these sites were then nearly full. Further dredging projects, must use disposal areas about three miles from the project, apparently doubling dredging costs. The Galveston district in 1979 reported that finding suitable disposal sites is now their major constraint to maintenance dredging.

It is understood that recreational activity imposes serious stricted width. Moreover, in 1979, the Port of Houston reported that its estimated reduced channel depths resulted in an annual loss of 197,000 tons of cargo with a value of $25,250,000 and attendant impacts on the local economy (1.75%) and employment (.01%). The Port of Galveston reported that reduced channel dimensions had not adversely impacted port operation or the local economy but that USCE commitments for levees and channel dredging will probably cause serious problems in the spring and summer of 1980.

### (d) Pacific Coast Ports - Reporting Regions 17, 18, 19 and 20

The geography of the Pacific Coast and the underwater topography of the continental shelf separates the port areas of the Pacific slope of the United States and Canada into two basic groups - those capable of developing very deep draft capabilities and those that cannot, regardless of the consequences. All significant ports of the United States Pacific slopes either presently have depths approximating 40 feet, or expect very little difficulty in improving their harbors to that depth. Several can easily increase the minimum depths to 45 feet.

General cargo ships, container ships and LASH type ships, most dry bulk carriers and a significant percentage of product tankers will be able to call freely up and down the coast as the flow of commerce demands. However, based on present engineering data, only four port areas can reasonably expect to be able to develop for very deep draft vessels in the immediate future. There are port areas that either already possess very deep water or could be deepened to accommodate the very deep draft vessels. From north to south they are the Valdez area in Alaska, most of the Puget Sound area in the State of Washington, the San Francisco Bay area, except for the southern arm of the bay and the estuary ports of Stockton and Sacramento and the San Pedro Bay encompassing the Ports of Long Beach and Los Angeles of Southern California. It is in these four port areas that facilities to meet the requirements of very deep draft vessels are presently planned. The underwater canyon cut into the continental shelf by the Columbia River affords an additional possibility for development of a very deep draft harbor just inside the jaws. The effect the control of river flow, made possible by the Canadian and Snake River dams, will have on the movement of bottom sands needs to be studied before a final evaluation of the economies of such a project can be made. There are no known physical impediments to preclude a major deepening of the San Diego Bay should the demands of commerce require. Should the future indicate even a greater density of very deep draft ports to be necessary, offshore unloading facilities are the only practical solution. The topography of the continental shelf is such that offshore facilities would be feasible. A very strong resistance by those organizations especially interested in the coastal ecology will probably preclude such development until all other possibilities have been taxed well beyond practical limits.

Those Pacific Coastal ports considered to be of primary importance for the purpose of this evaluation include Los Angeles/Long Beach, the San Francisco Bay Area, the Lower Columbia Ports, and Puget Sound.

1. Los Angeles/Long Beach - Reporting Region 19. The ports of Los Angeles and Long Beach together comprise one of the largest and most complex cargo terminals of the entire western coast of North America. The facilities are located on the southern coast of California, occupying a major part of San Pedro Bay. As a center of an international exchange of commerce, the ports of Los Angeles and Long Beach together contain over 400 capital berths capable of providing docking for small vessels, such as fishing boats and intercoastal merchant ships; medium-sized vessels, such as interocean containerships; and large ocean-going vessels, such as oil tankers and

international merchant ships. In 1977, these two ports handled a combined traffic of 64 million tons.

Both harbors were man-made by the construction of shore jetties accompanied by channel excavation. The harbor structures consist of stone breakwater, 11,150 foot long (San Pedro Breakwater), a rubblemound detached breakwater (Middle Breakwater) 18,500 feet long, and a rubblemound detached breakwater (Long Beach Breakwater) 13,350 feet long. The 1000 foot wide Los Angeles entrance channel is located between the San Pedro and Middle Breakwaters while the 800 feet wide Long Beach entrance channel lies between Middle and Long Beach Breakwater.

The authorized depth of the approach channel to both harbors is 45 feet deep. However, dredging activity coupled with subsidence caused by extraction of oil and gas from the underlying Wilmington Field has resulted in a fairway of 60 feet with maximum terminal depths of 55 feet at Long Beach Harbor accommodating 150,000 ton (DWT) vessels. Long Beach thus claims to be the deepest integrated port in the United States. In addition, Los Angeles has a 51 foot fairway to a bulk loading facility.

The rate at which harbors shoal is dependent upon the sediment fed into the harbors. The Los Angeles/Long Beach harbors have virtually no incoming sediment and are in naturally protected areas where littoral drift sediment by-passes the harbors. The Los Angeles River channel was relocated by the Corps of Engineers in 1923, which diverted the river flow to the east of the harbor into a large settling basin. Because of the nature of the drainage area and the fact that the channel itself is concrete lined at those locations where scouring velocities occur, this channel is not a major source of sediment.

Federal funds expended for harbor maintenance are generally minimal and are used for channel reconnaissance or condition surveys rather than active dredging programs.

As previously stated, no appreciable amount of silt is discharged into the developed sections of San Pedro Bay. Shoaling of the channels or basins is not a problem. Therefore, the controlling depths for the various basins and channels are the project depths except for those areas which have been deepened since construction of the existing federal project. However, large amounts of dredged materials have been used in construction of jetties, piers and shoreline landfill. A major constraint on dredging is the State of California regulations on shoreline construction.

Should future dredging be required, a major constraint to those operations might be the existing State of California regulations concerning construction along the shoreline.

The Los Angeles entrance channel (originally 1,000 feet wide and 40 feet deep) was redredged by the Port of Los Angeles to a 500 feet width and depth of 47 to 51 feet to provide for the supertanker berth and bulk-loading facilities. The Long Beach entrance channel has been dredged by the Port of Long Beach to approximately 750 feet wide and 62 feet deep. The remainder of Long Beach harbor varies in depth from 18 feet to 70 feet. The extreme depths (70 feet) are attributable to the subsidence caused by subsurface volume reduction from oil pumping rather than overdredging. The channels in Long Beach harbor have operating depths of 45 to 65 feet.

Based on existing depths and the lack of shoaling problems, both harbors have adequate channel dimensions to accommodate the existing traffic demands.

2. The San Francisco Bay Area. The San Francisco Bay system includes, via inland waterway connections, the important maritime ports of San Francisco, Oakland, Richmond, Stockton, and Sacramento. Currently, the United States Army Corps of Engineers performs maintenance dredging in approximately 20 different areas in the Bay system. The average volume of maintenance dredging performed in the Bay Area is about six million cubic yards, annually.

All projects in the Bay Area are serviced by a common entrance channel called the San Francisco Harbor Main Ship Channel located about five miles west of the Golden Gate Bridge. The Main Ship Channel has an authorized depth of 55 feet and an authorized width of 2000 feet. To maintain these dimensions approximately 1,000,000 cubic yards of material must be removed annually, on average. Prior to deepening to 55 feet, the 2000 foot wide project was maintained at a depth of 50 feet, requiring 650,000 cubic yards of dredging annually.

With the exception of the Main Ship Channel, projects in the Bay Area are authorized to depths of up to 45 feet (although greater depths occur naturally in some areas).

Within the Bay Area, individual project dredging requirements vary greatly depending on local conditions.

Most San Francisco Bay dredging is performed in January and February when the dredges are available from the North Pacific Division (NPD). This corresponds to the time of minimal dredging requirements in NPD and maximum sediment inflow in the Bay Area. Most dredging work is performed by hopper dredges.

An estuary such as San Francisco Bay is a sink or holding area for fluvial sediment in transit to the ocean from soil erosion in the Bay's extensive drainage system. Most new sediment enters the Bay system during the months of maximum runoff (winter). Inflowing sediment, however, is not, for the most part, carried directly to the ocean. A large percentage of the inflowing sediment remains in residence in the Bay for a number of years, being deposited, then resuspended, recirculated, and redeposited elsewhere, with the net effect of being transported (toward the mouth of the estuary) out of the Bay system into the ocean as suspended load and bedload. This complex process occurs many times before the sediment is either semipermanently deposited in the Bay or transported as suspended load into the ocean and deposited on the continental shelf. The mechanisms affecting sediment transport include tidal currents, freshwater inflow, salinity-density currents and wind generated waves.

Sites for disposal of dredged material in San Francisco are along the channel margins or in natural channels. Although dredged sediment, after disposal in the Bay, will be temporarily stored in the shallow areas, wind-wave action in these areas will resuspend and currents will recirculate the sediment. No net accumulation of dredged sediments in any of the disposal sites has been detected since disposal operations at the sites were initiated.

Dredging the shoaled sediment in navigation channels and disposing at one of the disposal sites in the Bay has the effect of redistributing the sediment within the system. Since dredged channels are out of equilibrium, a portion of the disposed dredged material will likely reenter the same or other dredged channels. Studies made a few years ago by the San Francisco District showed that redredging could be greatly reduced by transporting the dredged material to disposal sites closer to the ocean. This has the effect of eliminating one or more steps of the resuspension-recirculation-redeposition cycle in the process of transporting sediments through the estuary to the ocean. However, benefits gained by this procedure are offset to a, thus far, undetermined degree by increased transport costs.

3. The Lower Columbia Ports - Reporting Regions 17, 18. The lower portion of the Columbia River provides access for seagoing vessels to the Ports of Portland and Vancouver, over 100 miles from the mouth, and the Ports of Longview, Kalamo and St. Helens as well as Astoria at the mouth.

The Columbia River Estuary's deep draft navigation project includes a channel over the ocean bar 48 feet deep and one-half mile wide, two converging rubble-mound jetties, and a spur jetty (Jetty A) on the north shore. The north jetty is about 2.5 miles long, the south jetty about 6.6 miles long, and the spur jetty, constructed to reduce shoaling in the entrance channel, is nearly one mile in length.

The project for improvement of the Columbia and Lower Willamette Rivers from Portland to the sea provides for a main channel 40 feet deep and 600 feet wide. In this portion of the estuary, there are 18 pile spur dikes ranging in length from 160 to 4000 feet.

The estuary is two miles wide between the jetties at the entrance, broadens to a maximum width of nine miles upstream of Astoria, and narrows to about one-half mile wide in the upper portion of the tidal reaches. The estuary is classified as partly mixed, there being a definite density difference from surface to bottom but no well-defined salt water wedge.

Jetty A, constructed at the southeastern end of Cape Disappointment, is in a state of general disrepair with the outer 500 feet completely knocked down as a result of severe climatic and environmental conditions. An additional spur jetty (Jetty B) authorized for construction on the north shore has not been built pending completion of economic studies and bed tests to determine its cost-effectiveness.

The overall plan to maintain navigation channel depths in the Lower Columbia River consists of two principal methods: a limited amount of maintenance dredging and construction of control works. Control works are used to maintain or correct an existing alignment and to reduce the cross sectional area of the river such that river velocities are produced which are high enough to reduce shoaling in the channel. A system of pile dikes and dredge spoil embankments has been constructed to assist in reducing shoaling and controlling the river. Dredge spoil is utilized, where possible, for river control and constriction. Past years of experience have shown that sandfills, when stabilized by pile dikes, have been very effective.

The Columbia is not considered to be a heavy silt-bearing stream, and during much of the year it is relatively clear.

The greatest dredging priority goes to the entrance channel. Work, which begins in April or May and continues into September, is heavily dependent on weather conditions. Nearly all shoaling occurs during the spring run-off. Maximum shoaling during the average freshet is six to eight feet. In order to schedule dredging on a year-round basis as well as provide project depths for the entire navigation season, it has been customary to perform advance maintenance dredging plus two feet allowable over depth.

In 1978 8.3 million cubic yards were dredged, of which about half was in the river channels and half at the mouth. All the dredging at the mouth was done by the Corps hopper dredge Biddle while in the river about 48% of the dredging was by Corps hopper dredges, 37% by the Port of Portland 30" cutterhead dredge Oregon, and the rest by private contractors using unspecified types of dredges. Currently, it is found to be cheaper to dispose of dredged material in confined disposal sites rather than haul it to marine dumping sites.

In addition to dredging, there is a significant amount of coastal maintenance work on the breakwaters and jetties as a result of the severe climatic and wave conditions.

After the river level returns from spring flood to normal, nearly 50 miles of river experience shoaling above project depth. The total length of shoaled channel is about eight miles, annually. This presents a critical situation from the standpoint of navigation as the deeper draft ships are forced to delay arrival and sailing times so high tides can be utilized. The two major problems in the entrance to the Columbia River are shoaling of the entrance channel and the optimum degree of rehabilitation of the north and south jetties and Jetty A as related to the achievement of project dimensions. Deep draft navigation is hindered by delays and hazards occasioned by the encroachment of Clatsop Spit on the entrance channel between the jetties and by inadequate depths in this channel and over the bar.

On the Lower Columbia it is common practice to pilot ships through a partially shoaled channel. Accordingly, the Portland District of the Corps of Engineers claims that reduced dimensions have practically no impact on port operations or local economics. Although the National Dredging Study states that the Port of Portland Authority views the Corps of Engineers work as highly satisfactory, in 1979, in answer to the American Association of Port Authorities questionnaire, the Port Authority indicated that, "Reduced useable channel dimensions impacts on port operations and local economy are estimated as follows: Annual loss of 281,440 tons in port business with a value of $39,591,551 and a .8% reduction in the port area economy with a value of $3,303,899 (1975 dollars)."

Communications with the District offices indicate that the Columbia River entrance channel is maintained at a 48 foot depth by one-half mile wide about 95% of the time and the 40 foot channel from the sea to Portland is maintained at project depth nearly 100% of the time.

Any major deepwater oil handling facility would have to be placed offshore, while dry bulk cargo berths could be located at Astoria, there being a mean tide variation of eight feet at the mouth of the Columbia enabling deeper draft vessels to come inside the bar on high tide.

4. Puget Sound - Reporting Region 17. Puget Sound and the Strait of Juan De Fuca, located in the northwest corner of the State of Washington, are a major

center of ocean commerce in the northwestern portion of the United States with a traffic volume of 47 million tons reported for 1978. The Sound offers protected deepwater access to the ports located along its periphery. For example, the National Dredging Study reports that the shallowest water between Tacoma, one of the ports furthest inland, and the ocean is 180 feet, and the narrowest point is 1.4 miles wide. Dredging is therefore confined to providing access to shorefront berthing facilities and in the approach and connecting channels to the inland harbors.

The major ports located on the Sound are Seattle, Tacoma, Lake Washington and Bellingham. The largest ports are Seattle and Tacoma which handled a total volume of 15 and 11 million tons of commerce, respectively, in 1978.

The existing project in Seattle Harbor included the mainenance to two 34' x 750' channels 6,500 and 5,200 feet long, respectively. In Tacoma Harbor, the maximum authorized channel dimensions are 29' x 500' for the City Waterway and 30' x 200'-770' or the 3.1 mile long Hylebos Waterway. The Lake Washington Ship Canal project provides for a maximum channel dimension of 34' x 300' in addition to a double lock and fixed dam at the entrance to Salmon Bay. Authorized channel dimensions for the Bellingham Harbor channel are 30' x 363' from deepwater to 50 feet from the river end of the harbor.

Tides within the estuary have a mean range of 7.6 feet.

The Chief of Engineers Report for Fiscal Year 1978 indicates that condition surveys were conducted on the East and Duwamish Waterways in Seattle, the City and Hylebos Waterways in Tacoma, and the Whatcom Creek Waterway in Bellingham. The only dredging required was 118,000 cubic yards for Duwamish Waterway. Maintenance requirements for the Lake Washington Ship Canal were generally associated with lock upkeep and refurbishment. Funds contributed by the Port of Bellingham were expended for bulkheads, groins, dredging, mooring, mooring and terminal facilities.

Major problems in Seattle Harbor are the degree of contamination of bottom deposits and the finding of suitable disposal sites. There is also a problem of finding disposal sites for materials dredged in Tacoma Harbor.

While the Port of Seattle reported, in 1979, no adverse impact on port operations or the local economy through reduced channel dimensions, the NWS Inventory indicates that the controlling width of the authorized 750 feet wide channel is only 450 feet. However, the National Dredging Study reported that in the past Corps dredging activities have been able to keep up with navigational needs and there had been no impediments to traffic into Seattle.

Shoaling does not appear to be a significant problem and an annual maintenance dredging program is generally not necessary for the various ports within the Sound although periodic condition surveys are performed to ascertain potential shoaling locations and avoid critical loss of depths.

Controlling depth at the harbor entrances for the listed ports is essentially unlimited. Existing and planned facilities in Seattle and Tacoma Harbors have the capability of accommodating standard size cargo and combination break bulk and container vessels. However, Seattle is the only port on the Sound presently operating 100% container berths capable of accommodating vessels up to 50 feet in draft at MLLW. While specified terminals within the Sound have berthing facilities to accept dry bulk vessels to 75,000 tons, special facilities would have to be developed to accommodate unlimited dry bulk vessels. Generally, there is unrestricted access within the shipping lanes for unlimited class tankers and facilities existed in the vicinity of Bellingham to handle oil tankers of any size.

### (e) Great Lakes Ports - Reporting Region 16

Those portions of the Great Lakes within the United States are maintained and regulated by the St. Paul, Chicago, Detroit and Buffalo Districts of the North Central Division. While authorized channel dimensions in the smaller harbors and tributaries vary considerably, the Connecting Channel Project provides for an authorized depth of 27 feet in the major channels to provide a safe draft of 25.5 feet for Great Lakes freighters at low water datum.

To take full advantage of the 27 feet Connecting Channel Project, 31 harbors were improved by dredging. The same allowances between depth and draft used in the connecting channels were used in improving the harbors. Additional depth is provided in entrances and outer harbors as required to mitigate the effect of wave action in exposed areas, the squat of ships underway, and the presence of hard bottom. Depths providing for a safe vessel draft of 25.5 feet at low water datum vary from 27 feet to 30 feet.

The various types of dredging equipment used generally depends on the size and location of the shoaled site. Large deep commercial harbors are generally dredged by hoppers or cutterhead dredges. Smaller ports and channels may require the use of clamshell/dippers. Private contractors may do the dredging or the Corps may employ the use of one of its own hopper or cutterhead dredges depending on the exigencies of a given situation.

While specific procedures may vary, maintenance dredging on the Great Lakes generally follows uniform guidelines. EPA guidelines mandate strict controls on the type and quality of spoil material which may be disposed of in open waters. Consequently, many of the dredging projects in the Great Lakes require confined disposal or nourishment disposal areas which can result in deferment of maintenance dredging until such time as a suitable disposal area is selected. Prior to the removal of shoals by dredging operations, authorized navigation channels are inspected by the COE to determine the location and amount of sediment deposition. An initial inspection is conducted with the use of sounding equipment installed on a small survey boat. Upon completion of the survey, recorded sounding information is used to prepare maps that display the predredging depths in the project area. After the navigation project has been surveyed, the shoal areas are dredged, if necessary, to provide for efficient and safe navigation. Dredging operations involving the tasks of removing, transporting, and disposing of shoal material continue until desired depths have been reached. The duration of such activity is dependent upon the volume and physical composition of dredgings, the type of equipment used, weather and wave conditions, and other factors that may influence operational efficiency. Upon completion of dredging operations, a post-dredging survey, using a survey vessel, is conducted to determine depths in maintenance-completed channels and harbors. Advance maintenance dredging is performed in accordance with criteria determined by the individual Districts. The mean annual dredging volumes and deferred quantities for the Great Lakes are shown on Table IV-21. The average amount of material removed represents the last five years of maintenance.

Table IV-21
Dredging Quantities - Great Lakes

| | Annual Mean Volume | Deferred Volume |
|---|---|---|
| L. Ont. & St. Lawr. Seaway | 4,263 | 2,000 |
| Lake Erie | 42,921 | 350 |
| Lake Huron | 7,164 | 0 |
| Lake Michigan | 13,443 | 5,200 |
| Lake Superior | 2,308 | 392 |
| TOTAL | 70,000 | 7,940 |

As indicated on the above table, more than 11% of the total dredging work has been deferred primarily due to environmental restrictions. However, the reliability of channel controlling dimensions has been generally satisfactory. In the opinion of the District specialists, this may be explained, in part, as a result of favorable hvdrological conditions since the lake low water levels have remained relatively high during the last three to five years. Several channel improvements have been suggested in conjunction with the Great Lakes-St. Lawrence Seaway Navigation Season Extension Survey Study, March 1979. The proposed improvements include:

1. Dredging approximately 3,000,000 cubic yards along a 17 mile reach of the Mid- dle Neebish Channel on the St. Mary River to permit twoway traffic.

2. Dredging approximately 34,500,000 cubic yards from the St. Lawrence Seaway between Ogdensburg, N.Y. and Morrisburg, Ontario to increase the channel cross section and thus reduce the average navigational channel velocity.

3. Dredging approximately 20,000,000 cubic yards between Cornwall and St. Regis Island to increase the channel cross section and reduce flow velocities.

The Corps of Engineers has underway, a study investigating the feasibility of further improvements in the Great Lakes connecting channels and harbors for safe operation of vessels up to the maximum size permitted by the locks at Sault Ste. Marie, Michigan. The results of this study are not yet available for evaluation by the NWS Team. The study also includes an evaluation of additional lockage facilities and increased capacity of the locks at Sault Ste. Marie.

## THE DREDGING FLEET

The objective of this section is to describe the dredging plant available for maintenance of the nation's waterways, its performance and utilization. It is intended to indicate the ability of the plant to carry out the necessary work, taking into account constraints, environmental and others, placed on dredging. Finally, a number of options are addressed for improving the effectiveness of dredging. Dredging technology will be covered more completely in Element I.

### (a) Review of Present Dredging Technology, Capacity and Performance

Dredges can be divided into mechanical and hydraulic types. Mechanical dredges pick up and lift material by means of various types of buckets or shovels whereas hydraulic dredges utilize a centrifugal pump which moves a slurry of water and material from the bottom and transports it through a pipeline to a point of discharge.

Hydraulic dredges handle the great bulk of dredging for navigation purposes in the United States of America. Three types of hydraulic dredges - the hopper dredge, the cutterhead dredge and the dustpan dredge - accounted for 83% of the dredging volume for work done on federal navigation projects during the past three to five years.

By and large, hopper dredges are used in coastal bar entrance channels, on port approaches, and in the Great

Lakes; cutterheads on sheltered harbors and inland waterways; and the dustpan dredge has been designed and adapted for the lower Mississippi and Missouri Rivers, although it could and has been successfully used on other free flowing rivers with sandy bottoms.

The federal and private dredging fleet in the United States of America has in common the great average age and obsolescence of its equipment. The average age of Corps of Engineers' hopper dredges is 32.4 years, of cutterheads - 24 years, and of dustpans - 45.7 years.

1. Corps of Engineers Dredging Fleet. The existing Corps of Engineers' dredging fleet is shown on Table IV-22. The preponderance of dredging by the Corps in the United States is performed in approaches to coastal ports by seagoing trailing suction type hopper dredges. As indicated by the year built, the majority of these dredges is over 30 years old and must be considered to be obsolete not withstanding some major repowering and/or modernization work performed over the years to keep them operating effectively.

Seagoing hopper dredges are self-propelled vessels that resemble ocean tankers and bulk carriers, except for a larger amount of deck machinery and equipment they carry. In lieu of cargo space or tanks, the hopper dredge is provided with hoppers or bins that are used to load and carry material hydraulically dredged from the channel bottom. It is a completely self-contained dredging plant equipped with all necessary dredging equipment (i.e., centrifugal pumps, dragarms or trailing suction assemblages, discharge and distribution systems, etc.). The most significant characteristic of the hopper dredge is that it operates while underway and requires no anchors or other mooring devices. It usually works in channels or harbors in which wave action or heavy traffic makes a stationary dredging plant unusable or undesirable. Also, in some cases, particularly where shortages in nearby disposal areas develop as a result of waterfront industrialization, the mobility of the seagoing hopper dredge often makes them the most efficient dredging plant available to do the work.

Modern hopper dredges reflect more than a century of development and are particularly used in the United

# Table IV-22

## Inventory of Corps of Engineers Dredges

| Name | District | Hopper cap. cu yds. | Length | Dredging depth to | Type Power | Year Built |
|---|---|---|---|---|---|---|
| | | HOPPER DREDGES | | | | |
| Langfitt | New Orleans | 3,060 | 351' | 62' | Steam | 1947 |
| Comber | Philadelphia | 3,710 | 351' | 62' | Steam | 1947 |
| Essayons -retired | Philadelphia | 8,277 | 525' | 60' | Steam | 1950 |
| Goethals | Philadelphia | 6,422 | 476' | 60' | Steam | 1938 |
| Hoffman | Buffalo | 920 | 215' | 36' | Diesel | 1942 |
| Lyman | Buffalo | 920 | 215' | 36' | Diesel | 1945 |
| Markham | Buffalo | 2,780 | 339' | 45' | Diesel | 1960 |
| Hains | Detroit | 885 | 215' | 36' | Diesel | 1942 |
| Biddle | Portland | 3,060 | 351' | 75' | Steam | 1947 |
| Harding | Portland | 2,682 | 308' | 62' | Diesel | 1939 |
| Pacific | Portland | 500 | 180' | 45' | Diesel | 1937 |
| Davidson | Jacksonville | 720 | 215' | 45' | Diesel | 1945 |
| McFarland | Jacksonville | 3,140 | 300' | 55' | Diesel | 1967 |
| Currituck (split hull) | Wilmington | 315 | | 15' | | 1977 |
| | | SIDECASTING DREDGES | | | | |
| Fry | Philadelphia | | 104' | 20' | Diesel | 1972 |
| Merritt | Wilmington | | 104' | 20' | Diesel | 1964 |
| Schweizer | Wilmington | | 133' | 25' | Deisel | 1966 |

## Table IV-22 (continued)

| Name | District | Discharge Pipe Diameter-ins. | Length | Dredging depth to | Type Power | Year Built |
|---|---|---|---|---|---|---|
| | | CUTTERHEAD DREDGES | | | | |
| Ste. Genevieve | St. Louis | 20 | 268' | 35' | Steam | 1932 |
| Dredge - 6 | Vicksburg | 8 | 45' | 8' | Diesel | 1966 |
| Henderson | Omaha | 10 | 62' | 20' | Diesel | 1968 |
| Depoe Bay | Chicago | 8 | 71' | 12' | Diesel | 1944 |
| Dubuque | St. Paul | 12 | 60' | 25' | Diesel | 1971 |
| Thompson | St. Paul | 20 | 266' | 26' | Diesel | 1937 |
| Bethel | Alaska | | 65' | 22' | Diesel | 1971 |
| Dillingham | Alaska | 12 | 62' | 27' | Diesel | 1969 |
| Luckiamute | Portland | 12 | 104' | 26' | Diesel | 1944 |
| Guthrie -retired | Mobile | 16 | 200' | 30' | Diesel | 1940 |
| | | DUSTPAN DREDGES | | | | |
| Burgess | Memphis | | 249' | 40' | Steam | 1934 |
| Ockerson | Memphis | | 240' | 30' | Steam | 1932 |
| Potter | St. Louis | | 240' | 30' | Steam | 1932 |
| Kennedy | St. Louis | | 244' | 30' | Steam | 1932 |
| Jadwin | Vicksburgh | | 249' | 58' | Steam | 1934 |
| Mitchell | Kansas City | | 277' | 20' | Steam | 1934 |

States and Europe. In most hopper dredging work, the material dredged is loaded into the hoppers and transported to an openwater disposal site where it is dumped through bottom doors in the hoppers. However, other methods of disposal can be used under certain conditions. These are: dumping in rehandling basins (for subsequent disposal ashore by pipeline dredges); agitation dredging (where the material dredged is intentionally discharged overboard through the hopper overflows as it is pumped, such that most of the solids will be transported and deposited outside of channel limits by tidal, river or littoral currents); sump rehandling (self-unloading hydraulically into the hoppers of a floating rehandling plant that then pumps the dredged material ashore through a long discharge pipeline); and side-casting (where all the dredged material is pumped directly overboard through a boom-supported discharge pipe and deposited alongside the channel or transported by natural currents as in the case of agitation dredging described above.

Corps hydraulic cutterhead dredges are used extensively on the inland waterways as they are unsuitable for operation in open areas under wave conditions. The dredges utilize a revolving cutterhead to bite into and loosen bottom materials. Transport of the material is by pipeline. Methods of disposal, therefore, are limited by the pumping power of the dredge and attendant plant. Common methods of disposal are in open water, in confined shoreline disposal sites, in confined upland disposal sites and for beach creation.

Dustpan dredges have been designed to operate in waterways having relatively uniform, non-cohesive bottom material. Material is removed with water jets and picked up by a wide suction device. Transport is by pipeline and disposal is directly to open water.

2. Contractor Dredges on Federal Projects. The Contractor dredge inventory for cutterhead dredges, prepared as part of the National Dredging Study, is shown on Table IV-23. This indicates both the home base and size distribution of dredges. The majority of the dredges are in the smaller size, over 50% are 16 inches or less, and 75% are 20 inches or less.

It has been estimated that there are 270 to 300 contractor-owned hydraulic cutterhead pipeline dredges of all sizes above 12" (discharge pipe diameter) in the

# Table IV-23

# Hydraulic Cutterhead Dredge Inventory: Distribution by Size, All Regions

## (number of dredges home-based in region)

| | Discharge Pipe Diameter (inches) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 27 | 30 | 36 | TOTAL |
| West Coast | 1 | 2 | 3 | 6 | 3 | 10 | 1 | 3 | | 6 | | 2 | 1 | 38 |
| Gulf Coast | 1 | 3 | 3 | 11 | 1 | 8 | 3 | 14 | 2 | 12 | 12 | 5 | | 75 |
| Interior | 1 | | 2 | 3 | 7 | 4 | 7 | 3 | 1 | | 1 | 2 | | 31 |
| Great Lakes | 3 | 1 | 1 | 2 | 3 | 3 | 2 | 2 | 1 | | 1 | 3 | 1 | 23 |
| East Coast | | 7 | 11 | 28 | 5 | 15 | 10 | 6 | 1 | 3 | 9 | 2 | | 97 |
| Total Number of Dredges | 6 | 13 | 20 | 50 | 19 | 40 | 23 | 28 | 5 | 21 | 23 | 14 | 2 | 264 |
| Cumulative Percentage | 2 | 7 | 15 | 34 | 41 | 56 | 65 | 75 | 77 | 85 | 94 | 99 | 100 | |

SOURCE: National Dredging Study, 1972

United States and that as many as 70 to 75% of these dredges are 30 years or more old and are considered obsolete. There are only relatively few large cutterhead dredges, such as the Jim Bean (owned by C. R. Bean Corp.), and the Illinois (owned by Great Lakes Dredge & Dock Co.) that are considered modern and representative of the state-of-the-art.

As a result of the National Dredging Study (1975),[26] the initiation by the Corps of a comprehensive Industry Capability Program (previously known as the Testing-of-the Market-Program) and subsequent related federal legislation (e.g., P.L. 95-269) designed to establish the capability of private industry to accomplish, at reasonable prices, dredging works normally performed by the Government plant, dredging contractors have been encouraged over the past several years to acquire (construct) seagoing hopper dredges. Presently, there are several privately-owned hopper dredges (both self-propelled and non-self-propelled) that are available for trailing suction dredging operations such as those required for maintaining approaches to coastal ports. A list of these dredges is given in Table IV-24. Of these contractor-owned hopper dredges, only the Manhattan Island and the Sugar Island are specifically designed for and can be considered to be truly suitable for trailing suction operations (as in the case of all Corps-owned hopper dredges) in exposed, relatively rough waters generally encountered in approaches to coastal ports.

One modern dustpan dredge is privately owned.

3. Utilization. Utilization of Corps dredges is shown on Table IV-25.

## Table IV-24

## Privately-Owned Hopper Dredges (existing)

| SIZE OR CLASS | NAME | HOPPER CAPACITY (CU. YDS.) | PROPULSION | OWNED BY |
|---|---|---|---|---|
| Large Class (Over 6000 Cu. Yds.) | Long Island (1) | 16,000 | Push-towed | Great Lakes Dredge & Dock Co. |
| Medium Class (2000-6000 Cu. Yds.) | Manhattan Island (2) | 3,600 | Self-propelled | North American |
| | Sugar Island (2) | 3,600 | Self-propelled | Tidewater Dredging Co. (5) |
| | Esperance III (2) | 3,600 | Self-propelled | Roger J. Am Co. |
| Small Class (Under 2000 Cu. Yds.) | Manson (2) | 1,600 | Push-towed | Manson-Osberg Co. |

ALL OF THE ABOVE DREDGES ARE DIESEL-POWERED

NOTE: (1) Equipped for both bottom dumping and direct pump-out

(2) Split hull type; not presently equipped for direct pump-out; however, reportedly can be converted to include this responsibility

(3) Converted LST - equipped only for direct pump-out, no bottom dumping doors

(4) North American Trailing Co. is a consortium of Great Lakes Dredge & Dock Co. & Ballast-Needham (a Dutch firm)

(5) Tidewater Dredging Co. is a wholly-owned subsidiary of Great Lakes Dredge & Dock Co.

## Table IV-25

### Utilization of Corps Dredges Defined as Ratio of Hours Billed to Available Hours by Type of Dredge

| Type of Dredge | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 |
|---|---|---|---|---|---|---|---|---|---|---|
| | (Percent) | | | | | | | | | |
| Hopper | 85 | 81 | 84 | 77 | 79 | 79 | 81 | 78 | 81 | 81 |
| Cutterhead | 62 | 57 | 63 | 64 | 59 | 60 | 63 | 73 | 66 | 61 |
| Dustpan | 55 | 52 | 49 | 53 | 51 | 47 | 49 | 47 | 46 | 49 |
| Sidecasting | 38 | 90 | 90 | 87 | 80 | 85 | 67 | 99 | 88 | 69 |
| Dipper | 59 | 70 | 66 | 52 | 50 | 39 | 52 | 36 | 56 | 52 |
| Bucket | 44 | 36 | 52 | 46 | 50 | 42 | 46 | 44 | 44 | 49 |

Available hours as used here are the number of hours in the year (8,760 in a normal year and 8,784 in leap year) multiplied by the number of dredges of each type. This shows that hopper dredges have achieved by far the highest utilization levels, averaging 82% during 1964 to 1973. These very high levels of utilization are possible because hopper dredges, except for those in the Great Lakes, generally work for the all year.

Cutterhead dredges as a type also achieved consistent high utilization levels, averaging 63 percent over the ten year periods and going as high as 73% in 1971. Since these vessels as a type are not seagoing, their operations are generally limited to interior and protected coastal waters. Consequently, they are subject to strict seasonal requirements, mostly in periods of decreasing flow. This prevents them from achieving the higher utilization levels of the hopper and sidecasting dredges.

Utilization of dustpan dredges has also historically been seasonal. They are used intensively from May to November when river stages are low or decrease and do not allow sufficient depth of water in the crossing. During the high water season (usually December to April) they are usually laid up or only operated in emergencies. The annual utilization of dustpan dredges depends on the demand for dredging on the Mississippi, Here they are primarily used. It is well known that dredging demand on unstable alluvial rivers, like the Mississippi, is very sensitive to hydrological patterns; the height of the flood, the gradient of the recession and the magnitude and duration of low flows are among the factors which influence the degree of sediment deposition. The fluctuation of dredge utilization will be even more pronounced in low demand years if the hedges are not used for other purposes, such as construction and harbor maintenance.

Utilization of contractor owned dredges is shown on Table IV-26. This is based on a sample study carried out by Arthur D. Little. In 1973 essentially all private industry hydraulic dredges were cutterheads. Utilization of contractor cutterheads was therefore somewhat under 50%.

### Table IV-26

### Summary of Industry National Utilization by Type of Dredge 1970-1973

#### 55 HYDRAULIC DREDGES

| | Corps of Engineers | Ports and Munic. | Private Industry | Foreign | Total Utilization |
|---|---|---|---|---|---|
| 1970 | 22.1% | 6.4% | 14.7% | 1.3% | 44.5% |
| 1971 | 23.4% | 5.7% | 7.2% | 0.2% | 36.5% |
| 1972 | 19.0% | 10.9% | 11.4% | 2.2% | 43.5% |
| 1973 | 21.2% | 6.9% | 8.7% | 3.7% | 40.5% |

#### 21 CLAMSHELL DREDGES

| | Corps of Engineers | Ports and Munic. | Private Industry | Foreign | Total Utilization |
|---|---|---|---|---|---|
| 1970 | 11.5% | 12.5% | 11.5% | - | 35.5% |
| 1971 | 14.8% | 11.3% | 9.0% | - | 35.1% |
| 1972 | 14.9% | 10.7% | 10.6% | - | 36.2% |
| 1973 | 10.4% | 5.4% | 13.7% | - | 29.5% |

#### 14 DIPPER/DRAGLINE DREDGES

| | Corps of Engineers | Ports and Munic. | Private Industry | Foreign | Total Utilization |
|---|---|---|---|---|---|
| 1970 | 6.6% | 10.4% | 9.7% | - | 26.7% |
| 1971 | 8.6% | 14.1% | 6.2% | - | 28.9% |
| 1972 | 25.0% | 2.3% | 3.6% | - | 30.9% |
| 1973 | 17.7% | 1.1% | 5.3% | - | 24.1% |

SOURCE: National Dredging Study - Table VIII-3

4. Plant Capacity. Figures in Sub-section 3 above, indicate that there was surplus capacity amont the industry dredging plant. This has been further investigated as indicated on Table IV-27. The columns are not directly comparable as they represent different time periods. They do, however, clearly show that there appears to be surplus capacity of cutterhead dredges, unless there has been a significant reduction of the industry plant. Obviously, not all the industry plant is suitable for all waterway dredging projects, but the range of industry dredges would indicate that there is capacity to handle every job. As dredges enjoy a reasonable degree of mobility, there is sufficient capacity in each major geographical area.

Further, it must be noted that in calculating the capacity of industry dredges to handle federal work, the practical limits of actual dredging time versus total time available were taken into account based on both Corps and industry experience. Also taken into account were seasonal dredging needs on inland waterways so that capacity figures are those based on contractor dredges only working on Corps projects during the appropriate dredging season on each waterway. This effectively increases the capacity of industry to handle non-federal work in off (dredging) season periods. A complete program of interviews of COE Divisions was carried out as part of this study. At no meeting was there any indication of the lack of capacity of the dredging plant to handle the work load. In some divisions, Missouri River Division and LMVD, for example it was indicated that utilization of Corps dredges was decreasing due to decreased dredging needs.

5. Minimum Dredge Fleet Concept. Various Congressional reports relating to appropriations for the Corps of Engineers over the past several years have supported the employment of a mixture of public and private dredges. It has been and continues to be the policy of the Chief of Engineers to have dredging work performed by the industry plant whenever reasonable bids can be obtained and the nature of the work and the time available for its execution will permit. However, it is the expressed intent of Congress that the Corps of Engineers maintain a fully operational dredge fleet sufficient to provide for rapid response to national defense and emergency requirements and to supplement industry capability as may be required.

# Table IV-27

## Effective Capacity of Contractor Cutterhead Dredge Plant by Region

| Region | 1<br>Effective Annual Capacity Contractor Fleet (1973) (cu. yd. x $10^3$) | 2<br>Annual Dredging[2] Volume (1973-1978) (cu. yd. x $10^3$) | 3<br>Average Annual[2] Volume Dredged by Corps' Cutterhead Dredges (1964-1973) (cu. yd. x $10^3$) | 4<br>% Utiliz[3] of Contractor Plant on Corps' Work (1970-1973) | 5<br>Utiliz. on[3] Corps' Work on % of Total Utiliz (1970-1973) |
|---|---|---|---|---|---|
| West Coast | 53,700 | 19,213 | | 7 | 60 |
| Gulf Coast | 131,300 | 60,147 | | 32 | 54 |
| Interior | 59,500 | 33,167 | | 20 | 44 |
| Great Lakes | 7,800 | 34 | | 18 | 67 |
| East Coast | 84,100 | 10,832 | | 18 | 48 |
| TOTAL | 336,400 | 127,393 | 24,146 | | |

[1] Source - National Dredging Study, Tables VII-21 through 25.

[2] Source - Inventory of Waterway Physical Features.

[3] Source - National Dredging Study, Table VIII-2 (Refers to all hydraulic dredges. As nearly all contractor owned private dredges were cutterheads prior to 1973, these figures should correctly represent cutterheads.

Public Law 95-269 enacted on April 26, 1978 provides that a study be undertaken by the Corps to determine the size of the minimum federally-owned dredge fleet required to perform emergency and national defense work and, further provides that this fleet be kept fully operational and maintained to technologically modern and efficient standards. The study is to be submitted to Congress no later than two years after enactment of the Law or on April 26, 1980.

The Corps of Engineers has undertaken to perform the study directed by the Congress in two separate parts, namely to determine the number and size (or class) of seagoing hopper dredges required, and to determine the number of other types of dredges required. The first part of the study was expedited in view of particular Congressional interests and an apparent need for an early determination of hopper dredge requirements in order to preclude any possible undue industry difficulties in obtaining new hopper dredge construction loans.

The portion of the minimum dredge fleet study to develop hopper dredge requirements was given priority and has been completed. The report on this study has been submitted through the Secretary of the Army to the Office of Management and Budget. The latter has not as of the date of writing forwarded this report to the Congress.

Based upon the Corps assessment of overall national requirements, a total of 18 hopper dredges (both Corps and industry owned) of various sizes and of modern design and construction will be required in the foreseeable future. As new hopper dredges are constructed by the industry, the Corps is expected to retire various units of its existing fleet, presumably those that are most antiquated and least effective. The Congress has expressed concern that if private industry acquires retired government hopper dredges, then investment in new dredging equipment may be inhibited; consequently, Congress has requested that the Corps retain retired equipment until authorizing legislation is enacted to prevent this.

A comprehensive study (similar to that performed for hopper dredges) to identify the numbers of other types of dredges required in the Corps of Engineers minimum fleet is essentially complete except for review and approval of the Chief of Engineers.

The only dredges (other than hopper dredges) that the Corps may propose to own and operate that may impact on the maintenance of approaches to major coastal ports will be cutterhead pipeline dredges, but it is believed that the bulk of any work of that nature will be performed by contractor-owned cutterhead dredges. As indicated above, there seems to be an ample number of privately owned cutterhead dredges in the United States although a majority of them must be considered antiquated and obsolete. Nonetheless, it is believed that the industry can and will continue to respond to any requirements for cutterhead pipeline dredging that may be developed in the foreseeable future by acquiring a new dredging plant as may be needed. Also, in this regard, strict implementation of regulations by the United States Coast Guard under the Seagoing Barge Act (46USC395) might well serve as an impetus to the industry to replace existing dredges that may not be permitted to operate in coastal (off-shore) waters with new modern dredges of safe and more efficient design. The Congress has taken cognizance of problems that such implementation would cause and there is legislation pending (H.R. 1198) to redefine boundary lines dividing inland waters and the high seas for the purpose of providing some relief to the dredging industry. Strict enforcement of the Act as currently interpreted is expected to have a serious impact on various projects along the North and South Atlantic coastline where dredging in the coastal zone, particularly for beach nourishment purposes, has been performed with cutterhead dredges.

6. <u>New Dredges Under Construction and Planned</u>. As the first step towards the establishment of a reduced but modern state-of-the-art hopper dredge fleet, the Corps of Engineers presently has under construction three new hopper dredges, one each large class (LCHD), medium class (MCHD) and small class (SCHD). Pertinent physical data for these dredges are shown in Table IV-28. Names for the first two have not as yet been selected but the SCHD has been named the Yaquina. It is designed to be especially suitable for dredging relatively shallow draft ocean bar inlet channel projects on the West Coast. The LCHD is designed so that all four of its dredge pumps can be operated simultaneously for increased effectiveness when operating in the agitation dredging mode. The MCHD is designed essentially as a general purpose dredge suitable for efficient operation in most coastal navigation channel projects.

## Table IV-28

## Corps of Engineers Hopper Dredges Under Construction

### Physical Data

| | LCHD | MCHD | (YAQUINA) SCHD |
|---|---|---|---|
| Length x Beam x Depth (ft.) | 409x78x39 | 350x68x35 | 200x58x17 |
| Design Draft, Loaded (ft.) | 29.5 | 27 | 12 |
| Max. Hopper Capacity (Cu.Yds.) | 8400 | 6000 | 825 |
| Speed, Loaded (est. Knots) | 14.5 | 13.4 | 10 |
| Max. Dredging Depths (ft.) | 80 | 80 | 45 |
| No. of Dragarms (Suctions) | 3* | 2 | 2 |
| Dredge Pumps, Inboard: | | | |
| Number | 2 | 2 | 2 |
| Discharge Diameter (inches) | 30" | 26" | 16" |
| BHP, each | 3600 | 3000 | 565 |
| Dredge Pumps, Dragarm-Mounted: | | | |
| Number | 2 | 2 | - |
| Discharge Diameter (inches) | 26" | 26" | - |
| BHP, each | 1600 | 1450 | - |
| Equipped for direct pumpout | Yes | Yes | No |
| Crew Complement | 40 | 38 | 28 |
| Anticipated Delivery (Fiscal Yr.) | 1981 | 1981 | 1980 |

NOTE: Equipped W/3rd Dragarm in Centerwell

There are three new hopper dredges currently under construction for private contractors. All of these are self-propelled, designed for trailing suction operations, and of the split hull type. Two of them are in the medium class category, the Eagle I, being built for the Eagle Dredging Company (a consortium of C. F. Bean Corp. and the Volker/Steven Group, a Dutch firm) and the Dodge Island, being built for the Great Lakes Dredge & Dock Company (or its subsidiary, Tidewater Dredging Company) with completion anticipated in Fiscal Years 1980 and 1981, respectively. The third (name unknown) is in the small class and is being built for the T.L. James Company, with delivery expected in Fiscal Year 1980. In addition, it was announced in November 1979 that Zapata Marine Bos Kalis interests (Bos Kalis is a Dutch firm, part of the Westminster Group of Companies, which is considered to be one of the largest, if not the largest, firm of dredging contractors in the world) have contracted with a United States shipbuilder to construct a large class hopper dredge (approximately 8,800 cubic yards hopper capacity). This dredge could possibly be completed in Fiscal Year 1982 or early Fiscal Year 1983.

Looking further into the future, the Corps of Engineers has not as yet formulated plans for the construction of any additional hopper dredges, other than those indicated above. The Industry Capability Program is to be completed in 1981 and its impact assessed in conjunction with the apparent increasing interest on the part of United States dredging contractors to get into the hopper dredge business. It appears that the Corps might well hold in abeyance any plans to design and construct any additional hopper dredges, including possible replacements in the existing fleet. On the other hand, there are plans by various private dredging contractors to construct more hopper dredges over the next few years in addition to those currently under construction or contracted for as indicated above. For example, it was indicated that: Eagle Dredging Company has under design a split-hull type hopper dredge with a capacity in the range of 1000-1500 cubic yards, T. L. James Company is negotiating with shipbuilders for the construction of a split-hull hopper dredge with a capacity in the range of 2500-3700 cubic yards, and a German firm (Fruenne & Bilfinger) through a United States subsidiary (FRUCON) has contracted for the design of a medium class hopper dredge being considered for construction and operation in the United States presumably in a consortium or partnership with United States interests. Taking these plans for future construction into account, it appears that a total of 10 or 11 privately-owned hopper dredges (i.e., five existing, three under construction, two to three planned) may be available by Fiscal Year 1983.

As indicated above, the only type of dredge, other than hopper dredges, of any significant importance for maintaining approaches to major coastal ports is the hydraulic cutterhead pipeline dredge. Also, the major portion of cutterhead dredge work in coastal areas is performed by privately-owned plants under contract. It is reported that there have been a few instances, particularly in the North Atlantic region, during the past few years where work intended for large cutterhead dredges (24" or greater) did not attract sufficient interest among prospective bidders and consequently was carried out by government dredges because of no bids or unreasonably high bids by private industry.

It is difficult to determine whether any real shortage of cutterhead dredges exists or can be anticipated. It is presumed that, in general, a sufficient number of such dredges will be available to take care of currently estimated dredging requirements for maintaining approaches to major coastal ports. The only new cutterhead dredge (a 30" dredge) designed for coastal operations currently under construction is being assembled in an East Coast Shipyard for the American Dredging Company. As previously indicated, the anticipated strict enforcement by the United States Coast Guard of provisions of the Seagoing Barge Act might well force dredging contractors to replace the existing plant found to be not suitable for safe operation in coastal waters.

With reference to the minimum dredge fleet study, it appears likely that the Corps will plan for the design and construction of one or more new cutterhead dredges. Although these dredges may be required basically for rapid response to national defense and emergency requirements, they will be kept operational as intended.

### (b) Future Dredging Constraints and Directions

Existing and developing constraints on dredging are likely to have a significant impact on the maintenance of the nation's waterways. The major constraints are based on environmental concerns.

A major problem is determining direction in that the environmental constraints have not been fully defined either legally or technically. Recognizing the need to reconcile requirements of environmental protection with those of maintaining a viable system of national waterways and harbors, Congress authorized (under Public Law 81-611) a comprehensive nation-wide Dredged Material Research Program (DMRP).[27] The program was initiated in 1973 and completed in 1978.

The DMRP was designed to be as broadly applicable as possible on a national basis with no major type of dredging activity or region or environmental setting excluded. It thus resulted in methods of evaluating the physical, chemical, and biological impacts of a variety of disposal alternatives - in water, on land, or in wetland areas - and produced tested, viable, cost-effective methods and guidelines for reducing the impacts of conventional disposal alternatives. At the same time, it demonstrated the viability and limits of feasibility of new disposal alternatives, including the productive use of dredged material as a natural resource.

There are two extremely important fundamental conclusions that can be drawn from the DMRP. The first is that there is no single disposal alternative that presumptively is suitable for a region or a group of projects. Correspondingly, there is no single disposal alternative that presumptively results in impacts of such nature that it can be categorically dismissed from consideration. Put in different terms, there is no inherent effect or characteristic of an alternative that rules it out of consideration from a technical standpoint prior to specific on-site evaluation. This holds true for open-water disposal, confined upland disposal, habitat development, or any other alternative.

Specific on-site evaluations mean that each project must be considered on a case-by-case basis. It is not technically sound, for example, to make the general statements that ocean disposal must be phased out or that all material in the Great Lakes classified as polluted must be confined behind dikes. To do this would be contrary to research results that have indicated that there can be situations where there is greater probability of adverse environmental impacts from confined disposal than from open-water disposal. Yet, in other situations, other as when certain types of contaminants are present, confined disposal may provide the greatest amount of environmental protection.

In some areas, the program has established a need for further research, particularly where long-term environmental impacts may be involved.

DMRP has demonstrated that under some circumstances water disposal is less damaging to the environment than upland disposal, but existing trends, based on current interpretations of the Clean Water Act and Ocean Dumping Act, still favor upland disposal over open-water dumping. Under current legislation, upland disposal requires local cost sharing to provide sites. This is hard to obtain when the waterway largely benefits distant economic centers.

While possible productive uses of dredged material have been established, the mechanisms for connecting a variable supply of often mixed materials for the quantity and quality specific needs of sand, gravel, clay, etc., for industry and construction have not.

The implications of the foregoing are that the environmental constraints to be interpreted in terms of quantities of material to be dredged, the techniques to be used in dredging and disposal of dredged material, and the operational requirements for dredging equipment have yet to be defined and are unlikely to be fully defined in the short-term future. However, the following trends are discernible:

1. Efforts to minimize quantities of dredged material for a maximum level of service to shipping will be emphasized.

2. Dredging methods and methods of disposal of dredged material will determined on a site specific basis.

3. Transport distances from dredging site to final point of disposal of dredged material will probably increase.

4. Increasing emphasis will be placed on "beneficial" or "productive" uses or dredged material.

These trends have the following implications for dredging needs:

1. Improving procedures for determining dredging needs.

2. Increasing control of dredging and improving positioning technology to minimize differences between gross (actual volume dredged) and credited (material within designated dredging prism) volumes dredged.

3. Modifications and improvements to dredges and support equipment to improve their ability to handle different methods of disposal, such as upland, beach nourishment, marshland creation, scow load and for productive uses, etc.

4. Increased density of slurry to reduce overall dredging costs and possibly to reduce environmental problems.

5. Development of more efficient methods for transport of dredged material greater distances.

Private industry as well as government will undoubtedly seek innovative approaches in developing the Minimum Dredge Fleet, to meet these requirements at the lowest cost.

However, there may be conflict between the Corps' needs to maintain a minimum fleet to meet emergency and national defense needs and the ability to use this fleet efficiently for routine maintenance dredging. Emergencies and national defense imply the maintenance of waterways to move large quantities of material under arduous conditions. This may require equipment of such size as to have capacity for a high rate of production under varying dredging conditions. Such equipment may not be of the size characteristics to conform with existing and expected environmental constraints when operating on routine maintenance dredging.

### (c) Dredging Plant Requirements and Options for Improvements of Its Capabilities and Efficiency

There are a number of conflicting pressures against defining dredge plant requirements and providing for them. Firstly, there is pressure based on environmental concern and institutional problems to minimize dredging to the minimum required to maintain authorized channel dimensions. There is a lack of definition of the environmental constraints which makes it difficult to specify technical requirements for the dredging plant. Changes in dredging techniques required to meet environmental constraints may require different types of dredge plant and operational methods being employed, such as:

1. Loading scows with bucket or hydraulic cutterhead, hauling scows to an unloading site, unloading the dredged material by either bottom dumping, mechanical equipment, special hydraulic rehandling plant or other means.

2. Augmentation of hydraulic cutterhead plant with one or possibly two booster stations to reach more distant disposal areas.

3. Possible use of the sidecaster technique in waterways where the environmental conditions would permit.

And lastly, Public Law 95-269 has reduced the direct control of the Corps of Engineers in providing for new type dredging plant needs by limiting its mandate and providing for increased participation in dredging work by private industry.

A large part of both the federal and private dredging plant is outdated, has been discussed, resulting in the need for the acquisition of new equipment. Industry has indicated a reluctance to make the neccessary costly investments without some indication that the plant will have favorable utilization. Furthermore, dredging contractors, except for the very few large firms, tend to be small corporations by modern standards without the resources for any significant research and engineering development which might be indicated.

Taking this into account, the following options have been developed to improve the capabilities and efficiency of the dredging plant:

1. That the Corps of Engineers, through the minimum dredge fleet program, undertake a continuous and purposeful program of dredging equipment development and modification. And further, that the program be coordinated with the private dredging industry so that industry would be aware of the concepts and direction of the Corps efforts and thereby be in a position to provide useful input to the program.

2. That the Corps of Engineers publish an annual dredging report listing all federal projects dredged during the year, including such details as volume of material, number and location of sites, dredging dimensions, and depth of cuts, both as required by the project specifications and as actually dredged; also stating dredge plant and dredging techniques used, location and method of disposal and any special features or constraints (environmental or otherwise) associated with the work. The report should include a section giving an overview of dredging and disposal trends predominant during the year and an evaluation of the effect of these trends on future operations. In addition, it should include a review report on new dredging developments in plant and techniques. Such a report could provide the dredging industry with current data of dredging patterns and requirements.

3. That the dredging program of the Corps be based on the principle that full depths, as authorized or as required should be available for navigation at durations not shorter than duration of design reference water flow in the federal inland waterways. This concept will

assure the uninterrupted flow of commerce and at the same time, together with the greater participation in dredging work by private industry resulting from Public Law 95-269, will provide more effective utilization of industry dredging plant. This greater utilization of dredging plant would improve the industry's financial position and possibly make available those funds required to procure a new and modern plant to conform with changes in dredging methods or techniques resulting from environmental constraints.

## APPROXIMATE METHOD FOR ESTIMATING MAINTENANCE DREDING COSTS

This section presents a model for the determination of dredging costs on United States waterways. The model can be used to evaluate the effect of changes in the values of factors which affect the overall cost of dredging. The major dredger types hydraulic cutterhead, dustpan and seagoing hopper dredges are considered.

### (a) Cost Estimate Procedures

In order to estimate the cost of dredging for the various types of dredges in the United States, several sources of information were used.

For hydraulic cutterhead dredges, Engineer Regulation 1110-2-1300, "Government Estimates and Hired Labor Estimates for Dredging,"[28] dated February 15, 1978, provided information on production rates as a function of size of dredge, in-situ material density, bank height and pumping distance. The Regulation was established to improve the standardized dredge estimating procedures in the Corps and also serves as an aid in the selection of the proper size dredge for a particular job. Representative monthly operating costs for different size dredges were provided by the Corps. Barge cost and costs for certain elements of confined disposal area were obtained from the Dredged Material Research Program, Technical Reports D-78-28, "Dredged Material Transport Systems for Inland Disposal and/or Productive Use Concepts"[29] and D-77-33, "Feasibility of Inland Disposal of Dewatered Dredged Material: A Literature Review."

For dustpan dredges, information on production rates was obtained from "The National Dredging Study"[30] by Arthur D. Little, 1974, and "The Consolidated Statement of Operations for Cutterhead and Dustpan Pipeline Dredges for Fiscal Year 1974." The last year that this Annual Consolidated Statement was prepared by the Corps of Engineers was 1974. Current operating cost information was obtained from the Corps.

For seagoing hopper dredges, information on production rates was obtained from the "Statement of Operations for Hobber and and Sidecaster Dredges for Fiscal Year 1972"[31] (the last year such Annual Statements of Operations was prepared) and several recent Reports of Operations - Hopper Dredge, (Engineer Form 27). Current operating cost information was obtained from the Corps.

In estimating dredge plant performance one must consider both the cost of owning and operating the plant, the production capability of the plant and particular job requirements. The best way to evaluate a dredging operation is on the basis of the unit cost per cubic yard of material removed and disposed of as required. The cost model presented in the following sections shows the various factors which affect the dredging costs expressed in unit cost per cubic yard.

The model establishes a Base Unit Cost for each type of dredge. This Base Unit Cost is defined essentially as the annual operating cost of the particular size dredge plant divided by its theoretical production rate under certain assumed conditions. As the various factors (parameters) which affect dredging cost change, the actual unit cost of dredging varies from the Base Unit Cost and is depicted as a percentage of the Base Unit Cost and not in terms of a definitive unit cost (dollars per cubic yard).

A Base Unit Cost, in dollars per cubic yard, and the assumptions on which it is based are presented in Tables IV-29, IV-30 and IV-31 for various dredges to aid other NWS elements and tasks in using the model. However, it should be pointed out that for operating the model, a Base Unit Cost of unity could be substituted for any given size change in dredging cost for any given area can be determined if all of the conditions required by the model are known or can be approximated.

### Table IV - 29

### Base Unit Cost for Hydraulic Cutterhead Dredges

| Diameter | Approximate 1978 Cost | Pipeline Length Less Than | Production Rate | Base Unit Cost Per Cubic Yard |
|---|---|---|---|---|
| 10" | $ 79,000/mo. | 2,000' | 200 cy/hr. | $ 0.76 |
| 12" | 111,000 | 2,500' | 270 | 0.79 |
| 14" | 147,000 | 3,000' | 380 | 0.74 |
| 16" | 197,000 | 3,500' | 500 | 0.76 |
| 18" | 240,000 | 4,000' | 650 | 0.71 |
| 20" | 285,000 | 4,000' | 800 | 0.69 |
| 24" | 370,000 | 5,000' | 1,200 | 0.59 |
| 27" | 430,000 | 5,500' | 1,500 | 0.55 |
| 30" | 500,000 | 6,000' | 1,800 | 0.53 |
| 32" | 544,000 | 6,000' | 2,100 | 0.50 |

Assumptions: -Rental period of 6 months/year
-Dredging sand of in-situ density 2000 g/l
-Bank height (face of cut) equal to cutter diameter 7 day/week operation, approximately 200 hours of Non-Effective Working Time included per 30 day month
-Disposal by pipeline in open water at distances less than those shown

NOTE: Costs were developed for the Corps' South Atlantic Division. Cost in other regions could be as much as 20% greater.

### Table IV - 30

### Base Unit Cost for Dustpan Dredges

| Current Average Rental Rate Per Day | Average Cost Per Effective Minute | Production Rate | Base Unit Cost Per Cubic Yard |
|---|---|---|---|
| $15, 730 | $15.13 | 91,000 ey/Eff. Day | $0.24 |

Assumptions: - 200 hour Non-Effective Working Time, 30 day month, 7 day/week operation -
- Open Water Disposal

Table IV - 31

Base Unit Cost for Seagoing Hopper Dredge

| Hopper Capacity | Current Average Rental Rate Per Day | Average Cost Per Effective Minute | Base Unit Cost Per Cubic Yard |
|---|---|---|---|
| 8,000 cy | $25,740 | $19.86 | $0.39 |
| 6,000 | 24,350 | 18.79 | 0.49 |
| 3,000 | 20,140 | 15.54 | 0.76 |
| 800 | 9,720 | 7.50 | 1.36 |

Assumptions:

- 90% of Rental Time is Effective Working Time
- Average economic load of 70-80% of hopper capacity
- Average haul distance of 4 miles (10 mph average running speed, 60 minutes pumping and turning, and 10 minutes dumping per load)
- Open water disposal

While the operating costs of the cutterhead dredges are representative of average current industry dredges, the operating costs of dustpan and hopper dredges are based entirely on the operating costs for the existing Corps owned dredges, most of which are over 30 years old.

### (b) Hydraulic Cutterhead Dredges

1. Factors Which Affect the Cost of Dredging. The cost of operating a hydraulic cutterhead dredge includes depreciation of the capital cost of the plant, labor costs to operate the plant, interest on investment, fuel costs, repair costs, supplies, yard costs, insurance, lay-up costs, and any of those costs associated with disposal of the dredged material. The capital cost of the dredging plant includes the cost of attendant plants and miscellaneous equipment, such as tug(s), a derrick barge,

work barge(s), a fuel and water barge, a crew boat, a skiff and outboard, bulldozers, trucks and office trailers. Labor ranges from a crew of about 16 (for a three shift/day operation) on a 10" dredge to a crew of over 75 for a 32" dredge including attendant plant and other support activities at the dredging site. Labor charges accrue primarily while the plant is laid-up. Additional costs associated with disposal of the dredged material will be discussed in subsequent sections.

As previously mentioned, the total cost of plant operation, divided by its production, provides the best means to evaluate the cost of the dredging operation. This requires information about the production rate of the dredge.

While the cost of the dredge plant can be readily obtained, the hourly production rate, or the total number of cubic yards of material excavated per hour, is highly dependent upon a number of factors. These factors are:

(a) Effective Working Time.

(b) Type of material.

(c) Bank height.

(d) Length of pipeline.

Each of these factors will be discussed in more detail in the following sections.

The methods to estimate the cost of dredging by hydraulic cutterhead dredges for specific sites has been set out in E.R.-1110-2-1300. In brief, the method uses the following steps to determine the cost of dredging per cubic yard.

(a) Determine the volume to be dredged.

(b) Determine the production rate based on thefactors listed above.

(c) Divide the volume to be dredged by the production rate to determine the actual pumping time (or Effective Working Time) required to perform the work.

(d) Adjust by adding Non-Effective Working Time to obtain total Rental Time required.

(e) Divide the cost of the plant, including disposal costs for the period of time determined by the volume to be dredged to obtain the cost per cubic yard.

The following sub-sections are devoted to determining the variation in the cost of dredging per cubic yard with a hydraulic cutterhead dredge with respect to the factors listed above which affect the production rate. The variation in cost of dredging per cubic yard as a function of increased costs due to certain variations in disposal requirements is also evaluated.

A method is presented to evaluate the relative importance or impact of mobilization and demobilization on the total cost of the dredging project.

2. Effective Working Time. The Effective Working Time is defined to be that part of total Rental Time which is spent pumping and does not include time spent:

(a) handling pipelines.

(b) handling anchor lines.

(c) clearing pump and pipelines.

(d) clearing the cutter or suction head.

(e) making minor repairs.

(f) off shift, Saturdays, Sundays and holidays.

(g) moving to and from wharf or anchorage.

(h) changing location on the job.

(i) opposing natural elements.

(j) passing vessels.

(k) shoreline and shore work.

(l) waiting for booster, or other attendant plant.

(m) preparation for tow.

(n) transferring plant between projects.

Time thus spent is Non-Effective Working Time.

For all subsequent analyses for cutterhead dredges, a Rental time of six months per year has been assumed (while in some regions the Rental Time can be as great as eight months, an average of about six months is more common), and the Non-Effective Working Time is considered to be 200 hours per month.

Figure IV-G shows the change in the cost of dredging as a function of any change in the Effective Working Time due to the above factors. On the figure, 100% of the Base Unit Cost is shown as about 70% of Rental Time spent in Effective Work. This represents the 200 hours of Non-Effective Working Time per month, assuming seven-day per week operation. Generally, at least 40% of the Rental Time is spent in Effective Work; however, the curve is extended to show the effect of excessive Non-Effective Time,which might occur from unusual job conditions such as lost time due to extreme adverse weather or lost time associated with cleaning the cutter and pumps of excessive debris or extraneous matter found in bottom material.

3. <u>Type of Material</u>. Hydraulic cutterhead dredges utilize a revolving cutterhead to bite into and loosen (scarify) the bottom materials in order to facilitate their removal. The rate at which the dredge can remove the bottom material depends on the physical properties (e.g., density, grain size and uniformity, shear strength, etc.) of the material and on the capacity of the dredge.

According to E.R. 1110-2-1300 (February 1978), while the "effect of the material to be dredged is very pronounced...its effect can be determined with an acceptable degree of accuracy." A method is presented in th8e E.R. to determine the production of a given cutterhead dredge as a function of the in-situ density of thc dredged material. Based on the method presented in the E.R., it is possible to determine changes in production rates (and as a consequence, costs) as a function of in-situ density.

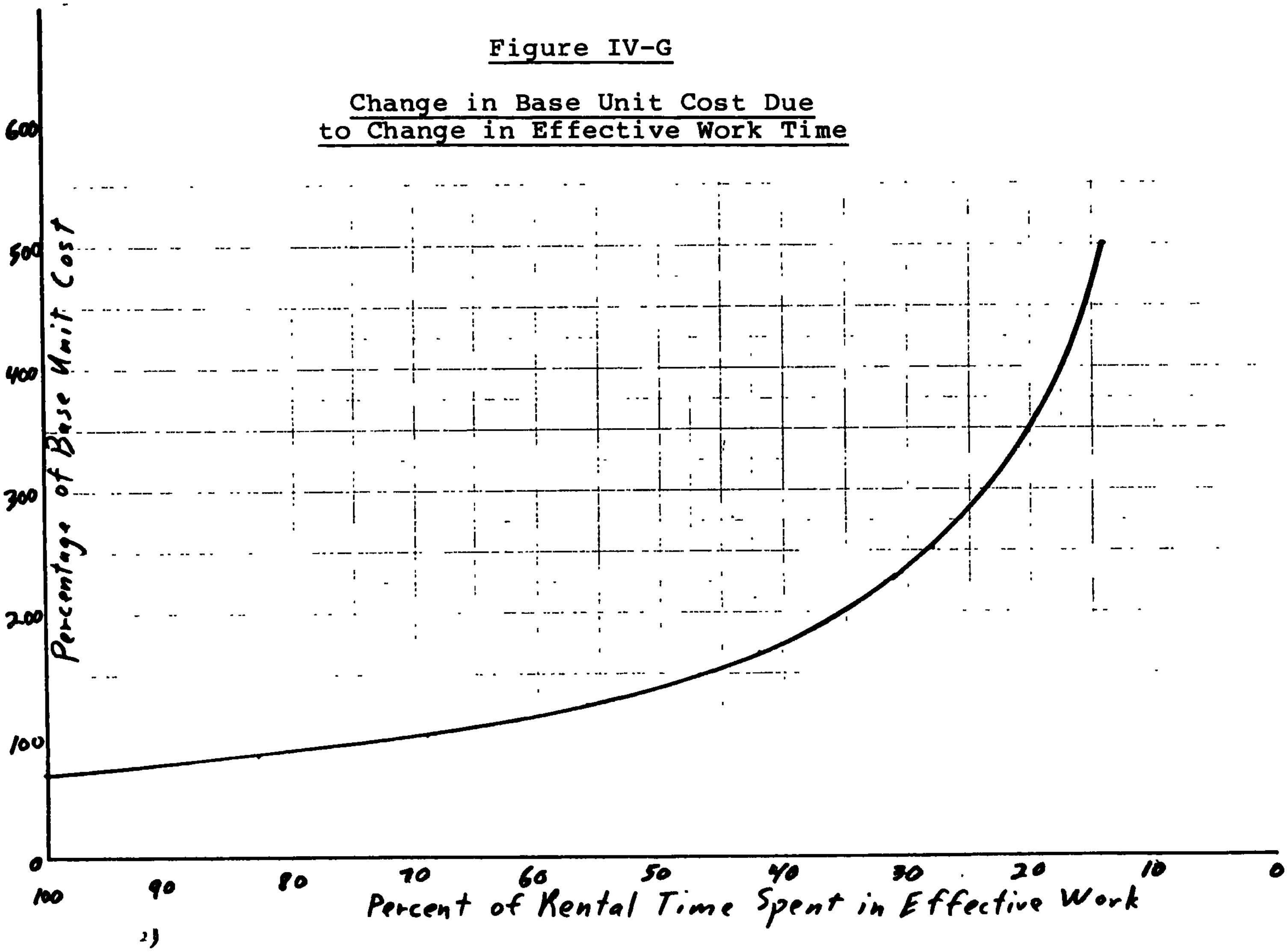


**Figure IV-G**

**Change in Base Unit Cost Due to Change in Effective Work Time**

Figure IV-H can be used by assuming an average density of a mixture of sand, silt and/or mud.

Figure IV-H shows the relationship derived in terms of a percent change in the Base Unit Cost. The cost to remove an inplace cubic yard of material generally decreases as the in-situ density decreases.

On the figure, the Base Unit Cost is established for free flowing sand of in-situ density 2000 g/l.

It should be pointed out that, in general, material of 2000 g/l density corresponds to dense sand and material of 1200 g/l density corresponds to very light loose silt. The materials encountered in navigation channel maintenance work generally fall within the range of these densities. In addition, Figure IV-H is only for free flowing materials. Costs related to production in stiff clay, heavy gravel, cobbles or broken stone must be evaluated by experience on similar work.

4. Bank Height. The rate at which bottom material can be removed is dependent upon either the rates at which the cutter can cut and the plant can pump or the speed at which the dredge can advance over the area to be dredged.

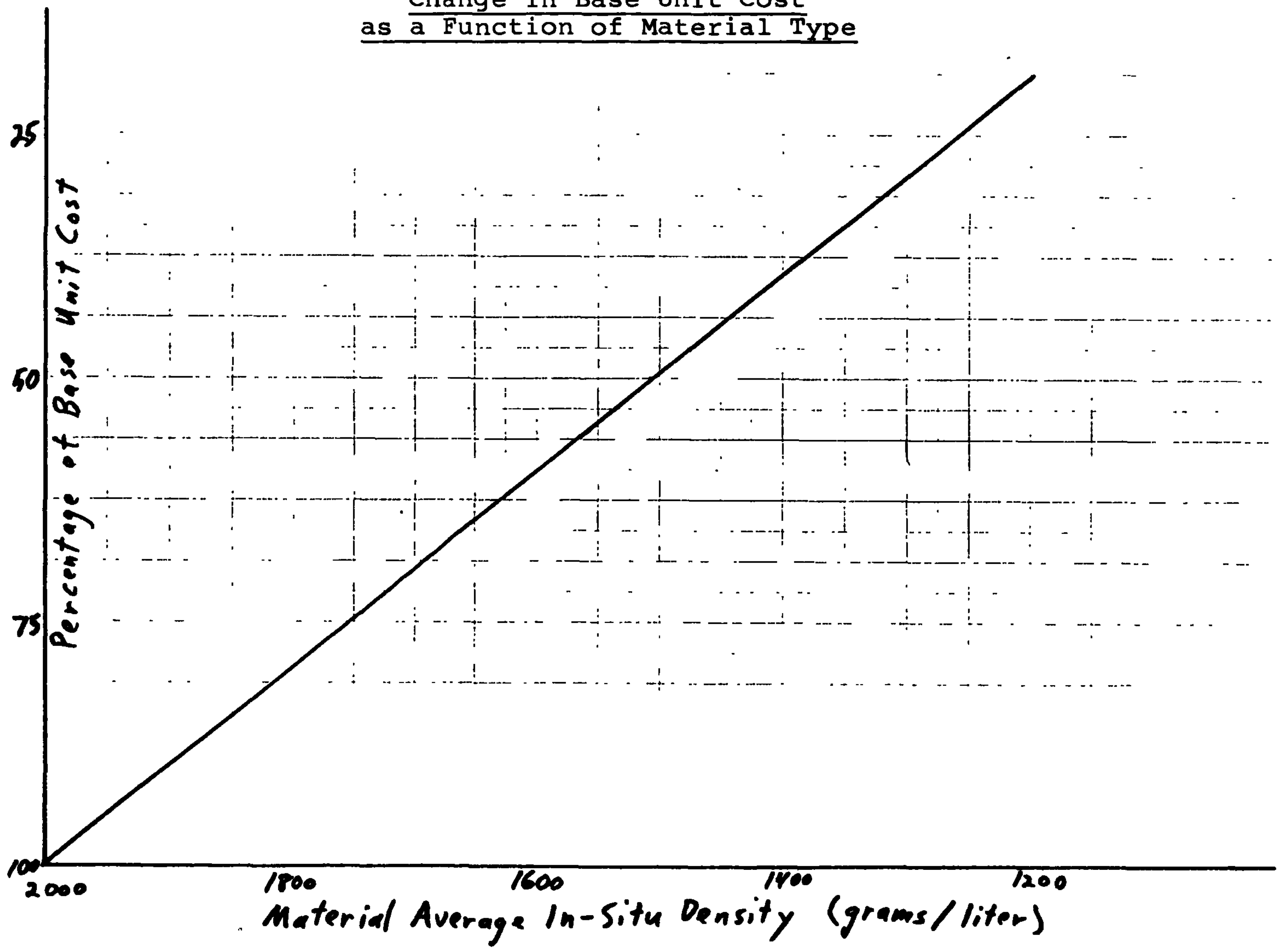
In sand of 2000 g/l in-situ density, as long as the height of the face of the cut (bank height) is greater than the cutter diameter, average production rates, equivalent to those shown in Table IV-29, can be expected. However, if the bank height is less than the diameter of the cutter, production is reduced because of decreased effectiveness of the cutter to feed material (sands) to the suction intake. Bank heights slightly greater than the diameter of the cutter can increase production somewhat. But, in general, bank heights greater than the cutter diameter do not significantly change the production rates.

A method of estimating production rates as a function of bank height is presented in E.R. 1110-1-1300. Based on this method, it was possible to develop changes in production rates (and as a consequence, costs) for various size dredges as a function of bank height.

Figure IV-I shows the relationship derived in terms of percent change in Base Unit Cost. The cost to

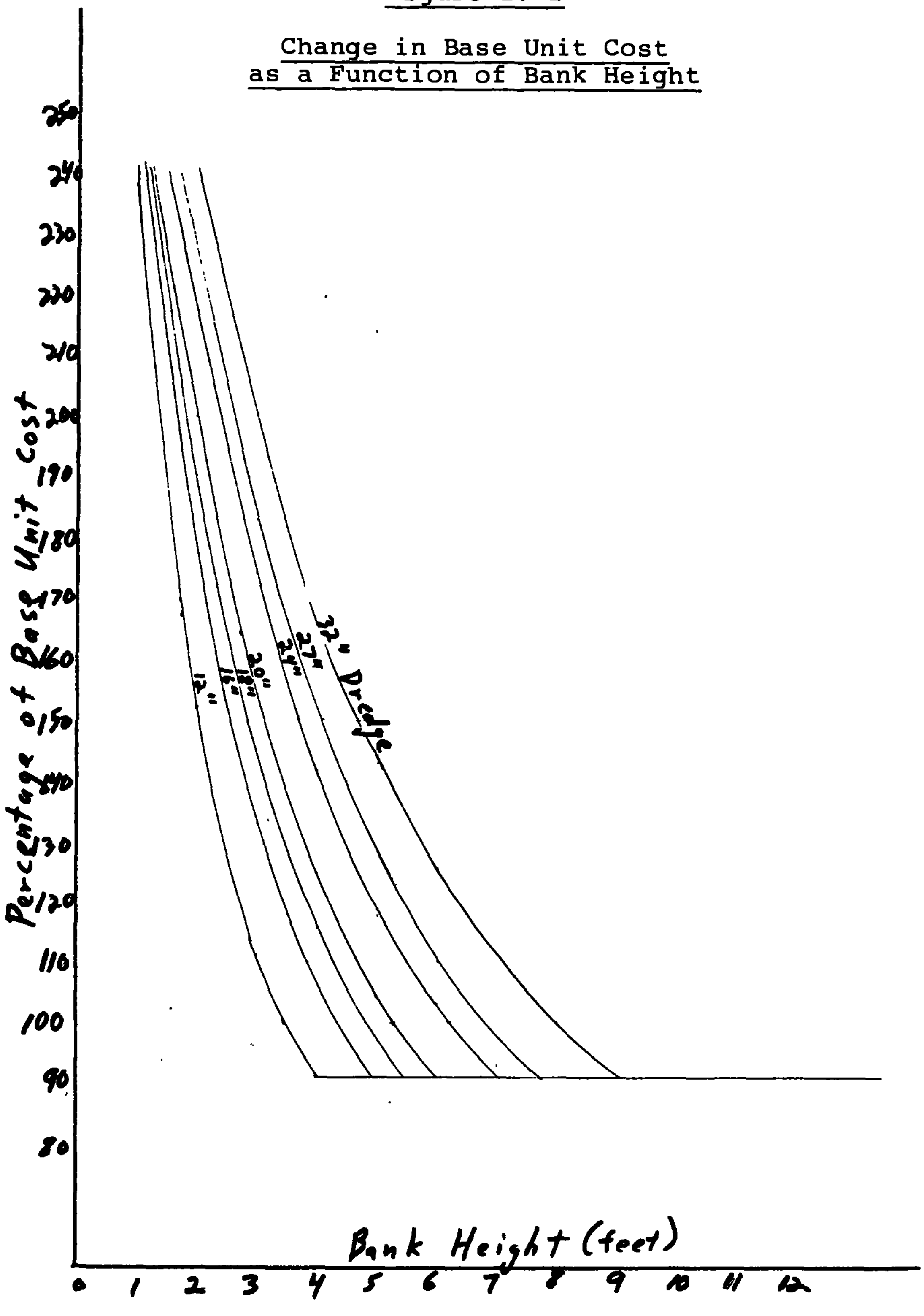
Figure IV-H

Change in Base Unit Cost
as a Function of Material Type



# Figure IV-I

## Change in Base Unit Cost as a Function of Bank Height



remove an inplace cubic yard of material increases rapidly as the bank height decreases below the diameter of the cutter.

5. Dredged Material Disposal. Thus far, the cost of operating a hydraulic cutterhead dredge has been evaluated with the assumption that disposal of the dredged material is at a distance within the pumping capability of the dredge itself.

Table IV-29, taken from E.R. 1110-2-1300, shows the lengths of discharge lines which can be used in free flowing sand (density 2000 g/l) for various size dredges without affecting, significantly, the production rate of the dredge plant.

Increasing the length of the discharge pipe beyond the lengths shown in Table IV-29, rapidly decreases the plant production capability because the discharge velocities are decreased. Doubling the pipeline lengths given in Table IV-29 has the effect of reducing the plant production by about 35% according to the E.R. referred to herein. At distances greater than double the distances shown in Table IV-29, flow velocities in the discharge pipeline become so low that solids may begin to settle out of the dredged material slurry.

For pipeline distances greater than the capability of the dredge plant, booster pumps are required. Up to two booster pumps usually can be added without significantly decreasing the basic production rate of the plant. Figure IV-J shows the change in the Base Unit Cost as a function of pumping distance using booster pumps. The maximum distance shown in the figure assumes two booster pumps are employed and no reduction in plant production. However, depending on job conditions, it might be more advantageous to consider decreased production. For example, if the decreased production rates (and subsequent higher costs) for distances greater than those shown in Table IV-29 are taken into account, then the pumping distances shown for each booster in Figure IV-J could be doubled. For small jobs, it could be preferable to use a single booster and accept a lower production rate. The increase is due mainly to the cost of the booster. The increased cost of the plant due to increased pipeline lengths is only nominal for the distances shown and does not significantly affect the Base Unit Costs. The production rate decreases by about 10% 0% as a result of introducing boosters (according to the E.R.).

At distances greater than those indicated as the upper limits for the various size dredges, as shown on Figure IV-J, different methods of disposal must be considered. A common method of disposal must be considered. A common method of disposal under those conditions utilizes a tug/scow combination for the transport phase of the operation. Scows are loaded with dredged material directly from the dredge, towed to a disposal site and unloaded. In such operations, the only feasible method of loading is to provide for overflowing excess water and any fines in the dredged material to permit the heavier and coarser fractions to settle in the scow. This assumes, of course, that there are no environmental constraints to loading in this manner and the material is essentially granular in nature such as sand having in-situ densities in the range of 1800 to 2000 g/l.

Figures IV-K and IV-L show the cost of transporting the dredged material by barge (scow). The figures assume that the barges will be loaded until they are filled with settled solids up to about 75% of barge capacity. Also, it is assumed that the overflow losses during loading amounts to 25% of the total volume pumped. Based on these assumptions, values for sand of 1800 and 2000 g/l densities are shown. However, it should be noted that heavier and larger grained sand settles faster so that less overflow losses and greater loads may be possible even though the pumping rate is lower. For this reason, costs are shown as a range for dense sand. For lighter materials (smaller than sand) costs become much greater than those shown because overflow losses are invariably greater.

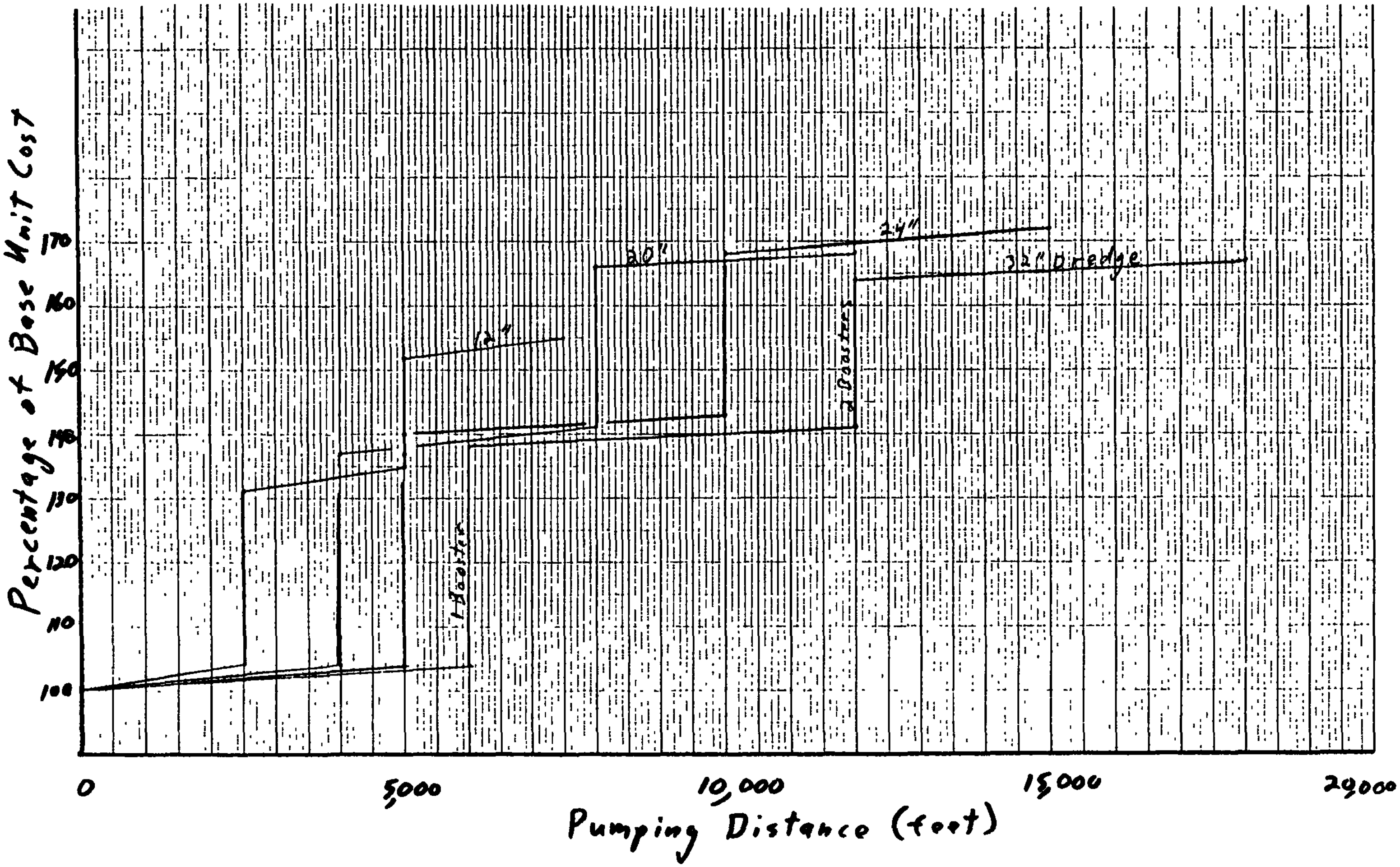
For long transport distances or for great volumes of material, where multiple dredges are employed, it should be noted that the number of tugs/barges can become unwieldly. For example, for a 12" dredge, 12 barges and four tugs are required to transport material about 100 miles, whereas for a 24" dredge, 12 barges and four tugs are required to transport material only about 25 miles.

6. Containment. Where the dredged material is to be disposed of on upland sites, the cost of construction and oeration of a confined disposal area is significant and could affect dredging costs.

Figure IV-M shows the percent of Base Unit Costs for various size dredges for a typical diked disposal

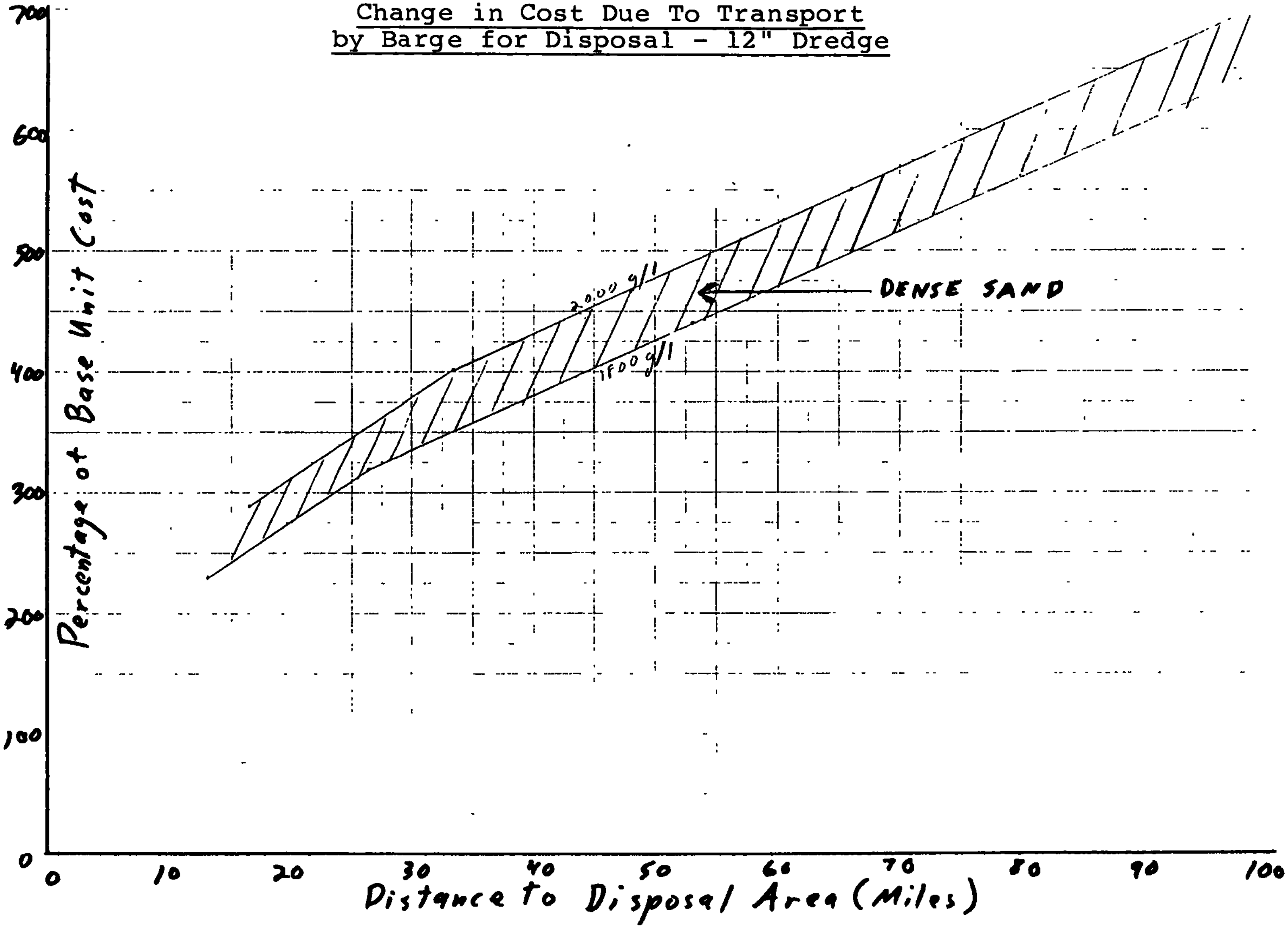
## Figure IV-J

## Change in Cost as a Function of Pumping with Up to Two Booster Pumps and No Decrease in Production Rate



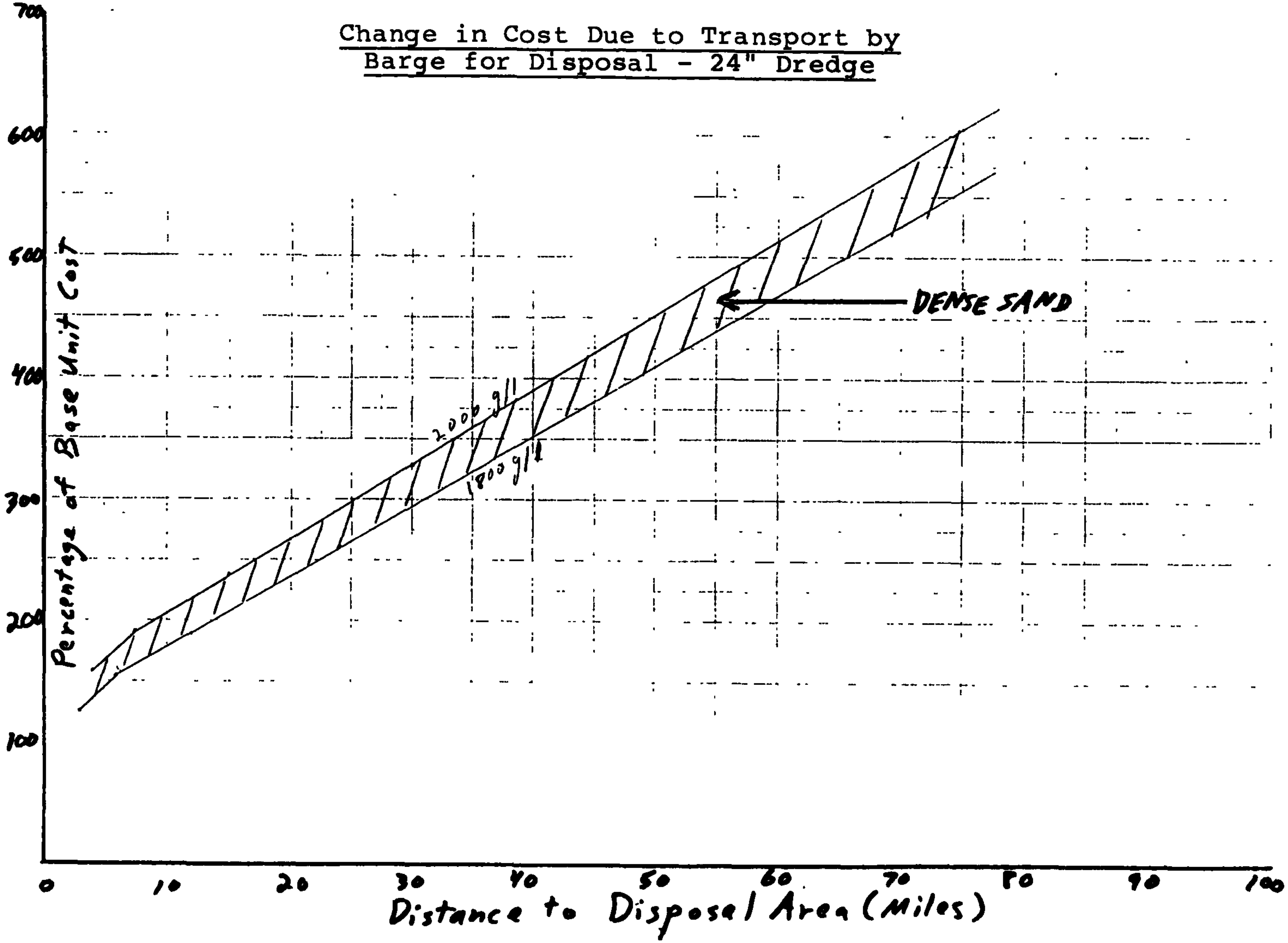
## Figure IV-K

### Change in Cost Due To Transport by Barge for Disposal - 12" Dredge



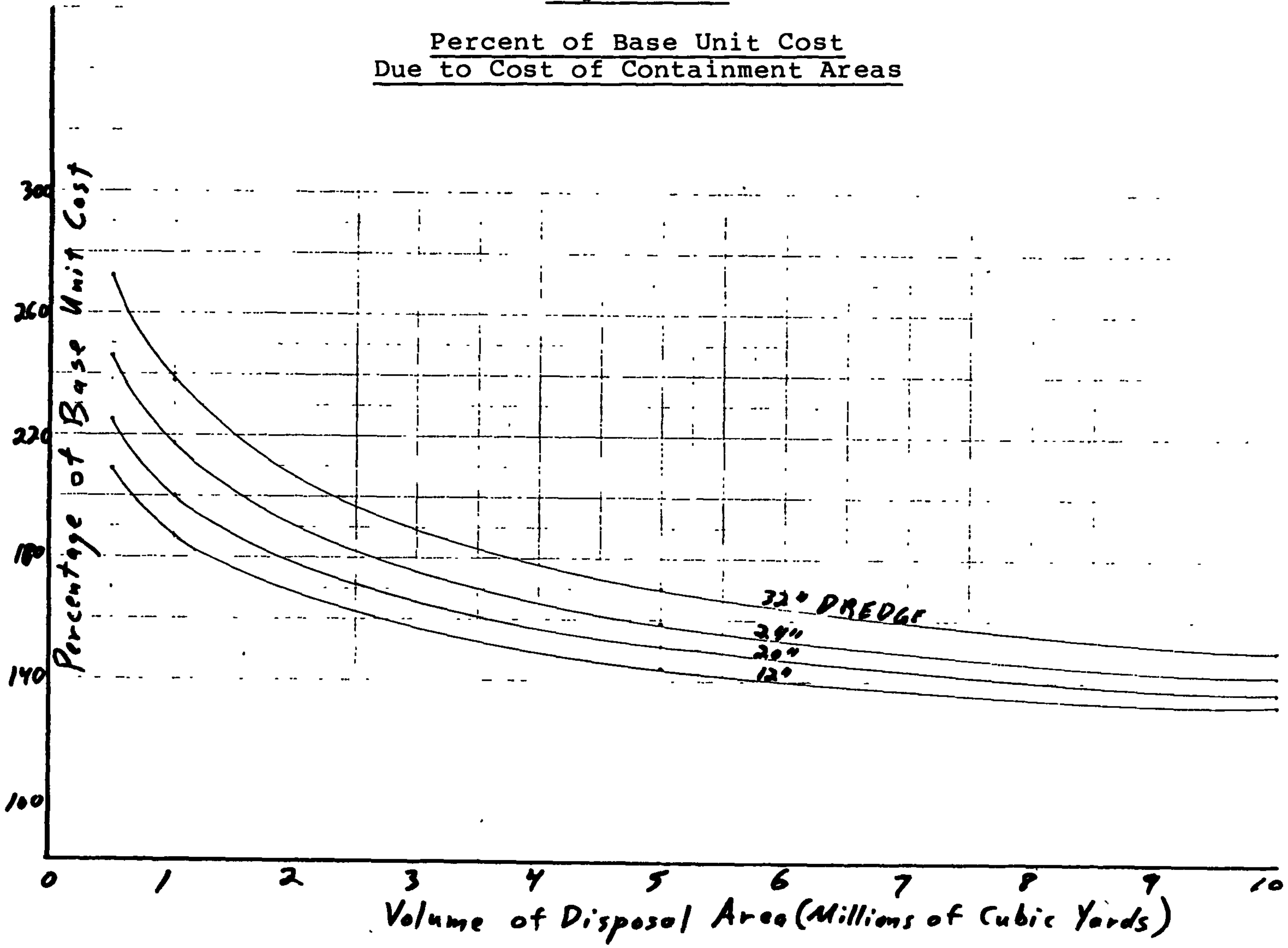
## Figure IV-L

## Change in Cost Due to Transport by Barge for Disposal - 24" Dredge



## Figure IV-M

## Percent of Base Unit Cost Due to Cost of Containment Areas



area. The major variable influencing the unit cost is the capacity of the area, (the density of the slurry also affects the cost of confinement but is not included in this simplified model). The cost of confining dikes, the dominant expense per confined acre, decreases as the area of the site increases, introducing an economy of scale.

The items of confinement cost included in Figure IV-M are:

(a) construction of confining dikes, spillways and weirs.

(b) site preparation (clearing, scarifying and grading).

(c) drainage features.

(d) monitoring well installation

(e) seeding.

(f) geophysical and engineering studies.

The confining dikes were assumed (for the purpose of this model) to be 15 feet high with slopes of 2.5 horizontal to 1 vertical.

''With the exception of the costs for confining dikes, unit costs were obtained from the "Dredged Material Research Program," [32] Technical Report D-77-33. The cost of confinement material was assumed to be $4.00 per cubic yard. At a particular site, thecost of confinement material should be evaluated based on the distance the material must be hauled to the site.

The cost of real estate and right-of-way acquisition is not included.

<u>7. Mobilization</u>. The total costs of dredging a particular project must also include the cost to mobilize and demobilize the dredge plant. The time required for mobilization and demobilization depends on the distance of the dredge from the dredge site prior to commencement of work and on the distance of the dredge from wharfage or the next project (transfer between works). The extent to which this factor affects the Base Unit Cost depends on the total project volume to be dredged.

Assuming that two days is a reasonable period required for mobilization, Figure IV-N presents the percentage of Base Unit Cost due to mobilization as a function of project volume.

### (c) Dustpan Dredges

1. Factors Which Affect the Cost of Dredging. Dustpan dredges generally are restricted to inland river usage. In the United States they are used mainly on the Mississippi and Missouri Rivers where the bottom material is generally granular (sand).

The annual cost of operating a dustpan dredge includes the same factors as described under "Factors Which Affect the Cost of Dredging" for hydraulic cutterhead dredges. The current Corps fleet includes eight dustpan dredges, of which five are in service. In addition, one contractor owned dustpan dredge was placed into service in 1979.

In order to determine the cost of the dredging operation, both the hourly operating cost and the production rate of the dredge must be known. While the operating cost can be readily determined, the production rate depends almost entirely on the Effective Working Time.

2. Effective Working Time. The dredging period each year is determined by the hydrological properties of the river, but on an average, is about six months. The total Rental Time is therefore assumed to be six months. The definition of Effective Working Time and the elements of Non-Effective Working Time described for hydraulic cutterhead dredges also apply to dustpan dredges.

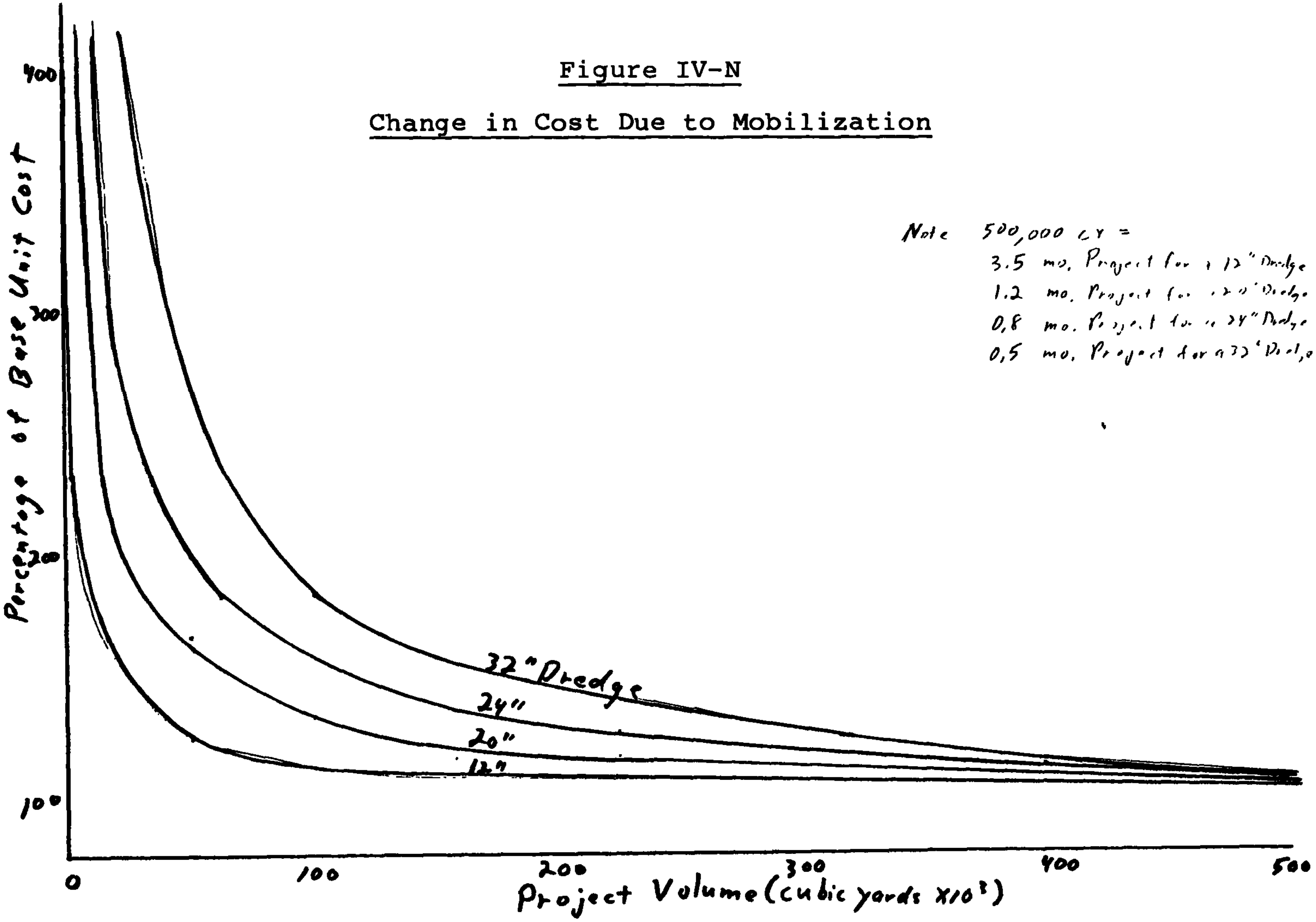
For all subsequent analyses for dustpan dredges, the Non-Effective Working Time is estimated to be 200 hours per month. The dredges operate generally on a seven day per week schedule.

Since the type of the material dredged is free flowing sand, 1800 to 2000 g/l, and the pumping rate is independent of the depth of the cut, the production rate is mainly a function of the Effective Working Time.

The effect on unit dredging costs of those factors which act to increase Non-Effective Working Time can be determined from Figure IV-G.

## Figure IV-N

## Change in Cost Due to Mobilization



Note 500,000 CY =
3.5 mo. Project for a 12" Dredge
1.2 mo. Project for a 20" Dredge
0,8 mo. Project for a 24" Dredge
0,5 mo. Project for a 32" Dredge

In general, the effect of allocation of dredging between multiple dredging sites is not an issue because it is a stable parameter on most waterways and not expected to be a variable under NWS Scenarios. The exceptions to this generalization, in our opinion, are those waterways where the construction of river training works has had the effect of reducing the number of sites requiring dredging. These waterways are primarily those maintained by dustpan dredges. The unit cost of dredging per cubic yard on these waterways would be reduced due to a reduction in the Non-Effective Working Time spent traveling between sites. To provide an estimate of the change in Non-Effective Working Time as a result of this phenomenon, Figure IV-O is included. The figure can be used together with Figure IV-G to determine the change in the Base Unit Cost.

### (d) Hopper Dredges

1. Factors Which Affect the Cost of Dredging. While there are several possible types of disposal using hopper dredges, such as agitation, pump-out and side casting (for those dredges equipped to side cast), for the purposes of this study, only conventional loading, hauling and bottom dumping operations are considered. The type of material pumped is assumed to be relatively retainable and pumping beyond overflow is permitted.

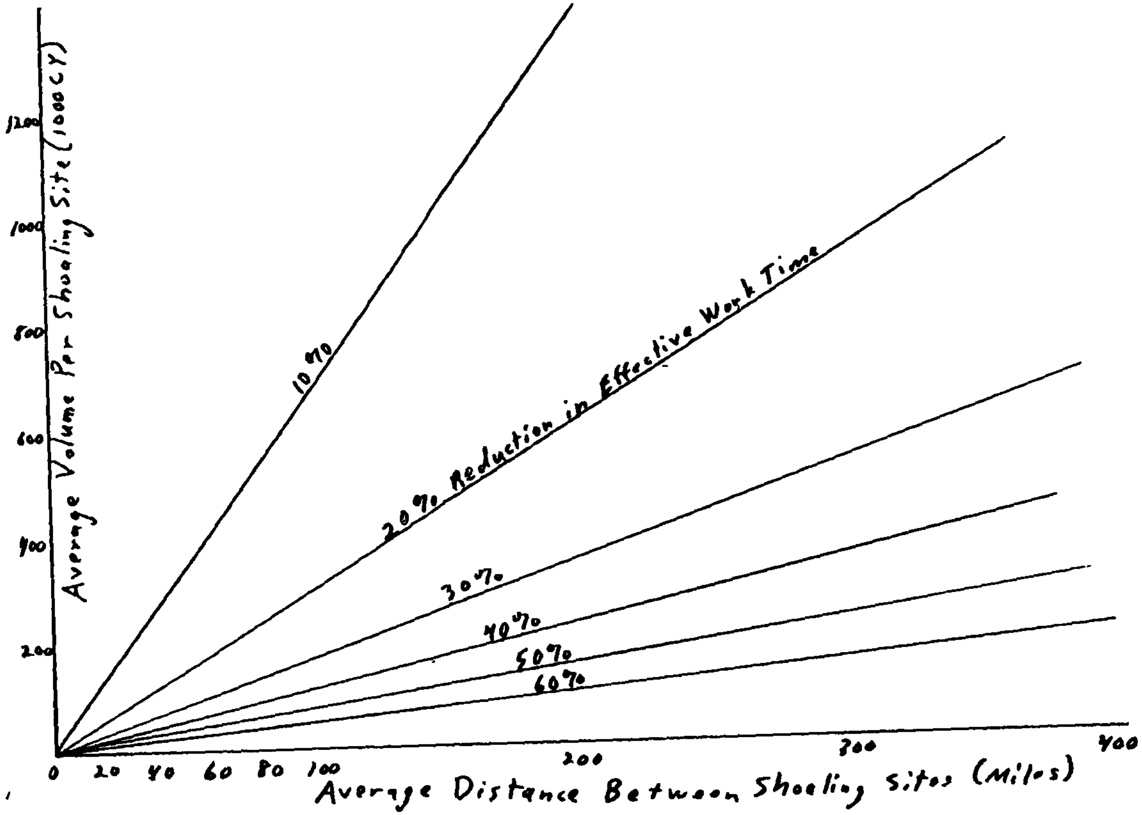
The cost of operating a seagoing hopper dredge includes factors similar to those as described under "Factors Which Affect the Cost of Dredging" for hydraulic cutterhead dredges. The current Corps fleet includes hopper dredges of a variety of hopper capacities varying from 500 cubic yards to over 8000 cubic yards. There are two contractor owned self-propelled hopper dredges in operation at this time and several others under construction or planned for the near future.

In order to determine the cost of the dredging operation, both the operating cost and the production capabilities of the dredges must be known. While the operating costs are readily obtainable, the production rate depends on the Effective Working Time and Haul Distance.

The following sections are devoted to determining the variation in the cost of dredging per cubic yard as a function of these factors.

## Figure IV-O

## Reduction in Effective Work Time as a Function of Distance Traveled Between Sites - Dustpan Dredge



2. Effective Working Time. Hopper dredges are usually utilized on a continuous year-round basis (except for time lost for shipping, overhaul and major repairs) with a seven day per week operation.

Effective Working Time is defined as that part of the total Rental Time spent pumping, turning, traveling to and from the dump and dumping. Non-Effective Working Time includes time:

(a) taking on fuel and supplies.

(b) transferring and from wharfage or anchorage.

(c) lost due to opposing natural elements.

(d) making minor operating repairs.

(e) transferring between works.

(f) for lay time.

(g) for drills.

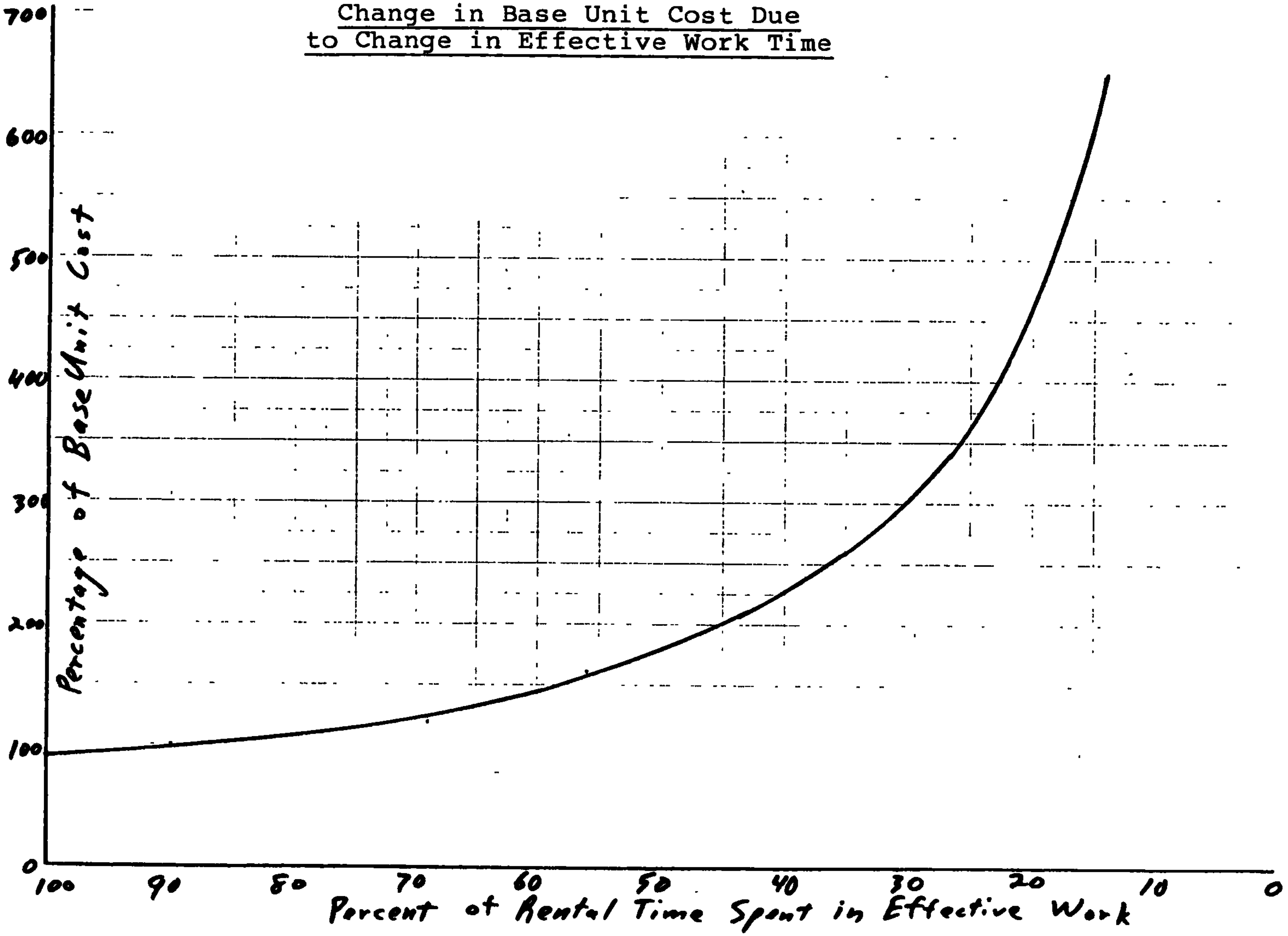
The elements associated with Non-Effective Working Time should be dealt with individually for each site as they depend upon the site conditions. For the purposes of this study, however, the Non-Effective Working Time is assumed to be 10% of the Rental Period. Figure IV-P shows the change in the cost of dredging as a function of changing the Effective Working Time.

3. Haul Distance. Figure IV-Q shows the production as a function of haul distance for various hopper capacities. Figure IV-R was prepared based on Figure IV-Q and shows the percent of Base Unit Cost as a function of haul distance. Figure IV-R is valid for all size dredges for the conditions assumed below.

The average speed of Corps seagoing hopper dredges has been conservatively assumed at 10 mph. In each case, the average load is assumed to be 70-80% of hopper capacity. In addition, pumping and turning time has been assumed to be an average of 60 minutes, and an average dumping time of 10 minutes has been assumed.

Figure IV-P

Change in Base Unit Cost Due to Change in Effective Work Time



## Figure IV-Q

## Haul Distance as a Function of Production Rate

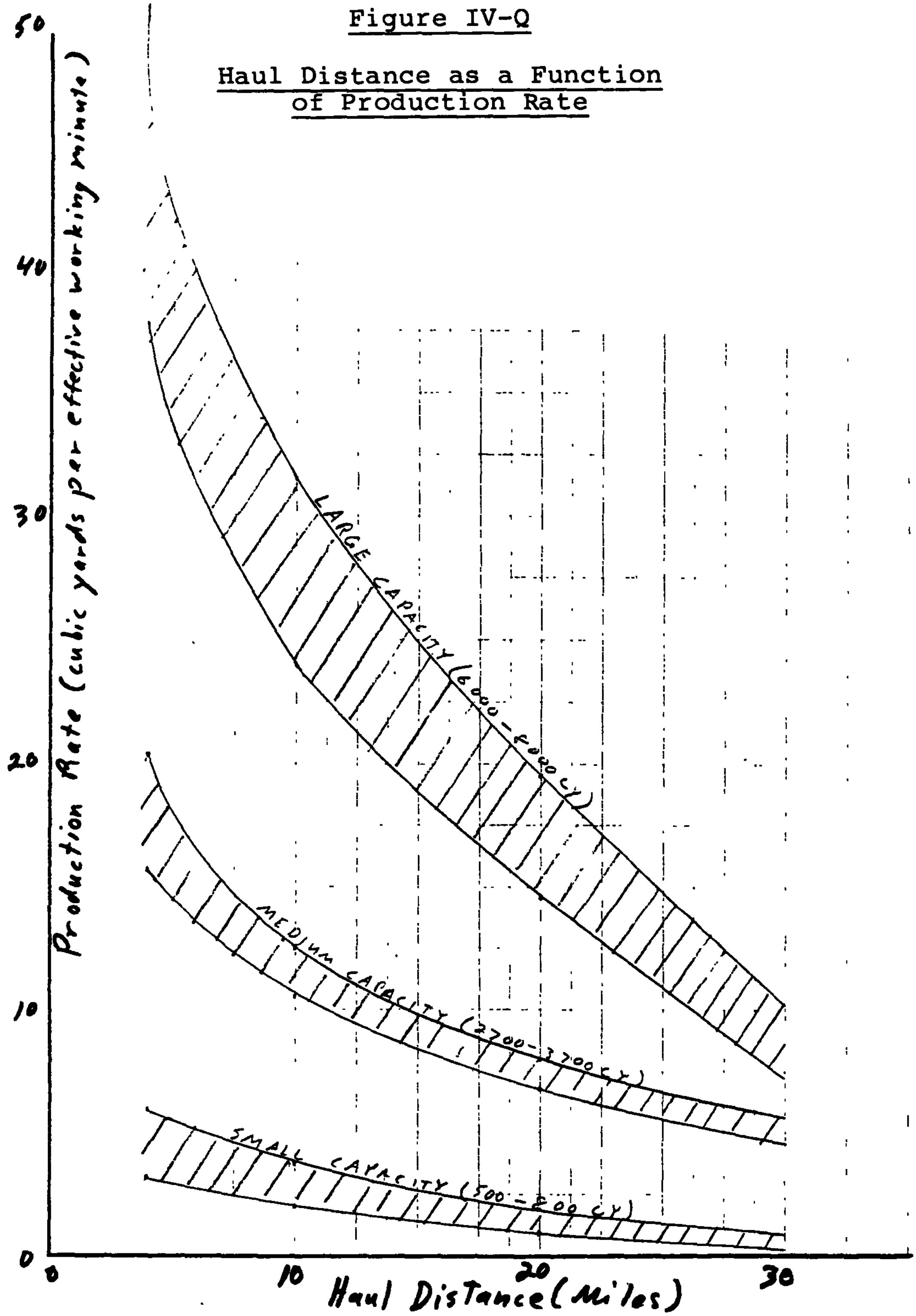
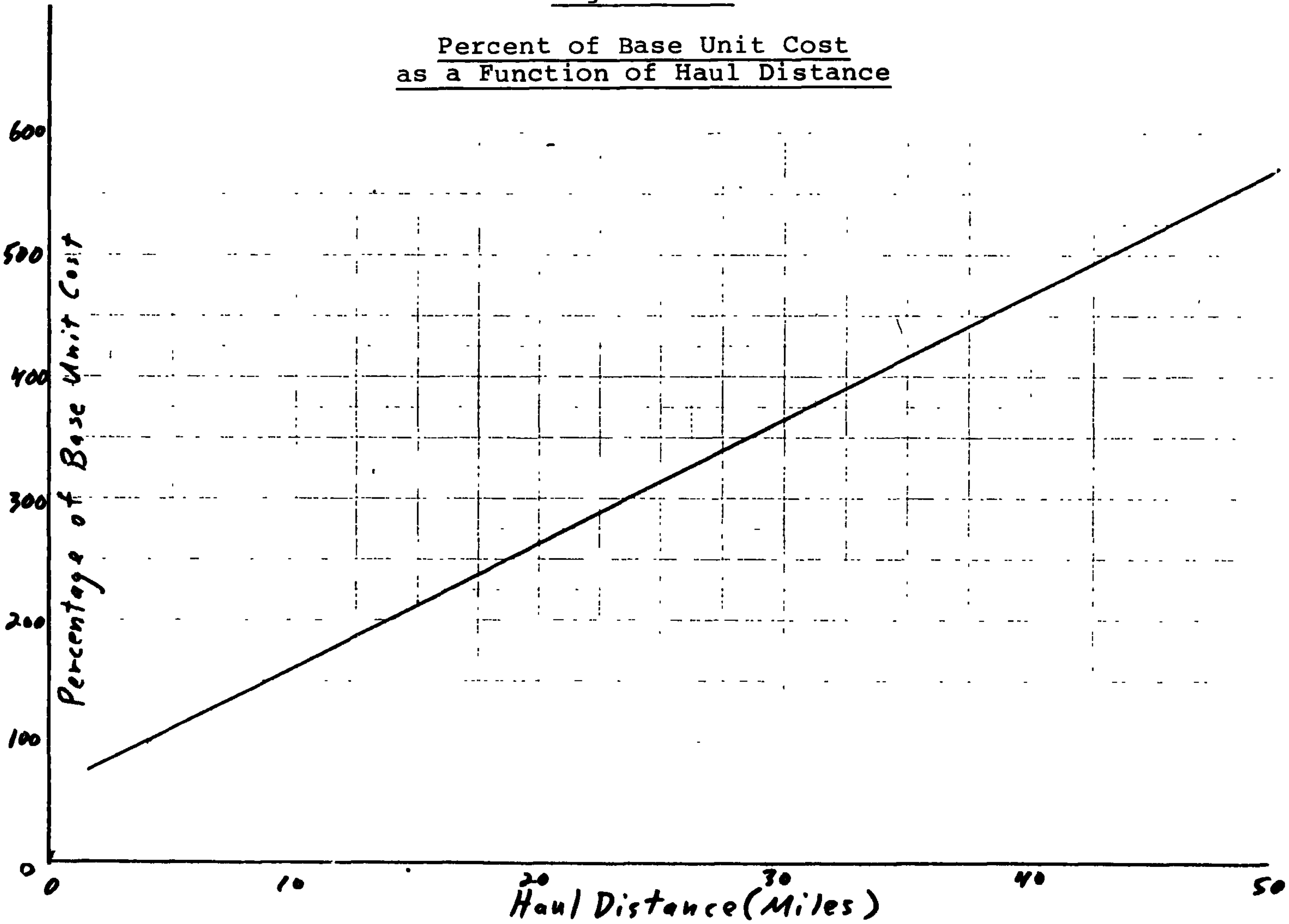


Figure IV-R

Percent of Base Unit Cost
as a Function of Haul Distance



## ALTERNATIVES FOR CHANNEL IMPROVEMENTS

The purpose of this task is to define and evaluate the technical and economical feasibility of alternative channel maintenance programs for those segments where channel problems now, or may in the future, create navigational difficulties.

Input to this task was derived primarily from reports or studies published by the various District Offices of the Corps of Engineers. These reports included feasibility studies, environmental impact statements for proposed channel work, design memoranda, research studies and interviews with Corps experts. The various reports differed considerably with respect to content, depth of detail, and purpose which limited the uniformity of presentation for individual segments within this section. The information available was generally more qualitative than quantitative with respect to channel improvement alternatives. Where available, quantities associated with channel maintenance, initial and annual costs, and estimated benefits are presented for all cited alternatives. Where sufficient information exists, the interrelationship between dredging volumes, flows, and morphological features of a segment is analyzed in order to estimate future dredging requirements associated with anticipated changes in channel maintenance criteria.

As previously stated, because there is no commonly accepted analytical method to evaluate dredging reqirements resulting from modification of channel dimensions in order to evaluate strategies directed towards channel improvements, the only available method of assessment is evaluation of existing projection for channel improvements prepared by the Corps.

All segments are discussed except thosennot having authorized inland waterways or containing one of the ten major coastal ports.

### (a) Existing Projections for Project Improvements, Measures and Costs

1. Reporting Region 1 - Upper Mississippi River. A 1972 study entitled "Mississippi River - Illinois Waterway 12-Foot Channel Study, Phase I Report[33] prepared under the auspices of the North Central Division in Chicago, Illinois evaluated several alternatives to improve navigation on the Upper Mississippi River. (The alternatives presented by the study are not currently being pursued or considered further.)

The reaches of the Mississippi River addressed by the study were those from Cairo, Illinois to Grafton, Illinois and from Grafton to Minneapolis, Minnesota, in addition to the Illinois Waterway from Grafton to Chicago, Illinois. The portion of the report germane to this segment of the work element concerns the slackwater reach from Grafton to Minneapolis.

The alternatives pertaining to physical improvement of the uppermost reach of the Mississippi River included:

(a) Additional locks.

(b) A 12-foot channel.

(c) A combination of additional locks and a 12-foot channel.

The subject of existing and projected lock capacities and future requirements is discussed in Section III and will not be addressed here except to note that the Additional Lock Alternative reviewed in the referenced Phase I study had an economically viable annual benefit/-cost ratio of 1.3.

The 12-foot channel alternative does not appear viable for either of the two following pool options. Option One necessitates lowering the sills of existing locks and dredging the pools to the required depths. Since many of the sills have pile foundations, structural instability may result if modifications are attempted. In addition, significant navigation delays would occur during the modification work. The second pool option involves raising the pool levels by three feet to provide the additional channel depth. This option is opposed by a number of private and quasi-governmental agencies which are located along the river as it could increase the flood hazard situation.

The combination alternative considers the construction of new locks to accommodate the 12-foot channel and dredging the pools to provide the necessary depth. The cost to deepen the Mississippi River in Segment 1 was estimated to be $218,590,000 (1977 dollars) with an average annual maintenance cost of $19,485,000 (1977 dollars) in the 1972 Mississippi River - Illinois Waterway 12 Foot Channel Study. Deepening would be achieved by dredging. The alternatives presented by the study are not currently being pursued or considered further. It was estimated that 23,000,000 cubic yards of material would have to be removed over 20% of the river length in the segment. Judging from the cost, the annual dredging volume would probably be in the order of 10,000,000 cubic yards.

Rock excavation in two pools (Pools 15 and 18) on the Upper Mississippi was considered as a necessary condition for improving navigation conditions for season extension in the report "Economic Analysis of Year-Round Navigation on the Upper Mississippi." These reaches are restrictive under normal conditions. The cost of rock excavation in these pools was put at $25,600,000 in 1979 dollars (about $21,000,000 in 1977 dollars). This cost is also included in the estimated cost of navigation season extension for Segment 1. Again, the feasibility of new lock construction is addressed in Section III and will not be repeated here. However, it should be noted that the provision of new locks makes the option to deepen the pools to 12 feet a more viable alternative. The average annual maintenance cost would be 19,485,000.

Although historically the reliability of channel maintenance in providing a 9 foot depth has been satisfactory, some concern has been elicited by environmental interests with respect to the quantity of material dredged annually on the Upper Mississippi River.

Based on the results of the GREAT study the Commercial Transportation Work Group has issued the following recommendations with respect to maintenance of channel dimensions.

(a) The channel should continue to be maintained, preserved, and expanded to meet current and future barge needs of vessels with 9-foot drafts.

(b) GREAT should acknowledge that the guidelines and standards for channel maintenance as historically practiced by the Corps of Engineers have provided an adequate navigation channel for 9-ft. draft vessel? and before any deviations from these practices are implemented, the following potential impacts must be considered: risk of grounding transit time, fuel consumption, cargo capacity, and dredging and disposal costs.

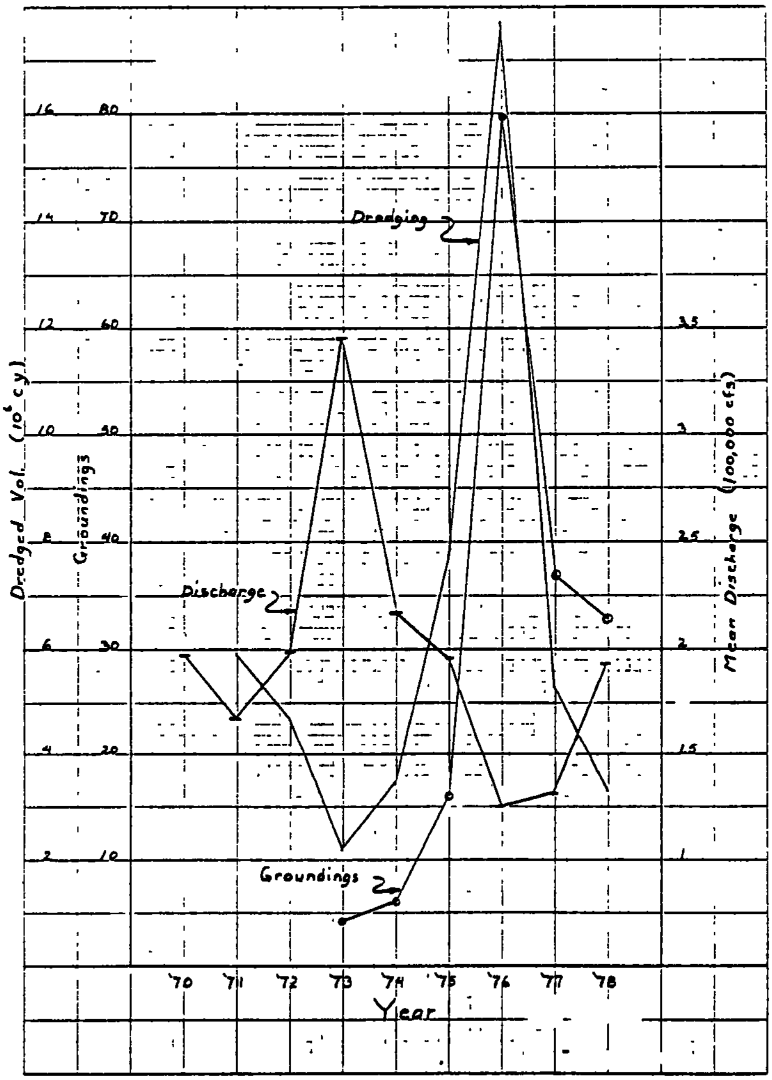
(c) Congress should define the Mississippi River 9 foot navigation project as "including allowances required for advance maintenance dredging, dredging tolerances, squat and trim for the class of vessel for which the project was designed, wave action, shoaling rates, and other overdepth allowances necessary to afford safe navigation for vessels with a draft of 9 feet."

2. Reporting Region 2 Lower-Upper Mississippi. As indicated under "Current Maintenance Programs " shoaling and occasional loss of the authorized nine foot minimum channel depth can be a periodic problem on this reach of the Mississippi River. Data obtained from the GREAT Study indicate that a significant increase in the number of groundings occurred during the low-flow year of 1976 despite intensit]e maintenance dredging efforts by the St. Louis District see Figure IV-S). The low flow problem appears to be amplified by the duration reliability of the LWRP (93%) which is somewhat lower than normal for the Mississippi River and may need to be redefined.

Although studies evaluating alternative solutions to the above conditions have not been completed at this time, the Commercial Transportation Work Group of the Great River Environmental Action Team (GREAT III) is assessing the problem.

## Figure IV-S

## Dredging-Discharge-Groundings Reporting Region 2, St. Louis Gauge



In GREAT III it was emphasized that channel maintenance in an open flow river is more critical than in pooled portions of the river because of greater river currents and more frequent shoaling. Reduced depth dredging has already proven to be less than satisfactory by GREAT I due to the adverse effects on navigation and the fact that 34.1 percent of the sites required dredging more frequently than prior to implementation of the reduced dredging program. In addition to the constraints imposed on barge traffic by channel designs and maintenance, the GREAT Work Group is concerned with the effects of inadequate locking capacities on commercial navigation and the lack of adequate fleeting areas. They have defined their planning objectives to:

(a) insure sufficient channel width and depth to provide for the safe and efficient passage of nine foot draft vessels.

(b) minimize the physical constraints to navigation caused by locks, bridges and other impediments.

(c) insure the availability of suitable areas for the development of terminals and fleeting areas to meet the present and future needs of water transportation.

(d) identify and evaluate the effects of commercial transportation activities for their social, economic and environmental beneficial or adverse impacts.

In order to accomplish these objectives, the work group recommends implementation of a series of studies defined as follows:

(a) A literature search to identify and correlate existing information concerning channel designs and their effect upon vessels with respect to the economics and safety of vessel operation.

(b) A study to determine which docks, terminals and harbor areas are experiencing access problems and possible solutions to identified access problems.

(c) Identification of the constraints to marine traffic caused by bridge clearances and other impediments as well as the existing or potential economic impacts and possible solutions.

(d) A study to determine the quantity, capacity and location of fleeting areas to meet the future needs of water transportation. A second phase of this study would be to determine the economic effect if fleeting areas are denied or not properly located.

The above investigations are to be performed as part of the second stage of the GREAT III planning process. Alternative solutions will be evaluated and the most viable options will be retained for detailed analysis. The third study will provide the vehicle for selection of a final plan through a comparison of technical, economic, social and environmental parameters of the stage two alternatives.

These evaluations should be conducted in conjunction with existing and ongoing studies germane to the problem area, including the draft report recently prepared by the Vicksburg District Corps of Engineers concerning the feasibility of a minimum 16 foot channel depth on the Mississippi River.

3. Reporting Region 3-Lower Mississippi. Channel depth reliability and dredging/hydrological relationships for the Lower Mississippi River have been documented under "Current Maintenance Programs." The presently authorized 12-foot channel depth project is not yet complete and has an eight year average duration reliability of about 78% between Baton Rouge and Cairo. While the 12-foot depth is provided the greater part of the time, the Corps of Engineers'primary intent is the maintenance of a nine foot channel and the low water plane is referenced to this latter depth. Although the 12-foot channel depth was authorized in 1944, where it is attained, it is a byproduct of the stabilization program scheduled for completion in 1995. Construction scheduling and completion of based on funding of $40,000,000 to $57,000,000 for Fiscal Year 78 through Fiscal Year 82 and $79,000,000 per fiscal year thereafter.

A draft reconnaissance report (October 1979) has been prepared for the Mississippi River from Cairo to Baton Rouge. The purpose of the report is to determine the economic feasibility of providing a navigation channel with greater dimensions than now authorized. While the data in the report are subject to revision, preliminary estimates indicate that dimensions grater than authorized for the Baton Rouge to Cairo reach of the is not cost effective at this time.

The study area was divided into segments to establish the upstream limit of the project's feasibility. Thus, initial construction and annual maintenance costs were developed for the reach from Baton Rouge to Natchez, Baton Rouge to Vicksburg; Baton Rouge to Greenville; and Baton Rouge to Memphis. Due to limited port development between Memphis and Cairo, no improvement was evaluated for that segment of the river. Two alternatives, a 16 foot by 30 foot channel from Baton Rouge to Cairo and a 40 by 500 foot channel from Baton Rouge to Natchez for use use by ocean-draft vessels.

The cost-effectiveness of the 16 by 300-foot channel was determined assuming shippers would phase in the use of 16-foot draft barges upon completion of the project. Benefits would accrue from increased tow speeds and a 30 percent greater barge capacity with the use of the deeper draft vessels. Since the required savings per ton to make the project feasible were owest for the Baton Rouge to Memphis reach, the benefit/cost analysis was limited to this segment with the rationalization that if this reach were unfeasible, the shorter segments would likewise be nonviable options. The transportation savings for this reach, when compared with the initial and annual costs over a 50-year project life, were found to have a benefit/cost ratio of only 0.6 indicating the project is economically unfeasible. Further sensitivity analysis considered the effect that the transference of some commodities from rail to water transportation might have on the benefit/cost analysis. Diversion of 25% and 50% of rail transported commodities adaptable to water transport only increased the benefit cost ratio to 0.7 and 0.8, respectively.

4. Reporting Region 4 - Baton Rouge to Gulf. The 1970 report "Ship Channel Capabilities for Merchant Vessels in United States Deepwater Seaports Trhough the Year 2000 - Gulf Region" reported a proposed improvement to the MRGO. The MRGO would be deepened to 50 feet and widened to 750 feet. Current project dimensions are 36'x 500'. The project (which also included port improvements) was estimated to cost about $115,000,000 (1977 dollars) including $80,000,000 (1977 dollars) for the dredging of 340,500,000 cubic yards of material. The increase in annual maintenance for the project was estimated to be on the order of $830,000 (1977 dollars) per year. To the project to deepen the MRGO would also have to be added the cost of a new lock at Inner Harbor, as this is considered to be a necessary improvement if traffic is shifted from the Head of Passes route to the MRGO. The cost of a 1200'x110' lock for 12 foot draft vessels would be on the order of $45,000,000 assuming conventional construction. The cost would be about $220,000,000 for a lock for 45 foot draft vessels (reference Figure III-Y).

A preliminary estimate of the cost of deepening the Mississippi River from New Orleans to the Gulf to a depth of 55 feet has been made by the New Orleans District as part of an ongoing deepening study. The study is not scheduled for completion for some time. Current project depths are 40 feet. The cost to deepen the river to 55 feet from mile 127 north of the Head of Passes to the Gulf by way of Southwest Pass was estimated to be $206.000.000 and involves 17,800,000 cubic yards of dredging in the River and 62,500,000 cubic yards of dredging in the Southwest Pass. Annual dredging volumes after deepening to 55 feet are expected to increase by 15,200,000 cubic yards in the river and 15,300,000 cubic yards in the Southwest Pass at a total estimated cost of $40,000,000 including 25% contingency. The project includes river training works in the Southwest Pass area. Costs are in 1980 dollars but can be reduced to 1977 dollars by dividing by about 1.3.

Deepening from Baton Route to the Gulf (to 55 feet), was estimated to cost $400,000,000 with an increase of $75,000,000 in annual O & M, in 1980 dollars.

It should be noted that the cost of dredging for deepening the Head of Passes is about $1.30 per cubic yard in 1980 dollars (i.e., about $1.00 per cubic yard in 1977 dollars) according to the Corps estimate. However, the cost of dredging to deepen the MRGO was estimated to be about $0.25 per cubic yard (1977 dollars). If dredging to deepen the MRGO is assumed to cost $1.00 per cubic yard the cost of the project would increase from $115,000,000 to $375,000,000.

5. Reporting Region 5-Illinois River. Review documents utilized in evaluating channel improvement alternatives for the Illinois Waterway include Duplicate Locks GDM Phase I, A Plan For Modernization of the Illinois Waterway[34] April 1975 by the Chicago District Corps of Engineers and a joint study by the North Central Division in Chicago, Illinois, and the Lower Mississippi Valley Division in Vicksburg, Mississippi, United States Army Corps of Engineers, entitled Mississippi River - Illinois Waterway 12 Foot Channel Study, Phase I Report which was submitted in 1972 and revised in May 1973. The latter report was prepared to consider the engineering, economic, environmental and social feasibility of increasing the navigation depth on the Illinois Waterway and Upper Mississippi River to 12 feet. Those portions of the study which pertain to existing and alternative methods of channel maintenance, river morphology and hydrological conditions on the Illinois Waterway are reviewed below, although the alternatives presented in the study are not currently being pursued.

The Illinois Waterway is a connecting link between the Great Lakes and the Mississippi River. A nine-foot deep channel is provided by a system of seven locks and dams and dredging. A 12-foot channel presently exists for some reaches of the Chicago Sanitary and Ship Canal from Calumet - Sag Junction to Lake Michigan. The 12-foot Channel Study considers deepening and widening the Illinois Waterway from Grafton to Lake Michigan via the Calumet-Sag Channel to new channel dimensions of 12 by 300 feet. Optional plans to provide a 12-foot channel on the Illinois Waterway include raising the level of the pools, dredging, or a combination of the two methods. New Locks authorized for construction would have adequate sill clearance for a 12-foot channel.

As indicated under "Current Maintenance Programs", high spring floods on the Illinois Waterway frequently necessitate travel restrictions and occasionally cause navigation to cease entirely in order to protect the levees. In order to minimize these and other environmental constraints as well as reduce initial cost, only the dredging pool plan option is considered feasible for the development of a 12-foot channel.

The dredge plan option entails dredging a channel 12 feet deed to a 300 foot width with a greater width in bends. It is estimated that initially 21,000,000 cubic yards of material would have to be removed at a cost of $174,000,000 (1977 Dollars), and the average annual maintenance charges would be $14,310,000. Annual benefits would be realized from deepening the waterway, primarily as a result of up to 30% increases in barge capacities and increased speeds and shorter travel times on the waterway.

However, deepening of the Illinois Waterway was con- sidered viable when combined with deepening of the Upper and Middle Mississippi River, (total cost $2,417,-270,000) or with the deepening of the Mississippi between Ohio and Illinois Rivers (total cost $791,760,000); costs again are in 1977 dollars.

Four plans consisting of various combinations of the alternatives were evaluated. The plan selected for implementation included removing the existing Brandon Road lock and dam; lowering the existing navigation channel upstream of Brandon Road through the city of Joliet to Lockport a total of 35 feet; constructing a new high lift (73 feet) lock, 1,200 feet long by 110 feet wide; and a new dam and controlling works near the existing Lockport lock and dam. A high lift recreation lock, 200 feet long by 40 feet wide, at the Lockport site and a 150-barge temporary fleeting area upstream of the new 1,200 foot lock would also be provided. New high level fixed bridges, having a 46.9-foot vertical clearance, would be provided at Caton Farm Road and Brandon Road. New fixed bridges, at or near their present elevations, would be constructed at Ruby Street, Jackson Street, Cass Street, Jefferson Street, the Chicago Rock Island and Pacific Railroad crossing and McDonough Street. The Sixteenth Street bridge would be removed. The piers of the Interstate 80 and Elgin, Joliet and Eastern Railroad bridges would be modified to accommodate the lowered waterway.

A 325 foot wide bypass channel would be constructed east of the existing navigation channel from mile 285.3 to Brandon Road Dam. New supplemental locks 110 feet wide by 1200 feet long would be constructed at the Dresden Island, Marseilles, Starved Rock, Peoria, and LaGrange sites.

Initial cost estimates for the recommended improvements are depicted on Table IV-32. Benefits from the project would result from increased traffic capacity on the waterway as well as decreased traffic congestion and delay.

The 1975 "Illinois Waterway Duplicate Locks" GDM estimated the cost to provide 1200'x110' locks on the Illinois Waterway and improve navigation conditions. Part of the project included channel improvements including channel widening. The total cost of channel improvements was estimated to be $159,570,000 in 1974 dollars (about $200,000,000 in 1977 dollars). The report specifies $22,500,000 for widening Brandon Road Poll and $2,700,000 for widening Marseilles Pool but does not specify the improvements proposed for the remainder of the costs (these values would be about $28,000,000 and $3,500,000 in 1977 dollars).

6. Reporting Region 6-Missouri River. The Missouri River is authorized for a 9 x 300 foot channel from Sioux City, Iowa to its confluence with the Mississippi River near St. Louis. The navigation project, which is 98% completed, is a continuous open-river type with a navigation channel that has no lockages or pooled areas within the project limits. The controlling dimensions on the lower one-third of the river is (8.5 x 250 feet and reouires additional improvements.

Flows on the river are maintained, during the eight month ice-free navigation season, by a system of six large main stem Reservoirs upstream of Sioux City. The actual length of the navigation season is predicated on the amount of upstream storage available at the start of the season. Winter releases normally range from 15,000 cfs to 20,000 cfs to maintain downstream river stages and provide winter power generation. A minimum of 6,000 cfs is required to preserve downstream water quality. Reservoir releases are increased in the spring to provide the flows necessary to evaquate flood flows and provide adequate flow for downstream navigation.

A discharge of 31,000 cfs at Sioux City with targets ranging up to an additional 10,000 cfs at downstream locations is generally considered to be the design flow necessary to maintain the authorized channel dimensions upon project completion. However, a minimum flow of 6,000 cfs less than the above targets would also permit

## Table IV-32

## Estimated Cost of Recommend Plan*
(X $1,000)

| Lock Site | Lands & Damages | Relocations | Dams | Locks | Roads & Bridges | Channels | Bldgs. & Grounds | Engin & Design | Supv & Admin. | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Lockport-Brandon Road | 15,485 | 72,579 | 10,056 | 91,566 | -0- | 135,431 | 509 | 18,609 | 21,710 | 365,945 |
| Dresden Island | 338 | -0- | 68 | 49,618 | -0- | 5,753 | 416 | 3,351 | 3,909 | 63,453 |
| Marseilles | 60 | -0- | 1,246 | 51,775 | 479 | 22,173 | 378 | 4,563 | 5,323 | 85,997 |
| Starved Rock | 146 | 941 | -0- | 52,974 | -0- | 14,382 | 388 | 4,121 | 4,808 | 77,760 |
| Peoria | 544 | 11 | -0- | 65,918 | 471 | 3,679 | 388 | 4,228 | 4,933 | 80,173 |
| LaGrange | 112 | 948 | -0- | 57,768 | -0- | 9,827 | 388 | 4,136 | 4,825 | 78,004 |
| TOTALS | 16,685 | 74,479 | 11,370 | 369,618 | 950 | 191,244 | 2,468 | 39,008 | 45,509 | 751,331 |

*Costs elevated to 1977 price levels

navigation although additional dredging would be required and a relatively high incidence of grounding could be expected. At present, groundings are infrequent but they are more likely to occur during the early portion of the navigation season which is believed to be due to the need for the river channel to adjust from the low winter releases to the higher level of the navigation flows. During the summer season, groundings may occur due to a combination of lowflows and temporary shoaling. The number of groundings may again increase in late fall due to rating curve shifts that result from colder water temperatures. The number of groundings however, has been minimal in recent years, and is expected to decrease as the channel responds to recently installed control structures.

The existing navigation problems and alternative solutions were addressed in Missouri River Bank Stabilization And Navigation Project, Final Environmental Statement (FES) Continuing Construction and Maintenance[36] prepared by the Missouri River Division, Corps of Engineers, July 1978. As of the date of that publication, completion of the project required the construction of about 50 new stabilizing structures and the modification of approximately 80 existing structures by the addition of L-heads or sills. The FES evaluated the impact of the projects continuation as well as alternative solutions for the multipurpose water requirements of the entire system.

Those federal actions necessary for the completion of the Missouri River Project include:

(a) The placement of rock on new and existing bank stabilization and channel maintenance structures;

(b) Dredging of river bed material from specific locations; and

(c) Disposal of the dredged material.

A summary of the significant beneficial and adverse effects of the project is presented as follows:

(a) Beneficial Effects:

Dikes, revetments and sills alter and maintain channel configuration to accommodate commercial waterway use.

Dredging assists in the maintenance of the channel configuration to accommodate commercial waterway use.

Continued maintenance of structures protects against bank erosion, thus maintaining the highest and best economic use of the adjoining lands.

Bank protection safeguards the numerous levees which provide a significant measure of flood protection from Missouri River flood waters.

Maintenance of dikes and revetments reduces the erosion of accreted lands and protects the riparian owner's use and occupancy of those lands.

Disposal of dredged material takes place within the river in areas of little or no agricultural economic value and not on adjoining lands of high agricultural economic value which would otherwise serve as disposal sites.

(b) Adverse Effects:

The maintenance of structures protecting against bank erosion prevents the river from forming additional shallow aquatic habitat and floodway storage.

Structure maintenance contributes to retention of river stages.

Continuing accretion behind structures inhibits development of a stable riverine vegetation community. Ultimately some of the accreted land will reach an elevation that will permit conversion to cropland. Stable riverine vegetation is more valuable wildlife habitat than cropland or riverine vegetation continually being covered by accretion.

> Use of new quarry rock to repair existing dikes and revetments destroys certain biological communities situated on old rocks and temporarily diminishes the rock structures' value as fish cover.

The alternatives to completion of the existing Missouri River bank stabilization and navigation project include:

(a) Termination of the navigation function of the project but retention of the bank stabilization function;

(b) Termination of all federal actions in support of navigation, bank stabilization, and recreation;

(c) Structural modification of the existing project design; and

(d) Changes in draft of towboats and barges.

It will be noted that, with the possible exception of modification of structural design, none of the alternatives addresses the existing navigational problems or satisfies the oroject objectives as authorized by Congress.

Maintenance dredging on the Missouri River has been almost non-existent since 1976 and, as the project draws near to the completion date, is expected to be eliminated entirely except for the most unusual of hydrologic conditions i.e. drought conditions existing for a period of three years or more. Accordingly, it is recommended that no significant alteration of the project's direction be made at this time. The flow regulation problems, future plans of multipurpose use of water and their impact on navigation should be addressed in Element G of the NWS.

7. Reporting Region 7-Ohio River. Monongahela River: The Monongahela River is presently authorized for a nine foot deep by 250 foot wide channel and except where constricted by bridges the controlling width of the river is 250 feet (the authorized width upstream of Lock 8 is 300 feet). Existing channel maintenance to provide the nine foot depth consists of dredging to remove bars, shoals and debris within the navigation pools, at the

mouth of tributary streams and at the lower approaches to lock channels. During the period from 1960 to 1974, annual dredging quantities at 21 sites ranged from 0 to 368,655 cubic yards with an annual average for the period of 78,200 cubic yards.

In October of 1975, the United States Army Corps of Engineers, Pittsburgh District published The Final Environmental Statement on the Operation and Maintenance of the Navigation System for the Monongahela River.[37] Within this report, the Corps evaluated the benefits and adverse impacts of the existing operations and channel maintenance procedures as well as possible alternative solutions to the existing plans.

The channel maintenance options evaluated included:

(a) a no-action alternative.

(b) a self-maintenance, river construction program.

(c) an alternative dredging methodology.

(d) alternative dredge spoil disposal methods.

A brief description of each alternative, their respective advantages and the adverse impacts associated with each is presented on Table IV-33.

In addition to the channel improvements described in Table IV-33, the EIS considers navigational improvements such as the replacement of Locks and Dams 2, 3 and 7, and Locks 4 and 8.

Locks 2, 3, 4, 7 and 8 are being studied as part of the Monongahela River Navigation Study. Locks 7 and 8 have passed the advanced engineering and design phase. While implementation of the structural replacements will have a high initial cost, the present operational constraints on capacity will be reduced as will be lockage time. This subject was addressed in Section III.

Allegheny River: The authorized channel dimensions of the Allegheny River are 9' x 250'. At present, channel maintenance consists of dredging to remove sand

# Table IV-33

## Alternative Channel Maintenance Procedures
## Monongahela River

| OPTION | DESCRIPTION | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|
| No-Action | Complete and immediate cessation of all operation and maintenance activities on the Monongahela River. | Implementation of this option would result in elimination of the $3,900,000 annual Federal expenditures for the project, improvement of air and water quality, and enhancement of the environment in the vicinity of the river. | Implementation of this option would include eventual cessation of all commercial navigation on the river with its attendant economic losses; alteration of the social fabric of the region due to industry closures and loss of employment opportunities; and increased transportation costs. |
| Self-Maintenance Structures | This option entails the construction of spur dikes or groins to concentrate river flows in problem shoaling areas. | Implementation of this option would reduce or eliminate maintenance dredging and its associated cost and impacts. | Disadvantages of this option include poor applicability due to a lack of recurrent shoaling problem areas, potential creation of unfavorable current conditions; and destruction of aquatic habitat at the site and downstream of the structures |
| Alternative Dredging Methodology | Conversion of dredging operations from clamshell to hydraulic equipment. | The implementation of hydraulic dredges can result in faster more efficient operations, lower unit costs, and single-handling of the dredged material | Dredging requirements are insufficient for efficient hydraulic operations; suitable disposal areas are often unavailable within reach of areas to be dredged; material in the Monongahela River is frequently too large for effective use of hydraulic equipment; mobilization costs for the nearest Corps dredge would be prohibitive; and land disposal would require excessive acreage compared with present clamshell operations. |
| Alternative Dredge-Spoil Disposal | Removal of dredged spoils by truck or railcars to strip mines, sanitary land fills, etc. | Spoils would be put to beneficial use; habitat of present disposal areas would be enhanced. | Implementation of this option would entail a significant increase in truck traffic and transportation costs. |

bars, shoals and debris and widening the channel to maintain the authorized dimensions. Those areas requiring dredging most frequently include the mouths of tributaries and the lower approaches to lock chambers. From 1960 to 1974 annual dredging quantities at 4 sites ranged from 0 to 44,342 cubic yards with a total of 81,200 cubic yards of material removed during the entire 15 year period.

The Final Environmental Statement on the Operation and Maintenance of the Navigation System for the Allegheny River[38] prepared by the United States Army Corps of Engineers, Pittsburgh District, October 1975, contains an evaluation of the cost/benefit effects of continuing the present channel maintenance procedures and a description and evaluation of possible alternative solutions to the existing project. Those alternatives which are germane to channel maintenance operations include:

(a) a no-action alternative.

(b) a self-maintenance river construction program.

(c) alternative dredging procedures.

(d) alternative dredge spoil disposal methods.

A brief description of the alternatives, their respective advantages and disadvantages is presented on Table IV-34. They are similar to the Monongehela River situation.

The FES considered the possibility of major modifications at L/Ds 2 and 3 to alleviate usage conflict between commercial and recreational traffic during the summer recreational season. However, delays seldom exceed one hour and it is doubtful if existing traffic warrants such significant cost at this time.

Cumberland River: Tow operators frequently avoid the Cumberland River by utilizing the Lower Tennessee even faced with delays at the Kentucky Locks. Experience has indicated that the navigation problems encountered are due in part to physical characteristics of the channel as well as unusual flow conditions. Traffic moving on the Cumberland River below the Barkley Dam encounters sharp bends,

# Table IV-34

## Alternative Channel Maintenance Procedures
## Allegheny River

| OPTION | DESCRIPTION | ADVANTAGE | DISADVANTAGES |
|---|---|---|---|
| No-Action | Complete abandonment of the present project including immediate cessation of all channel maintenance activities on the Allegheny River. | Implementation of this option would result in a federal savings of $2,000,000 annually as well as improvement of air and water quality and enhancement of the rivers environment. | Abandonment of the present project would eventually lead to complete cessation of commercial navigation on the river, industrial closing, loss of employment opportunities; huge capital investment losses, both federal and private; alteration of the social structure of the region; and serious water supply problems. |
| Self-Maintenance Structures | This option includes the construction of dikes or groins to concentrate river flows in problem shoaling areas | Implementation of this option could reduce or eliminate maintenance dredging and its current costs and impacts | Dredging volumes and recurrence frequencies are generally too low to warrant the construction costs; potentially adverse cross-currents may be created; and destruction of habitat at and immediately downstream of the structures would result from this option. |
| Alternative Dredging Methodology | Conversion from clamshell to hydraulic dredging. | Hydraulic dredging can result in faster more efficient operations with lower unit costs if dredging quantities warrant their utilization. | Dredging volumes are insufficient for effective hydraulic operations; suitable disposal sites are often unavailable within reach of areas to be dredged; material to be dredged in the project area is frequently too large for hydraulic operations; mobilization costs would be excessive; and larger areas for disposal sites would be required. |
| Alternative Dredge Spoil Disposal | Removal of dredge material by trucks or railroads for disposal in sanitary landfills, strip mines or other beneficial disposal areas. | Dredged spoils would be put to beneficial use while enhancing the quality of existing disposal sites. | Implementation of this option would result in a significant increase in local truck traffic and transportation costs. |

restrictive channel widths, fluctuating pool levels, variable currents and high flow velocities. Within this section of the river there are nine major bends which substantially restrict the size of tows which can safely navigate this reach under normal conditions. Within several of these bends, tows may be required to alter course by 60 or 70 degrees within a distance of 300 to 500 feet and must frequently reverse and flank to negotiate the more severe curves. In addition, power plant releases create fluctuating pool levels and unusually high velocity flows downstream of the Barkley Dam. These pool conditions in combination with crosscurrents in the approaches to the lock create extremely difficult, if not prohibitive, navigational conditions on this reach of river.

The above problems were addressed in a report prepared by the United States Army Corps of Engineers, Nashville District entitled, Reconnaissance Investigation - Improvement of Navigation Conditions in the Lower Cumberland-Tennessee Rivers Below Barkley Canal, November 1972[39] In this report, the Corps considered the alternative structural and non-structural solutions which could be implemented immediately and long range concepts requiring further evaluation.

A brief description of the alternatives considered viable solutions which could be implemented in the near future is as follows:

Channel Improvements: short range channel improvements consist of a continuation of the dredging program at critical locations on the lower Cumberland. There are only three major areas where maintenance dredging could be performed, within the limits of existing authority, that would reduce navigational difficulties. These three areas which have restrictive channel width, are located at miles 4.8, 19, and 24 and would require about 30,000 cubic yards of dredging. In addition, smoothing of some of the bends and rounding the point of the Kentucky chute confluence is necessary to improve maneuverability, which would require removal of 1,200,000 cubic yards of material.

Modified Power Operations at Barkley: Peaking releases from Barkley would be modified in such a way as to improve flow conditions enabling tows to increase average upstream speeds.

Dissipating/mooring cells below Barkley Lock: Cells constructed below Barkley Lock would serve the dual purpose of improving approach conditions and providing an area for mooring tows awaiting lockage. Cells properly located could dissipate crosscurrents which are experienced in the lower approach.

A brief description of those variable alternatives considered to be long range options requiring further evaluation included a canal between miles 27.7 on the Cumberland and 19.4 on the Tennessee consisting of a five mile long 300 foot wide channel with a 110' x 600' lock. Long range channel improvements include elimination of all sharp bends and narrow channels by an extensive widening program requiring 9,500,000 cubic yards of dredging.

Costs of the above alternatives are depicted on Table IV-35.

## Table IV-35

### Cost Evaluation of Alternatives*

| Option | Initial Cost | Annual Cost |
|---|---|---|
| Modified Power Releases | N/A | 1,870,000 |
| Channel Improvements | | |
| Kentucky Chute | 4,998,000 | 743,000 |
| Maintenance Dredging | 76,000 | Undetermined |
| Widening Bends | 36,572,000 | 2,468,600 |
| Tenn.-Cumberland Canal | 99,013,000 | 5,821,000 |
| Dissipating/Mooring Cells | 1,707,000 | |

NOTE: 1977 Dollar Values

From the above table it may be seen that regulation of downstream flow conditions by modifying power releases at Barkley would involve a significant economic loss annually. While initial channel improvement costs are quite high, these alternatives would appear to warrant further in-depth evaluation in view of current accelerating energy costs. At a very minimum, channel dredging should be performed with consideration given to gradually increasing bend radii as funding becomes available. Studies are to evaluate the economic value of a recommendation to Congress are underway. A canal between the Cumberland-Tennessee River would increase utilization of the Barkley Lock but divert downstream traffic from the Lower Cumberland. This alternative would not address the problem of traffic moving south on the Ohio River which wishes to proceed up the Cumberland River. In addition, crosscurrents, fluctuating pools and high flow velocities would still be encountered between Barkley and the canal. Irrespective of the structural alternatives for channel navigation improvement, it would appear prudent to address the problem of irregular flow conditions at the lower approaches to Barkley by installation of dissipating/mooring cells. Detailed study would be required to evaluate the location and effectiveness of such structures. A possible viable alternative is the combination of modifying power releases, channel improvement, and the installation of mooring cells, current studies are also evaluating training dikes. Further analysis of the economic and practical feasibility of such a combination of alternatives should be undertaken before a final plan is selected.

### 8. Reporting Region 9-Arkansas (White) River.

White River: As indicated under "Current Maintenance Programs",the White River has several types of channel problems which affect not only navigation on the White but traffic movements on connecting waterways, such as the Mississippi and Arkansas Rivers, as well. In general, the White River is shallow with unreliable depths, restrictive channel bottom widths, and a crooked alignment with very small bend radii.

The Memphis District Corps of Engineers prepared the *Feasibility Report, White River Navigation to Batesville, Arkansas*[40] in May 1979. In this report, the existing conditions on the White River are described as follows:

> The existing White River project provides only a five foot minimum depth from mile 10 to Augusta (mile 198). From Augusta upstream to Newport (mile 254) the minimum depth maintained is only 4.5 feet. A fully loaded

barge on the White River reouires a nine-foot minimum depth.

As previously indicated, there is a lack of sufficient and reliable depth on the River during late summer, fall, and early winter. In addition, many river crossings and wide reaches of the river are subject to freouent shoaling. This problem is compounded by the limited availability of maintenance funds for dredging.

Existing channel bottom widths are both obstacles and hazards to navigation on the river. The typical barge size on the White River is 35' wide and 195' long. A minimum 125 foot bottom width exists from Augusta downstream to mile 10 and with a tow make-up one barge wide, only 18 feet of clearance is available when tows pass. Upstream of Augusta to Newport, only 10 feetare available to passing tows and when not passing, tows have less than 35 feet of clearance between the barge and the limits of the navigation channel. Moreover, the narrow channel combined with extremely sharp river bends makes maneuvering extremely difficult. Many of the "tight" bendways require the tow operator to strike the bank and reverse the tow several times to negotiate the turn. Accordingly, the restrictive channel bottom width and bend radii limit the size of tows which can navigate the White River and constrain the interchange of traffic with the Arkansas and Mississippi Rivers.

Three basic methods of increasing the reliability of minimum channel dimensions were considered in the Feasibility Report. These included low-flow augmentation, lock and dam construction, and open-river improvements such as channel contraction structures and lower channel bottoms.

Low-flow augmentation would require an estimated upstream storage capacity of 3.1 million acre feet to provide a nine-foot channel depth throughout the entire year. Since the power and flood control benefits of the existing reservoir far outweigh navigational benefits, new storage reservoirs would have bo be developed. However, limited sites suited for major reservoirs, public opposition to additional dam construction, lack of streamflow diversion sources, and cost in excess of those required by other means of improving navigation eliminated the low-flow augmentation option from further consideration as a viable solution.

Dependable channel depths and widths for navigation could be provided on a year-round basis by the construction of a series of low lift locks and dams on the White River between mile 10 and Batesville (mile 296). Bendway smoothing and cutoffs to provide a greater turning radius for tows and channel deepening to provide navigable depths would also be included as an integral part of a lock and dam system. This alternative was determined to be technically feasible with enough potential economic benefits to warrant further consideration in the planning process.

Open river channel improvements for navigation were considered from mile 10 on the White River upstream to Batesville (mile 296). Hydraulic studies indicated that a nine-foot navigable channel depth could be provided to Newport 95% of the time by increased dredging. However, between Newport (mile 254) and Batesville (mile 296) dependable channel depths of nine feet could only be provided by locks and dams. The plan of improvement included cutoffs from mile 10 to Batesville, which would allow White River navigation by a four barge tow. Based on a preliminary analysis, this plan seemed to be the least costly alternative while still promising significant economic benefits and was retained for further consideration.

Two plans (Dismal LaGrue Route and Modified Dismal LaGrue Route) were considered which would promote greater Industrial growth in the area while bypassing the White River National Wildlife Refuge. Both consisted of navigation channel from the Arkansas Post Canal north along Dismal Swamp to LaGrue Bayou. An overland canal would then be cut to White River. One plan considered the cut joining the White below DeValls Bluff, and the other considered the cut to join the White north of Crockett's Bluff. Both plans required locks, dams, pump facilities, a water control dam on the White downstream of the canal, channel deepening and cutoffs.

In the next planning phase of the study, seven navigational alternatives were developed for possible implementation on the White River. They were:

(a) Locks and Dams to Batesville.

(b) Open River Navigation to Newport, Locks and Dams from Newport to Batesville (with cutoffs).

(c) Open River (with cutoffs) to Augusta.

(d) Open River (without cutoffs) from Augusta to Newport

(e) Combined Open River Plan (with cutoffs to Augusta, and without cutoffs from Augusta to Newport)

(f) Dismal LaGrue Route

(g) Modified Dismal LaGrue Route.

The only viable alternatives were as follows:

Open River Navigation with Cutoffs to Augusta: Open river improvements including smoothing and cutting off of bendways and channel deepening and widening (where existing channel dimensions do not meet design requirements) to obtain a nine foot deep channel 95% of the time with a 200 foot bottom width and a 1000 foot minimum bend radius were considered and found to be justified up to Augusta.

Open River Navigation without Cutoffs, Augusta to Newport: This plan would provide for channel deepening and widening between Augusta and Newport to achieve a nine foot depth 95% of the time with a 200 foot bottom width channel. Channel deepening and widening would only occur in those areas not meeting project design requirements. The river mileage to be dredged is only a portion of the total mileage between August and Newport. There would be no cutoffs and the existing configuration of the river would remain the same. This plan is incrementally justified but would be fully functional only if the downstream reach from mile 10 to Augusta were improved. Improvements with cutoffs in the reach from Augusta to Newport were estimated to be economically unfeasible but marginal. Therefore, both the "with" and "without" cutoff open river alternatives in this reach were retained for further consideration.

Combined Open River Navigation to Newport: Combining the above alternatives results in an overall "open river plan" from mile 10 upstream to Newport. Channel deepening and bendway modification, including smoothing and cutoffs, would be constructed between Augusta and Newport. This plan would provide for a nine foot deep channel 95% of the time and 20) foot bottom width from mile 10 to Newport. The bendway modification would allow for navigation by a four barge tow up to Augusta. A two barge tow would be accommodated from Augusta up to Newport. This plan was designated for further study.

An environmental quality plan was also developed during this phase of study. It consisted of: (1) scenic overlooks, (2) boat ramps, (3) bottomland hardwood preservation including small streams and lakes, (4) small parts, (5) hiking trails, (6) provision of attendant minimum facilities and adequate public access, (7) the encouragement of sound land use and wildlife management practices, and (8) improvements on the White River for navigation by channel deepening and widening, with bendway smoothing and cutoffs to Augusta and without bendway alterations from Augusta to Newport. Most of the environmental quality measures were not justifiable on a quantifiable monetary basis, but the plan was used as a base in stage III studies to develop a more acceptable plan.

A public meeting was held on 1 December 1975 in Newport, Arkansas. Comments and of the plans presented at this meeting led to the following four plans being considered in the Stage III planning:

(a) Plan I (Rational Economic Development Plan) - Open river navigation with no cutoff to Newport. This plan would construct and maintain a channel nine-feet deep and 700-feet wide, 95% of the time.

(b) Plan II - Open river navigation with cutoffs to Augusta and without cutoffs to Newport, Arkansas.

(c) Plan III - Environmental quality including open river navigation (without cutoffs) to Newport.

(d) Plan IV - Environmental quality with open river navigation (with cutoffs) to Newport.

According to the study, Plan I plus terrestrial mitigation features recommended by the United States Fish and Wildlife Service was selected for implementation. A summation of the amount of channel work required for implementation of the selected plan as well as the estimated costs for the respective tasks are shown on Table IV-36. Costs are in July 1977 dollars.

The existing channel dimensions for the GIWW West are 12 x 125 feet although Congress, in 1962, authorized the enlargement of several portions to 16 x 150 feet and 16 x 200 feet. Navigational problems on the GIWW are described in the 1975 National Water Assessment and the GIWW Reconnaissance Report, January 1979.

In general, the existing channel dimensions of 12 feet deep by 125 feet wide on the GIWW are inadequate for efficient movement of waterborne commerce and limit the size and depth of vessels that can utilize the waterway.

Two 50 foot wide barges must use extreme caution when passing in a 125 foot wide channel making travel slow and hazardous. It would be advantageous for the transport industry to shift to larger barges and more powerful tows but the present channel dimensions inhibit the larger, faster vessels. In addition, a large number of curves in the channel still exist where the degree of curvature is too acute to be navigated, except at verv low speeds.

The 1962 Act which authorized the improvements to the GIWW also stipulated that local interest provide all lands, easements, and rights-of-way required for construction and subsequent maintenance of the waterway. In addition, the cost of all pipeline, cable and utility relocations were to be borne locally. To this date local interests have been unwilling to provide those items and, therefore, with the exception of the relocation of the channel in Corpus Christi Bay, none of the 1962 authorized improvements listed below have been implemented.

The authorized enlargement of the GIWW provides for:

(a) a channel 16 x 150 feet through the reach between the Mississippi and Atchafalaya Rivers.

(b) a channel 16 x 150 feet through the Algiers Alternate Canal.

# Table IV-36

## Estimated Costs-Plan I-White River

| TYPE OF CHANNEL WORK | Estimated Quantity | Unit Cost $ | Federal Cost $ | Non-Federal Cost $ | Total $ |
|---|---|---|---|---|---|
| Excavation | 4,125,000 Cy | 0.48 | 1,980,000 | | 1,980,000 |
| Preparation of Disposal Areas | | | | | |
| Woodland | 679.6 Ac | 875 | | 595,000 | 595,000 |
| Cropland | 313.3 Ac | 675 | | 211,000 | 211,000 |
| Seeding | 992.6 Ac | 292 | 290,000 | | 290,000 |
| Navigation Aids (Shore Aids) | 381 | 200 | 76,000 | | 76,000 |
| Stabilization | | | | | |
| Revetment | 24,900 LF | 125 | 3,113,000 | | 3,113,000 |
| Dikes | 9,190 LF | 120 | 1,098,000 | | 1,098,000 |
| Bankheads | 37 | 2,500 | 93,000 | | 93,000 |

SOURCE: Feasibility Report, White River Navigation to Batesville, Arkansas

(c) a channel 16 x 150 feet through the bypass route around Houma.

(d) a channel 16 x 200 feet through the reach from the Atchafalaya River to the Sabine River.

(e) a channel 16 x 150 feet through the reach from the Sabine River to the Houston Ship Channel.

(f) a channel 12 x 125 feet through the relocated channel in Matagorda Bay.

(g) a channel 12 x 125 feet through the relocated channel in Corpus Christi Bay (has been completed).

(h) a channel 12 x 125 feet to be maintained through the existing 12 x 125 foot Lydia Ann Channel between Aransas Bay and Aransas Pass.

(i) maintenance of the existing channel alignment through Houma, Louisiana.

(j) abandonment of those channels shortened by new channels in the Texas section.

A preliminary evaluation in the GIWW Reconnaissance Report of the above list of possible improvements eliminated several of the measures from further consideration.

The remainder of the preliminary measures are considered appropriate for more detailed studies in the second planning phase. Brief descriptions of those major measures specifically aimed at channel improvement of maintenance are presented below. The benefits and adverse impacts attributed to each of the processes are included.

<u>Deepen Gulf Intracoastal Waterway</u>: Consideration given to deepening the waterway from the existing depth of 12 feet to a maximum depth of 16 feet dependent on volume of traffic and vessel size. Should the desired 16 foot depth prove justifiable, the benefits of greater depths will be investigated. Benefits would entail increased efficiency in tow operations and a possible reduction in tow generated wave wash.

Adverse impacts include continued loss of land to bank erosion if erosion control measures are not implemented, increased requirement for dredged material disposal areas, loss of privately owned land to federal ownership, increased maintenance requirements, increased salt water intrusion in some areas, possible interruption of natural flow patterns, possible decline in water quality, increased turbidity during dredging operations, and required pipeline and cable relocations.

Widen Gulf Intracoastal Waterway: The feasibility of widening the waterway from the present 125 feet to a maximum of 300 feet will be evaluated. As with deepening, consideration will be given to widening selected reaches dependent on the volume of navigation and other pertinent factors.

Benefits include reduced congestion on the waterway, increased efficiency in tow operations, possible reduced towgenerated wave wash, and an increased margin of navigation safety.

Adverse impacts are possible damage to a National Wilderness area, loss of critical habitat of the whooping crane and damage to several wildlife refuges and management areas, direct loss of adjacent lands to be used as dredged material disposal areas, loss of privately-owned land to Federal ownership, increased maintenance requirements, required pipeline and cable relocations, increased salt water intrusion in some areas, increased turbidity during dredging operations, and possible interruption of natural drainage patterns.

Clear and snag mile 6; straighten bends at miles 17 to 25, 80 to 88, 111, 118 to 122, 211 to 212, 235 and 390 to 395: The feasibility of widening, relocating and increasing the radius of curvature in the above locations are desired to improve safety, maneuverability, and speed in the waterway.

The benefits to be derived from this operation include improvements to navigational safety, reduction in waterway congestion through increased allowable speeds and improved efficiency in navigation operations.

Adverse impacts include increased loss of wetlands and other lands to channel realignment and disposal areas, loss of privately-owned land to federal ownership, relocation of families and physical property from the project area, loss of wildlife habitat, and possible isolation of private property.

Relocate Colorado River Locks: The feasibility of relocating these locks to increase the distance between them and widening the connecting channel will be investigated.

Beneficial contributions would be improved and safer navigation through the locks and better alignment for barges when crossing the river, primarily during periods of high river flow. Shoaling rates on the GIWW may also be reduced, which would in turn reduce the amount of maintenance dredging required in the area.

Adverse impacts include loss of wetlands and other wildlife habitat due to relocation of the locks and the channel.

Protect channel banks from erosion: Various methods reducing wave wash and resulting bank erosion will be investigated. Measures to be considered may include bulkheads or revetments on the channels; tow speed, size, and draft limitation; and other methods such as bank stabilization or sloping to prevent tow-generated waves from washing against channel banks.

Beneficial contributions would be a reduction in channel bank erosion and the annual loss of wetlands due to erosion, a reduction in channel maintenance requirements, and preservation of the environment adjacent to the waterway.

Adverse impacts include increased maintenance requirements on the protective works.

No action: Beneficial contributions would include no expenditure of funds or resources for construction, no relocation of families or property,.no financial charges to local agencies, and no alteration of the resources of the project area.

Adverse impacts would include increased traffic congestion in the waterway, continued erosion, further salt water intrusion, decreasing margin of safety, and loss of navigation efficiency.

An evaluation of the above improvement measures and alternative solutions should be performed as part of the second study phase of this section of the GIWW. The most viable options should be retained for a detailed cost/benefit and environmental impact investigation. Final improvement plans should be formulated upon consideration of the comparative technical, economical, social and environmental aspects of the various alternative solutions.

Houston/Galveston Ship Channels: A preliminary reconnaissance report was recently prepared by the Galveston District which evaluated deepening and widening the present 40'x400' Houston Ship Channel projection from Bolivar Roads to the Washburn Tunnel to 45'x600'. The initial cost of the project was preliminarily estimated by the Galveston District, based on information available in the preliminary reconnaissance report, to be $178,000,000 (1977 dollars), and include 86,300,000 cubic yards of dredging. The project would primarily involve dredging. The cost of maintenance was estimated to increase by roughly $2,500,000 (1977 dollars) annually as a result of the improvement project, over the present annual maintenance cost of $4,500,000 (1977 dollars).

A plan to deepen Galveston Harbor to 50 feet is presently undergoing Stage III feasibility studies, scheduled for completion in 1981. The plan is considering deepening the Texas City Channel to Texas City at a preliminary estimated cost of $119,000,000 in 1979 dollars. The initial dredging volumes are estimated to be 18,900,000 cubic yards inshore and 33,200,000 cubic yards offshore. The increase in annual O & M costs and volumes are estimated to be $4,000,000 in 1979 dollars and $250,000 cubic yards inshore and 2,100,000 cubic yards offshore.

Above the Baytown Tunnel, the maximum practical depth ranges from 36 to 45 feet. The Port of Galveston on the other hand considers a 70 foot (200,000 DWT) channel feasible. The need for such a deep channel for very large tankers would be eliminated by construction of the proposed single point buoy mooring off Freeport, Texas. In any case the channel cannot be deepened above the Shell Oil Refinery at Boggy Bayou Basin, about halfway up the Houston Ship Canal, due to a highway tunnel across the channel at that point.

10. Reporting Region 11 Gulf Coast East. This region includes the GIWW East from New Orleans to Key West Florida; the Apalachicola, Chattahoochee and Flint Rivers; and Mobile Harbor.

Apalachicola, Chattahoochee, and Flint Rivers: A indicated under "Current Maintenance Programs", the open river training works originally authorized for the Apalachicola River below the Jim Woodruff Lock and Dam have not been capable of adequately maintaining the authorized nine foot depth navigation channel during periods of low flow. In addition, the 100-foot authorized width is not always available at some locations.

It has been determined that a minimum release of 13,000 cfs from the Jim Woodruff Dam and some maintenance dredging is necessary to provide a reliable nine foot channel depth. Since the system's storage capacity is insufficient to maintain a release of that magnitude throughout the entire low-water season, severe decreases of the channel depth reliability occur in September, October and November. The percent of time the required flow is maintained is depicted in the section entitled "Channel Maintenance Programs" on monthly flow-duration curves for the Apalachicola River at Chattahoochee, Florida.

*The Coordination Report on Navigational Improvements For Apalachicola River Below Jim Woodruff Dam, Florida, October 1978*[41] presented several possible solutions which were formulated and evaluated at meetings and workshops between the COE and concerned parties.

An initial evaluation of these alternatives was performed and several "possible solutions" were eliminated from further consideration. Elimination of those alternatives considered unfeasible resulted in a second cut of options warranting additional consideration. From the second cut of options two were considered viable. The first is a plan for complete low-flow open-river regulation at the existing minimum discharge rate of 9300 cfs. This plan includes six cut-offs, 41 sites to change the radii at sharp bends, 86 dike sites to maintain the channel through crossing bars, 91 dredging sites, realignment of dike sites, and bend widening at other locations. The second plan calls for the construction of a relatively low dam at a site called Suttons Lake. Construction of the dam would eliminate most of the navigation difficulties between the dam site and Jim Woodruff Dam and allow a greater maintenance dredging effort downstream of the dam site. The costs associated with these options are presented in Tables IV-37 and IV-38.

### Table IV-37

### Open-River Regulation Plan

| Type of Channel Work | Quantity | Unit Cost | Total Cost |
|---|---|---|---|
| Dikes | 489 | - | $25,265,000 |
| Bend Enlargement | 52 | - | 13,638,000 |
| Initial Dredging (97 sites) | 3,700,000cy | 0.94 | 3,478,000 |
| Annual Dredging | 300,000cy | 0.94 | 282,000 |

### TABLE IV-38

### SUTTONS LAKE LOCK AND DAM PLAN

| Item | Quantity | Unit Cost | Total Cost |
|---|---|---|---|
| Total Capital Cost | | | $46,713,000 |
| Annual Charges: | | | |
| Lock and Dam | | | 3,227,000 |
| Lock and Dam operation and maintenance | | | 198,000 |
| Annual channel dredging | 1,100,000cy | 1.011 | 1,112,000 |

The physical and navigational benefits to be derived from each of the viable alternatives is summarized below:

Open River Regulation Plan - The length of the navigation channel below Jim Woodruff Dam would be reduced by 3.3 miles due to the new cutoffs. Annual maintenance dredging would be reduced from 1,100,000 c.y. to about 300,000 c.y. Caving and erosion of banks will be reduced due to the stabilization effect of the dikes. A minimum channel dimension of 9' x 100' will be maintained 95% of the time at the minimum flow of 9,300 cfs.

Suttons Lake Lock and Dam Plan - Most of the navigation difficulties between this dam site and the Jim Woodruff Lock and Dam would be eliminated due to the 12-foot increase in the water surface elevation. Maintenance dredging would be concentrated downstream of the dam site reducing unit costs.

It was originally estimated that increasing maintenance dredging to double the present maintenance amount could attain the desired channel dimensions at an annual cost of about $2.3 million. However, further study revealed that with present flow condition, greatly increased dredging would provide only about a 5% increase in the time a 9-foot channel would ensue. This alone would produce insignificant benefits. Since flow augmentation to about 12,000 cfs would also be required to maintain an adequate navigation channel a satisfactory percent of the time, this method of operation would result in losses to power capacity and recreation benefits in excess of the navigation benefits gained.

This conclusion appears logical. On waterways with limited water discharge and intensive dredging in a channel which constitutes more than about 10% of the natural crosssection, lowering the channel bottom results in lowering the water level as well, which reduces the effectiveness of the dredging. Therefore, an alternative combining dredging with river training would appear to be the most logical option. However, as indicated under "Current Maintenance Programs", previous training works on the Apalachicola have not fully satisfied expectations and additional analyses of the relative proportion of dredging and river training works which should be implemented are recommended.

Mobile Harbor: The 1980 Draft Summary Report, "Mobile Harbor Alabama Feasibility Report - Channel Deepening for Navigation," evaluated deepening parts of Mobile Harbor to 55 feet. The proposed project includes deepening 40 foot deep sections to 55 feet up to Bankhead Tunnel. The total project cost in August 1980 dollars is estimated to be $392,549,000 (this would be about $300,000,000 in 1977 dollars). The project includes dredging of about 140,000,000 cubic yards in addition to dike construction, dredging for berths and construction of mooring dolphins. Annual maintenance dredging is expected to increase by about 700,000 cubic yards as a result of the project. Docks and major industrial facilities are being located 2.5 miles south of Mobile in an area referred to as Theodore Industrial Park on the western shore of Mobile Bay. The Theodore Industrial Park was selected as the area with the greatest potential for development and expansion of heavy industry. A deep-draft channel to the new terminal would be required, and the effects of deepening the existing channel and the dredged material disposal island on existing conditions in Mobile Bay were the subject of a model study performed by the Hydraulics Laboratory of the WES at Vickburg, Mississippi. This study included construction and maintenance of a channel 40 feet deep and 400 feet wide extending from the main Mobile Bay Ship Channel via land cut 40 feet deep and 300 feet wide. First cost of this project was estimated at about $16 million (1977 dollars). As a part of that study, several alternative disposal island configurations were evaluated and a plan was selected for further testing and possible implementation.

11. Reporting Region 12 Tombigbee-Alabama, Coosa, Black Warrior Rivers. The 1976 Supplement To The Design Memorandum of the Tennessee-Tombigbee Waterway Study[42] consists of three basic areas of evaluation:

(a) the basic project plan.

(b) works for navigation down river from the Demopolis Lock and Dam.

(c) duplicate lock construction at the Demopolis and Coffeeville projects.

Each of the alternative plans are described in the following paragraphs to provide insight to the magnitude and scope of the projects involved.

Basic project plan: This plan consists of the authorized project works extending from the Demopolis Lake to the Pickwick Reservoir and is divided into three parts:

(a) a 148-mile-long river section.

(b) a 44-mile-long canal section.

(b) a 40-mile-long divide section to provide for eight barge tows and two-way navigation.

The river section will consist of four navigation locks and dams and channel works along the Tombigbee River to provide minimum channel dimensions of 300 feet wide and nine feet deep. At the upstream terminus of the river section near Amory, Mississippi, the canal section will be dredged along the east bank of the East Fork. A series of five canal locks and an earth levee between the canal and the East Fork will provide a channel having minimum dimensions of 300 feet wide and 12 feet deep. The divide section will consist of the Bay Springs Lock and Dam located at the upstream end of the canal and the cut through the divide separating the Tennessee and Tombigbee Rivers. The channel through the divide section will be 280 feet wide and 12 feet deep.

Downriver navigation works: The existing navigation channel on the Tombigbee and Mobile Rivers downstream from the Demopolis project were studied to determine the maximum tow size which could navigate that part of the system. It was found that eight-barge tows would be impractical because of channel widths, curvature or configuration at 44 locations and the clearances at three bridges spanning that reach. These constraints to traffic would impose limitations on traffic volumes, tow sizes and tow speeds. During the investigation of this area, a total of 16 cutoffs, 28 bend or channel widenings, and three bridge modifications were evaluated and preliminary plans were developed.

Cost estimates were based on typical sections, bend radii and dredged material disposal methods currently in effect for the waterway upstream from the Demopolis project. Excavation quantities were estimated on the basis of typical cross-sections developed along map layouts of channel center lines. General geologic data and available information were used to estimate excavation costs; however, no subsurface investigations have been undertaken.

The construction of the down river navigation works as described are not presently authorized although they are deemed necessary to preclude a constraint on the capacity of the waterway.

In order to evaluate the economic feasibility of the project, the down river works were incorporated with the authorized project plan described above.

Duplicate lock construction: The future construction of duplicate locks at the Demopolis and Coffeeville projects was studied during the preparation of the Supplement Report of 1966. At that time it was estimated that the structures would be needed in the year 2010, 34 years after the then estimated project completion date of 1976. During the preparation of the commerce studies on the Tennessee-Tombigbee and Black Warrior-Tombigbee Waterways, it was found that the construction of the duplicate locks would be required far sooner after completion of the initial project. Since the construction of duplicate locks has not been authorized, a study of their economic feasibility is the third evaluation area.

Principal project features and constraints for the TTWW under the above plans are shown on Table IV-39.

Based on the project features shown on Table IV-39, the design tow size for the TTWW under the authorized Plan is an 8-barge toy above Demopolis and a six-barge tow below. A comparative analysis of relative costs indi- cates that fleeting eight-barge tows at Demopolis will be more cost effective than using 6barge tows between Pick- wick and Mobile. The design tow size under the other Plans would be an eight-barge tow throughout the system. It is anticipated that up to a 15-barge tow could be accommodated through the waterway with double locking (possibly with tow haulage units or winches). However, navigation conditions on the waterway under all altern- ative plans would not permit this tow size without costly delays and one-way navigation at constraining points.

An eight-barge tow makes full use of lock chamber capacity (nine positions) and exploits the full capacity of the waterway for two-way navigation above Demopolis.

The estimate of costs for the authorized Plan is the result of detailed study, whereas the estimates of costs for the added work under the other Plans, while not as detailed, are considered adequate for plan evaluation. A summary of total project costs for the above plans is given in Table IV-40.

12. Reporting Region 14-Middle Atlantic Coast. This report includes the ports of New York, Delaware River, Baltimore and Hampton Roads.

## Table IV-39

## Tennessee-Tombigbee Waterway - Project Features and Operating Characteristics

| Feature | Plan A | Plan B | Plan C |
|---|---|---|---|
| Channel Depth: | Maintain 12 feet through the divide cut and canal, and 9 feet in river section above Demopolis | Maintain 12 feet through the divide cut and canal, and 9 feet in the river section above Mobile | Maintain 12 feet through the divide cut and canal, and 9 feet in the river section above Mobile |
| Channel Width: | Maintain 280 feet through the divide cut and 300 feet elsewhere above Demopolis | Maintain 280 feet through the divide cut and 300 feet in river section above Mobile | Maintain 280 feet through the divide cut and 300 feet in river section above Mobile |
| Tow Size: | Maximum of an 8-barge tow above Demopolis and 6-barge below | Maximum of an 8-barge tow from Mobile to Tennessee River | Maximum of an 8-barge tow from Mobile to Tennessee River |
| Typical Barge Size: | 195' x 35' x 8.5' with 1,400 ton carrying capacity | 195' x 35' x 8.5' with 1,400 ton carrying capacity | 195' x 35' x 8.5' with 1,400 ton carrying capacity |
| Number of Sites/ Size of Locks: | Ten (10)/110' x 600' | Twelve (12)/110' x 600' | Fourteen (14)/110' x 600'(1) |
| Bends and Channel Constraints: | Suitable for two-way navigation up to a tow length of 685 feet without breaking tow above Demopolis | Suitable for two-way navigation up to a tow length of 685 feet without breaking tow between Mobile and Tennessee River | Suitable for two-way navigation up to a tow length of 685 feet without breaking tow between Mobile and Tennessee River |
| Total Project Distance | 232 miles | 428 miles - Plan provides for 21 miles of cutoffs below Demopolis | 428 miles - Plan provides for 21 miles of cutoffs below Demopolis |

Note: (1) Provides for the construction of duplicate locks at Demopolis and Coffeeville.

Table IV-40

Summary of Total Project Costs in Millions of Dollars
Tennessee-Tombigbee W/W
1977 Price Levels)

| | Plan A | plan B | Plan C |
|---|---|---|---|
| Total Federal Costs for Initial Project | 1,451 | 1,547 | 1,547 |
| Total Non-Federal Costs for Initial Project | 234<br>234 | 247<br>247 | 247<br>247 |
| Total Cost for Initial Project Works | 1,685 | 1,794 | 1,794 |
| Total Cost for Delayed Project Works | 25 | 25 | 145 |
| Total Project Cost | 1,710 | 1,819 | 1,938 |

New York Harbor: The realignment of the Sandy Hook approach channel to New York Harbor is being studied to reduce dredging requirements. However, the recent study "Channel Non-Maintenance in New York Harbor"[43] indicated that if all dredging of the harbor ceased, passenger ship activity would cease within two years, and nearly half of the harbor's general cargo traffic would be lost due to shoaling at the berths. The overall impact of non-maintenance includes the loss of 61,000 jobs and personal income losses of more than $1 billion. Business income losses would amount to approximately $500 million. The cost of moving general cargo and petroleum in and out of the region would increase $660 million per year. The New York Dredged Material Disposal Alternatives Workshop determined the feasibility of the alternatives depicted in Table IV-41.

A possible deepening of the New York and New Jersey Channels from 35 feet to as much as 45 feet has been under study by the Corps since 1955. The Port has requested that the Corps dredge to the authorized depth at 45 feet at an estimated cost of $160 million (1979 dollars). The Port's key tanker problem, as already stated, is focused on the New York and New Jersey Channels. A 45 foot channel benefits tankers no larger than 80,000 tons,

# Table IV-41

## Results of Disposal Alternatives Screening Process

| NOT CURRENTLY REASONABLE | CURRENTLY REASONABLE | |
|---|---|---|
| | Possible in Special Cases | Possible in Special Cases and Feasible for Large Volumes of Material |
| No Dredging | Selective Dredging | Shallow Ocean Open Disposal (e.g., Mud Dump, Christiansen Basin) |
| Deep Ocean Disposal | Long Island Sound | Subaqueous Borrow Pits |
| Offshore Island Containment (e.g., Energy Island) | River/Harbor Disposal (Open) | Confined Upland Disposal |
| Ocean Disposal with Other Waste Material | Protected Water Containment (e.g., Hoffman-Swinburne Islands) | |
| Ocean Spreading | Beach Nourishment | |
| Containerized Ocean Disposal | Enhancement of the Environment (e.g., Artificial Reefs, Bird Habitat Islands, Artificial Marsh, Landscape Reclamation) | |
| Filling Mines | Wetlands Disposal (Filling Wetlands) | |
| Production of Construction Materials | Sanitary Landfill Cover | |
| Incineration | Abandoned Piers | |

a situation that is extremely useful for product ships, but not for mammoth crude oil tankers. An offshore unloading structure is about the only possible way that 200,000-ton crude oil tankers could be accommodated in the Port of New York. It is possible that a single point mooring buoy would be more economically feasible to handle the Port's crude oil volumes to its four refineries on the Arthur Kill than a more costly, fixed, offshore terminal. Such a facility was proposed in the ocean about seven miles off Long Branch, New Jersey, in the summer of 1969, but was strongly opposed, largely because of the fear of collision and oil pollution along the New Jersey seashore attributed to mammoth tankers.

Such a facility should be viewed as a "new port" from which crude oil can be transferred by smaller tanker, barge and/or pipeline to one or more existing and shallower harbors.

Delaware River Ports: Although it is assumed that the requirements for deep draft channels and harbors will increase, the Delaware channel is inherently incapable of being deepened.

Although a minor deepening, say from 40 to 45 feet or even to 50 feet (80,000 DWT), might be feasible, a major deepening which would allow deep draft tankers or ore carriers in the 60 to 80 feet draft range (180,000 to 300,000 DWT) to operate freely in the Delaware even up to the vicinity of the refineries is beyond possibility. It is impossible from cost, maintenance, and conservation viewpoints and for a multitude of other reasons as well. Even if it were technically feasible, it is doubtful whether it could be maintained at anything near a project depth of the magnitude required.

It has been suggested that the four major ports of the North Atlantic, Philadelphia, New York, Baltimore and Norfolk should coordinate to solve their common problem with bulk ships of the future. A major deep draft interchange point should be made available to serve the four major North Atlantic ports. It could serve as well, of course, the ports north of New York and the South Atlantic ports, although it is less close to these facilities. Such a major interchange point could, on the basis of studies already made, be located in the Lower Delaware Bay just inside the breakwater. There is natural deep water over 70 feet at present. The entrance at the outer end of the Bay has a bar which recent surveys show at a depth of 58 feet over a limited distance. Preliminary estimates by the Army Corps of Engineers indicate that a 72 foot channel, which would accommodate 65 foot drafts, (200,000 DWT) could be dug at a cost of about $26 million (1977 dollars). A deeper channel to 78 feet would increase the cost to $50 or $75 million (1977 dollars).

Another possible solution exists in the form of an offshore unloading facility along the coast. While there is no question but that offshore facilities are feasible, there is considerable doubt as to their environmental advisability. It is also possible that it may be found economical to transship from deep draft to shallow draft at sea although it seems doubtful, as a long term solution. In any case, an offshore operation of either type is limited to bulk oil use and does not solve the problem for ore and other bulk products.

Baltimore Harbor: A plan to deepen the Port of Baltimore to 50 feet is in the advance engineering and design phase. Based on condition surveys the project would involve about 72,000,000 cubic yards of dredging (41,000,000 in Maryland and 31,000,000 in Virginia) and an annual increase in dredging of 315,000 cubic yards. The total cost of the project is estimated to be $278,150,000 in 1980 dollars ($215,000,000 in 1977 dollars) including about $100,000,000 in non-federal funds.

Norfolk/Hampton Roads: A feasibility report was recently completed for the deepening of Norfolk Harbor. The July 1980 report "Norfolk Harbor and Channels, Virginia, Deepening and Disposal" proposed the following projects:

(a) 57' deep by 1000' wide Atlantic Ocean Channel.

(b) 55' deep by 1000' wide Thimble Shoal Channel.

(c) 55' deep by 1500' wide channel from the Hampton Roads Bridge - Tunnel to Lamberts Point.

(d) 55' deep by 800' wide channel from the Hampton Roads Bridge - Tunnel to Newport News.

(e) 45' depth from Lamberts Point to mile 15 on the southern branch of the Elizabeth River.

(f) 40' depth from mile 15 to mile 17.5 on the southern branch of the Elizabeth River.

Present project depths are 45 feet from the Hampton Roads Bridge - Tunnel to Lamberts Point and to Newport News, 40 feet from Lamberts Point to the junction of the southern and eastern branches of the Elizabeth River and 40 feet in parts of the southern branch of the Elizabeth River.

The total cost of the improvement project was estimated to be $320,500,000 at April 1980 prices, including about $217,000.000 for dredging 98,700,000 cubic yards of material and about $10,250,000 for dredged material disposal areas. Other major features of the project are tunnel protection for Thimble Shoal Channel, fixed mooring facilities and landside facilities.

The proposed improvements were estimated to increase annual maintenance requirements by 1,150,000 cubic yards, 680,000 of which would have to be confined. The annual cost of operation and maintenance of the proposed project was estimated to be about $4,500,000 of which $3,700,000 is for channel maintenance and operation and maintenance of disposal areas.

Costs can be converted to 1977 dollars by dividing by about 1.3.

13. Reporting Region 15-North Atlantic Coast. This region includes the major port of Boston.

Although Boston Harbor has not been dredged in ten years, due to a lack of sediment, there is an ongoing study to deepen portions of the entrance channel of the harbor from 40 feet to 45 feet, the main channel from 40 feet to 45 feet, the reserve channel from 35 feet to 40 feet and the Mystic River Channel from 35 feet to 40 feet. It is believed that deepening the harbor would not significantly increase the maintenance dredging requirement.

14. Reporting Region 16-Great Lakes - St. Lawrence Seaway. The Great Lakes-St. Lawrence Seaway System provides a 27-foot deep channel from Duluth-Superior to Montreal and 35-foot channels from Montreal to Quebec City. The Great Lakes Channels are designed to provide a safe draft of 25.5 feet at low water datum. The draft of ships utilizing the St. Lawrence Seaway is limited by controlling channel depths since all the locks have sill depths equal to or exceeding channel depth. Several channel improvements have been suggested in conjunction with the Great Lakes St. Lawrence Seaway Navigation Season Extension Survey Study,[44] March 1979. The proposed improvements include:

(a) Dredging approximately 3,000,000 c.y. along a 17 mile reach of the Middle Neebish Channel on the St. Mary River to permit two-way traffic.

(b) Dredging approximately 34,500,000 c.y. from the St. Lawrence Seaway between Ogdensburg, New York and Morrisburg, Ontario to increase the channel cross section and thus reduce the average navigational channel velocity.

(c) Dredging approximately 20,000,000 c.y. between Cornwall and St. Regis Island to increase the channel cross section and reduce flow velocities.

The Corps of Engineers has underway a study investigating the feasibility of further improvements in the Great Lakes connecting channels and harbors for safe operation of vessels up to the maximum size permitted by the locks at Sault Ste. Marie, Michigan. The results of this study are not yet available. The study also includes an evaluation of additional lockage facilities and increased capacity of the locks at Sault Ste. Marie. The 1978 "St. Lawrence Seaway New York Feasibility Study for Additional Locks and Other Navigation Improvements" estimated the cost of dredging the channels of the Great Lakes and St. Lawrence Seaway to accommodate larger vessels. At the present time, vessel widths in the St. Lawrence Seaway are limited to about 76 feet in order to pass the 80 foot wide locks. The study investigated improvements required for vessel widths of 105, 130 and 175 feet. The cost to dredge the St. Lawrence Seaway in order to accommodate 105 foot vessels was estimated to be $2,195,149,000, $2,874,690,000 for 130 foot vessels and $4,566,138,000 for 175 foot vessels. These figures assume that the draft will remain as at present, 25.5 feet.

15. Reporting Region 17-Washington-Oregon Coast. This region includes the major ports of the Lower Columbia River and Puget Sound.

Lower Columbia River: Model studies of the entrance. channel of the Columbia River Estuary were conducted by the WES to determine if rehabilitation of Jetty A could be justified on the basis of reduced maintenance dredging requirements, construction of Jetty B would result in a sufficient reduction in entrance channel shoaling to be economically justified, and relocation of the entrance channel into naturally deep water adjacent to the present alignment would result in a reduction of maintenance dredging.

Results of the shoaling test indicate that rehabilitation of Jetty A would not significantly alter the present shoaling rate or distribution pattern.

Results of the shoaling test of Jetty B (located between south jetty and Jetty A) indicate significant changes in both the shoaling rate and distribution pattern. The data indicate that the rate of shoaling in the navigation channel would be reduced by about 28%, the upstream peak in the shoaling distribution pattern would be eliminated, and shoaling at the downstream end of the bar would be somewhat increased.

Congress has recently authorized a study of a deeper channel at the mouth of the river. Consideration will be given to a channel 70 feet deep (200,000 DWT) to Astoria. The authorized study entitled Columbia River Entrance Channel Deep Draft Vessel Motion Study is being implemented at the present time, but recommendations are not yet available for review.

In connection with an investigation to locate a coal export facility on the Lower Columbia River, the North Pacific Division roughly estimated the cost of two deepening alternatives to the Columbia River entrance bar and the 17 miles of channel between the entrance bar and the proposed facilities. To deepen the entrance bar from its present depth of 48 feet to 55 feet was estimated to cost $13,500,000 for the dredging of about 9,000,000 cubic yards of material. The resulting increases in annual cost of maintenance was estimated to be the same as the initial cost and entails dredging the same volume. To dredge to 60 feet was estimated to cost $29,400,000 for the dredging of about 19,600,000 cubic yards. The increases in annual costs and volumes was also estimated to be equal to the initial values. Dredging the 17 miles from the entrance bar to Tongue Point was estimated to involve 10,000,000 cubic yards of material at a cost of $15,000,000 for 50 foot depths and 13,500,000 cubic yards at a cost of $20,300,000 for 55 foot depths. Annual maintenance volumes and costs were estimated to be 131,000 cubic yards and $200,000 for 50 foot depths and 263,000 and $400,000 for 55 foot depths. These later figures can be used as estimates for deepening to the port of Astoria, however, Portland is over 100 miles inland from the entrance bar. (Costs are in 1980 dollars but can be changed to 1977 dollars by dividing by about 1.3).

Puget Sound: There is a proposal to increase the depth of the Duwamish Waterway, which connects Lake Washington and the Sound, to 40 feet. In Seattle, berthing accommodations are being completed for bulk grain carriers with drafts up to 73 feet 200,000 DWT).

16. Reporting Region 18-Columbia Snake Waterway. A review study was prepared by the United States Army Corps of Engineers entitled Columbia River and Tributaries - Inventory of Problems and Areas of Concern in August 1974. This report contained an inventory of site specific navigational problems for the Columbia River System and comments addressing the handling of each problem. Those areas of concern which are germane to channel maintenance, river morphology and hydrologic conditions are considered below.

Several potential hazardous conditions exist at or near lock approaches on the Columbia River. These problems include cross currents in the channel generated by powerhouse discharges and a bridge restriction on the Snake River. While investagation of the constriction problem is being undertaken, tailrace dredging is being utilized to mitigate the hazardous cross-current condition.

Given certain wind conditions, crabbing may cause long tows to approach or exceed the 250 foot authorized width and an increasing number of barges are being loaded to more than the 14-foot draft. A study of the adequacy of current authorized channel dimensions to accommodate existing and future navigation is recommended. At the present time a study to evaluate the adequacy of the current authorized dimensions has not been implemented. It is the opinion of the NWS team that such an investigation is urgently needed and should be undertaken as soon as authorization can be obtained.

Wind, wave and tidal effects create delays for ocean traffic entering and leaving the Columbia River. Congress has recently authorized a study of a deeper channel at the mouth of the river. Consideration will be given to a channel 70 feet deep to Astoria and 40 feet to Portland. The authorized study entitled Columbia River Entrance Channel Deep Draft Vessel Motion Study is being implemented at the present time but recommendations are not yet available for review.

A great number of agencies are concerned over the disposal of the high volumes of sand dredged from the mouth of the river to Portland. Concerns range from loss of a natural resource by open water dumping to fear of habitat destruction by disposal of spoils along banks, on flats, or behind levees. While the Corps administers a dredge spoil research program and is conducting a study of the effects of maintaining the navigation projects on the river, there is no present authority to develop a comprehensive dredge spoil investigation. The Corps recognizes the need for a review of spoil disposal effects. At the present time the District performs continuing evaluations of the effects of dredge spoil disposal resulting from their open water disposal programs.

17. Reporting Region 19-California Coast. This region includes the major ports of Los Angeles/Long Beach.

Los Angeles/Long Beach: While the Los Angeles/-Long Beach port facilities have no significant maintenance problems at the present time, a 10 to 15 year harbor expansion program has been designed for these ports in order to meet growing future demands. Plans for both harbors include deepening their channels to depths up to 82 feet (300,000 DWT) and increasing the amount of terminal space and berthing areas to efficiently accommodate the newest and largest ocean going vessels in existence such as the supertankers. The channel deepening program and port expansion will be combined with extensive land fill operations designed to absorb much of the dredged material. The port has recently requested that the Corps dredge some parts of the harbor with current controlling depths of 35 feet to the authorized depth of 45 feet at an estimated cost of $44 million (1979 dollars).

San Francisco: The Port of San Francisco has recently requested that the Corps deeper the Stockton Ship Channel (San Francisco Bay to Stockton) to its authorized depths. The increase would involve deepening the current project with depths ranging from 30 to 50 feet, by five feet, at a cost of $162,000,000 in 1979 dollars (approximately $135,000,000 in 1977 dollars).

# V - CHANNEL CONDITIONS FOR FLEET OPERATION

The capacity of most United States waterway channels have very large reserves. This is evident if an attempt is made to measure the capacity of a channel using the common definition of capacity as the maximum tonnage which can be passed per unit time. This condition exists only when the level of traffic is so high that there are only a few minutes between consecutive vessels traveling in the same direction. On most waterways the distance between consecutive vessels traveling in the same direction is currently measured in hours instead of minutes. Thus, most United States waterways are many years away from having the level of traffic that would be associated with operation at capacity. On the other hand, the suitability or capability of the waterway channel to safely and economically pass traffic is a matter of continuing concern. Whereas Section IV evaluated current and alternative channel maintenance programs, this section deals with fleet operating characteristics with respect to channel conditions, constraints and operating costs.

Unlike capacity, which is a measurable quantity (i.e., tons per year), the concept of capability is more abstract and not directly measurable. An important aspect of this section, therefore, is to develop measures which can be used, such as capacity for locks, to evaluate the capability of waterway channels. Theoretically, any factor which would tend to restrict the size of vessels on a waterway, the draft to which vessels can be loaded or the speed of the vessels would be factors which decrease channel capability and adversely affect transportation economics.

## METHODOLOGY

The condition of the current waterway system was investigated with respect to the operation of the current industry transportation fleet. In addition, functional relationships have been developed to allow the evaluation of the interaction between modified navigation conditions and fleet operation. The dimensions, width, depth, bend radii, channel alignment and density of constraints to navigation determine the type and size of vessels which can operate on the waterway. In addition, these factors also determine the speed with which vessels can transit the waterway. All of these factors, in turn, help to define the economics of waterway transportation. These interrelationships will allow the evaluation of changes in transit times and transportation costs due to waterway improvements.

First, and most importantly, the economic operation of vessels requires a consideration of "economy of scale." The larger the vessel the more economical the unit cost of transporting cargo. This is evidenced by the gradual increase in size of inland waterway vessels over the decades as larger and larger channels and larger lock dimensions become available.

This section naturally begins, therefore, with an evaluation of the maximum tow size which the waterway can accommodate.

Second, this section analyzes existing operating conditions in terms of interaction between accommodated tow size and channel constraints, and defines standards which provide safe, dependable channel dimensions. The standards are evaluated based on existing and ongoing studies.

The degree of restriction of a waterway is best analyzed from the point of view of the largest tow commonly operating on that waterway; the common maximum tow size is determined by the interaction of the economics of tow operation and the degree to which the waterway can be considered restrictive. The configuration of the marine fleet is analyzed by segments based on PMS records and other published sources.

Existing channel conditions on each NWS segment are compared with the design standards which represent unrestrictive navigation for the common maximum tow size now operating on that segment. The relative importance of constraints on navigation in each segment is represented by an index of the constraining effect of sharp bends, the number of bridges with narrow navigable spans, and the density of marinas and commercial sites. The bend index is estimated from such information as is available, and the methodology and data requirements for a more precise calculation of the index are presented. The behavior of tows at bends, bridges, marinas and landings, and one-way reaches is described in the section on "Tow Industry Travel Time." Together, the comparison of channel dimensions and constraint indicators describe each segment as unrestricted, partially restricted, or very restricted.

Third, this section evaluates tow speeds and segment transit times in relation to existing navigation conditions. Most past analysis related to speeds has emphasized hydrodynamic phenomena determining speed limitations. This is a convenient starting point, and the evaluation of tow speeds begins with a discussion of the effects of resistance and thrust; this is followed by an analytical formulation for estimating tow speeds that will account for these factors. The uncertainty of the problem is represented by segment-specific navigation constraints, which can be described only empirically. Again, PMS records as well as other available studies dealing with transit time were used.

Transit times under present navigation conditions of locks, channels and traffic levels are tabulated by analysis segment. Lock delays and service time are incorporated into the tabulation.

Finally, waterway transportation costs are analyzed as a function of navigation conditions. The sensitivity of waterway transportation costs to channel depth, width, frequency of oneway reaches, density of constraints (bridges, landings), lock utilization and level of traffic are developed.

The sensitivity of transportation costs to waterway characteristics was determined by parametric analysis, varying the value of one parameter of the waterway at a time, and holding all others constant. In this way, channel modifications, which may be suggested to increase waterway capability, can be analyzed in order to determine the magnitude of the improvement (reduction in constraints or changes in dimensions) offered in terms of cost impacts resulting from increased tow speeds and decreased transit time. These, of course, can be analyzed at any anticipated level or distribution of traffic in conjunction with lock capacity and delay.

## MAXIMUM ACCOMMODATED TOW SIZE AND NAVIGATION CONSTRAINTS BY NWS SEGMENTS

Substantial economies can be realized by the use of large tows. This is due in part to the fact that the manning requirements of tows are nearly constant over a wide range of tow sizes. In addition, the increase in hydrodynamic resistance of a tow is less than proportional to increases in tow size, as is the increase in investment costs of towboats. These factors are amply demonstrated in practice where tows of 15 barges headed downstream from the Upper Mississippi River refleet into 25 barge tows below L/D 27 and into 40 barge tows below Cairo. It is well known that carriers, in most situations, do everything possible to increase tow size in order to fully utilize the channel's capability to accommodate tows.

There are no abrupt cut-off points of channel width and bend radius or lock size which preclude tows of a certain size from using a waterway. Rather, the channel dimensions, density of navigational constraints, and tow size interact to define the waterway as unrestricted, partially restricted, or very restricted. The tow of maximum size that operates on a given waterway is the result of an economic decision balancing the economies of large tows against the increased travel time, fuel consumption, delay, risk, and crew stress associated with navigation on a more restricted waterway. The analysis of these factors to the degree necessary to predict maximum tow size on any waterway is well beyond the scope of the NWS. This report is limited to the tabulation of the observed maximum tow size on each NWS segment and the presentation of a conceptual approach toward measuring the degree of restriction on each segment. The conceptual method involves the comparison of existing channel dimensions with design standards in order to illustrate the degree of restriction of the waterway given the current maximum tow size in use.

This section also identifies the waterway segments where channel improvements are most needed to provide adequate navigation conditions.

### (a) Summary of Design Standards

Element I presents channel dimension design standards in detail; this section summarizes the main results. Design standards are generally formulated on the basis of unrestricted two-way navigation. Navigation is still possible in channels which do not meet these standards, but those channels may be considered restricted to some degree. For example, the fact that the clearances in a channel are not as large as those recommended does not imply that collisions will occur but that collisions are more likely and tow pilots must be more cautious.

Another important consideration is the density of reaches which do not meet design standards. A waterway can hardly be considered restricted if its dimensions are ample over 95% of its length, even if the remaining 5% is severely constrained. The maximum size of tows is governed by the degree of restriction of most of the waterway, and not by the single worst spot.

This observation is particularly relevant to waterways in the United States, which consist mainly of relatively large rivers, in contrast to Europe, where man-made canals constitute a large part of the waterway network. In natural or improved rivers, restricted reaches are always followed by wider segments; in canals, the same dimensions are maintained over the entire length. Thus, there is a more definite limit on the maximum accommodated vessel size.

The depth of a channel, once the minimum physical requirements of the design vessel have been met, is the result of a trade-off between the additional cost of maintenance (and for man-made waterways, the initial cost, as well) and the reduced transportation cost associated with greater depth. In practice, tow operators adjust the draft of their barges to the maximum value which they feel is acceptable, based on current depth conditions. No further consideration will be given to depth at this point as more detailed discussions of depth limitations were presented in Section IV.

The width of a channel in straight reaches should be sufficient to accommodate two-way traffic with safe clearance between the lanes and between the tows and the edge of the channel. EM 1110-2-1661, "Layout and Design of Shallow Draft Waterways,"[45] recommends a total clearance of 35 feet & L sin $\alpha$ ; where L is the tow length and $\alpha$ is the drift angle, taken as about 3 degrees. Daggett and Shows present a table of recommended channel widths with clearances varying from 50 feet for small tows to almost 300 feet for 18 barge tows.

Channel width must be greater in bends than straight reaches, as tows assume an additional drift angle with respect to the channel line when traversing bends. The drift angle in bends is a function of the tow size, current, and radius of the bend and is usually much larger than the drift angle on straight reaches. The INSA report and the publication "Layout and Design of Shallow Draft Waterways" describe methods of computing the drift angle and the required extra channel width. Clearances must also be wider on bends because of the presence of cross currents.

The INSA report recommends 45 feet clearance between tows and 15 feet off the edges of the channel. The report "Layout and Design of Shallow Draft Waterways" describes model tests of bends in which 50 feet between tows and 20 feet off the channel margins were used.

The design minimum bend radius is directly related to the channel width on bends. The initial cost of developing a waterway with sharp bends and wide channels, for example, may be less than one with gradual bends and narrower channels. However, the ability of the waterway to carry sediment must be considered, as the cost of training works, revetments, and maintenance could push the cost of the waterway with wide, sharp bends over that of the narrower channel with gradual bends.

Cross sectional area is not an important consideration in natural rivers where the cross sections are usually quite ample. The cross sectional areas of canals like the GIWW usually determine the power requirement and speed of tows, although depth has a stronger effect than width.

The effect of cross sectional area to the maximum wetted cross section of the tow is greater than about eight.

### (b) Comparison of Channel Dimensions to Design Standards for Maximum Accommodated Tow Size

This section presents accommodated tow sizes and compares the channel dimensions recommended for the accommodated tow size operating on each segment. The purpose of this comparison is to gain insight into the degree to which each waterway is restricted under present operational practices. This information can feed into decision-making with respect to alternative methods to increase waterway capability. For example, if the channel dimensions of a waterway are such that the site of the largest accommodated tow is limited to the existing tow size, it is possible that large locks which could accommodate larger tows would not significantly increase waterway capacity. On the other hand, the size of tows on waterways which are not restricted by channel dimensions or other constraints could be limited by the need for multiple lockages given the existing lock chamber size.

Table V-1 summarizes the comparison of controlling channel dimensions and recommended design standards. The controlling channel width according to the NWS Inventory is shown, with the width in straight reaches as recommended by INSA (as discussed in Element I, these channel widths are close to those suggested by Daggett and Shows) for the common maximum tow size currently operating on the segment. The maximum tow size given in Table V-I of National Transportation-Trends and Choices (to the year 2000), U.S.D.O.T., January 1977, was the source for the common maximum tow size. These tow sizes are expressed in "jumbo barge equivalents;" that is, the product of the length and width of the common maximum tow (not counting the towboat) on each waterway has been divided by the product of the length and width of a jumbo barge (195'x35') and rounded to an integer. For example, the six "stumbo" (195'x26') barge tows on the Monongahela are converted to four jumbo equivalents.

# Table V-I

## Comparison of Existing Channel Dimensions to Design Standards for the Maximum Accommodated Tow Size

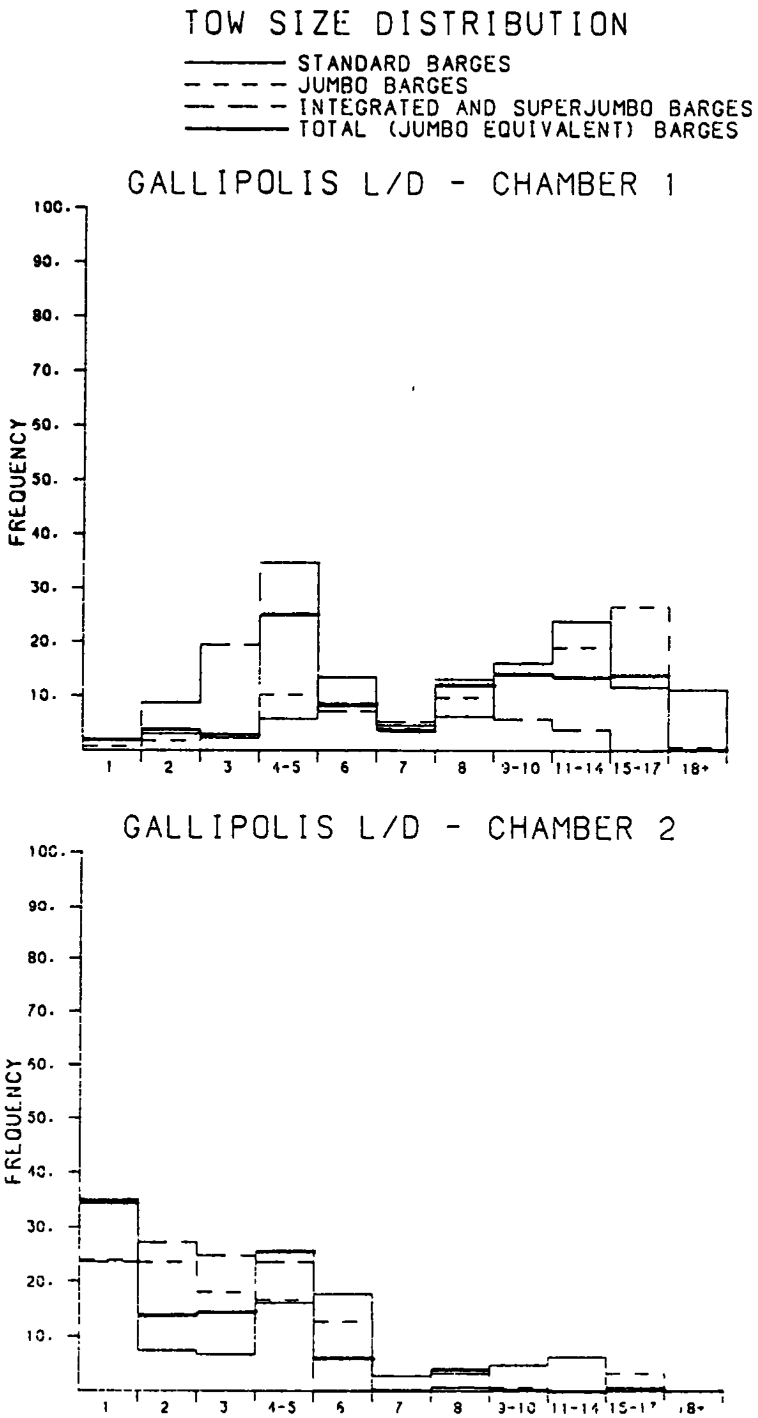
| Map Reg | Segment Name | Common Maximum Tow Size | Absolute Maximum Tow Size | Average Tow Size | Controlling Width ft | Recomm Width ft. | Controlling Radius | Bend Index |
|---|---|---|---|---|---|---|---|---|
| 1 | U. Miss. | 15 | 18+ | 8 8 | 300 | 380 | 1,800 | 40 |
| 2 | Lower U. Miss | 15 | 18+ | 9.4 | 300 | 380 | 13,000 | 100 |
| 2 | Middle Miss | 25 | 18+ | 7 5 | (3) | 520 | 3,000 | 65 |
| 3 | Lower Middle Miss | 45 | N.A. | 10.6 | (3) | 620 | 2,600 | 70 |
| 3 | U. Lower Miss | 45 | N.A. | 10.6 | (3) | 620 | N A | 80 |
| 3 | Lower Miss | 45 | N.A. | 10.6 | (3) | 620 | N A | 100 |
| 4 | Baton Rouge to N O | 45 |  |  | (1( | 620 | N A | 100 |
| [illegible] | N O to Gulf | 45 | N.A. | 10.6 | (3) | 620 | N.A | 100 |
| 4 | Ouchita | 2 | N.A. | 7.0 | 100 | 160 | N A | N A |
| 4 | Atchafalaya | 4 | U A | 3.3 | 125 | 235 | N A | U A |
| 4 | Morgan City-Port Allen | 5 | U A | 4.2 | 125 | 250 | N A. | N A |
| 5 | Illinois W/W |  |  |  |  |  |  |  |
|  | Mouth to Lockport L/D | 15 | 18+ | 5 9 | 300 | 380 | 800 | 25 |
|  | CSSC | 15 | 18+ |  | 175 | 380 | 500 | N A |
|  | Calumet-Sag Channel | 15 |  | 2.2 | 200 | 380 |  | N A |
| 6 | Missouri |  |  |  |  |  |  |  |
|  | Lower | 9 | U A. | 4.8 | 300 | 3.5 | 1,700 | 70 |
|  | Upper | 6 | U A. | 4.8 | 100 | 260 | 4,800 | 100 |
| 7 | U Ohio | 15 | 18+ | 7 6 | (3) | 380 | 1,500 | 100 |
| 7 | Middle Ohio | 15 | 18+ | 9 1 | (3( | 380 | 1,100 | 100 |
| 7 | Lower Ohio III | 15 | 18+ | 9.1 | (3) | 380 | 2,000 | 100 |
| 7 | Lower Ohio II | 15 | 18+ | 9 3 | (3) | 380 | 3,000 | 100 |
| 7 | Lower Ohio I | 15 | 18+ | 8 2 | (3( | 388 | 9,000 | 100 |
| 7 | Monongahela |  |  |  |  |  |  |  |
|  | Lower | 4 (1) | 9-10 | 6 0 | 400 | 260 | 2,000 | 100 |
|  | Upper | 4 (1) |  | 4.7 | 250 | 260 | 1,000 | 70 |
| 7 | Allegheny |  |  |  |  |  |  |  |
|  | Lower | 6 | 7 | 3.2 | 350 | 350 | 4,200 | 100 |
|  | Upper | 3 |  | 2 5 | 250 | 350 | 1,900 | 50 |
|  | Great Lakes/St. Lawrence Seaway | 1 750 foot ship | N.A. | 1 (ship) | UA | 670 | UA | 100 |

## Table V-I (Continued)

| Rep. Reg. | Segment Name | Common Maximum Tow Size | Absolute Maximum Tow Size | Average Tow Size | Controlling Width ft. | Recomm. Width ft. | Controlling Radius | Bend Index |
|---|---|---|---|---|---|---|---|---|
| 7 | Kanawha | 9 | 18+ | 4.5 | 400 | 325 | 300 | 98 |
| 7 | Green/Barren | 4 | 8 | 3.8 | 200 | 230 | 800 | 40 |
| 7 | Cumberland | 8 | 18+ | 10.7 | 300 | 315 | U.A. | U.A. |
| 8 | U. Tennessee | 15 | 18+ | 5.5 | 300 | 380 | U.A. | U.A. |
| 8 | Lower Tennessee | 15 | 18+ | 7.7 | 300 | 380 | U.A. | U.A. |
| 9 | Arkansas | 9 | 15-17 | 3.7 | 250 | 325 | 2,100 | 85 |
| 10 | GIWW/W I | 5 | U.A. | 3.0 | 125 | 250 | N.A. | 100 |
| 10 | GIWW/W II | 5 | | 3.0 | 125 | 250 | N.A. | 85 |
| 10 | GIWW/W III | 5 | 18+ | 2.1 | 125 | 250 | 2,000 | U.A. |
| 11 | GIWW/E | 5 | | 2.6 | 125 | 250 | 2,000 | U.A. |
| 11 | A/C/F | 1 | 4- 5 | 2.4 | 80 | 140 | 400 | 50 |
| 12 | Black Warrior/ Tombigbee | 6 | 7 | 3.6 | 200 | 250 | 400 | 15 |
| 12 | Alabama/Coosa | 2 | 18+ | 3.5 | 150 | 160 | 800 | 50 |
| 18 | Lower Columbia/Snake | 7 (2) | U.A. | 3.0 | (3) | 270 | U.A. | 100 |
| 18 | U. Columbia/Snake | 7 (2) | U.A. | U.A. | 250 | 270 | U.A. | U.A. |

Notes:
(1) Monongahela River tows use six "stumbo" (195'x26') barges, equivalent to four jumbos.
(2) Columbia/Snake River tows use five (220'x42') barges, equivalent to seven jumbos.
(3) Channel width varies seasonally and is extremely wide most of the year. Channel width never drops below 300 feet.

**Figure V-A**


TOW SIZE DISTRIBUTION
STANDARD BARGES
JUMBO BARGES
INTEGRATED AND SUPERJUMBO BARGES
TOTAL (JUMBO EQUIVALENT) BARGES
GALLIPOLIS L/D - CHAMBER 1
FREQUENCY
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
1
2
3
4-5
6
7
8
9-10
11-14
15-17
18+
GALLIPOLIS L/D - CHAMBER 2
FREQUENCY
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
1
2
3
4-5
6
7
8
9-10
11-14
15-17
18+

The absolute maximum and average tow sizes are taken from NWS printouts of PMS data. The absolute maximum is the size of the largest tow recorded passing through a lock on that segment. The size is reported according to the categories used in the printout, such as 11-14 or 9-10. These are also expressed in jumbo equivalents; average tow size, however, is not.

Figure V-A contains computer generated histograms of the detailed tow size distribution at the two chambers of Gallipolis Lock and Dam. The horizontal axis is divided according to the categories used in the NWS printout of PMS data. The vertical axis is plotted in percentage of total barges. Tow size distribution depends on many factors including the waterway channel dimensions, the channel dimensions at the eventual destination of the tows, the number of local movements, and so on. The traffic through Gallipolis Lock is used only as an example and should not be considered necessarily typical of the Ohio River, or of any other waterway.

The effect of sharp bends as restrictions is illustrated by the "bend index." Conceptually, the index is computed in the following manner.

The minimum required radius for unrestricted two-way traffic is determined for each bend on the segment, given the maximum tow size presently operating on the segment and channel width in the bend. The ratio if the actual bend radius to the design value is calculated. If the bend is more gradual than the requirement (actual radius greater than design radius), the ratio is set to one. Straight reaches have an infinite radius, and thus their ratio is one. The Bend Index is the average of these ratios, expressed as a percent, weighted by the length of the bendways. An index of 100 indicates that no bend is sharp enough to restrict two-way traffic of the maximum tow size. A low value of the index implies that the largest tows are restricted to one-way travel at some bends or at least must exercise particular caution during two-way transits. The index is valid only as an ordinal measure of the degree of restriction of maximum size tows on bends, and not as a cardinal measure.

The detailed data on channel width and radius at each bend in the inland waterway system required to compute the bend index are not currently available. Thus, such data as were immediately available as well as various approximations were used.

For most segments, the channel width in bends was assumed to be 150% of the authorized channel width in straight reaches. The best source of data on bend radius that is currently available is the waterway description report of the INSA simulation program. Every navigable waterway connected to the Mississippi River system is divided into short segments, and the controlling radius tabulated. (The smallest radius on each NWS segment is shown in Table V-1.) These tabulated values and the lengths of the INSA segments were used to compute the bend index. Where these radii were not available, inspections of navigation charts assisted in estimating values of the bend index using comparisons with other waterways for which the index had been computed. The very sketchy information available on bendways along the inland waterway system suggests that an effort be made to systematically assemble these data on a national basis.

The bend index values shown in Table V-1 are by no means exact, but their ordinal ranking appears quite reasonable.

Table V-2 lists the number of bridges on each segment with spans less than the INSA recommended width of the channel.

One column indicates the number of bridges wide enough to accommodate one-way passage of the maximum size tow without restriction, but not wide enough to allow two-way passage. The next column contains the number of bridges for which spans are narrow even for one-way traffic. The last column in this section of the table presents the number of narrow bridges of both types scheduled to be removed from the 1975 Coast Guard report, "Bridges Over Navigable Waterways of the United States."

# Table V-2

## Constraints on Navigation and Accidents Reported 1972-1976

| Rep. Reg. | Analysis Segment | Narrow 2-way Bridges | Narrow 1-way Bridges | Bridges to be Removed | Density of Marinas per 100 miles | Density of Comm'l. Sites per 100 miles | Collision | Ramming | Grounding | Total Accidents |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | U. Miss | 16 | 43 | 4 | 15 | 30 | | | | |
| 2 | Lower U. Miss. | 1 | 1 | 0 | 35 | 95 | 18 | 178 | 87 | 283 |
| 2 | Middle Miss. | 6 | 1 | 0 | U.A. | U.A. | | | | |
| 3 | Lower Middle Miss. | 0 | 0 | 0 | U.A. | U.A. | | | | |
| 3 | U. Lower Miss. | 0 | 0 | 0 | U.A. | U.A. | 85 | 110 | 90 | 285 |
| 3 | Lower Miss | 0 | 0 | 0 | U.A. | U.A. | | | | |
| 4 | Baton Rouge to N.O. | 0 | 0 | 0 | U.A. | U.A. | | | | |
| 4 | N.O to Gulf | 3 | 0 | 0 | U.A. | U.A. | 75 | 123 | 15 | 213 |
| 4 | Ouachita | 13 | 0 | 0 | U.A. | U.A. | | | | |
| 4 | Atchafalaya | 1 | 3 | 0 | U.A. | U.A. | | | | |
| 4 | Morgan City-Port Allen | 0 | 1 | 1 | U.A. | U.A. | | | | |
| 5 | Illinois W/W | 14 | 51 | 1 | 9 | 84 | 20 | 124 | 21 | 165 |
| 6 | Missouri | | | | | | | | | |
| | Lower | 2 | 4 | 1 | 2 | 16 | 0 | 6 | 2 | 8 |
| | Upper | 7 | 0 | 0 | 2 | 16 | | | | |
| 7 | U. Ohio | 1 | 0 | 0 | 13 | 76 | | | | |
| 7 | Middle Ohio | 0 | 0 | 0 | 26 | 55 | | | | |
| 7 | Lower Ohio III | 0 | 1 | 0 | 14 | 36 | 38 | 220 | 88 | 346 |
| 7 | Lower Ohio II | 0 | 0 | 0 | 6 | 36 | | | | |
| 7 | Lower Ohio I | 0 | 0 | 0 | 0 | 37 | | | | |
| 7 | Monongahela | | | | | | | | | |
| | Lower | 0 | 0 | 0 | 26 | 125 | 0 | 14 | 2 | 16 |
| | Upper | 2 | 2 | 0 | 26 | 125 | | | | |
| 7 | Allegheny | | | | | | | | | |
| | Lower | 3 | 1 | 1 | 38 | 79 | 0 | 3 | 1 | 4 |
| | Upper | 2 | 4 | 0 | 38 | 79 | | | | |

# Table V-2 (Continued)

| Rep. Reg. | Analysis Segment | Narrow 2-way Bridges | Narrow 1-way Bridge | Bridges to be Removed | Density of Marinas per 100 miles | Density of Comm'l. Sites per 100 miles | Collision | Ramming | Grounding | Total Accidents |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Kanawha | 0 | 1 | 1 | 2 | 89 | 0 | 8 | 2 | 10 |
| 7 | Green/Barren | 1 | 6 | 0 | U.A. | U.A. | | | | |
| 7 | Cumberland | 26 | 6 | 0 | 6 | 9 | 0 | 10 | 6 | 46 |
| 8 | U. Tennessee | 30 | 7 | 1 | 24 | 7 | | | | |
| 8 | Lower Tennessee | 3 | 0 | 0 | 17 | 19 | | | | |
| 9 | Arkansas | 18 | 2 | 0 | 5 | 11 | 0 | 5 | 1 | 6 |
| 10 | GIWW/W I | 0 | 7 | 2 | U.A. | U.A. | | | | |
| 10 | GIWW/W II | 2 | 16 | 4 | U.A. | U.A. | 229 | 173 | 71 | 473 |
| 10 | GIWW/W III | 1 | 6 | 0 | U.A. | U.A. | | | | |
| 11 | GIWW/E | 1 | 52 | 5 | U.A. | U.A. | 27 | 46 | 41 | 114 |
| 11 | A/C/F | 10<br>6 | 5<br>6 | 2 (A/C)<br>1 (F) | U.A. | U.A. | | | | |
| 12 | Black Warrior/ Tombigbee | 8 | 21 | 1 | U.A. | U.A. | | | | |
| 12 | Alabama/Coosa | 19 | 7 | 0 | U.A. | U.A. | | | | |
| 18 | Lower Columbia/Snake | 2 | 0 | 0 | U.A. | U.A. | | | | |
| 18 | U. Columbia/Snake | 5 | 1 | 1 | U.A. | U.A. | | | | |

The next section of the table lists the density of commercial landings, marinas and fleeting areas per waterway mile determined in Element G. The effect of these constraints on navigation on transit time as well as the sensitivity of transit time to the density of these constraints is discussed in later sections.

The last section of the table presents the number of accidents (reported between 1972 and 1976) by river in which the primary vessel was a towboat or barge. The source is Report No. CG-D-30-78, Human and Physical Factors Affecting Collisions, Rammings, and Groundings on Western Rivers and Gulf Intracoastal Waterways[47], by Paramore, Dayton, Parricelli, and Willis, Coast Guard, January 1979. These accident statistics are discussed below.

No attempt has been made to combine the lateral restriction in straight reaches, the degree of constraint bends, the number of narrow bridge spans, and the frequency with which each of these restrictions occur into a single measure of restriction on a waterway. The theoretical analysis and empirical validation of such a methodology is beyond the scope of the NWS, but is a possible area for future research. For now, the various indicators in Tables V-1 and V-2 can suffice for a qualitative estimate of the degree of restriction on segments of the inland waterway system. This information is used in Section III in order to identify waterways on which tow size is limited by channel dimensions rather than lock dimensions and has provided a baseline for consideration of alternative modifications to improve navigation conditions.

Several waterways appear to be very restrictive to the largest tow operating at present: the Illinois, the Upper Mississippi (to the Illinois), the GIWW, the Green/Barren, the Lower Cumberland, the Black Warrior/Tombigbee, and the Apalachicola/Chatahoochee/Flint Rivers. All of these waterways have relatively poor bend indices, controlling widths narrower than the ideal width for two-way traffic, and a number of narrow bridge spans. Although no bend index has been computed for the Cumberland, as a whole it is known that the Cumberland has several bad bends which require tows to flank. The ACF has a particularly narrow channel which undoubtedly restricts commercial navigation.

At the other extreme are rivers which are nearly ideal transportation arteries: the Mississippi River from St. Louis to the Gulf of Mexico, the Ohio, the Lower Monongahela, the Upper Missouri, the Kanawha, and the Columbia River up to the confluence of the Snake River. These waterways provide ample width for two-way traffic of the largest tow sizes now operating: the bendways are wide, gradual or both so as to present no difficulties, and there are few, if any, narrow bridge spans. It is likely that tow sizes could increase on these waterways without exceeding the capabilities of the channels. The reasons why tow sizes have not already grown include increased lockage delay (the Ohio River Division will not permit double lockages through 1200 feet locks; Bonneville Lock on the Columbia is only 500'x76'), more restricted channels upstream (e.g., the Upper Monongahela), more technological frontiers (how does one steer more than 45 barges?).

The remainder of the waterways fall into the middle ground between highly restricted and unrestricted. Certain rankings are possible within this group. The Atchafalya and Morgan City-Port Allen Route have narrow channels, about half of the ideal value, and are saved from the "very restricted" group only because they are fairly straight with few sharp bends. The upper Allegheny, and Monongahela, as well as the lower Missouri and Alabama/Coosa are a bit narrow, but have problem bends and some tight bridges and so can be ranked above the GIWW. The Arkansas is perhaps less restrictive than the waterways immediately above. No judgment could be made about the Ouachita, Tennessee, and Snake Rivers because of the lack of data on bends. However, the width and bridge indicators suggest that they belong somewhere in the middle group.

It is interesting to consider the accident statistics in light of these conclusions on a level of channel restriction. Eighty-six percent of the accidents, analyzed in the Coast Guard study referred to above, occurred on four of the 13 waterways considered: the Mississippi River, the Illinois Waterway, the Ohio River, and the GIWW. Although the Illinois, Upper Mississippi and GIWW are considered restricted here, the Lower Mississippi and Ohio are not. The Coast Guard study found, however, that the accidents on these four waterways are clustered over about 10% of their navigable length. The accident prone areas tend to have the following characteristics:

- one or more bridges.
- one or more locks.
- both a bridge and a lock.
- a bend, intersection or junction.
- a very narrow available width.

These are the same characteristics as those considered when ranking the level of restriction of waterways. They occur over much of the length of restricted waterways, such as the Illinois, but are localized and limited to only a few locations on unrestricted waterways such as the Ohio. The Lower Mississippi is largely free of all these constraints, however. The high accident rate there can be ascribed to adverse and ever-changing hydrological conditions. The problem of navigating the tricky currents and cross-currents on the free-flowing river have been well known since the time of Mark Twain. The Coast Guard report states that currents were the single most frequently cited causal factor in both rammings and grounding, and were also frequently cited as a cause of collisions.

## TOW SPEED AND TRANSIT TIME

The speed of tows is a function of many factors, the most important being:

- horsepower of the towboat.
- size and configuration of the tow.
- width and depth of the channel current.

Thrust, the force in the direction of motion developed by a tow, is proportional to the towboat horsepower, but depends on the channel cross section as well. Neither conventional propellers nor kort nozzles can generate the same thrust in a restricted channel as in open water, the effect of depth being much more important than width.

Resistance, or drag, the force on the tow acting opposite to the direction of motion depends on the size, shape, and draft of the tow, the channel dimensions, and the speed of the tow. Resistance arises from the friction of water movement along the surface of the hull, the energy needed to maintain the wave system in the wake of the tow, vortices generated by the separation of the flow from the hull surface at points of abrupt change in the shape of the wetted surface of the tow, and the change in the water level caused by the passage of a tow in a restricted channel. Restricted channels also create "walls" of resistance at certain critical speeds which cannot be overcome by tows.

The thrust and drag forces are in equilibrium when a tow moves with constant speed. The components of thrust and drag which are functions of speed depend on the tow speed with respect to the water. In the presence of a current, speed over the ground is found by adding or subtracting the speed of the current.

The INSA report "Waterway Analysis" presented an analytical formulation for tow speed proposed by Hochstein. This methodology, the most generally applicable and accurate technique of estimating tow speed available today, is based on the equilibrium of thrust and resistance at constant speed. Various empirical formulas are used to estimate thrust and resistance as functions of the tow size, towboat horsepower, and channel dimensions. The basic force identity is then solved for the tow speed. The report cites the equations for the limiting speeds in finite channels, which come from hydrodynamic theory, and presents a detailed algorithm for the determination of tow speed.

This methodology has been successfully used in many applications, including sensitivity analysis of tow speed presented later in this section, but the user must be aware that no account is taken of the effects of constraints on navigation of the type described in the next section. The values output by the Hochstein method represents bow speeds in channels unhindered by obstructions (restrictive channel dimensions are included), which may differ from observed average tow speeds over the length of a waterway. At present, this average speed can be determined only by observation.

### (a) The Effect of Channel Dimensions and Alignment on Transit Time

1. Channel Dimensions. It is well established that tows operating in restricted channels encounter greater resistance to motion than those in open water. This effect has been treated analytically and experimentally by many authors, including van de Kaa, McNown and the Corps of Engineers, Ohio River Division. A particularly useful formulation is found in the report "Waterways Analysis." This source contains a methodology for the calculation of tow speeds which was developed for the INSA simulation model. The equations are applicable to a wide range of tow sizes and explicitly illustrate the effects of channel dimensions on tow speed.

Depth has a strong effect on tow speed, both through the enhancement of resistance and the limitation of the thrust which can be developed by the propellers. An empirical formula has been developed that accounts for both these effects:

$$e_h = ((1 + 2 \sqrt{\frac{7b}{l}}\, \frac{d}{h}\, \frac{V_0^2}{gh})^{-1/2}$$

where,

$e_h$ is the shallow water speed coefficient of the tow
$l$ is the length of the tow
$b$ is the width of the tow
$d$ is the draft of the tow
$h$ is the channel depth
$g$ is the acceleration due to gravity

and $V_0$ is the open water speed of the tow (consistent units; $e_h$ is dimensionless)

The shallow water speed coefficient is the fraction of the open water speed which the tow can achieve in a channel of finite depth. It should be noted that the open water speed of a tow can only be reached in a channel that is completely unrestricted in both depth and width. This is not generally possible on inland waterways. Specifically, depth becomes a constraining factor for tows with more powerful towboats which can achieve relatively higher speeds in constrained conditions.

Channel depth also imposes an upper limit on the speed of tows. When displacement vessel approaches the speed at which waves propagate in a channel of finite depth, it encounters an insurmountable wall of resistance. The only way vessels can surpass this limiting or critical speed is by planing or "surfing" on the waves. The propagation speed of waves is a function of depth and channel cross section:

$$V_l = k \sqrt{gh}$$

where $V_l$ is the finite-depth limiting speed, g and h are defined as above and k depends on the channel cross section. In practice, tows rarely exceed 70% of the critical speed since resistance increases rapidly as speed approaches the limiting speed.

2. Width and Cross Section. The width of a channel does not, per se, affect the speed of tows as long as enough width is available for safe transit. Design widths were discussed briefly in this subsection and are discussed in more detail in Element I. Width does affect the channel cross sectional area, which can influence tow speeds. If the ratio between the cross sectional area of the channel and the largest wetted cross sectional area of the tow is greater than 8.0, the effect of the channel cross section on tow speed can usually be ignored. This is generally the case in open and canalized rivers. However, the cross sectional area ratio often becomes important in canals. The speed of tows in restricted channels does not depend on the power of the tow so much as the channel dimensions. Hochstein cites the following relation derived by applying continuity and Bernoulli's equation to a tow in a restricted channel:

$$V^w = 1.97\sqrt{\cos^3 \left\{ \frac{\pi + \cos^{3(1-\frac{1}{A})}}{3} \right\}} \sqrt{gh}$$

where $V_w$ is the channel-limited speed in miles per hour, A is the cross sectional area ratio, g is the acceleration due to gravity, h is the channel depth in feet. Figure V-B illustrates some values of $V_w$. It should be noted that the area ratio of a tow in a canal can be suddenly reduced by the passage of another vessel in the opposite direction. The existence of two-way traffic must be considered when computing the speed of tows in restricted channels.

3. Bend Radius. A gradual bend with a channel wide enough to accommodate two-way traffic safely has no effect on tow speed. As bends become sharper, tow pilots begin to use their engines to help maneuver, reducing tow speed in the direction of the sailing line. At very sharp bends and under adverse wind or current conditions, pilots are forced to flank. Flanking involves steering and maneuvering the tow not along the desired direction, but rather into such a position that the current and/or wind will slew the tow into place. This often means that the pilot will not only reduce speed in the desired direction, but must even reverse the motion of the tow for a time. These reductions in speed depend on the particular bend, pilot, tow, towboat (a more powerful towboat may be able to steer through a bend where a smaller towboat must flank) and the wind and current conditions, and would appear to be impossible to quantify without site-specific study of navigation conditions and operational practices. The effect on transit time of sharp bends as one-way reaches is treated in the following section of this report.

### (b) Constraints on Transit Times

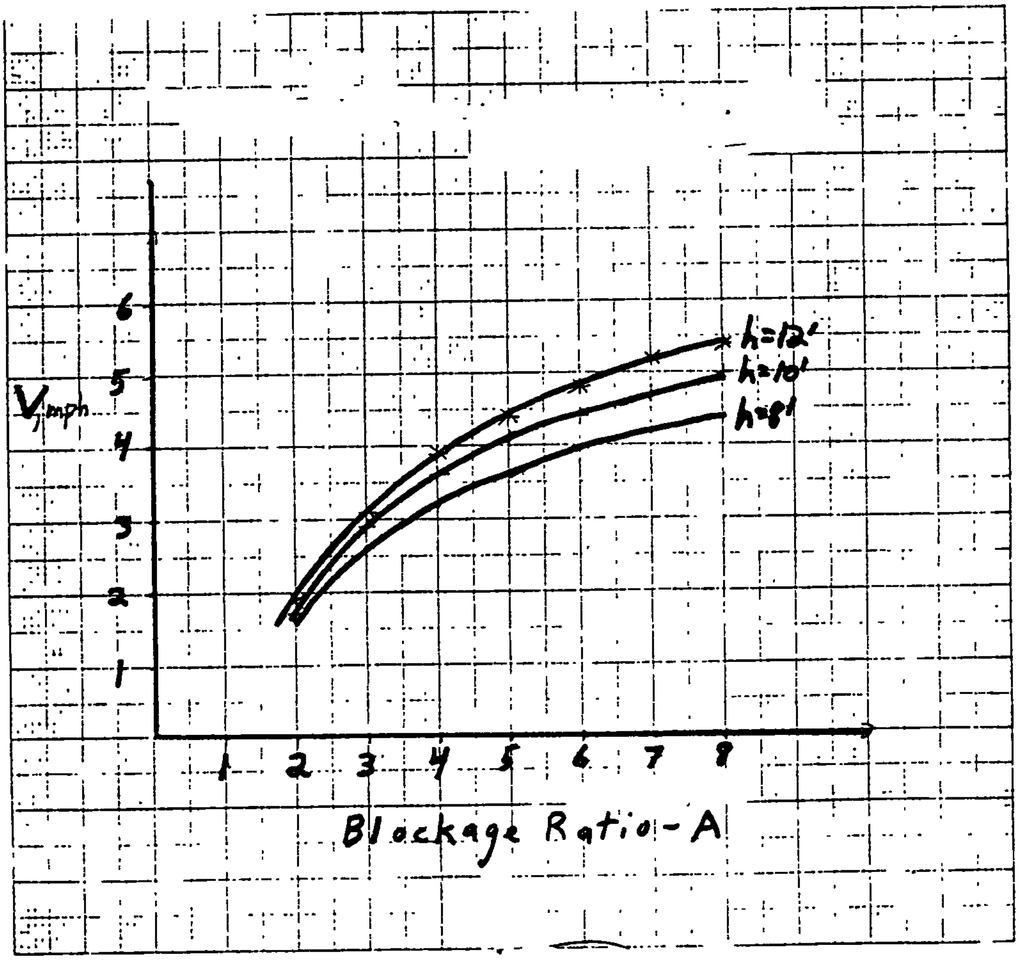
Tow transit times are hard to calculate even if the speed of tows in unrestricted reaches is known. Transit times are affected by random factors, including current, wind, fog, and stage of river, and by constraints on navigation. Constraints on navigation are obstructions which require tows to either slow down from their normal speed for some distance, or to stop and wait for some period of time.

Tows slow when passing marinas, landings, fleeting areas, and recreational craft in order to avoid swamping small boats, breaking mooring lines, or even damaging light structures with the wake of the tow (see Element I). A tow will also reduce speed when encountering another tow in a narrow reach in order to avoid undue stress on towlines and hawsers caused by driving through the wake of the passing tow.

By definition, only one tow at a time can negotiate a one-way reach, such as is often found at sharp bends. In

# Figure V-B

## Channel Limited Speed



these cases, the upbound tow will hold until the downbound tow has cleared the bend. Downbound tows have the right-of-way, and upbound tows will stop below one-way reaches if the speed and position of an oncoming tow is such that they might meet on the bend. Since tows are in radio communication with each other, pilots of upbound tows will often reduce their speed so as to arrive at one-way reaches after the downbound tow is clear, rather than stopping and holding a position immediately below the reach. The time lost by the upbound tow is the same in either case.

Tows must sometimes flank in order to negotiate sharp bends with swift currents. A flanking maneuver is one in which the pilot does not point the tow directly in the direction in which it is supposed to go, but rather puts the tow in such a position that the current will push the tow into place. "Wind flanks," using the wind to maneuver the tow, are often necessary with empty barges. A bend which requires tows to flank is a constraint on navigation because flanking requires more time. During a flanking maneuver, not only is the tow often pointing in a direction different from the one in which the pilot desires to go, but the pilot must reverse the engines and back the tow into place, consuming additional time.

Bridges with narrow navigable spans or limited vertical clearances constitute constraints on navigation. Tow pilots proceed under such bridges with great care because of the potential damage to property and loss of life which could result from a collision. Fortunately, the length of the reach controlled by bridge spans is not large and there is usually little delay and virtually no "one-way reach" effect as described above. The exceptions are those bridges set across bends which cause pilots to flank when they would otherwise drive through bends and bridges in areas susceptible to hydrometerological conditions unfavorable for navigation. That is, tow pilots must be extremely careful passing under narrow or low bridges during high water, strong current (usually occurring at the same time as high water), or poor visibility conditions. Sometimes, these conditions can force navigation to cease completely because of the consideration of safety at bridges.

The effects of all of the different types of constraints on transit time cannot be treated analytically. Extensive observations of a particular waterway are necessary for an accurate estimation of the effects of constraints on that waterway.

### (c) The Effect of Density of Constraints and Level of Traffic on Transit Time

1. Density of Constraints. The presence of one-way reaches at sharp bends and bridges increases transit times. The formula below gives expected delay due to one-way reaches:

$$T = \frac{JL\,[1/V_u + 1/V_d\,]}{2V_d/pc - J}$$

T is the expected total delay, c is the average length of reaches controlled by one-way segments, p is the fraction of the waterway length controlled by such reaches (a one-way reach own length because an upbound tow will not enter a one-way reach if a downbound tow will arrive at that reach before the upbound tow is clear of it), L is the length of the waterway, J is the average arrival rate of downbound tows at the upper end of the waterway, $V_u$ is the speed of upbound tows and $V_d$ is the speed of downbound tows. The density of restricted reaches is proportional to p. If p is rewritten as bc/L where L is the number of one-way reaches, then the density of one-way reaches appears explicitly as b/L. The expected delay increases almost linearly with b/L. As traffic grows, J increases and expected delay (T) increases strictly monotonically at an increasing rate. This is discussed in greater detail below.

2. Level of Traffic. The level of traffic affects en route time, lock delay time, and to a lesser degree, lock service time. Each of these is treated here in turn.

Increasing traffic often increases en route time because of the greater numbers of encounters that can occur between tows bound in opposite directions. When tows arrive at one-way reaches simultaneously, the upbound tow is delayed while the downbound tow negotiates the reach. The equation for the expected delay as a function of the density of one-way reaches is analogous to the equation for the delay at locks as a function of traffic given in Section III. The term $2V_d/pc$ is the capacity in tows/hour of a waterway constrained by one-way reaches, that is, a restricted but free flowing river. This "capacity" is extremely high and of little practical importance. For example, if the entire length of a waterway is controlled by one-way reaches, downbound tows move at 6 mph and the length of each controlled reach is 1.5 miles; the waterway capacity is eight downbound tows per hour or one downbound tow every 7.5 minutes. The capacity of the Upper Mississippi is estimated to be 13.3 downbound tows per hour (4.5 minutes per tow). Assuming that the average loaded tow moves 7,000 tons of cargo and the fraction of empty movements is 50%, the downbound arrival rate of 13.3 tows/hour (corresponding to 26.6 tows/hour counting both directions) implies a capacity of just over eight hundred million ($8x10^9$) tons/year.

This same equation can be used to describe the behavior of pilots in narrow two-way reaches. In these situations, passing pilots often throttle back to avoid driving through the wake of the passing tow and placing extra stress on towlines. The only modifications needed are the definitions of c and p to reflect operational practices during bypasses. The effect of bypasses on transit time is not very significant, however. If tows must slow for bypasses over 20% of the length of the Upper Mississippi River (in addition to one-way reaches), the expected additional time an upbound tow would spend en route is 3.3 hours.

Lock delay time, the time spent queued up waiting for lockage, increases with the level of traffic. Section III deals with this problem in detail, and thus, the presentation of the equation for delay time will suffice here. Expected delay time at a lock is given by:

$$D = \frac{aT_f}{k - T_f}$$

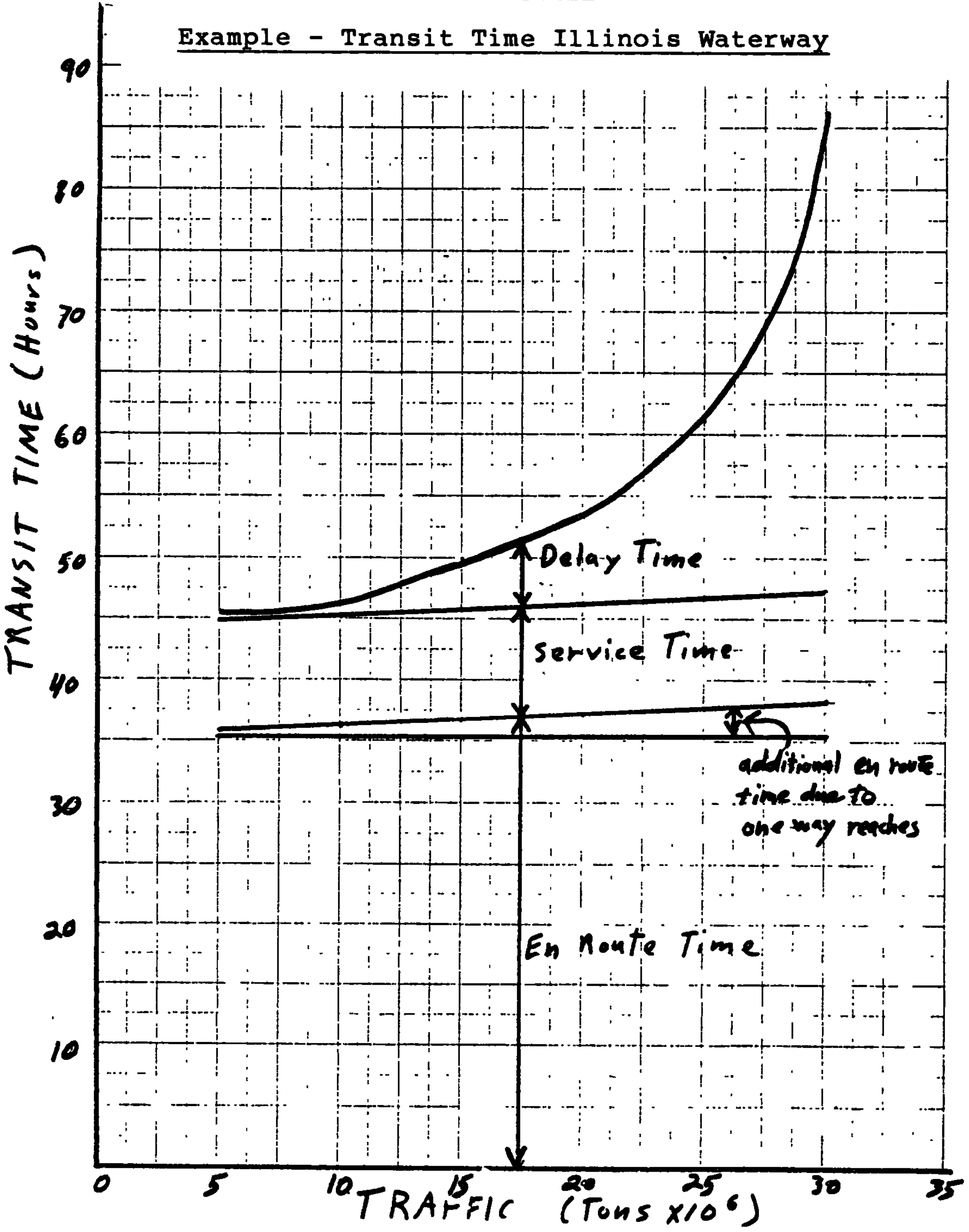
where the value of a depends on the characteristics of the lock, $T_f$ is the traffic through the lock in tons, and k is the capacity of the lock. Clearly, delay becomes infinite when the traffic reaches the capacity of the lock.

Lock service or processing time is the actual time spent in the lockage process: approach, entry, chambering, and exit. As the level of traffic increases, tow operators will probably shift to larger tows, perhaps requiring more double lockages. Multiple lockages require more time than single lockages, and so the average service time is longer. However, the increase in service time with traffic is small compared to the increase in delay time with traffic and can be safely ignored at this level of generality.

Figure V-C illustrates the relative importance of each of the comments of total transit time. The curves show transit times for the Illinois River at various levels of traffic. The basic en route time is calculated from the speed of upbound tows and the river mileage. The additional en route time due to one-way reaches is calculated using the formula above and conservative (tending to yield greater transit times) estimates of the extent of one-way reaches. Specifically, 75% of the length of the Illinois River was assumed to be controlled by one-way reaches averaging .7 miles in length. Service time, based on the sum of service times at all of the locks along the river was considered constant for all levels of traffic. Lock delays, again the sum of delays at all locks, were calculated assuming that the level of traffic was constant over the lengths of the rivers. This assumption is, of course, unrealistic, but it serves to illustrate the effect of traffic on lock delays. Figure V-C shows the cumulative magnitudes of each of these components of transit time. It can be seen that additional en route time due to one-way reaches is noticeable on the Illinois. Similar calculations for other waterways, such as the Upper Mississippi and Ohio Rivers, shows that this effect is even smaller than on the Illinois River. The lock delay time is small at low levels of traffic, but increases rapidly as the traffic approaches the capacity of the constraining lock on the segment. Calculations show that delays at one-way reaches can add substantially to transit time at very high levels of traffic.

Figure V-C

Example - Transit Time Illinois Waterway



### (d) Transit Times Under Present Conditions

The time required for a tow to transit the length of a waterway can be divided into two parts: en route time and lockage time. Port and fleeting times for tows are often very important and sometimes larger than the sum of the other two; this task, however, is concerned only with non-stop movements of tows along the full length of each NWS analysis segment. A study of transit time including port and fleeting times would require detailed origin-destination analysis within each waterway and very extensive empirical observations, both of which are beyond the present scope. Waterway navigation conditions are the primary concern here.

En route time consists of time spent underway at full throttle plus the extra time due to slowdowns and stoppages resulting from constraints on navigation. The unhindered underway time can be found by dividing the length of the waterway segment unaffected by constraints by the speed of the tow in those reaches. Unfortunately, most sources of tow speed information cite average speed over the entire length of a waterway, or at least over the length of a pool. These averages obviously include reaches affected by constraints. Furthermore, it is not easy to estimate the fraction of the length of a waterway unaffected by constraints without detailed study of navigation charts, current conditions, tow size distribution, and the operational practices of the tow operators on the waterway.

Estimating the extra time due to constraints is perhaps even more difficult. All of the different constraints to navigation must be identified (as above, the number of constraints depends on current conditions, channel dimensions and alignment, tow size distribution, and operational practices on the particular waterway) and models of pilot response to the different types of constraints then applied. The problem is compounded by the stochastic factors which affect pilot responses. For example, a bendway or bridge span may permit two-way traffic under normal navigation conditions, but becomes a constraint on navigation during high river stages or poor visibility periods. Another random factor is the frequency of tow encounters. Many obstructions to two-way traffic do not constrain one-way navigation at all; the only delay occurs when an upbound tow encounters a downbound tow at the constrained reach.

Lockage time is defined broadly here as the sum of the delay time plus the service time of all the locks on a segment. This usage is specific to this section and should not be assumed for other portions of the National Waterways Study.

Delay time is the time spent in a queue waiting for permission to begin approaching the lock; tows wait at or beyond the arrival point at each lock. The delay at a lock depends on the physical characteristics of the lock, the tow size distribution, and the level of traffic at the lock.

Service time comprises the approach, entry, chambering, and exit of tows. Service time depends on the physical characteristics of the lock and approaches and on the tow size distribution. Both delay and service time are discussed in greater detail in Section III.

Table V-3 has been compiled in order to facilitate comparisons of transit times under present conditions between waterway segments. Transit times are divided between en route time and lockage time.

1. En Route Time. The total en route time for each segment was calculated by dividing the length of the segment (determined from the NWS Inventory) by the annual average speed (mean of average up and downbound speed) of tows in the segment. These average speeds came from two sources. Speeds on the GIWW, Upper and Lower Mississippi River, Illinois Waterway, Tennessee River, Arkansas River and Ohio River are from results of the "Vessel Characteristics Survey."[48]. Speeds on the remaining segments were calculated from January 1976 PMS reports of transit times between locks (the distances between locks were provided in a table by OCE).

It should be noted that the speeds yielded by both sources are averages over the length of each segment incorporating implicitly the effects of constraints on navigation. A weak correlation may be observed between the average speeds in Table V-3 and the level of restriction of each segment described by Tables V-1 and V-2; the more restrictive segments seem to show lower speeds. The correlation is not strong, however, and is probably not statistically significant because the effect of constraints on navigation on transit time is overwhelmed by other factors, including the horsepower of towboats, the type of commodities moving on each segment, the percentage of empty movements, and the presence of integrated tows and dedicated movements. Further study is required in order to understand and estimate the magnitude of each of these effects in a disaggregated way.

The problem of allocating the total en route time between unhindered underway time and the extra time due to constraints remains. The difficulties associated with calculating the extra transit time resulting from constraints on navigation have been described above. However, in the interest of examining the importance of the effects of constraints under present conditions, a methodology was developed which attempts to estimate the effects of certain constraints on navigation. It must be emphasized that because the development of an exact model of the effects of constraints would require extensive and detailed observations of site-specific operational practices, current methodology is approximate. Nonetheless, it is possible to demonstrate the relative importance of constraints on navigation to transit time.

The magnitude of the extra transit time for upbound tows due to one-way reaches was computed for present speffic levels.

Because downbound tows have the right-of-way, this expected delay affects only upbound tows. Table V-3 presents the average transit times for up and downbound tows combined, and so the computed delay for upbound tows is halved to obtain the average delay for both up and downbound tows.

The extra transit time because of one-way reaches is apparently insignificant even on the most restricted waterways. At worst, 4% of the en route transit time is due to encounters at one-way reaches. Two percent or less

# Table V-3

## Transit Times Under Present Conditions

| | | | | En Route Time | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Restrictions | | | | | | | | | |
| Rep. Reg. | Analysis Segment | Length miles | V. Avg. mph | One-way Delays hours | Marina Delays hours | Comm. Landing Delays hours | Gross en route Time hours | % en route | Lock Delays hours | Lock Service Time hours | Lockage Time hours | % Lockage | Transit Time hours |
| 1 | Upper Miss. | 640 | 6.3 | .6 | 1.8 | 3.8 | 101.6 | 80 | 13.5 | 12.5 | 26.0 | 20 | 127.6 |
| 2 | L. Upper Miss. | 23 | 6.3 | 0 | .1 | .1 | 3.6 | 34 | 5.8 | 1.1 | 6.9 | 66 | 10.5 |
| 2 | Middle Miss. | 195 | 6.3 | 1.3 | U.A. | U.A. | 31.0 | 97 | .3 | .6 | 0.9 | 3 | 31.9 |
| 3 | L. Middle Miss. | 356 | 7.4 | 1.5 | U.A. | U.A. | 48.1 | 100 | - | - | - | 0 | 48.1 |
| 3 | Upper L. Miss. | 270 | 7.4 | 1.5 | U.A. | U.A. | 36.5 | 100 | - | - | - | 0 | 36.5 |
| 3 | L. Miss. to B. R. | 75 | 7.4 | 0 | U.A. | .2 | 10.1 | 100 | - | - | - | 0 | 10.1 |
| 4 | Baton Rouge to N. O. | 128 | 7.4 | 0 | U.A. | 3.1 | 17.3 | 100 | - | - | - | 0 | 17.3 |
| 4 | New Orleans to Gulf | 100 | 7.4 | 0 | U.A | .2 | 13.5 | 100 | - | - | - | 0 | 13.5 |
| 4 | Ouachita Black | 336 | U.A. | U.A. | U.A. | U.A. | U.A. | U.A. | .1 | 1.9 | 2.0 | U.A. | U.A. |
| 4 | Old and Atchafalaya | 146 | 6.5 | U.A. | U.A. | U.A. | 22.5 | 97 | .1 | .6 | .7 | 3 | 23.2 |
| 4 | Morgan City-Port Allen | 64 | 5.9 | .2 | U.A. | .4 | 10.8 | 78 | 1.5 | 1.5 | 3.0 | 12 | 13.8 |
| 5 | Illinois | 326 | 4.4 | 1.5 | .5 | 4.8 | 74.1 | 86 | 8.3 | 4.0 | 12.4 | 14 | 86.5 |
| 6 | Missouri | 732 | 5.4 | .9 | .3 | 4.7 | U.A. | 35.6 | - | - | - | 0 | 135.6 |
| 7 | U. Ohio | 266 | 7.3 | .1 | .6 | 2.5 | 36.4 | 86 | 3.9 | 2.1 | 6.0 | 14 | 42.4 |
| 7 | Middle Ohio | 281 | 7.3 | .1 | 1.2 | 1.9 | 38.0 | 86 | 3.4 | 2.8 | 6.2 | 14 | 44.2 |
| 7 | Lower Ohio III | 239 | 7.3 | .1 | .6 | .4 | 32.7 | 91 | 1.1 | 2.0 | 3.2 | 9 | 35.9 |
| 7 | Lower Ohio II | 150 | 7.3 | 0 | .2 | .67 | 20.5 | 94 | .5 | .7 | 1.2 | 6 | 21.7 |
| 7 | Lower Ohio I | 46 | 7.3 | 0 | 0 | .22 | 6.3 | 55 | 3.9 | 1.3 | 5.2 | 45 | 11.5 |
| 7 | Monongahela | | | | | | | | | | | | |
| | Lower | 42 | 6.9 | 0 | .2 | 1.8 | 6.1 | 67 | 1.1 | 1.8 | 2.9 | 33 | 9.0 |
| | Upper | 87 | 6.9 | .2 | .4 | 3.6 | 12.6 | 68 | 2.3 | 3.6 | 5.9 | 32 | 18.5 |

## Table V-3 (Continued)

| Rep. Reg. | Analysis Segment | Length miles | V. Avg. mph | En Route Time Restrictions: One-way Delays hours | En Route Time Restrictions: Marina Delays hours | En Route Time Restrictions: Comm. Landing Delays hours | Gross en route Time hours | % en route | Lock Delays hours | Lock Service Time hours | Lockage Time hours | % Lockage | % Transit Time hours |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Allegheny | | | | | | | | | | | | |
| | Lower | 24 | 6.3 | 0 | .2 | .6 | 3.8 | 84 | .1 | 6 | .7 | 16 | 4.5 |
| | Upper | 48 | 6.3 | .2 | .4 | 1.2 | 7.6 | 78 | .3 | 1.8 | 2.1 | 22 | 9.7 |
| 7 | Kanawha | 91 | 7.7 | 0 | 0 | 2.7 | 11.8 | 72 | 1.6 | 3.0 | 4.6 | 28 | 16.4 |
| 7 | Green/Barren | 212 | 8.2 | .4 | U.A. | U.A. | 25.9 | 95 | .6 | .8 | 1.4 | 5 | 27.3 |
| 7 | Cumberland | 385 | 5.6 | .1 | .4 | 1.4 | 98.7 | 98 | .4 | 1.5 | 1.9 | 2 | 100.6 |
| 8 | U. Tennessee | 437 | 7.3 | .1 | .6 | 2.5 | 59.9 | 92 | 1.4 | 3.5 | 4.9 | 8 | 64.8 |
| 8 | Lower Tennessee | 215 | 7.3 | .1 | .7 | 1.5 | 29.4 | 87 | 2.6 | 1.8 | 4.4 | 13 | 33.8 |
| 9 | Arkansas | 397 | 6.0 | 2.8 | .3 | .07 | 66.2 | 87 | 1.5 | 8.1 | 9.6 | 13 | 75.8 |
| 10 | GIWW/W I | 102 | 6.8 | .4 | U.A. | .3 | 15.0 | 96 | 0.4 | .2 | .6 | 4 | 15.6 |
| 10 | GIWW/W II | 249 | 6.8 | 1.7 | U.A. | 1.1 | 36.6 | 97 | 1.1 | .2 | 1.3 | 3 | 37.9 |
| 10 | GIWW/W III | 329 | 6.8 | U.A. | U.A. | .1 | 48.4 | 100 | - | - | - | 0 | 48.4 |
| 11 | GIWW/E I | 32 | 6.0 | .3 | U.A. | .7 | 5.3 | 41 | 7.3 | .3 | 7.6 | 59 | 12.9 |
| 11 | GIWW/E II | 343 | 6.0 | U.A. | U.A. | .2 | 57.1 | 100 | - | - | - | 0 | 87.1 |
| 11 | Okeechobee | 155 | U.A. | U.A. | U.A. | U.A. | U.A. | U.A. | .3 | 1.0 | 1.3 | U.A. | U.A. |
| 12 | Black Warrior | 124 | 5.7 | .3 | U.A. | 2 | 21.8 | 84 | 2.9 | 1.4 | 4.3 | 16 | 26.1 |
| 12 | Alabama/Coosa | 592 | 7.0 | U.A. | U.A. | U.A. | 84.6 | 92 | 5.2 | 1.7 | 6.9 | 8 | 91.5 |
| 12 | Tombigbee | 216 | 5.7 | .5 | U.A. | .4 | 37.9 | 96 | 1.0 | 0.6 | 1.6 | 4 | 39.5 |
| 11 | AIW | 261 | 7.9 | U.A. | U.A. | U.A. | 33.0 | 95 | .5 | 1.2 | 1.7 | 5 | 34.7 |
| 18 | U. Columbia/Snake | 171 | U.A. | U.A. | U.A. | U.A. | U.A. | U.A. | .6 | 4.7 | 5.3 | U.A. | U.A. |
| 18 | Lower Columbia | 146 | U.A. | U.A. | U.A. | U.A. | U.A. | U.A. | 1.0 | 6 | 1.6 | U.A. | U.A. |

Data Source: P.M.S. Data and Vessel Characteristics Survey,
St. Louis District, June, 1980

is more typical. One factor contributing to this result is that the need to flank on sharp bends has not been considered in this analysis. The number of bends which need to be flanked on a particular waterway depends on tow size, towboat horsepower, bend radius, channel width, current, and wind conditions. There is no way to make a meaningful assessment of the number of bends which need to be flanked in each analysis segment without site-specific observations. However, the effect of flanking on delays at one-way reaches can be demonstrated for hypothetical cases. If, say, half of the bends on a waterway segment need to be flanked, and flanking requires three times the time of a conventional maneuver, then this will increase the computed delay by about a factor of two at typical traffic levels, and more as the water-way becomes busier. The channel capacity will be halved, but still remains beyond practical limits.

Even with flanking accounted for generously, the small value for the calculated extra time at one-way reaches seems smaller than one would expect intuitively. The most likely explanation is that traffic levels are very low compared to the channel capacities and that tows simply do not meet at one-way reaches very often. For instance, there were only 2,250 tows passing through L/D 22 on the Mississippi in 1976; assuming a 10 month navigation season, the arrival rate of tows was .35 tows/hour, or 2.9 hours between tows. This corresponds to downbound tow arrival rate (J) of .18 tows/hour. When tows are almost six hours apart, it is little wonder that encounters occur infrequently, and rarely on one-way reaches. Lock service times are almost never less than 30 minutes, corresponding to a maximum arrival rate of two tows per hour or one downbound tow per hour. The busiest lock (in terms of arrival rate) in the United States is L/D 27 on the Mississippi witn an arrival rate of about one tow per hour, or one downbound tow every two hours. With two hours between downbound tows, it is not surprising that upbound tows rarely encounter them on reaches which require perhaps 15 minutes to negotiate. When these encounters do occur, the upbound tow need wait only half the time required for the downbound tow to traverse the entire controlled reach, on average.

Delays due to encounters at one-way reaches can become significant at very high levels of traffic, but these traffic levels are higher than the service times present locks can permit. Free-flowing waterways, or even canalized waterways with several parallel lock chambers (as are found in Europe), could someday physically reach these levels of traffic.

Narrow navigable bridge spans and by-passes of tows in channels wide enough to permit two-way traffic, but narrow enough to require that the tows slow to avoid driving through each other's wake, can be treated in ways similar to one-way reaches. However, the very short lengths of the reaches controlled by bridge spans or passing tows would lead to even shorter delays than those calculated for one-way reaches. One can therefore safely assume that the effects on transit time of bridges and bypasses in narrow two-way reaches are small.

It should be emphasized that the values for extra time because of one-way reaches shown in Column 4 of Table V-3 do not include all of the effects of sharp bends on transit time. Even though most one-way reaches occur at bends (except for the GIWW), Column 4 does not attempt to account for extra time in bends when there is no meeting of tows. Sharp bends which require tows to flank certainly take more time to negotiate than straight reaches of the same length (and obviously more than straight reaches with the same endpoints as the bendway), but this extra time is accounted for in the overall average speed. For example, consider a rather restricted 100 mile waterway segment with 100 bends, each .6 miles long. If the average tow speed in straight, unrestricted reaches is 9 mph and tows need not flank or slow at any bend, then the transit time will be 100/9 = 11.1 hours. If one-half of the bends are sharp or narrow enough to require tows to flank, and flanking reduces average tow speed to 3 mph, then the transit time for the waterway will be 70/9 + 30/3 = 17.8 hours, corresponding to an average speed of 5.6 mph. If wind, current, fog, and river stage combine during the worst months of the year to force tows to flank around all the bends, transit time becomes 50/9 + 50/3 = 22.2 hours for an average speed of 4.5 mph. If the worst conditions prevail over two months of the year and during the rest of the year tows must flank at only half of the bends, annual average transit time and speed are 18.5 hours and 5.4 mph, respectively. This represents an almost 70% increase in transit time over the no-flank condition. As has been stated above, the need to flank and the extra time needed to do so are very site-specific and hard to estimate without local observations. It is clear, however, that significant improvements in transit time might well be achieved by eliminating the need to flank around bends.

Table V-2 includes estimates of the component of transit time required because of tow slowdowns as they pass marinas, commercial landings, and fleeting areas. Although the sizes of marinas, landings, and fleeting areas vary, an estimate suggests that tows lose about one minute when passing marinas and two minutes when passing commercial sites. These estimates are of course very rough, but they serve to specify the order of magnitude of the effect of these slowdowns. The numbers of marinas and commercial sites on several segments were counted as part of Element G work.

The products of the number of sites and the extra time at each appear in Columns 5 and 6. These represent allocations of the gross en route time in Column 7; they are not added to the transit time. The results indicate that marinas are relatively few in number and in general do not have much of an effect on tow transit time. Commercial landings and fleeting areas, however, can add as much as 30% to the time required to transit waterway segments. This additional time is substantial, but clearly waterborne commerce cannot exist without landings and fleeting areas. The number of these sites is expected to grow, as well, with the growth in waterborne tonnage.

2. Lockage Time. The lock delay time for each NWS analysis segment in Column 8 of Table III-3 is the sum of the delay at all the locks along the segment at the present level of traffic. The delay at each lock was taken directly from the NWS Inventory report on locks; where this number was omitted, the present delay was estimated from Section III. The effect of the level of traffic on lock delay time was discussed in Section III. Lock service time, again cumulative over all the locks in each segment, was again taken from the Inventory and from PMS reports, where necessary. The sum of delay and service times is shown in Column 10.

The lock delay time varies from about 25% of the total transit time on waterways with heavily utilized locks to about 2% on segments with lock capacity in excess of current traffic. Lock service time varies from as much as 20% of total transit time on waterways with closely spaced locks (such as the Upper Monongahela), to 2% on segments with only one to two locks. More typical are values in the range of 9% to 15% of total transit time for most canalized rivers.

3. Allocation Of Transit Time Between En Route Time And Lockage Time. The overall allocation of transit time between en route time and lockage time varies with the density of locks on each segment and the level of traffic. The Alabama/Coosa, Black Warrier/Tombigbee, and ACF River Systems have fairly widely spaced locks and little traffic, so that over 90% of transit time on these segments is spent en route. The Lower Ohio River, on the other hand, has heavy traffic, closely spaced locks, and over 50% of transit time spent in lockages. Some smaller segments with one busy lock show even more skewed allocations, such as the Lower Upper Mississippi and L/D 26 and the GIWW East-I and Inner Harbor Lock, but these are special cases because of the definitions of the segments and the utilization of locks close to or even above their practical capacitv. A more typical allocation is between 60% and 80% of transit time en route, and 20% to 40% of transit time in lockages.

## PARAMETRIC ANALYSIS OF THE SENSITIVITY OF TOWING COSTS TO NAVIGATION CONDITIONS

This subsection deals with the sensitivity of waterborne transportation costs to waterway characteristics. The results can be used to identify the reductions in transportation cost which would be associated with certain waterway improvements and, conversely, the cost increase accruing from policies leading to poorer waterway conditions.

The subsection first develops a simplified cost model of waterway transportation considering the cost of en route movements and lockages. The equations of the cost model are described, and the most important parameters in the equations are discussed in detail. The use of the cost model for sensitivity analysis and the present set of assumptions are described.

Results are shown in graphical and tabular form for transportation cost versus controlling channel depth, versus maximum tow size, and versus the density of traffic. Lockage delay costs figure prominently in the latter two, and varying densities of locks are included in these analyses.

### (a) Relationship Between Towing Costs and Transit Times

The methodology used to determine the sensitivity of marine transportation costs to various parameters is straightforward. A cost model consisting of a set of equations is formulated The sensitivity of the cost to any parameter can be calculated by systematically varying that parameter while holding all others constant. The following sections of this chapter describe the individual equations which make up the cost model and the specific calculations which are performed in the sensitivity analysis.

1. Cost En Route. A large portion of total tow transit time is spent en route and hence, much of towing cost is generated en route. En route transit time is given by the following equation:

$$T_1 = D\left\{\frac{1}{V_u - V_c} + \frac{1}{V_d + V_c}\right\}$$

Where $T_1$ is round-trip transit time between two points, D is the round-trip distance, $V_u$ and $V_d$ are the average up and downbound tow speeds through the water, respectively, and $V_c$ is the speed of the current. The speed of the tow through the water depends on the tow size and draft, towboat horsepower, the channel dimensions, and the presence of constraints on navigation. Up and downbound speeds can therefore be different even in the absence of current because of differences in barge loading and draft or the need to flank around bends, for example.

Tow speeds were calculated using the methodology of Hochstein, "Inland Waterway Systems Analysis - Waterway Analysis" (1976)[49]. This approach treats the number of barges per tow, the size and draft of the barges, the towboat horsepower, and the channel depth and cross sectional area explicitly. The effect on speed of the various waterway modifications under consideration could thus be shown explicitly. Unfortunately, this analytical methodology does not include the effects of constraints on navigation on vessel speed. It would have been preferable to use the empirically observed average tow speeds presented in Table V-3 in order to include the effects of constraints, but then the effects of waterway characteristics on speed could not be shown. Because the purpose of this task is to analyze the consequences of changes in waterway characteristics, the analytical methodology for determining tow speeds was used. The speeds thus calculated are representative of unconstrained waterways (however, effects of restrictive channel dimensions are considered).

The costs associated with en route time are given by the following formulas:

$$C_{tb} = \frac{c_{tb}T_1}{2nU_t qU_b D(1-E)}$$

$$C_b = \frac{c_b T_1}{2qU_b D(1-E)}$$

$$C_c = \frac{c_c T_1}{2D(1-E)}$$

where,

$C_{tb}$ = tow boat cost per ton-mile
$c_{tb}$ = tow boat en route operating cost per hour
$n$ = maximum number of barges per tow
$U_t$ = utilization of tow size (average number of barges per town/n)
$q$ = nominal barge capacity (vessel tonnage fully loaded)
$U_b$ = utilization of barge capacity
$D$ = one-way distance
$E$ = fraction of empty movements
$C_b$ = barge cost per ton-mile
$c_b$ = barge operating cost per hour
$C_c$ = cargo holding cost per ton-mile
$c_c$ = cargo holding cost per hour

Flotilla costs as a function of usable draft may be computed using the following formula by Hochstein (1975):

$$C_i = C_f \frac{q - \delta BL(t_f - a_{av} + t_n)}{q}$$

where, $C_i$ = fleet cost for partial vessel loading
$C_f$ = fleet cost for full vessel loading
$B$ = width of vessel
$L$ = length of vessel
$\delta$ = block coefficient (ratio of displaced volume to the product of length, beam and draft)
$a_{av}$ = average usable depth (between $a_{min}$ and $a_{max}$
$t_f$ = vessel (tow) draft fully loaded
$t_n$ = clearance between keel and riverbed

Each of the cost component equations is in the form:

$$\text{cost/ton-mile} = \frac{\underline{\text{operating cost per round-trip}}}{\text{ton-miles moved per round trip}}$$

The structure of the operating costs, which include fixed and variable costs, are discussed in detail below.

The total cost associated with the en route part of a round-trip is the sum of the towboat, barge, and inventory costs.

$$C_l = C_{tb} + C_b + C_c$$

This sum, $C_l$, is the total towing cost on open rivers, or for any round-trip completely within one pool of a canalized river. The additional time and costs associated with lockages are described in the following section.

2. Costs For Lockages. The analysis of waterborne transportation costs incurred at locks is analogous to the analysis of en route costs. Each cost component is given by an hourly cost times the time required divided by the ton-miles produced by the trip. The time required for lockages is the sum of processing time, the delay time and service time. The calculation of these quantities for a given lock for varying traffic levels and average tow sizes was discussed in detail in Section III.

The analysis of changes in waterborne transportation costs in response to waterway parameters was facilitated by approximating the detailed analysis presented in Section III with some simple formulas. These formulas were derived through regression of the delay and service time data on several locks and yield results adequate for use in the analysis of transportation costs.

These equations are only approximations of more precise calculations and should not be used for analysis of lock capacity.

Lock delay time is approximated by:

$$D = \frac{Kpct}{Qpct} \quad \frac{S}{Spc}$$

where,

D = delay time (min.)

t = traffic level (tons)

k = lock delay parameter (see Section III) (min./tow)

Q = lock capacity (tons)

s = average tow size (barges/tow)

and the subscript (pc) denotes present conditions.

Service time is given by:

$$T = T_{pc} + 7.65(s - s_{pc})$$

The total lock processing time ($T_2$) is the sum of service time and delay time:

$T_2 = T + D$

The costs associated with lockages are given by the following formulas:

$$C_{tb} = \frac{c'_{tb}T_2}{nU_t qU_b D(1-E)}$$

$$C_b = \frac{c_b T_2}{qU_b D(1-E)}$$

$$C_c = \frac{c_c T_2}{D(1-E)}$$

Where $c_{tb}$ is the towboat operating cost at locks. This is taken as the cost of the underway towboat with fuel consumption reduced to one-half (see next subsection).

These equations have the same form as the en route cost equations: cost divided by ton-miles.

Total towing cost associated with each lockage is, therefore:

$C_2 = C_{tb} + C_b + C_c$

Total towing cost for a round-trip including lockages is:

$$C = C_1 + \sum_{i=1}^{j} C_{2_i}$$

where, j is the number of locks on the route.

3. Structure of Towboat, Barge, and Cargo Hourly Costs. This section elaborates on the meaning of the

parameters $c_{tb}$, $c'_{tb}$, $c_b$, and $c_c$, which are used as the hourly costs of towboats en route, towboats at locks, barges, and cargo.

The cost of operating towboats, like that of most capital equipment, has fixed and variable components. The fixed component of the cost consists mainly of the cost of the capital invested in the towboat. The remainder of the fixed cost is that fraction of the tow operator's overhead allocated for administration and supervision of the towboat. The total annual fixed cost is divided by the number of operating hours in order to derive the fixed cost component of the hourly operating cost. The operating hours would not include light boat movements or port delays unless these were considered in the cost model.

The variable cost of towboat operation includes fuel, wages and benefits, maintenance and repairs, supplies, subsistence, insurance, and other miscellaneous items. Fuel cost is by far the largest of these. Variable costs are by definition stated in terms of dollars per hour component. Fuel consumption is a function of speed, however, and must be separated out from the rest of the variable costs in order to account for the reduced towboat operating cost at locks and during fleeting operations. As a practical matter, fuel consumption is commonly expressed as the product of the towboat specific fuel consumption (gal/hp-hr) and the towboat horsepower. An OCE letter on towboat and barge operating costs gives fuel consumption as:

$$F = .0311 \text{ X horsepower X operating hours}$$

where F is total fuel consumption and .0311 is the specific fuel consumption in gallons/hp-hr. Marbury cites a value of .0496 gal/hp-hr for the line-haul s.f.c. of a 5,000 hp towboat.[50] Various other sources, including studies done at the Universities of Minnesota and Iowa, and a shipyard and barge line suggest line-haul s.f.c. values of .0417 to .0500 gal/hp-hr. Thus, a value of .045 gal/hp-hr was used here, and the OCE value of .0311 gal/hp-hr attributed to a weighted average of line-haul and lockage and maneuvering time. The towboat specific fuel consumption at locks was taken as half of the en route value, based on a study of fuel consumption for tows waiting to lock through Lock and Dam 26 on the Mississippi River and the cost of fuel computed separately from the other variable costs, both at lockages and en route.

The towboat hourly operating cost en route is therefore given by:

$c_{tb}$ = annual fixed cost/annual hours of operation
+ variable cost not including fuel
+ specific fuel consumption en route
x hp x dollars/gallon

Substituting specific fuel consumption at locks will yield $c'_{tb}$:

Barge costs similarly have fixed and variable components, although the variable cost of barge operation is minimal. Barges have a much lower utilization rate than towboats, and hence the number of operating hours for barges is less than that of towboats. The fraction of fixed cost allocated to each operating hour will therefore be greater for barges than towboats. Barge hourly operating cost is given by:

$c_b$ = annual fixed cost/annual hours of operation
+ variable cost

The cargo hourly holding cost represents the inventory and insurance cost per ton per hour of the cargo in transit. The inventory and insurance costs will both be proportional to the value of the cargo. The holding cost of refined petroleum products will be greater than that of grain, and the holding costs of grain greater than that of coal.

### (b) Sensitivity of Transportation Costs to Navigation Conditions

The equations presented above were incorporated into modular computer programs in order to facilitate the calculations of transportation cost sensitivity. This section describes the formulation of each sensivity run and lists the values of each of the parameters.

1. Cost vs. Channel Depth. The sensitivity of marine transportation cost to controlling depth is illustrated for 12 foot maximum draft barges in Tables V-4 and V-5, expressed in mils/ton-mile. (Typical values of lock

delay time and lock service time are used in Table V-5. Variations in service time which may occur depending on lock size, clearances in approach and over the sill...etc., are not included in the example to maintain its simplicity.) It is clear from the tables that cost decreases dramatically with channel depth up until the maximum draft of the vessel is reached. Thereafter, cost decreases slowly with increasing channel depth. An examination of the tables explains these effects very simply.

First, in the range of 7.5 feet to 13.0 feet, the rapid decrease in cost with increase in depth shown in Table V-4 reflects the fact that 12 feet maximum draft barges can be loaded more deeply with increased depth. Strictly speaking the transportation cost using the deeper barges should be slightly greater because of the higher fixed cost associated with the deeper vessels. This effect is small, however, and does not affect the substance of this discussion. In this range, tow speed increases significantly with depth, reducing the towboat and cargo holding costs. The more important effect, however, is the increase in the barge capacity factor made possible by the increasing depth. The deeper loading of the barges allows more cargo to be carried in each movement, decreasing costs per ton-mile. Costs incurred during lockages, as shown in Table V-5, also decrease because of the improved utilization of barge depth (assuming that the depth over the sill at locks is sufficient for unrestricted entry).

The Hochstein tow speed methodology approximates the effect of depth on tow speed through the use of the shallow water coefficient, $e_h$, presented in the subsection entitled, "Tow speed and Transit Time". The value of $e_h$ is always less than one, and thus it is multiplied by the open water tow speed to yield the speed in a channel of finite depth. For large values of depth, $e_h$ approaches one.

In the range of depths between 13.0 feet and 20.0 feet, the costs of transportation using 12 foot draft barges remain stable, decreasing very slowly due to the slight increase of tow speed with depth. If tow speed were held constant while depth increased, cost savings from reduced fuel consumption would be expected.

2. Cost vs. Tow Size. Marine transportation cost/ton-mile decreases with the size of the vessel. The

decrease in cost is proportional to the percentage increase in vessel size, and thus equal increases in vessel size bring greater cost reductions to smaller vessels than larger ones.

Figure V-H illustrates this effect in the case of tows with varying numbers of barges. The horizontal axis measures the maximum tow size permitted on a waterway. The average tow size is assumed to be 75% of the maximum. The vertical axis measures transportation cost in mils/ton-mile. Three curves are shown, illustrating the effect of the density of locks on transportation cost. The lowest of the curves plots cost/ton-mile on an open river. The middle curve is for a waterway with two locks in 100 miles, roughly comparable to the Ohio River; and the highest curve is for seven locks in 100 miles, roughly comparable to the Monongahela. Each of the locks is considered identical for the purpose of illustration.

Table V-6 shows the detailed breakdown of the costs, (in mils per ton-mile) incurred en route and during lockages. The largest cost saving with increasing tow size is associated with the towboat cost excluding fuel. The towboat horsepower ratio has been held constant at .15 hp/ton for each maximum tow size, but the fixee and variable towboat operating costs, except fuel, do not increase proportionally. While tow size and horsepower increase by a factor of ten, the towboat cost/ton-mile excluding fuel decreases by a factor of three, indicating that the towboat cost has increased by only a factor of three and one-third. The remainder of the en route costs decrease slightly with increasing tow size because of the increase in tow speed due to the less than proportional change in tow hydrodynamic drag. In actual practice, this apparent increase in speed would probably be negated by the additional time required to maneuver the larger tow at constraints. For example, bends which would not hinder smaller tows could force larger vessels to flank. Thus, this result is strictly accurate only for completely unconstrained waterways. The fundamental validity and usefulness of the illustration remains, of course.

Lock service time increases with tow size owing to the increasing number of multiple lockages, and lock delay time decreases with increasing tow size at a constant level of traffic because tow interarrival times at locks are increased at the particular lock in this example. The directions and net effect of these changes depend on the traffic level at the particular lock, chamber characteristics, and tow configuration.

3. Cost vs. Density of Traffic. Traffic affects waterborne transportation cost primarily through the delay at locks. As the level of traffic at a lock increases toward the capacity of the lock, delay, and thus the cost of the lockage, approaches infinity. Figure V-I displays this effect; the cost of transportation on an open river is unaffected by traffic, while costs increase sharply on canalized waterways as the traffic level approaches the capacity of the locks (taken as 54 million tons/year for these examples).

## (b) Sources of Data

Design standards for the bridge replacement schemes were based on current design criteria and the recommendations of AASHTO and A.R.E.A. ( American Railway Engineering Association specifications.

For 100 feet span bridges, the quantities of concrete, reinforcing steel and prestressing steel were calculated assuming AASHTO-PCI Type IV girders. For spans of 200 to 500 feet, box-girder type superstructures were assumed and the quantities of concrete, reinforcing steel and prestressing steel were calculated using charts from the paper SP23-39, "Design Of Long-Span Concrete Bridges with Special Reference o Prestressing, Precasting, Erection, Structural Behavior and Economics," published in the ACI (American Concrete Institute) Special Publication SP-23. Unit prices for concrete, reinforcing steel, prestressed steel and piling were taken from unit bid prices published by the New Jersey Department of Transportation.

## (c) Bridge Replacement Costs

Figure V-G shows the construction cost of bridge replacement per square foot of deck area as a function of bridge span.

To obtain the total estimate construction cost of bridge replacement, quantities were taken from Figure V-F and multiplied by current unit costs, and then 25% was added to the cost of the primary quantities to allow for miscellaneous works associated with bridge construction.

Current unit costs are based on 1979 bid prices published by the New Jersey Department Of Transportation, reduced to 1977 levels using a factor of 1.2, and are applicable to the New York New Jersey area. The regional cost indices provided for lock construction, Table III-15, can be used to adjust the costs for other regions of the United States.

To estimate the cost of replacement for any bridge in any reporting segment, the cost for one square foot of deck area for a typical span can be taken from Figure V-G, multiplied by the length and width of the bridge and adjusted by the regional cost index.

### (d) Limitations

The model presented and costs obtained in using the model are highly dependent upon the assumptions presented. It should be recognized that a change in any one of the elements of the bridge will bring about a change in the total cost. For example, the cost of the substructure can change substantially depending upon the length and quantity of piles required, a factor which depends heavily upon subsurface conditions.

In addition, the total cost of a bridge greatly depends on unit prices which are closely related to the general economic climate existing at the time of bidding.

Understanding the limitations of the model, the results can be used for estimating the cost of bridge replacement at the level of accuracy required by the NWS or other similar reconnaissance studies.

## CONSTRUCTION COST ESTIMATES FOR BRIDGE REPLACEMENT

This section presents a model for the determination of construction costs for bridge replacement on United States

## Table V-4

## Costs for 12' Maximum Draft Barges (mils/ton-mile)

| CHANNEL DEPTH FT | EN ROUTE COSTS/TON-MILE SPEED UP MPH | SPEED DOWN MPH | BARGE CAPACITY FACTOR | TOWBOAT COST EX FUEL | TOWBOAT FUEL COST | TOWBOAT TOTAL COST | BARGE COST | CARGO COST | TOTAL EN ROUTE COST |
|---|---|---|---|---|---|---|---|---|---|
| 7.5 | 5.7 | 7.4 | 0.72 | 3.17 | 1.41 | 4.59 | 1.29 | 1.25 | 7.12 |
| 8.0 | 5.7 | 7.7 | 0.78 | 2.89 | 1.29 | 4.18 | 1.18 | 1.22 | 6.58 |
| 8.5 | 5.8 | 7.9 | 0.83 | 2.65 | 1.18 | 3.83 | 1.08 | 1.20 | 6.12 |
| 9.0 | 5.8 | 8.1 | 0.89 | 2.45 | 1.09 | 3.54 | 1.00 | 1.18 | 5.72 |
| 9.5 | 5.8 | 8.3 | 0.94 | 2.27 | 1.01 | 3.28 | 0.93 | 1.17 | 5.37 |
| 10.0 | 5.9 | 8.6 | 1.00 | 2.12 | 0.94 | 3.06 | 0.86 | 1.15 | 5.07 |
| 10.5 | 5.9 | 8.8 | 1.06 | 1.98 | 0.88 | 2.86 | 0.81 | 1.14 | 4.81 |
| 11.0 | 5.9 | 9.0 | 1.11 | 1.86 | 0.83 | 2.69 | 0.76 | 1.12 | 4.57 |
| 11.5 | 5.9 | 9.2 | 1.17 | 1.75 | 0.78 | 2.53 | 0.71 | 1.11 | 4.36 |
| 12.0 | 5.9 | 9.3 | 1.22 | 1.66 | 0.74 | 2.41 | 0.68 | 1.11 | 4.19 |
| 12.5 | 5.9 | 9.3 | 1.26 | 1.59 | 0.71 | 2.29 | 0.65 | 1.10 | 4.04 |
| 13.0 | 6.0 | 9.4 | 1.33 | 1.52 | 0.68 | 2.19 | 0.62 | 1.10 | 3.91 |
| 13.5 | 6.0 | 9.4 | 1.33 | 1.50 | 0.67 | 2.17 | 0.61 | 1.09 | 3.87 |
| 14.0 | 6.1 | 9.4 | 1.33 | 1.49 | 0.66 | 2.15 | 0.61 | 1.08 | 3.83 |
| 14.5 | 6.2 | 9.5 | 1.33 | 1.47 | 0.66 | 2.13 | 0.60 | 1.07 | 3.80 |
| 15.0 | 6.3 | 9.5 | 1.33 | 1.46 | 0.65 | 2.11 | 0.60 | 1.06 | 3.77 |
| 15.5 | 6.3 | 9.5 | 1.33 | 1.45 | 0.65 | 2.10 | 0.59 | 1.05 | 3.74 |
| 16.0 | 6.4 | 9.6 | 1.33 | 1.44 | 0.64 | 2.09 | 0.59 | 1.05 | 3.72 |
| 16.5 | 6.4 | 9.6 | 1.33 | 1.43 | 0.64 | 2.07 | 0.58 | 1.04 | 3.70 |
| 17.0 | 6.5 | 9.6 | 1.33 | 1.43 | 0.64 | 2.06 | 0.58 | 1.03 | 3.68 |
| 17.5 | 6.5 | 9.6 | 1.33 | 1.42 | 0.63 | 2.05 | 0.58 | 1.03 | 3.66 |
| 18.0 | 6.6 | 9.6 | 1.33 | 1.41 | 0.63 | 2.04 | 0.58 | 1.02 | 3.64 |
| 18.5 | 6.6 | 9.7 | 1.33 | 1.41 | 0.63 | 2.03 | 0.57 | 1.02 | 3.62 |
| 19.0 | 6.7 | 9.7 | 1.33 | 1.40 | 0.62 | 2.02 | 0.57 | 1.01 | 3.61 |
| 19.5 | 6.7 | 9.7 | 1.33 | 1.39 | 0.62 | 2.02 | 0.57 | 1.01 | 3.59 |
| 20.0 | 6.7 | 9.7 | 1.33 | 1.39 | 0.62 | 2.01 | 0.57 | 1.01 | 3.58 |

Costs are in mils per ton-mile

## Table V-5

## Costs for 12' Maximum Draft Barges (mils/ton-mile)

| | LOCKAGE COSTS/TON-MILE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CHANNEL DEPTH FT | DELAY TIME MIN | SERVICE TIME MIN | TOTAL LOCKAGE TIME, HR | TOWBOAT COST EX FUEL | TOWBOAT FUEL COST | TOWBOAT TOTAL COST | BARGE COST | CARGO COST | TOTAL LOCKAGE COST |
| 7.5 | 125. | 52. | 2.9 | 0.60 | 0.13 | 0.73 | 0.24 | 0.24 | 1.21 |
| 8.0 | 125. | 52. | 2.9 | 0.56 | 0.12 | 0.68 | 0.23 | 0.24 | 1.15 |
| 8.5 | 125. | 52. | 2.9 | 0.52 | 0.12 | 0.64 | 0.21 | 0.24 | 1.08 |
| 9.0 | 125. | 52. | 2.9 | 0.49 | 0.11 | 0.60 | 0.20 | 0.24 | 1.03 |
| 9.5 | 125. | 52. | 2.9 | 0.46 | 0.10 | 0.56 | 0.19 | 0.24 | 0.98 |
| 10.0 | 125. | 52. | 2.9 | 0.43 | 0.10 | 0.53 | 0.18 | 0.24 | 0.94 |
| 10.5 | 125. | 52. | 2.9 | 0.41 | 0.09 | 0.50 | 0.17 | 0.24 | 0.91 |
| 11.0 | 125. | 52. | 2.9 | 0.39 | 0.09 | 0.48 | 0.16 | 0.24 | 0.87 |
| 11.5 | 125. | 52. | 2.9 | 0.37 | 0.08 | 0.45 | 0.15 | 0.24 | 0.84 |
| 12.0 | 125. | 52. | 2.9 | 0.35 | 0.08 | 0.43 | 0.14 | 0.24 | 0.81 |
| 12.5 | 125. | 52. | 2.9 | 0.34 | 0.08 | 0.42 | 0.14 | 0.24 | 0.79 |
| 13.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 13.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 14.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 14.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 15.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 15.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 16.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 16.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 17.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 17.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 18.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 18.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 19.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 19.5 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |
| 20.0 | 125. | 52. | 2.9 | 0.33 | 0.07 | 0.40 | 0.13 | 0.24 | 0.77 |

Costs are in mils per ton-mile

waterways. The model can be used to evaluate the cost of the replacement of bridges which are constraints to navigation. Only common bridge types with navigation spans of 100 to 500 feet are considered. Although a detailed cost comparison would be required to determine the optimum type of bridge which is most economical to span a given waterway, costs for only one type of bridge are provided to give estimates sufficient for use in the NWS.

### (a) Basis of Estimate

The general arrangement of a typical bridge currently in use to cross inland waterways is shown in Figure V-D. The navigation span can range from 100 to 500 feet depending on the wateway considered. A vertical clearance of 60 feet above the mean high water level and 40 feet depth to riverbed is shown as typical. In light of the wide variation in water depths and other site conditions, these vertical dimensions have been selected as representative for United States inland waterways.

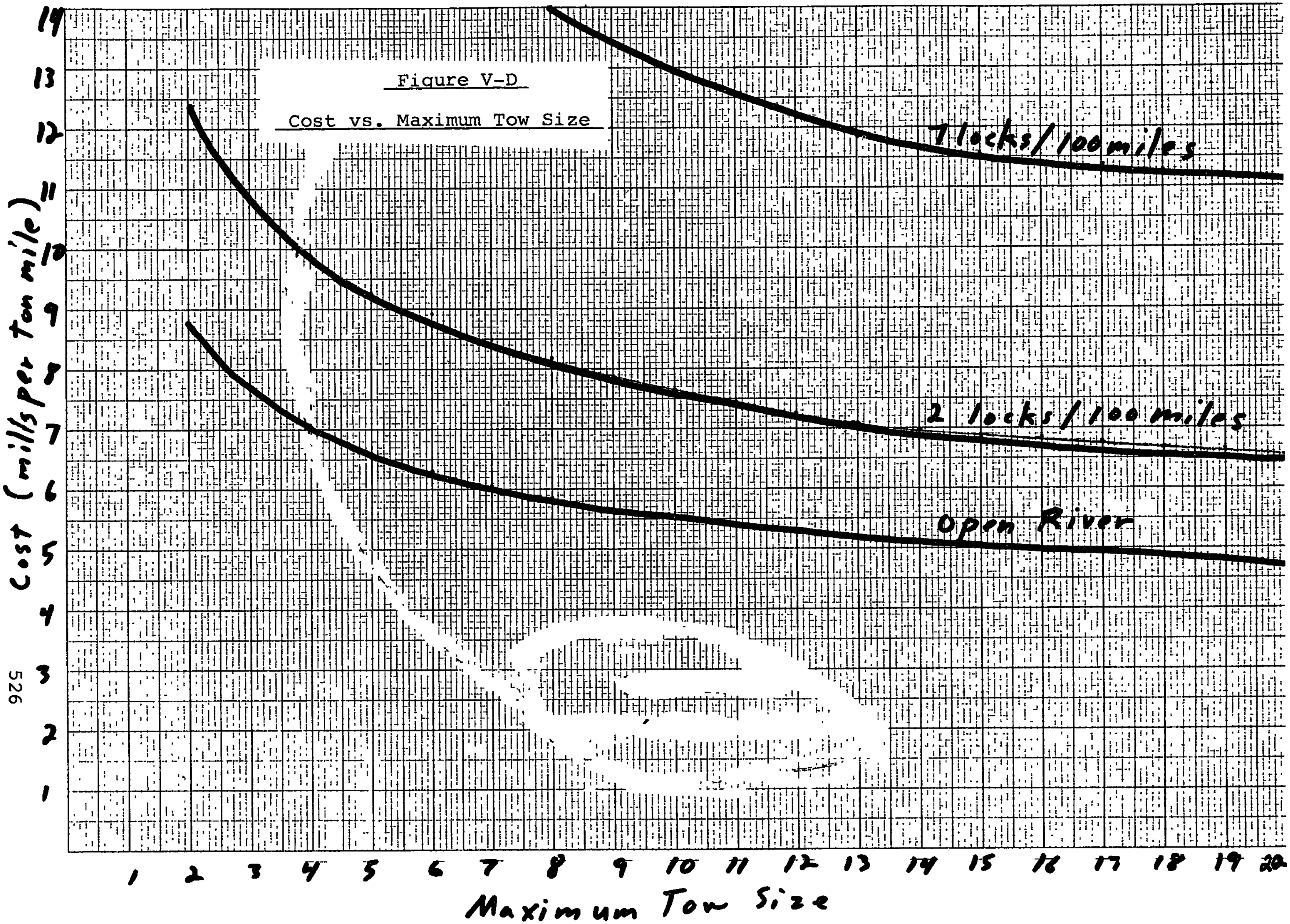
Typical deck sections for a two-lane highway, a four-lane highway and a two-track railroad bridge with their respective minimum required widths are shown in Figure V-E.

Based on the typical arrangements of Figures V-D and V-E, quantities of contrete, prestressing steel, reinforcing steel and pilings were calculated for the range of bridge spans considered. Graphs were prepared which relate quantities of concrete, prestressing steel and reinforcing steel to the deck area of the bridge. These relationships are shown in Figure V-F.

For 100 feet span bridges, quantities were calculated assuming AASHTO-PCI Type IV girders (American Association of State Highway and Transportation Officials and Prestressed Concrete Institute). For spans of 200 to 500 feet, a box-girder type superstructure was assumed. Following present day trends for long span bridges, all new bridges are considered to be constructed using prestressed concrete. Pier footings on pilings are assumed to be located at the riverbed elevation.

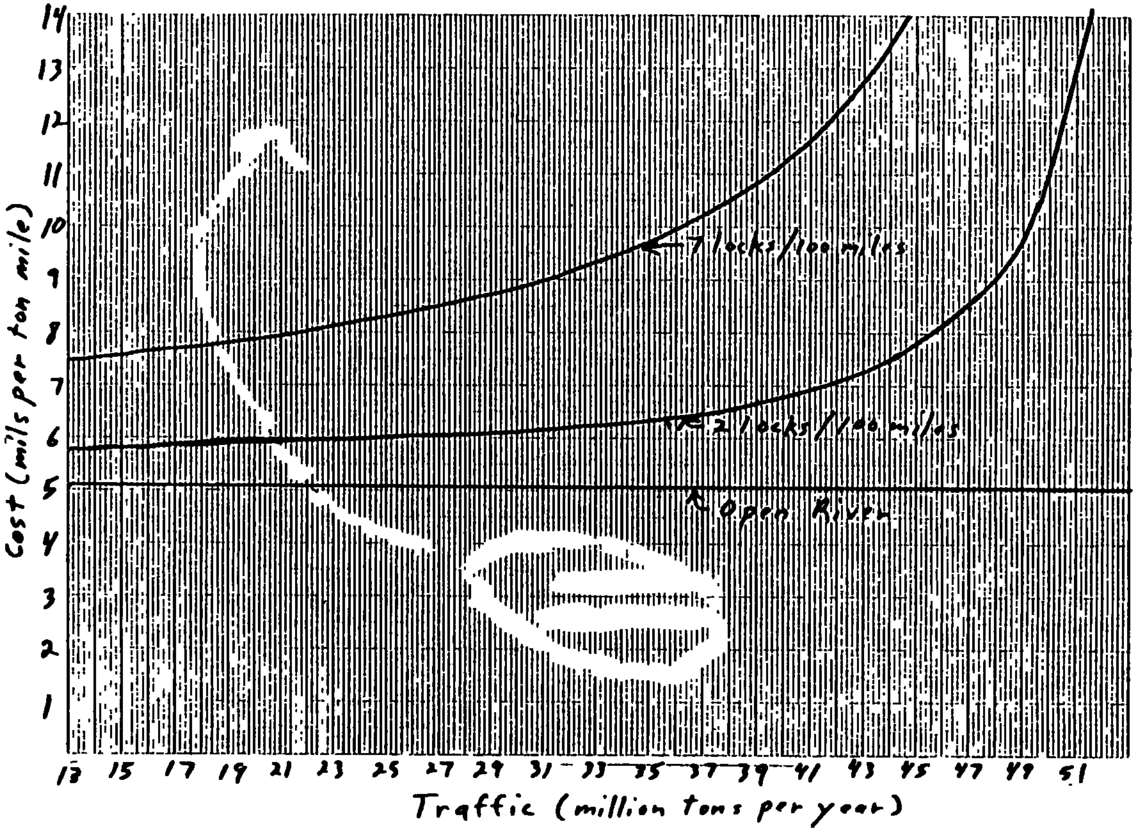
## Figure V-D

Cost vs. Maximum Tow Size



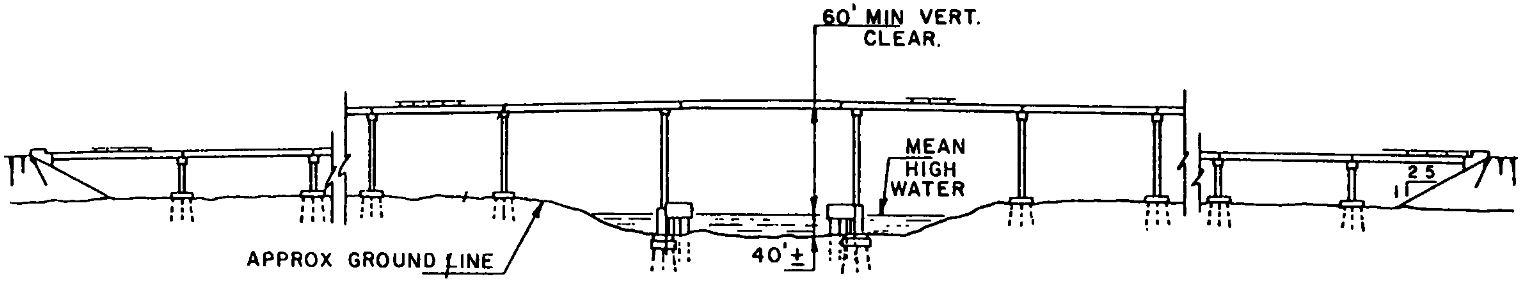
<u>Figure V-E</u>

<u>Cost vs. Traffic</u>



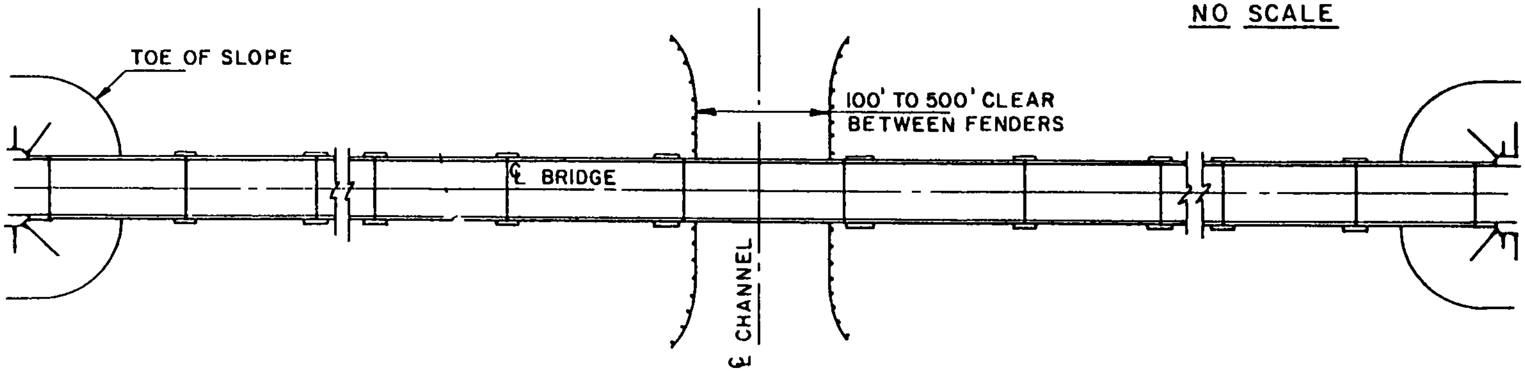
## Figure V-F

## General Arrangement



ELEVATION

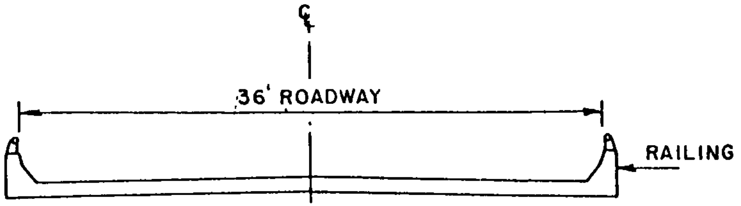
NO SCALE



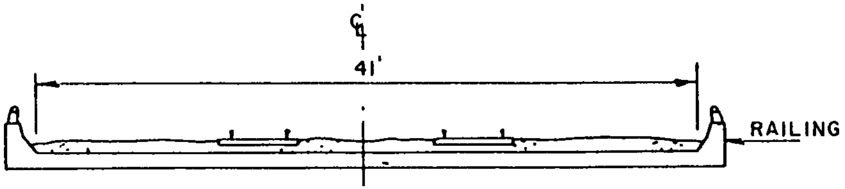
PLAN

## Figure V-G

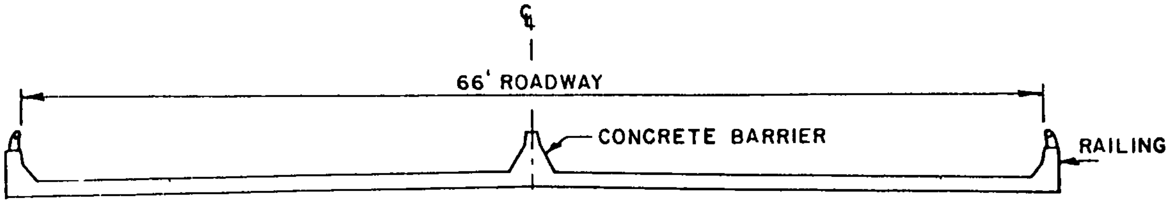
## Typical Sections



TYPICAL SECTION-2 LANE HIGHWAY



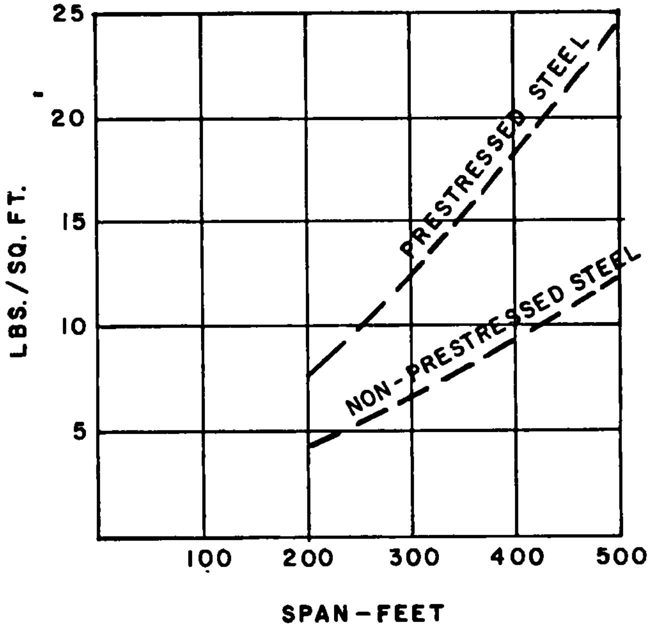
TYPICAL SECTION-2 TRACK RAILROAD



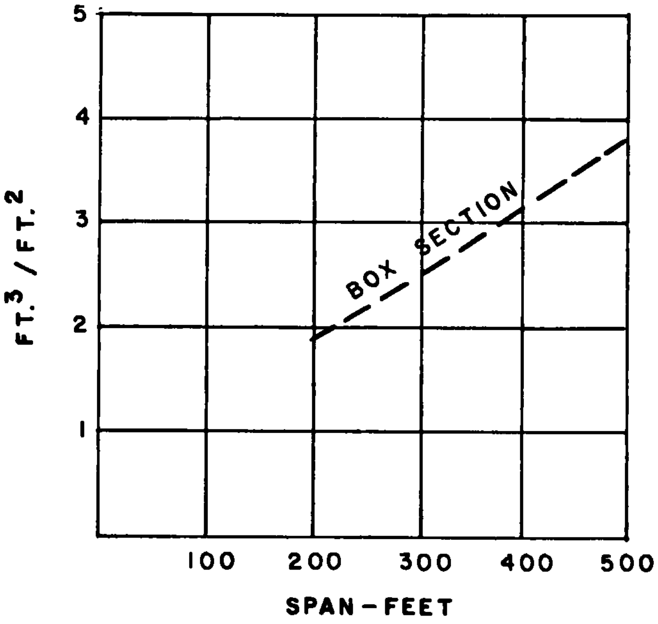
TYPICAL SECTION-4 LANE HIGHWAY

## Figure V-H

## Quantity of Steel and Concrete



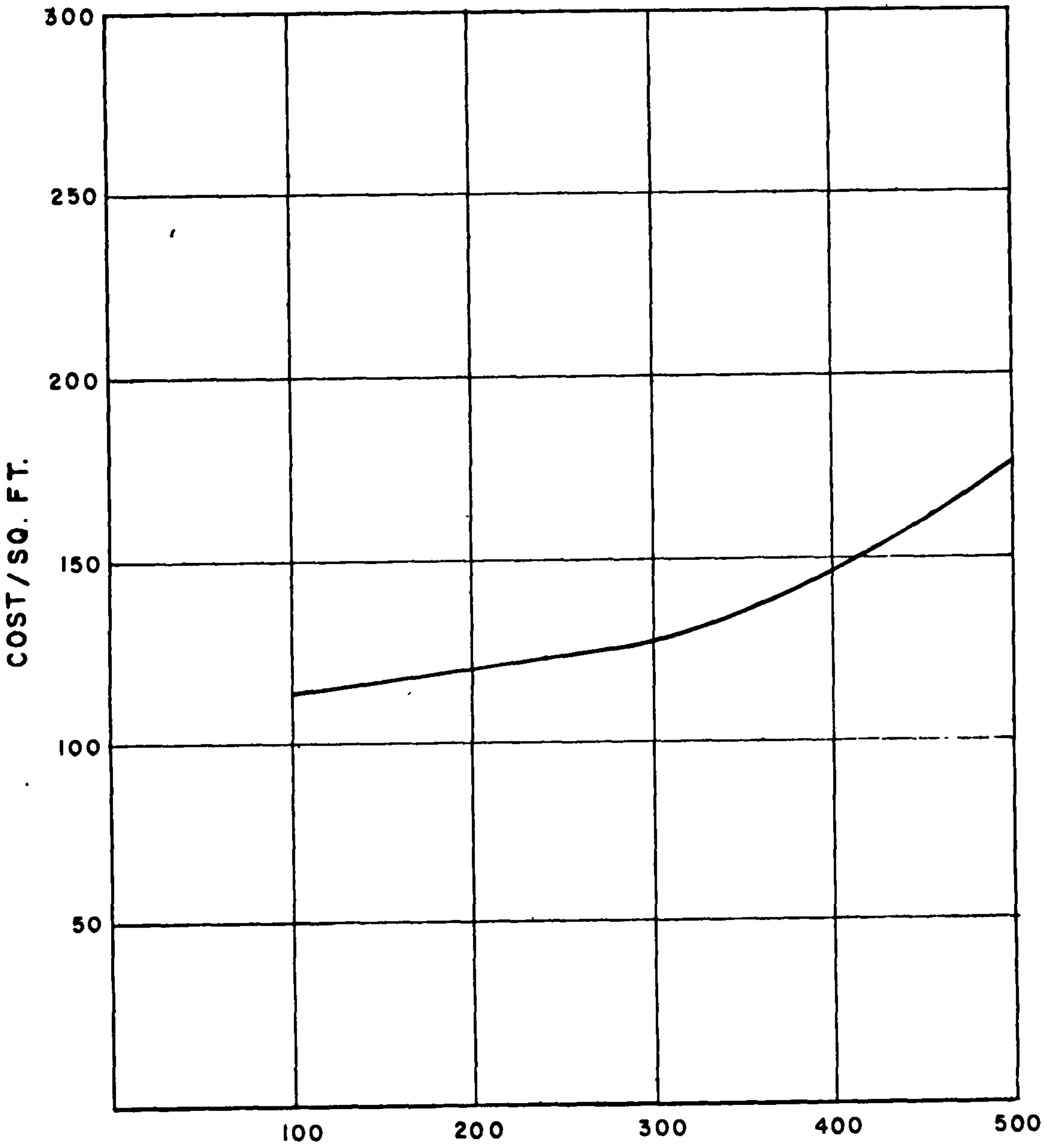
QUANTITY OF STEEL



QUANTITY OF CONCRETE

## Figure V-I

## Bridge Cost



**NOTE:**

To obtain the total cost of any bridge to be replaced, multiply the value from the graph by the area (Length x Width) of the bridge.

## Table V-6

## Cost vs. Maximum Tow Size

COST VS TOW SIZE
EN ROUTE COST/TON-MILE

| MAX TOW SIZE | TOWBOAT HP | SPEED UP MPH | SPEED DOWN MPH | TOWBOAT COST EX FUEL | TOWBOAT FUEL COST | TOWBOAT TOTAL COST | BARGE COST | CARGO COST | TOTAL EN ROUTE COST |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 400. | 5.0 | 7.5 | 5.44 | 1.01 | 6.45 | 0.99 | 1.32 | 8.77 |
| 3 | 600. | 5.2 | 7.9 | 4.42 | 0.98 | 5.41 | 0.96 | 1.29 | 7.65 |
| 4 | 800 | 5.2 | 8.0 | 3.84 | 0.97 | 4.80 | 0.95 | 1.26 | 7.01 |
| 5 | 1000. | 5.3 | 8.2 | 3.44 | 0.95 | 4.40 | 0.93 | 1.25 | 6.58 |
| 6 | 1300 | 5.5 | 8.5 | 3.22 | 0.99 | 4.21 | 0.90 | 1.20 | 6.30 |
| 7 | 1500. | 5.5 | 8.6 | 2.98 | 0.98 | 3.96 | 0.89 | 1.19 | 6.05 |
| 8 | 1700 | 5.6 | 8.6 | 2.80 | 0.97 | 3.77 | 0.89 | 1.19 | 5.84 |
| 9 | 1900 | 5.6 | 8.6 | 2.65 | 0.96 | 3.60 | 0.89 | 1.18 | 5.67 |
| 10 | 2100 | 5.6 | 8.6 | 2.52 | 0.95 | 3.47 | 0.88 | 1.18 | 5.53 |
| 11 | 2300 | 5.7 | 8.6 | 2.41 | 0.94 | 3.35 | 0.88 | 1.17 | 5.40 |
| 12 | 2500. | 5.7 | 8.6 | 2.31 | 0.93 | 3.25 | 0.86 | 1.17 | 5.29 |
| 13 | 2700 | 5.7 | 8.6 | 2.23 | 0.93 | 3.15 | 0.87 | 1.17 | 5.19 |
| 14 | 2900 | 5.8 | 8.6 | 2.15 | 0.92 | 3.07 | 0.87 | 1.16 | 5.10 |
| 15 | 3100 | 5.8 | 8.6 | 2.08 | 0.91 | 3.00 | 0.87 | 1.16 | 5.02 |
| 16 | 3400 | 5.9 | 8.6 | 2.05 | 0.93 | 2.98 | 0.86 | 1.15 | 4.99 |
| 17 | 3600 | 5.9 | 8.6 | 1.99 | 0.93 | 2.92 | 0.86 | 1.14 | 4.92 |
| 18 | 3800 | 6.0 | 8.6 | 1.94 | 0.92 | 2.86 | 0.85 | 1.14 | 4.85 |
| 19 | 4000 | 6.0 | 8.6 | 1.89 | 0.91 | 2.80 | 0.85 | 1.14 | 4.79 |
| 20 | 4200. | 6.0 | 8.6 | 1.84 | 0.91 | 2.75 | 0.85 | 1.13 | 4.73 |

Costs are in mils per ton-mile

## Table V-6 (Continued)

| MAX TOW SIZE | LOCKAGE SERVICE TIME MIN | COST/TON-MILE DELAY TIME MIN | TOTAL LOCKAGE TIME, HR | 2 LOCKS TOWBOAT COST EX FUEL | TOWBOAT FUEL COST | TOWBOAT TOTAL COST | BARGE COST | CARGO COST | TOTAL LOCKAGE COST |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 41. | 176. | 3.6 | 1.19 | 0.11 | 1.30 | 0.22 | 0.29 | 3.61 |
| 3 | 41. | 172. | 3.5 | 0.98 | 0.11 | 1.09 | 0.21 | 0.28 | 3.16 |
| 4 | 41. | 168. | 3.5 | 0.85 | 0.11 | 0.95 | 0.21 | 0.28 | 2.88 |
| 5 | 41. | 164. | 3.4 | 0.76 | 0.10 | 0.86 | 0.21 | 0.27 | 2.68 |
| 6 | 41. | 160. | 3.4 | 0.72 | 0.11 | 0.83 | 0.20 | 0.27 | 2.60 |
| 7 | 41. | 156. | 3.3 | 0.66 | 0.11 | 0.77 | 0.20 | 0.26 | 2.45 |
| 8 | 41. | 152. | 3.2 | 0.61 | 0.10 | 0.71 | 0.19 | 0.26 | 2.33 |
| 9 | 41. | 149. | 3.2 | 0.57 | 0.10 | 0.67 | 0.19 | 0.25 | 2.22 |
| 10 | 41. | 145 | 3.1 | 0.53 | 0.10 | 0.63 | 0.19 | 0.25 | 2.12 |
| 11 | 41. | 141. | 3.0 | 0.50 | 0.10 | 0.59 | 0.18 | 0.24 | 2.04 |
| 12 | 41. | 137 | 3.0 | 0.47 | 0.09 | 0.56 | 0.18 | 0.24 | 1.96 |
| 13 | 42 | 133. | 2.9 | 0.45 | 0.09 | 0.54 | 0.18 | 0.23 | 1.90 |
| 14 | 47 | 129 | 2.9 | 0.44 | 0.09 | 0.53 | 0.18 | 0.23 | 1.88 |
| 15 | 52. | 125 | 2.9 | 0.42 | 0.09 | 0.52 | 0.18 | 0.24 | 1.86 |
| 16 | 56 | 121 | 3.0 | 0.42 | 0.10 | 0.52 | 0.18 | 0.24 | 1.87 |
| 17 | 61. | 117. | 3.0 | 0.41 | 0.10 | 0.51 | 0.18 | 0.24 | 1.85 |
| 18 | 66. | 114. | 3.0 | 0.41 | 0.10 | 0.50 | 0.18 | 0.24 | 1.84 |
| 19 | 70. | 110. | 3.0 | 0.40 | 0.10 | 0.50 | 0.18 | 0.24 | 1.83 |
| 20 | 75. | 106. | 3.0 | 0.39 | 0.10 | 0.49 | 0.16 | 0.24 | 1.82 |

# VI - WATERWAY AVAILABILITY

A physical limitation to the capacity of waterway locks and the capability of waterway channels exists which merits discussion and evaluation. Specifically, it should be noted that often, due to natural phenomenon, the waterways are not available to commercial navigation interests. As a result of normal wear and tear (and occasional collisions), locks require periodic maintenance and rehabilitation. While some repair work is routinely performed without interfering with navigation, some repair activities require lock downtime. On many northern waterways ice conditions pervail in winter months. Ice conditions range from waterway to waterway and from year to year, from conditions which hamper navigation to conditions which "close" the waterway. On waterways which operate under mild ice conditions, special equipment must be used and additional safety precautions taken. Many waterways are merely impassable during part of the year. Waterway closures can also occur when waterways become unnavigable due to adverse hydrometeorological conditions, such as extreme high or low water, fog, or accidental blockages of the navigation channel or lock approaches.

## METHODOLOGY

This report addresses closures due to lock downtime and weather only briefly, presenting a table of lock downtime covering each NWS Analysis Segment. The table includes both closures due to downtime of the lock itself and due to weather conditions. Closure due to adverse hydrological conditions are stochastic phenomenon and were analyzed in Section V.

The major emphasis of this report is on current, ongoing, and anticipated programs to extend the navigation season. Earlier sections briefly describe the available techniques which are currently in use on waterways in America to make navigation possible under winter conditions. More detailed descriptions of new techniques will be presented as part of Element I. Later sections describe the locations where these techniques have been, or are expected to be, applied according to the latest available studies.

Alternatives which are laid out in this section will form the basis for assessing the potential for increasing the availability of the waterways in response to future demands.

The dates of navigation season opening and closing are presented in the final section.

Information from this section which is required to evaluate lock capacity is presented in appropriate form in Table III-8 of Section III.

## REVIEW OF PRESENT WATERWAY AVAILABILITY

### (a) Assessment of Lock Downtime

The tabulated data on lock downtime, which follow in Table VI-1 were gathered from documents provided by Corps personnel.

As much as possible, the downtime is shown for those locks which are selected, in Section III, as representative of others on the same analysis segment. Where this was not possible, the downtime of a lock with similar dimensions and age is shown.

Information on current downtime was used in the evaluation of capacity in Section III. In addition, this information will be used to evaluate strategies which may have potential for decreasing lock downtime. It should be noted that the lock downtime does not constitute a significant portion of the year (except during winter closings for northern waterways), usually only between 2% and 5% of the time. Still, in some strategies which deal with measures to improve lock efficiency during adverse hydrometeorological conditions or by prevention of accidents, improved scheduling of maintenance activities may be suggested.

Several aspects of Table VI-1 deserve further explanation. On many waterways, no lock closure data are available. On waterways which are currently underutilized, this can often be explained by the fact that much maintenance work is performed between tow arrivals and, as such, is not recorded as actual downtime. Waterways with no available data are: the Middle Mississippi River (L/D 27), the Mississippi River from New Orleans to the Gulf (Inner Harbor Lock), the Kentucky River, the Ouachita - Black and Red Rivers, the Old and Atchafalaya Rivers, the Baton Rouge to Morgan City Bypass, the GIWW West, the Apalachicola, Chattahoochee and Flint Rivers, the New York State Waterway and the Sacramento Ship Locks. On the Upper Mississippi River all maintenance is performed during winter closure and no high water closure data are available. At L/D 26, the high water closure results from a 35 day shutdown in 1973 averaged over 8 years. All downtime within the Ohio River Division is based on the best estimate of the district personnel of what downtime would be under capacity conditions. Downtime for locks in the Allegheny River is similar to downtime on the Monongahela River. Locks on the Arkansas River are approximately 10 years old and have required no maintenance yet. SWD expects 2 week closures every 10-15 years. Values given for Mobile District Locks are averages for the District; no breakdowns by lock or cause are available. For Lake Ontario and the St. Lawrence Seaway, maintenance is performed during winter closure. At least one parallel chamber is always available at the Soo Locks during the navigation season so lock downtime is not recorded. Major maintenance is done during the winter closure.

### (b) Technology Currently in Use on United States Waterways for the Extension of the Navigation Season

The methods of extending the navigation season can be divided into three categories: the special efforts required in order to operate locks in ice conditions, the techniques used to maintain navigation in channels, and the methods of harbor maintenance and shore protection during the ice season. The following subsections briefly describe the technology which presently exists in the United States in each of these areas.

It should be noted that there are costs associated with the extension of the navigation season beyond the direct cost of implementing the techniques used to extend the season. Water transportation is more expensive in ice conditions for several reasons. A greater amount of maintenance is required on vessels operating in cold regions, and the service life of the vessels and equipment is shortened. Crew members must be compensated for working in conditions which are not only unpleasant, but hazardous as well. The capacity of towboats operating in sheet or drift ice is severely reduced because of the loss of maneuverability due to the ice. The overall capacity of the fleet of towboats or lake ships is reduced because of the slower speeds and increased delays at locks in the winter.

The environmental consequences of extension of the navigation season is a subject of great concern. The disruption of the natural ice pack or the formation of a stable ice cover in order to permit navigation may affect waterway stages, recreational patterns, and the behavior of fish and wildlife. The importance of the environmental impact of winter navigation and whether the effect on the environment would be positive or negative are both uncertain.

1. Operation of Locks During Ice Conditions. Ice presents several difficulties to lock operations. Brash ice, floating pieces of ice up to 6 feet in diameter, drifts or is pushed ahead of vessels into lock chambers and can take up so much of the chamber that vessels cannot enter until the ice is locked through. If a vessel does enter the chamber, along with floating ice, the ice is pushed up against the lock walls where it accumulates and effectively narrows the chamber. Floating ice often drifts into miter gate recesses where it prevents the gates from closing fully.

Both drifting and frozen-on ice accumulates in the structural niches of lock gates where the buildup may overload the gate sill or prevent the secure closing of the gates. Intake valves are clogged by small pieces of ice, and machinery breaks down more frequently. Ladders and walkways become covered with ice and unsafe for use, as are floating mooring bitts which may freeze in place at the level of the lower pool and then shoot up to the surface of the upper pool unexpectedly.

# Table VI-1

## Lock Downtime - Days/Year

| Reporting Region | Segment Name | Lock Name | | Dredging | Maint. | Ice | High Water | Low Water | Fog | Accid. | Misc. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Upper Miss. | | | | | | | | | | | |
| 2 | Lower Upper Miss. | L/D #26 | | - | 4 | 1 | 4 | - | - | - | - | 9 |
| 7 | Upper Ohio | Emsworth | Main | .5 | 7.3 | - | .3 | - | - | 1.5 | 1 | 10.6 |
| | | | Aux. | .5 | 6.3 | - | .3 | - | - | 1 | 1 | 9.1 |
| | | Willow Is. | Main | 3 | 13 | - | - | - | 1 | 3.5 | - | 20.5 |
| | | | Aux. | 3 | 13 | 1.33 | - | - | - | 1.8 | - | 19.1 |
| 7 | Middle Ohio | Gallipolis | Main | 3 | 16 | 1.5 | .6 | - | 1.9 | 4.5 | - | 27.5 |
| | | | Aux. | 3 | 15 | 3.5 | 1.5 | - | 2 | 2.5 | - | 27.5 |
| | | Meldahl | Main | 3 | 16 | 1 | - | - | - | 2 | - | 22 |
| | | | Aux. | 3 | 12 | - | - | - | - | 1 | - | 16 |
| 7 | Lower Ohio (3) | McAlpine | Main | 1 | 5 | 1 | - | - | 2 | 1 | - | 10 |
| | | | Aux. | 2 | 6 | 1 | 2 | - | 2 | 1 | - | 14 |
| 7 | Lower Ohio (2) | Newburgh | Main | 1 | 5 | 1 | - | - | 2 | 1 | - | 10 |
| | | | Aux. | 1 | 4.5 | 1 | - | - | 2 | 1 | - | 9.5 |
| 7 | Lower Ohio (1) | L/D #52 | Main | - | 4 | 1 | - | - | 1 | 2 | - | 8 |
| | | | Aux. | - | 6 | 1 | - | - | 1 | 5 | - | 13 |
| 7 | Monongahela River | L/D #3 | Main | .5 | 7.5 | - | 2.1 | - | - | 1 | 1 | 12.1 |
| | | | Aux. | .5 | 6.6 | - | 2.1 | - | - | 1 | 1 | 11.2 |
| | | L/D #7 | | 1 | 6.3 | - | 1.3 | - | - | 1 | 1 | 10.6 |
| | | L/D #8 | | 1 | 6.3 | - | .2 | - | - | 1 | 1 | 9.5 |
| 7 | Kanawha River | Winfield | Main | 3 | 21 | - | - | - | 1 | 3 | - | 28 |
| | | | Aux. | 3 | 21 | - | - | - | 1 | 3 | - | 28 |
| 7 | Green River | L/D #1 | | .5 | 3.5 | - | - | - | 1 | 2 | - | 7 |
| 7 | Cumberland River | Barkley L/D | | 1.75 | 12.25 | - | .25 | - | 6 | - | - | 20.25 |
| | | Cheatham L/D | | 2 | 12.25 | - | 1 | - | 6 | - | - | 21.25 |
| 8 | Tennessee River | Kentucky L/D | | 1.5 | 14.25 | - | .25 | - | 6 | - | - | 22 |
| | | Chickamauga L/D | | .75 | 16.25 | - | .25 | - | 6 | - | - | 23.25 |
| 9 | Arkansas River | | | | | | | | | | | 1 |
| 12 | Warrior River | | | | | | | | | | | 20 |
| 12 | Tombigbee-Alabama-Coosa | | | | | | | | | | | 20 |
| 16 | L. Erie/Welland Canal | | | | | | | | | | | 0 |
| 16 | Soo Locks | | | | | | | | | | | |
| 18 | Columbia/Snake | | | | 14 | | | | | | | 14 |

The problem of ice drifting or being pushed into lock chambers can be approached in two ways: either the ice can be kept out of the lock or it can be removed as expeditiously as possible. High flow air screens or "bubbler" systems have been set up in the approaches to locks, and the curtain of air bubbles which they create deflects floating ice away from the lock chamber. Nevertheless, sooner or later enough floating ice will accumulate in the lock chamber to necessitate an ice lockage. A simple lockage, however, will not remove the ice. Opening the intake valves helps push the ice out, but this often takes time. Special ice flushing systems reduce the amount of time required.

The traditional method of dealing with floating ice in miter gate recesses is to hire additional personnel to push the ice out with pike poles. A more sophisticated technique uses bubblers, like those in approach channels, in the gate recesses.

Frazil ice, small irregular pieces of ice which form in supercooled water too turbulent for sheet ice to form, mixes easily in fast flowing water and is carried to depths where it adheres to intake screens, valves, and valve seats. Thus, valves are often opened only partially to prevent ice from being drawn in.

The accumulation of ice on lock walls reduced the already narrow clearance between most ships or tows and the lock walls. The ice is either chipped away manually, using shovels or poles, or scraped by a backhoe. The United States Army Cold Regions Research and Engineering Laboratory (CRREL) has developed a specialized ice cutter by combining the vehicle and power plant of a trencher with a 16 foot chainsaw used in coal mines. CRREL has also developed a polymer coating which is sprayed on lock walls in order to reduce the adhesion of ice. The coating inhibits the accumulation of ice and makes the ice easier to remove. It has been suggested that lock walls be heated to just above the freezing point of water so that no ice could form. The ice which accumulates on the sides and bottom of barges must often be chipped off so that the tow can fit between the lock walls and over the gate sill without damaging the lock.

The downstream sides of lock gates are generally open, and ice tends to collect on and to freeze in the recesses. The accumulated ice is either chipped away or thawed with steam hoses. One preventative measure is to cover the recesses with a metal plate and to spray the plate with the same polymer coating used on lock walls. Another method in use is the heating of the gates.

Floating mooring bitts are tied off at the level of the upper pool, lest they freeze at the lower level. Ladders and walkways are cleared of snow and ice as much as possible, but the level of safety for personnel at the lock is reduced.

Machinery is prone to breakdowns when exposed to winter conditions, and thus lock machinery is often heated in order to limit the number of mechanical failures.

2. Navigation in Channels and Open Water in Ice Conditions. Many vessels, especially newer, higher powered ones, can navigate through a stable cover of sheet ice, albeit at slower speeds and with lower efficiency. Vessels which are strengthened for ice conditions according to the rules of the American Bureau Of Shipping, generally sustain no damage in sheet ice for which they have been designed. The critical factor, though, is the maintenance of a stable ice cover. If the sheet ice breaks up into brash ice and begins to move and drift, ice jams will form at bends, bridges, landings, and anywhere else where large pieces of ice are caught up. Ice jams create thick layers and ridges of ice through which vessels cannot pass easily, if at all. They also form hanging dams, which lower water levels downstream and can flood upstream areas. Hydroelectric power production is adversely affected by ice jams as well. Hydrostatic heads are decreased and water intakes may be blocked.

The most common measure to stabilize river ice cover is the deployment of an ice boom, a string of timbers stretched across a river, to reduce the velocity of the current at the surface to below the critical velocity at which stable ice cover can form. The ice boom also inhibits the subsequent break-up and movement of the ice cover. Conventional ice booms, installed for the benefit of hydroelectric plants and for flood control, do not allow navigation. On navigable channels, the booms are deployed with openings at the center of the channel which permit vessels to pass.

Two alternatives to booms for the prevention of ice jams are the modification of rivers and the redesign of obstacles along the waterway. Bends in rivers and obstructions, like bridge piers, are major causes of ice jams. So far, river modifications and training work to prevent ice jams from forming have been applied only on small, nonnavigable rivers.

In the areas where stable ice covers cannot be maintained, vessels often travel in convoys, taking turns at the lead. Tow operators sometimes resort to "mule-training," using one tow boat to push and another to pull, in order to gain greater maneuverability in brash ice. Tows are often reduced to two or sometimes one barge; the pilots simply back up and ram the ice until the tow can proceed or a frozen-in barge can be freed. Deckhands are usually restricted to the inboard gunwales of tows to reduce the chance of falling overboard into freezing water, and tow pilots will ferry deckhands in a light boat while making up tows, rather than forcing them to walk along an outboard gunwale.

Ice breaking services are provided by the Coast Guard whenever they determine that it is in the national interest.

The Coast Guard deploys their fleet of icebreakers of various sizes and types to open channels through ice to keep channels clear, and to relieve vessels beset in ice. The size and power requirements for icebreakers in a particular area depend on the thickness of the ice and the extent of the navigation season. If navigation is extended year-round, usually a number of smaller boats is sufficient to maintain ice-free channels, or at least to prevent ice jams. If the navigation season is extended only partially, larger icebreakers are needed, as ice will accumulate during the closed season. In rivers where the Coast Guard does not yet break ice, private carriers will sometimes use their towboats as icebreakers. Open wheel towboats are preferred over nozzle-equipped boats, as frazil ice tends to clog kort nozzles.

The techniques and tools for navigation in ice conditions described above have all been known and used for many years. Current interest in the extension of the navigation season has led to research and development of several new technologies, such as the use in inland waterways of electronic position-finding equipment. Traditional navigational aids, especially those placed in the water, cannot generally survive the rigorous demands placed on them by winter use and are usually removed at the beginning of the ice season and replaced in the spring. Electronic navigation equipment accurate to as little as 3 feet to 10 feet, is in common use on deep water vessels and can replace many inland navigational aids. Fixed rather than conventional floating navigational aids, strenthened for ice, are also available.

Improved ice forecasting techniques, combined with extensive aerial surveillance of ice conditions and coordinated dispatching of commercial vessels and icebreakers assist winter traffic in finding the best routes through the ice. Safety and survival equipment developed especially for winter navigation reduce the risks to life of operation in ice. Warm affluent discharges, such as cooling water from power plants, are being re-examined as a means to inhibit the formation of ice. The Coast Guard has experimented with air cushion vehicles (ACV) as icebreakers. ACVs use the waves generated by the air cushion to break up sheet ice or ice jams.

3. Harbor Maintenance and Shore Protection in Ice Conditions. The dates of the navigation season are largely determined by the availability of harbors. Sheltered harbors will freeze before open water, and all of the structures associated with ports provide potential ice jam sites. Vessels are also limited by the size of the harbor approaches in their ability to seek the path offering the least ice resistance.

Ice breaking, therefore, tends to be concentrated in and around harbors and approaches. Bubblers are used to keep ice from forming at piers, and high pressure water jets and steam hoses are used to remove ice which has accumulated.

Both the shore and structures projecting from it are affected by ice. The loading placed on structures by stationary ice is severe enough, but extension of the navigation season causes sheet ice to be broken up and floes set adrift. Moving floes impose tremendous loads on docks, especially small boat facilities, as well as on piers, breakwaters, and the shore. Either new ice control structures, such as rubble breakwaters or sheet piling, are installed, or existing structures are rebuilt or strengthened to withstand ice loads. Wooden structures are typically rebuilt with steel and include features such as recessed ladders, which will not be torn off by moving ice floes. Shore erosion is combatted with bigger riprap or longitudinal booms, which hold the ice cover stable from the edge of the channel to the shore.

Residents of islands in navigable waterways are accustomed to using the winter ice cover as a bridge to the mainland because it is capable of supporting snowmobiles and even cars. Extension of the navigation season has both disrupted the solid bridge and created difficulties for ferries, because of the drifting floes. Alternative vehicles have been developed for the residents of these islands, including air boats and air cushion vehicles.

### (c) Applications of Current Technology and Ongoing and Anticipated Programs for Extension of the Navigation Season

It is difficult to prepare a detailed list of every method in use to extend the navigation season on each waterway segment. Most of the techniques used to operate locks in ice conditions, such as scraping the lock walls, poling drift ice out of the gate recesses, and thawing ice with steam hoses, are considered standard operating procedures at all locks affected by ice. Means of continuing navigation in channels, especially in areas with year-round navigation, are either routine, such as designing structures to withstand ice loads, or are undertaken by the carriers themselves, as in the case of two convoys.

Therefore, the following lists of present methods of extending the navigation season in use on the NWS reporting regions consist mainly of the applications of relatively new techniques, such as bubblers and polymer coatings, which, so far, have been used in a relatively limited number of areas.

The sources of information on present applications include:

1. Projected United States Coast Guard Icebreaking and Icebreaker Requirements 1975 - 2000[51].

2. Ice Engineering For Civil Works[52].

3. St. Lawrence Seaway System Plan for All-Year Navigation[53].

4. Ice Control at Navigation Locks, TL 110-2-237[54].

There are draft or final reports on ongoing programs in three areas: the Upper Mississippi River ("Draft Economic Analysis of Year Round Navigation on the Upper Mississippi River")[55], the Great Lakes - St. Lawrence Seaway ("Draft Survey Study for Great Lakes and St. Lawrence Seaway Navigation Season Extension")[56], and Alaska ("Marine Technology for the Arctic and Western Regions of Alaska")[57].

For segments which experience closings due to ice, season extension programs are discussed below.

1. Reporting Region 1 - Upper Mississippi River. Local heating and insulation on miter gates are currently in use in the St. Paul and Rock Island Districts. The St. Paul District has also used waste heat to inhibit the blockage of channels by frazil ice. Lock 21 has bubblers in the upstream approach and in the gate recesses.

The "Draft Economic Analysis of Year Round Navigation Season on the Upper Mississippi River" considered several options.

A four week extension of the navigation season up to L/D 11 would require:

- polymer coating on lock walls.
- heaters for valve machinery.
- bubbler systems at gates.
- bubbler systems at terminals.
- additional channel markers.

at Locks and Pools 11 through 25. The estimated investment and operating cost of these improvements, along with the expected additional maintenance cost of the locks, discounted over the 50 year economic life of most of the improvements, is approximately $12.6 million.

According to the same study, year-round navigation to L/D 11 would require, in addition to the improvements mentioned above, skin plates and polymer coatings on lock gate recesses, lock gate skin plates, a 5000 hp towboat and barge for icebreaking, and rock excavation in Pools 15 and 18 to straighten circuitous reaches. These reaches impede navigation in all conditions, but would be impassable in ice unless the bends are eased.

The investment and operating costs necessary to maintain year-round navigation discounted over 50 years is approximately $54 million.

This study calculated the costs and benefits of each of a total of 12 alternative season extension proposals. The cost summary by extension alternatives is shown in Table VI-2. The major benefits were due to reduced stockpiling requirements of grain, agricultural chemicals and coal and to saving grain traffic transfer.

The recommendation of the draft study, based solely on economic analysis of costs and benefits without considering environmental or other factors, is that a phased implementation plan for the extension of the navigation season be adopted.

The following plan is recommended by the study:

(a) Phase I - 4-week extension to Lock 19.

(b) Phase II - 4-week extension to Lock 16.

(c) Phase III - 4-week extension to Lock 11.

(d) Phase IV - Full season extension to Lock 19 and a 4-week extension for the incremental reaches between Lock 19 and 16.

After one phase is implemented, it is recommended that several years of traffic be observed prior to proceeding to the next phase. If, in fact, winter traffic

## Table VI - 2
## Cost* Summary by Study Alternative - Reporting Region 1

| Alternative | Total, 50-year discounted costs ($000) |
|---|---|
| **Four-week season extension** | |
| To: Lock 22 | 2,656 |
| Lock 19 | 5,557 |
| Lock 16 | 8,149 |
| Lock 11 | 12,615 |
| **Eight-week season extension** | |
| To: Lock 22 | 2,920 |
| Lock 19 | 7,115 |
| Lock 16 | 19,119 |
| Lock 11 | 34,311 |
| **Full season extension** | |
| To: Lock 22 | 2,920 |
| Lock 19 | 7,439 |
| Lock 16 | 21,763 |
| Lock 11 | 54,377 |

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* 1979 Dollars

occurs as anticipated, the next phase would be implemented. If the anticipated traffic does not materialize, then the season extension program would be curtailed.

It should be noted that the draft study was released in March, 1979, and thus the final version is not yet available.

2. Reporting Region 2 - Lower Upper Mississippi. Year-round navigation is maintained from Grafton, Illinois, south. L/D 26 is closed because of ice for one day each year, on average. The St. Louis District has increased the sized of dikes and riprap because of ice scour problems. Bubbler systems are being considered for Lock 26.

3. Reporting Region 5 - Illinois Waterway. Year-round navigation is maintained on the Illinois Waterway. The Chicago District uses local heating and insulation on miter gates. Diversions of water from Lake Michigan are used to clear blockages of channels by frazil ice. The Coast Guard has tested an air cushion vehicle icebreaker on the Illinois Waterway.

4. Reporting Region 6 - Missouri River. The Missouri River is closed to navigation each year when ice begins to form and is not reopened until the ice thaws. When ice begins to form, the stage of the river is lowered to 6 ft. from 9 ft., to allow for the buildup of water behind ice jams. Larger riprap has been used to reduce bank erosion due to ice in the Omaha District.

5. Reporting Region 7 - Ohio River And Tributaries. Year-round navigation is maintained on the entire Ohio River system with the exception of Locks 6 through 9 on the Alleghany River which are normally closed from December through March. Ice closures average less than one day per year. The Pittsburgh District uses local heating and insulation on miter gates. The District is experimenting with polymer coating on lock gates and walls. Bubbler systems have been installed in the gate recesses at Maxwell and Emsworth Locks and in the upstream approaches to Emsworth and Markland Locks. The Pittsburgh and Huntington Districts tie off floating mooring bitts during ice conditions. The Louisville District also opens intake valves only partially to prevent them from clogging with ice.

Tow operators use their own boats as icebreakers, and tows from various carriers often form convoys alternating in the lead. Tows are sharply reduced in size and transit times, and the unpredictability of transit times increase dramatically.

6. Reporting Regions 14 and 15 - Middle and North Atlantic Coast. Coastal ports are open year-round. Coast Guard icebreakers keep channels and harbors clear for small craft and fishing vessels. No major ports freeze over, but the Coast Guard will clear floe ice from harbors if necessary. The Philadelphia District has replaced timber mooring dolphins with steel ones.

7. Reporting Region 16 - Great Lakes and St. Lawrence Seaway. Inter-lake shipping, on a large scale, currently takes place roughly between April 1 and December 15, although there are small movements between lakes and significant inter-lake traffic year-round. Some of the newest techniques and equipment for operating locks in ice conditions have been tested at the Soo Locks and along the St. Lawrence Seaway. These include polymer coatings on lock walls, flushing systems for ice lockages, and a specialized ice cutter for lock walls. There is substantial Coast Guard icebreaking in harbors and channels.

The GL/SLS Navigation Season Extension Demonstration Program has proven the technical feasibility of year-round navigation between the lakes. The most recent economic study, still in draft form, has found favorable cost-benefit ratios for year-round navigation on the lakes and 11 month navigation on the St. Lawrence. (Annual maintenance on the locks requires a one month shutdown. The locks on the St. Mary's River, connecting Lake Superior and Lake Huron, have parallel chambers, which may be shut down alternately.) The estimated costs and benefits of various navigation season extensions considered by the study are shown in Table VI-3. The benefit to cost ratios do not include any environmental disbenefits of the program because of their unquantifiable nature. The ratios do include the estimated cost of implementing the environmental plan of action associated with the proposed season extension. Environmental disbenefits are not expected to substantially alter the calculated benefit/cost ratio.

# Table VI-3

## Average Annual Benefits and Costs (In $1,000 at 6-7/8%) - Reporting Region 16

| Average Annual Costs | Proposal 1[1] | Proposal 2[1][2] | Proposal 3[1][2] | Proposal 4[1] | Proposal 5[1] | Proposal 6[1] | (Proposed Plan[1] Proposal 7 |
|---|---|---|---|---|---|---|---|
| Total Investment Costs | $431,581 | $505,083 | $707,678 | $781,100 | $792,304 | $809,938 | $1,004,411 |
| Annual Costs: | | | | | | | |
| Interest & Amortization | $ 30,781 | $ 36,023 | $ 50,469 | $ 55,711 | $ 56,504 | $ 57,766 | $ 71,632 |
| Operations & Maintenance | $ 16,505 | $ 18,453 | $ 25,526 | $ 27,474 | $ 28,088 | $ 29,005 | $ 30,184 |
| TOTAL | $ 47,286 | $ 54,476 | $ 75,995 | $ 83,185 | $ 84,592 | $ 86,771 | $ 101,816 |

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[1] Definition of Proposals:

| Extended Season Proposals | Estimated Starting Date | Lake Superior St. Marys River Lake Michigan Straits of Mackinac Lake Huron | St. Clair River Lake St. Clair Detroit River Lake Erie | Welland Canal Lake Ontario St. Lawrence River |
|---|---|---|---|---|
| 1. | 1990 | Year-round | 1 Apr. - 31 Jan. | 1 Apr. - 15 Dec. |
| 2. | 1990 | Year-round | 1 Apr. - 31 Jan. | 1 Apr. - 31 Dec. |
| 3. | 1990 | Year-round | Year-round | 1 Apr. - 15 Dec. |
| 4. | 1990 | Year-round | Year-round | 1 Apr. - 31 Dec. |
| 5. | 1990 | Year-round | Year-round | 15 Mar. - 31 Dec. |
| 6. | 1990 | Year-round | Year-round | 15 Mar. - 15 Jan. |
| 7. | 2000 | Year-round | Year-round | 15 Mar. - 15 Feb. |

[2] Note: Proposals 2 and 3 are mutually exclusive. Proposal 2 considers season extension to 31 January on Lake St. Clair/Detroit River/Lake Erie and to 31 December on the St. Lawrence River. Proposal 3 considers year-round season extension on Lake St. Clair/Detroit River/Lake Erie, but no extension on the St. Lawrence River. Therefore, phased implementation of season extension would have to proceed via proposals 1, 2, 4, 5, 6 and 7 or via Proposals 1, 3, 4, 5, 6 and 7.

## TABLE VI - 4

## Measures Necessary to Implement Year-Round Navigation on the Great Lakes-St. Lawrence Seaway System

### LAKES - CONNECTING CHANNELS, INCLUDING THE ST. LAWRENCE RIVER

- Icebreaking Requirements

  5 Type B* Icebreakers
  17 Type C* Icebreakers

  *Type B is a major icebreaker capable of breaking 2-3 ft. of ice without backing and ramming, i.e., Mackinaw and Westwind.

  *Type C is a vessel specially equipped for breaking 1.5 to 2 ft. of ice without backing and ramming, i.e., 140 ft. WTGB class.

- Vessel Traffic Control
- Ice Data Collection/Dissemination
- Ice and Weather Forecasts
- Aids to Navigation
- Ice Control Structures
- Air Bubbler Systems
- Lock Modifications
- Dredging and Spoil Disposal
- Compensating works (if required by levees and flows considerations)
- Shoreline Protection
- Island Transportation Assistance
- Water Level Monitoring
- Vessel Speed Control and Enforcement
- Channel Clearing Craft - (2) wide beam barges and (2) towing vessels
- Vessel Captain/Pilot Training

### HARBORS

- Icebreaking Requirements; Commercial tugs on an "as-needed" basis
- Ice Control Structures
- Air Bubbler Systems
- Aids to Navigation

Table VI-4 lists the various measures which would be necessary to implement the plan proposed by the draft study, that is, year-round navigation.

8. Reporting Regions 18 and 20 - Columbia/Snake Waterway and Alaska. Year-round navigation is maintained on the Columbia/Snake Waterway. There is a bubbler system in the upstream approach to Bonneville Lock. Floating mooring bitts are tied off in the winter.

The southern peninsular region of Alaska, including the ports of Ketchikan, Sitka, and Juneau, has a climate similar to that of Puget Sound, and year-round navigation is possible without any special measures to extend the season.

The Gulf of Alaska coast, including Valdez, Cook Inlet, and Anchorage, is navigable year-round with icebreaking assistance. The Coast Guard maintains a fleet of small icebreakers, which clears normally ice free harbors for small craft and responds to calls for assistance from commercial vessels in Cook Inlet.

The regions subject to severe ice conditions begin along the Bering Sea coast of Alaska. From December to June most of the Bering Sea coast and all of the Arctic coast are iced in. During the Bering Sea navigation season, between July and November, the coast is ice-free up to Nome. Along the North Slope, from Point Barrow to the Canadian Border the ice is least between July and September, although in some years the polar ice pack never recedes very far from shore. All vessels operating in the Bering Sea and Arctic are ice strengthened year-round because of drifting ice.

Organized efforts to extend the navigation season in these waters, and in Alaska generally, are limited to Coast Guard icebreaking. The Coast Guard uses three Polar Class icebreakers in the Bering Sea. In winter they can transit as far north as Nome.

Vessels headed for points north of the Bering Strait usually must wait for the August "ice window." The summertime conditions along the North Slope rival in severity the worst winter navigation conditions elsewhere in the world. Ice forecasts from the Arctic Research Laboratory and from private concerns are not always reliable, especially near the beginning and end of the navigation season.

Many shipping companies use their own aerial surveillance. There are some Coast Guard installed navigational aids put in place at the start of the season; they are removed for the winter, but the knowledge and skill of the ship captains, as well as radar and depth finders, are vital for safe transit. The low level of traffic has not yet justified the use of more extensive and permanent navigational aids.

There are few suitable harbors along the North Slope for ships with 40 ft. drafts. The anchorages currently in use are exposed to strong current, winds, and severe storms. Cargo is thus usually lightered to shore. The Bureau of Indian Affairs Alaska Resupply Operation uses modified military landing craft carried on board the North Star III, the break-bulk ship used in the operation.

There is barge traffic on the main rivers of Alaska, but so far there is no maintenance dredging, river training works, or canalization. The natural navigation channels are found by pilots by trial and error. In winter, river navigation ceases and the barges and towboats are taken south for use in warmer areas.

The uncertainty surrounding the future of marine transportation in Alaska is as great as the uncertainty of the development of that region. Should the development of Alaska's vast natural resources lead to increased demand for water transportation, there are several feasible alternatives.

Icebreaking tankers designed on the basis of tests of the S.S. Manhattan could carry crude oil from offshore terminals at Prudhoe Bay. The September 15, 1979 issue of Maritime Reporter/Engineering News reports that the Globtik shipping group has plans reportedly costing up to $14.6 billion to transport Alaskan oil to the United States East Coast using a fleet of 350,000 ton and 80,000 ton icebreaking tankers traveling through the Northwest Passage.

As has been stated above, the policy of the Coast Guard is to provide icebreaking services whenever they are considered to be in the national interest. The report on Alaska cited above states that the Coast Guard will undoubtedly add to its fleet of icebreakers should sufficient need be proven. Tests of ACV icebreakers are continuing and they could come to be used in Alaskan waters.

The report also states that the most likely direction for growth in inland waterway navigation in Alaska is toward dredging of rivers along which development occurs. Unfortunately, Alaskan rivers are typically unstable, and the cost of maintaining navigation channels and navigational aids over a long distance would be high. Extending the river transportation season into the winter would be even more costly.

### (d) Dates of Navigation Season Opening and Closing

Table VI-5 presents the dates of navigation season openings and closings as obtained from the sources referenced above. Several additional notes are helpful.

The navigation season at the southern extreme of Region I is year-round. At the northern extreme, the winter closure can be as long as four months. The dates shown are for Lock II, approximately in the middle of the segment. The average and extreme dates are taken for the period 1969 to 1978.

Year-round navigation is maintained on the lower Allegheny. The upper reaches of the river are mainly used for recreation and are closed for three months during the winter.

The average dates for the Great Lakes are cited by various studies. There is intralake traffic and a small number of interlake movements throughout the year, but the dates given represent the period of major interlake shipments.

Alaska has three regions with substantially different navigation seasons. Southern Alaska, including the southeast peninsula and the major port of Anchorage, has year-round navigation. The Bering Sea coast of western Alaska up to the Bering Strait is generally navigable from July to November. Areas beyond the Bering Strait and along the North Slope are as free of ice as they ever are from July to September. Most vessels heading through the Bering Strait do so in August.

# Table VI-5

## Dates of Navigation Season Opening and Closing

| Reporting Region | Segment Name | Average | | Extreme | | | |
|---|---|---|---|---|---|---|---|
| | | Opening | Closing | Opening | | Closing | |
| | | | | Early | Late | Early | Late |
| 1 | Upper Miss. | March 9 | Dec. 15 | Feb. 26 | March 30 | Dec. 1 | Dec. 22 |
| 2 | Lower Upper Miss. | Year-round | | | | | |
| 5 | Illinois | Year-round | | | | | |
| 6 | Missouri | March 15 | Dec. 15 | Varies only a few days each year. | | | |
| 7 | Upper Ohio | Year-round | | | | | |
| 7 | Middle Ohio | Year-round | | | | | |
| 7 | Lower Ohio (3) | Year-round | | | | | |
| 7 | Lower Ohio (2) | Year-round | | | | | |
| 7 | Lower Ohio (1) | Year-round | | | | | |
| 7 | Monongahela | Year-round | | | | | |
| 7 | Allegheny (Locks 6-9) | March 30 | Dec. 1 | | | | |
| | (Below Lock 6) | Year Round | | | | | |
| 7 | Kanawha | Year-round | | | | | |
| 15 | Upper Atlantic Coast | Year-round | | | | | |
| 16 | Ont. & SLS | April 1 | Dec. 15 | | | | |
| 16 | Erie | April 1 | Dec. 15 | | | | |
| 16 | Huron | April 1 | Dec. 15 | | | | |
| 16 | Michigan | April 1 | Dec. 15 | | | | |
| 16 | Superior | April 1 | Dec. 15 | | | | |

# VII - CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

As a result of analyses performed during the investigation for this report, several general observations can be made.

The majority of existing navigation locks have large reserves of capacity. Only a few locks presently operate at or near capacity. These are:

- Inner Harbor Lock.
- Locks and Dam No. 26 (Mississippi River).
- Gallipolis Locks.
- Marseilles Lock.
- Lock and Dam No. 22 (Mississippi River).
- Bonneville Lock.
- Winfield Locks.
- Kentucky Lock.
- Vermilion Lock.
- Calcasieu Lock.
- Algiers Lock.

These locks are bottlenecks which already present, or may be in the future, a potential barrier to the growth of waterborne commerce on the waterways and cause underutilization of the existing navigation channels as well as underutilization of most navigation locks. This is a result in part, of staged construction which was undertaken to develop the national waterways system. In many cases, highly interactive segments of the waterways network have a variety of lock sizes which were constructed during different periods of technological development. Due to the long technical life of navigation structures, there are many locks still operational which were constructed during the early stages of waterway network development.

In recent years, efforts have been made to select lock dimensions taking into account system wide requirements. Now that the waterway system is essentially complete, future efforts should be directed towards improvement of the present system, which will make the necessary system wide type of evaluation possible.

Maintenance programs conducted by the Corps of Engineers are generally adequate so that authorized channel dimensions are available with a high degree of reliability. There are, however, a few exceptions, notably, the Missouri and Apalachicola/Chattahoochee/Flint Waterways. On these waterways, the maintenance of authorized channel dimensions are extremely difficult due to significant hydrological changes induced by other than navigation users of water resources.

Efforts to reduce environmental impacts have become a decisive factor in channel maintenance programs, causing changes in operating procedures, technology and costs. Although the combined capability of the Corps and private dredging fleets is considered to be sufficient to meet the workload, the fleet is, in general, very old. There is a current trend to replace outmoded dredges by new dredges which are more efficient under current and projected operating conditions.

A serious deficiency of the present waterway system exists in that channel dimensions (including bridge clearances) on some important waterways such as the Illinois, Upper Mississippi and Gulf Intracoastal Waterways, are more restricted than existing standards would indicate is safe for unconstrained two-way navigation. The primary reason for this is that these waterways have never been completed to their full authorized dimensions. Enlargement of the channels on these waterways, at least to the full authorized dimensions would permit the operation of larger tows, reduce seasonal disruption of navigation, reduce the time required to transit the waterways and reduce the occurence of accidents.

The following sub-section presents a brief summary of findings and includes observations, results of analyses and conclusions drawn from methods developed in this report.

## LOCK CAPACITY

Locks are major navigation structures and in most cases represent the primary constraint to expansion of physical waterway capacity. At the same time, lock replacement is a measure of waterways development, demanding great capital investment, associated with both systemwide and long-term impacts. Obviously, the analysis of existing lock capacity as well as possible measures to increase lock capacity to meet future demand is one of the most important priorities of the NWS. A review of existing estimates of lock capacity revealed a diversity of assumptions, input data and methodologies for computation of lock capacity as well as differences in opinions relative to the concept of lock capacity. Hence, it became essential for this national level study to develop an approach to lock capacity estimation based on a uniform and consistent set of assumptions and level of accuracy. It is recognized, however, that the approach developed for the NWS scope and purpose cannot replace a detailed lock capacity analysis at the project level of evaluation.

It is important to emphasize that lock capacity is not a stable entity but, in addition to being sensitive to lock physical characteristics and changes, is a product of many variables which change with the level of utilization, fleet composition, traffic structure and so forth. Hence, the primary objective in lock capacity estimation was first to present it with an explicit definition of input and second, to provide a method of estimating lock capacity using a sensitivity analysis of capacity to major input variables. The capacity estimates presented are based on the LOKCAP computer model. The approach developed, evaluating locks by class eliminated the necessity of exhaustive computer runs. The nomographs and equations developed for the NWS lock capacity sensitivity analysis provided an efficient way to adjust lock capacity resulting from potential changes in input variables.

Input for capacity estimation is based primarily on Performance Monitoring System data. A program was set up to verify the accuracy and applicability of PMS records.

PMS data on lockage time were found to be satisfactory and reliable in most locations. Histograms obtained from PMS data have a shape that confirms expectations. The data are relatively well grouped, even though the speeds or times were directly compared from lock to lock without controlling for differences in tow sizes, conditions of approach and entry, weather conditions, and eventual non-observation of waiting distances. After verification with appropriate Corps field offices, even abnormal or unstable data are found to be acceptable in most cases, due to the particular conditions existing at the lock. The data were rejected in only a few instances and replaced by the appropriate average value of normal PMS recordings for other locks.

Many locks in the United States have similar chamber dimensions. A strong linear relationship exists between unadjusted technical capacity and chamber area, regardless of site specific input data. This phenomenon justified the grouping of locks into size classes. A methodology was developed to group all locks into 22 classes representing each chamber size (or combinations of sizes for multichamber locks). Capacity estimated for these lock classes can then be adjusted for differences in lock service time, average vessel size and other specific input variables.

The NWS approach to estimating lock capacity was applied to existing locks under present conditions. Capacity under present conditions can only provide an order of magnitude estimate of what capacity will be in the future, when a modified set of conditions might exist. In many cases, increases in present lock capacities are probably due to increases in tow sizes and consequently improved utilization of lock chamber dimensions, especially for locks which are presently underutilized.

Calculated tow delay based on queuing theory provided results of the same order of magnitude as the delay values obtained from the PMS records even for congested locks for which delay time is very sensitive to even minor interferences.

To adjust capacity under present conditions to reflect potential changes in commodity pattern, waterway modifications, and structural and non-structural measures to increase lock capacity, a set of simplified equations and graphs have been developed.

The relationships between average tow size and percent double lockages were investigated in some detail. Linear relations were found to hold for major lock size classes, across all waterways. This strongly supports the notion that tow size distributions adapt to lock sizes in a similar fashion throughout the inland waterway system and provides a firm basis for handling the potentially complex relations between tow size and lockage type in a relatively simple and straightforward manner.

Lock capacities for any average tow size are obtained by interpolation between the capacity values corresponding to 0% and 100% double lockages (and their related average tow sizes). In general, capacity is found to increase with tow size, at least up to the point where all tows execute double lockages, but at a decreasing rate. In some cases, capacity decreases with increasing tow size, the maximum being obtained with few double lockages.

Lock capacity varies in a simple proportional manner with percent empty barges, downtime, recreational traffic, and seasonality. Correspondingly simple mathematical and graphical techniques are presented to calculate these effects.

The relations between capacity and changes in lockage times are a bit more complex, but an easy to use nomograph was developed to simplify these calculations. Reductions in chambering and approach times produce the largest gains in capacity. Improvements in setover and double lockage efficiencies can also produce significant capacity increases.

Relations between capacity and lock operating policy and percentage of multiple-vessel lockages were also derived. In general, where approach timings are such that an N-up/N-down lockage policy is efficient, capacity increases with N, but at a decreasing rate. Analysis of multiple-vessel lockages is not amenable to generalized analysis, but a methodology was developed which can quickly yield results for specific locks. For typical conditions of underutilized chambers, capacity increases as the percentage of multiple-vessel lockages increases.

Statistical data related to lock operation and maintenance costs were found to be inadequate. However, an attempt was made to present correlations based on statistical averages as a function of major parameters. An attempt to correlate O & M costs with the effective age of a lock was not successful because of the absence of sufficient data on lock rehabiliations, and because any such correlation is influenced by many factors (extensiveness and quality of rehabilitation, the mechanical equipment employed, operational effectiveness, etc.) which did not lend themselves to analysis within the confines of this task. Lock maintenance costs versus lock size, while not presenting a strong correlation, did tend to divide locks into three size groups with respect to maintenance cost. Lock operating costs showed a strong correlation with lock utilization, which can be explained by increasing usage of utilities with increasing lock utilization.

Curves were developed from statistical data which related lock and dam construction costs to basic physical parameters, lift for locks and river width, and magnitude of water level fluctuations for dams. Costs for structures on soil foundations can be more than double the cost for structures founded on rock. Increasing lock length is less expensive per foot than increasing lock width.

For locks which are or are likely to become bottlenecks, an evaluation was made of measures to increase capacity. The measures investigated included minor structural and maintenance improvements, non-structural policy options and physical lock replacement.

Instituting a Ready-to-Serve policy was found to be of significant benefit at most locks in increasing capacity and should become more useful as traffic levels increase. Full implementation of a Ready-to-Serve policy, however, could be very expensive, costing two to three million dollars per year per lock. Less costly methods would also increase capacity at the same locks, but to a lesser degree. Partial implementation of a Ready-to-Serve policy by using switchboats or a traveling kevil is also possible. Several locks were also identified as potentially deriving benefits from the implementation of an N-up/N-down operating policy.

All representative locks were evaluated for potential improvement by minor structural and maintenance measures to the extent possible using available data. Whenever existing studies to increase capacity were available, the conclusions were included. Whenever inefficiencies in the present lockage operation could be identified, the type of improvement required and the approximate possible increase in capacity is shown. Locks identified as having inefficient chambering times include Marseilles Lock (Illinois R.), Emsworth Lock (Ohio R.) and the auxiliary chamber of McAlpine Lock (Ohio R.). Locks identified as prohibiting normal approach and/or entry speeds include L/D 19 and L/D 22 on the Mississippi River, Kentucky Lock (Tennessee R.), Morgantown Lock (Monongahela R.).

Recreational usage was identified as having an impact on capacity. The impact is most acute when the time devoted to peak recreational demand coincides with the time of peak commodity movements. Major problems of this sort were identified in the Upper Mississippi River, the Columbia/Snake Waterway and the Lower Tennessee River (Pickwick Lock).

Alternatives for lock replacement to meet demand were formulated. The alternatives were presented sequentially, in order of increased level of capacity provided. As demand increases, this often shifts the location of the most constricted lock.

## CHANNEL MAINTENANCE

The maintenance of navigable channels can generally be divided into four distinct problem areas on the basis of the type of waterways. These are represented by man-made canals, canalized rivers, free-flowing rivers, and approach channels to deep-draft ports, in which category the Great Lakes may be included.

In general, maintenance requirements on highly controlled and regulated rivers with chains of slack water pools are significantly lower than on the less stable, free-flowing rivers. In turn, the methods of channel maintenance on free-flowing and channelized waterways can be determined by the relative stability of the river bed. For relatively unstable waterways such as the Lower Mississippi River, with relatively fine sediments and a high variation of seasonal flows, the dredging sites and annual dredging requirements are virtually impossible to predict. For more stable rivers, such as the Apalachicola or Columbia Rivers, with coarser sediments and more regulated seasonal flows, the major dredging sites are more or less identifiable.

The relationship between hydrological conditions and channel depth is very complex. For rivers which are relatively stable, flow and depth are directly related. On the other hand, for rivers which are relatively unstable, low flow alone cannot be the only criterion for assessing the reliability of depth maintenance. In addition to low flow, the following hydrological parameters were identified as having a significant effect on the establishment of controlling depths:

- the rate of high flow recession.
- the peak flow during the high flow period.
- the duration of the high flow period.
- the duration of the low flow period.

- the level of flow during the low flow period.

The maintenance of adequate navigation channels on freeflowing rivers appears to be an art and involves as much spot judgement as empirical rules or formulae. In addition to an intimate knowledge of the river, a precise sense of timing is required to determine at what point of a river's stage dredging of a particular site will be most effective in helping the river stabilize its own channel. While extremely high spring floods followed by a rapid decrease in river stage is the prime reason for shoaling problems, rapid fluctuations and minor peaks following extended low-water stages can also result in hazardous shoaling conditions.

In general, most channel maintenance deficiencies can be corrected or significantly mitigated by implementation of a well-designed training program in conjunction with periodic maintenance dredging. While one or two feet of over-depth dredging has been found to be almost indispensable in maintaining authorized channel depths within a season, advance maintenance dredging is considered ineffective for periods greater than one season.

Environmental constraints appear to be exerting increasing influence on the cost, and possibly on the continuing effectiveness, of various dredging programs. The need for confined disposal areas has resulted in upward-spiraling unit cost and reduced or deferred volumes of dredging.

The inland waterways with maintenance problems are discussed below.

On the Upper Mississippi River, environmental considerations have resulted in a drastic reduction in the amount of maintenance dredging performed. Although hydrological conditions have been favorable, some increase in the number of groundings has been reported. However, the amount of data available is insufficient statistically to indicate a definitive trend in impact on maintenance reliability; additional study and evaluation are necessary.

Although annual dredging volumes have remained relatively uniform, the number of dredging sites on the Lower Mississippi River has declined in recent years due to the continuing training works construction program. Extended periods of extreme low-flows following rapid recess of flood stage creates the greatest problem with respect to maintenance of authorized dimensions.

Flows on the Missouri River are regulated by upstream reservoirs to accommodate multipurpose uses of the water. While navigation is shut down each winter due to ice, the date that the channel closes each year is predetermined in May and June on the basis of the amount of upstream storage available at that time.

Barge capacity on the White River is severely reduced and ceases entirely from mid-August to mid-December as a result of shallow and unreliable channel depths. This problem seems to stem from several factors including severe bends, low-flows and limited maintenance funding.

Low-flow stages on the Red River between Lock and Dam 1 and the Mississippi River should be corrected upon completion of the 9 feet navigation channel project presently being implemented.

The GIWW has numerous reaches where the controlling dimensions are less than authorized due to local resistance to implementation of the various authorized projects.

The reliability of the controlling dimensions on the Columbia River downstream of Portland is somewhat less than it should be according to the duration of design flows. Channel depth between Portland and the Bonneville Lock and Dam is maintained at 17 feet rather than 27 feet as authorized since there is no practical requirement for the greater depth.

In addition, several waterways in the United States were identified as having either dimensional deficiencies or an insufficient probability of maintaining authorized depth as a result of adverse hydrological conditions at low flow stage. These waterways are: the Middle Mississippi River, the Lower Middle Mississippi River, the Upper Lower Mississippi River, the Lower Mississippi River, the Missouri River and the Apalachicola River. All of these segments are composed of free flowing waterways for at least a portion of their length.

Authorized depth in the Lower Mississippi is 12 feet, but the project has not yet been fully implemented and, as a result, depths are maintained at 9 feet a considerable amount of time. During the 19 year period of record, controlling depths greater than 10 feet were measured 88% of the time and controlling depths greater than 12 feet were measured 69% of the time in the 700 mile reach. Controlling depths often drop to less than 10 feet even at intermediate to high flows; however, during the period of lowest flows, controlling depths greater than 10 feet are often maintained by a combination of dredging and natural scour.

The Lower Upper Mississippi River has an authorized depth of 9 feet like the Lower Mississippi; controlling depths less than 9 feet can occur even at intermediate flows. During the 10-year period, 1969-1978, the controlling depth was less than authorized about 2% of the time. However, the period of time when depths were less than authorized only partly coincided with the period of time when water levels were below the low water reference plane.

The authorized depth on the Apalachicola River is 9 feet As a result of the completion of training structures and an increase in the efficiency and intensity of the dredging program since 1971, the duration of controlling depths less than authorized has decreased, although depths greater than authorized only occurred 83% of the time in the period 1971-1977.

On the Missouri River, flows are kept very regular throughout the navigation season by a series of upstream storage and regulation projects. Thus, rapid flow fluctuations in the flow region where major sedimentation or scour would occur are avoided.

No dredging has been performed on the Missouri River since 1976. Controlling depths less than authorized occur even at design flow, but only for very short periods of time before natural scour increases the depth.

It is conceivable that even though future water usage may decrease flows, particularly low flows, waterway navigation conditions may improve as a result of improved patterns of releases for navigation purposes, continued basin reservoir development, and continued river training activities.

No accurate method with which to relate the reliability of depth or depth itself to dredging requirements is available. This subject is always a matter of project level evaluation. In the total absence of a generalized method, a simple empirical ratio was recommended which can be used to provide very rough, order of magnitude values.

Finally, the following alternatives were identified as measures which can mitigate the effects of adverse hydrological conditions:

1. periods occurring during an extremely adverse combination of hydrological conditions.

2. river training works at persistent shoaling locations.

3. improved reservoir releases for navigation purposes.

4. increased reserves for lock capacity

5. increased reserves of fleet capacity.

In the past decades there have been major developments in ocean shipping technology, namely the growth of container traffic, the construction of very large dry bulk carriers and petroleum tankers, and the evolution of the LASH concept. On the other hand, serious problems exist in the United States for the handling of very large bulk carriers. These developments have led to two trends. One trend is toward port consolidation, where a single port or facility may handle traffic for a sizeable region using coastwise shipping, inland waterways, surface transport, and pipelines to distribute cargo to an area previously served by a number of ports. The second trend is towards specialization of ports for certain trades, e.g., general goods/containers, petroleum, coal, grain, etc. Each port is equipped to handle a specific type of ship and requires appropriate approach channels.

These trends will have a profound impact on requirements for coastal approach channels and will establish requirements for expanding the size of some and the reduction of others. This leaves a number of alternative solutions available to maintain approaches to coastal ports.

The trend to larger and deeper vessels has prompted many ports to request the Corps of Engineers to deepen their harbors and channels.

Many problems are associated with the deepening of harbors and channels, including having to go through rock in a growing number of East Coast ports, disposal of the material excavated in an acceptable environmental/-ecological manner, and constraints imposed by the Corps of Engineers' budget.

These problems emphasize the need for the development of more efficient dredging technology and, even more importantly, implementation of alternative solutions to decrease dredging requirements. There is a wide range of possible mitigating measures, depending on site specific conditions and objectives, including such actions as construction of jetties, sediment traps, offshore handling/-mooring facilities, etc. In addition, more hydraulic studies of estuarian and coastal zone problems, as well as more complete and frequent hydrographic surveys, would allow better assessment of maintenance requirements.

While channel reliability is of primary concern to shippers and operators alike, statistical information of this nature is not consistently available for all coastal and port channels. Since accurate data on channel reliability can be critical to safe waterway utilization as well as to the optimization of operating economics, it is considered imperative that a uniform program be developed whereby sufficient statistically significant channel data are recorded by each of the District offices concerned.

Dredging continues to be a major method of maintaining reliable authorized channel dimensions. Several general observations or conclusions can be drawn with respect to the current and future federal dredging activities and operations by both private and government owned dredging plants. These observations focus on the basic question as to whether the present dredge plant in the country, both privately owned and government owned, can in a timely and efficient manner, adequately maintain the nation's inland waterways.

The present capacity of the existing federal and private dredging plant is generally adequate to meet current dredging needs and it is generally geographically distributed in proportion to work requirements. Although there could be an occasional deficiency in plant of a specific type, it would in all probability be confined to a particular region and be of short duration and of minor consequence. There is a degree of mobility in the dredging industry, especially between adjacent regions, and the industry has often demonstrated that it can respond positively to crisis situations. This is specifically important for many of the inland waterways with marked seasonal and annual variations in dredging requirements.

However, the present dredging fleet, both private and government is generally old and some of it obsolete. Despite its condition, the existing dredge plant is generally adequate and technically capable of meeting current dredging needs of the federal waterways project. The condition of the dredging plant is probably reflected in somewhat higher costs of dredging; but as the plant is improved and modernized, unit dredging cost should stabilize. It is expected that with the greater utilization of the plant by industry and the highly competive nature of the dredging market, a more positive plant modernization and replacement program will develop to meet the challenge of the requirements of new dredging techniques and procedures to conform with current and future environmental constraints and needs. By Public Law 95-269 Congress has provided for equipping the nation with adequate and modern dredging plants to handle its needs. The first aspect of the law is to encourage private industry to invest in new equipment by guaranteeing the opportunity to compete for government work on equitable terms. The second is to replace the existing Corps dredges with a minimum fleet of state-of-the-art vessels to handle emergencies.

As a result, private industry has already procured five hopper dredges, two of which are of a modern design, having had no hopper dredges previously. In addition, there are three new hopper dredges under construction and three in various stages of planning. The Corps also has three new hopper dredges under construction. In addition, industry has recently acquired a new modern dustpan dredge, the first one to be owned by other than the Federal Government. Other dredges, both of similar and different types are in the planning stages. This indicates that a positive industry program of plant replacement, modernization, and addition is now in progress. Additionally, the plant in the government's minimum dredge fleet will be of the most modern type and should include features necessary to provide for future environmental constraints.

Dredging techniques and procedures, in the future, will be governed to a large extent by the environmental constraints existing or imposed at the time. Technology to meet environmental considerations has been developed and documented in reports in connection with the Corps' recent Dredged Material Research Program.

The development of a model to evaluate the effect of potential changes on dredging costs provided several conclusions. The cost of dredging increases with decreasing material density, decreased height of cut, increased dredging frequency, increased distance to disposal areas and requirements for containment.

## WATERWAY CONDITIONS FOR FLEET OPERATION AND WATERWAY AVAILABILITY

Channel capacity, in terms of potential throughput, is rarely a limiting factor on United States waterways. The primary reason is that because of the large size of tows typically in operation on United States waterways, the frequency of movement is very low. Channel capacity, defined by delays at one-way reaches, is an order of magnitude higher than the capacity of the locks. However, for competitive economic effectiveness of water transportation, channel navigation conditions are a critical factor. Numerous interactions between channel navigation conditions and fleet operation determine the three most important impacts on waterway transportation cost: accommodated vessel size, travel time, and duration of the navigation season.

There is, in general, no definite cutoff point of tow size which a waterway can accommodate for the majority of the United States inland waterways; rather, navigation conditions on the waterway can be described in association with maximum tow size commonly accommodated by the degree of restriction. Canals and approaches to coastal ports are exceptions to this general rule, in that there is usually a well-defined maximum vessel size for a set of canal dimensions. The common maximum tow size accommodated by a channelized waterway is a result of the tradeoff of the economies of large tows against the increased transit time, fuel consumption, crew stress, and risk associated with operations in a more restricted channel. More study is needed to be able to estimate the magnitudes of the effects on maximum tow size of several parameters, especially human factors.

Based on a comparison of the maximum tow sizes currently operating on United States waterways and design standards for unrestricted two-way navigation and the density and severity of constraints to navigation, the waterways have been classified as unrestricted, partly restricted, and very restricted. The relatively unrestricted segments include the free-flowing portion of the Mississippi River, the Ohio River, the Lower Monongahela River, the Upper Missouri River, the Kanawha River, and the Columbia River up to the confluence with the Snake

River. The very restricted segments include the GIWW, the Upper Mississippi River to the Illinois River, and the Illinois, Green/Barren, Black Warrior/Tombigbee and Apalachicola/Chatahoochee/Flint Waterways.

A more detailed analysis would be desirable in order to best identify the areas in which the need to improve navigation conditions is the greatest. To this end, it would be advisable to study further the operation of tows on sharp bends, especially on those bends which require tows to flank. This study should attempt to specify, as much as possible, the effects on transit time of bend radius, channel width and depth, current, and wind.

Transit time between origin and destination can be divided into two components: en route time and lockage time. En route time depends on tow speed and effects of various constraints on navigation. Lockage time comprises delay while waiting for service at locks and the actual lockage process itself. Transit time is 60 to 80% en route time and 20 to 40% lockage time on typical waterways.

Tow speed depends on tow size and configuration, towboat horsepower, and channel dimensions. There is an approximate analytical formulation for estimating tow speed in unobstructed reaches (it does account for restrictive channel dimensions), but it does not consider the effects of other constraints on navigation on overall average speed. Transit time is undoubtably sensitive to the density of constraints (such as bends to be flanked, narrow bridges, marinas, and commercial landings and fleeting areas), due to the need for tows to slow down as they pass these areas. However, no analytical approach is available with which to quantify the effects of these constraints on transit time.

Our preliminary analysis shows that the increase in transit time due to one-way reaches appears to be relatively small at present traffic levels. However, one way constrictions could become important limitations on travel time on free-flowing rivers and canalized waterways with very high capacity locks. Also, the need to flank on sharp narrow bends, especially during poor navigation conditions can substantially increase transit time in extreme cases.

The short distances controlled by bridges means that the added transit time due to these constraints is not significant. However, the worst bridges may completely stop navigation for extended periods of time during adverse hydrometeorological conditions.

The effect of marinas on transit time is apparently small, perhaps adding an additional 4% to en route time when marinas are closely spaced. Commercial landings and fleeting areas, however, are much more important. As much as 30% of total en route time can be due to slowdowns for commercial facilities. This problem will grow with increasing waterborne commerce. A possible solution might be a change in the legal liability for damage to structures and broken mooring lines away from tow operators. The owners of landing and fleeting facilities would then be responsible for building and maintaining their structures and securing their barges sufficiently to withstand normal wave loads.

A program of channel improvement with the ultimate goal of bringing all navigable waterways up to design standards for two-way traffic should be formulated. The most restricted waterways should be given priority for improvement. Hence, the need is for further study to properly identify the most restricted waterways and the causes of restriction along these waterways.

The major factors which affect the availability of waterways are: lock downtime, hydrological and meteorological conditions and limitation on the navigation season due to ice.

Locks may be closed to traffic because of routine maintenance, breakdowns, accidents, or dredging in the approaches. Routine maintenance often takes place during winter closures, whenever possible. In the majority of cases, the approximate two week period required for maintenance is coordinated with users, shippers and consignees in order to minimize adverse effects. At newer locks, routine maintenance is planned for a two month period every 10 years. Unplanned maintenance time due to breakdowns or accidents rarely accounts for more than a few days each year, on average.

Adverse hydrological conditions, such as high flows and bad weather conditions, can halt navigation. Low flows decrease waterway capacity and increase cost, but do not disrupt navigation entirely since authorized depths are maintained. High flows sometimes stop navigation, specifically on reaches with hazardous bridges. An extremely high flow in 1973 caused a 35-day shutdown on ports of the Upper Mississippi River and Illinois River because of potential damage to dikes by vessel wakes. This was an extreme case, however. Fog rarely stops navigation for more than a few days a year.

The geographical areas in which efforts to extend the navigation season are of the greatest concern are the Great Lakes/St. Lawrence Seaway System and the Upper Mississippi River. Navigation is completely stopped in these areas for a portion of each winter. Other waterways which are subject to ice conditions, such as the Monongahela and Illinois Rivers, are not affected so severely as to curtail navigation for more than a few days. Programs in these areas are directed toward facilitating navigation and the operation of locks during winter conditions.

Alternative programs under study include extenstions of the navigation season on the GL/SLS of four weeks to yearround. A matrix of proposals has been considered for the Upper Mississippi River encompassing navigation season extensions of four weeks, eight weeks, and year-round and geographical ranges up to Locks 11, 16, 19 and 22. Problems associated with extension of the navigation season include increased operational risk, wear and tear on equipment and decreased speeds of vessels, compared with ice-free conditions. Environmental considerations of navigation in ice conditions are uncertain and are under continuing study.

Techniques used to extend the navigation season can be divided into three areas:

1. methods of operating locks in ice conditions.

2. techniques used to maintain navigation in channels.

3. efforts required to protect shorelines and shore structures during winter navigation.

Traditional methods include the scraping or melting of ice with steam lines from lock walls and gates, the application of booms to stabilize the ice cover in channels, the use of icebreakers, "muletraining" of barges, the placement of heavy riprap, and the replacement of wooden structures with steel.

More sophisticated methods, in various stages of development, include the use of polymer coating to reduce ice adhesion on lock walls and gates, air screens to divert floating ice away from lock chambers, the use of air cushion vehicles as ice breakers, longitudinal bubblers used to mix deep, warmer layers of water with colder surface layers, and the use of warm effluent to inhibit ice formation.

The integrated effect of all waterway navigation conditions is reflected in the impact on flotilla transportation costs. Parametric analyses of the interrelationship between channel dimensions, constraints, lock delay, density of traffic and transportation costs have been performed and provided the following general conclusions.

The greatest cost savings from increased channel depth comes from increased utilization of barge draft, with much smaller savings associated with increased tow speed in deeper water. An analysis of the potential economies resulting from increased controlling depth should therefore consider the maximum possible draft of the existing fleet of barges. Once the controlling channel depth is sufficient to allow tow operators to load their barges as deeply as possible, the cost savings of additional depth is minimal, as tow speed is increased (or fuel consumption decreased) very little.

For wider channels accommodating increased tow sizes and with a constant ratio of horsepower per ton of cargo, the fixed and variable costs of towboat operation, except for fuel, increase more slowly than the tonnage hauled. The structure of operating costs indicates that the investment required for new towboats and maintenance costs grow much more slowly than the costs associated with towboat horsepower and that all of the crew related costs (wages, benefits, and subsistance) remain largely constant for towboats of 2800 hp and up.

Changes in service and delay time as a function of average tow size depend on the lock chamber size, traffic level, and tow configuration at the particular lock. Lock service time generally increases with the tow size, as the percentage of double lockages will increase. At a constant level of traffic, lock delay will usually decrease as tow size increases, because of better chamber utilization.

Transportation costs increase with increased traffic on canalized waterways. The change in cost follows from the delay at locks; the increase is gradual at low levels of traffic, but rises sharply as traffic approaches the capacity of the locks. Traffic affects the transportation cost relatively little on open rivers. Locks which are bottlenecks can thus represent substantial transportation cost increases.

# VIII - POSSIBLE ACTIONS

This section presents a segment by segment summary of actions which could be taken to improve navigation conditions. This summary is not meant to be a list of recommended actions, nor is it meant to be comprehensive. All costs are in 1977 dollars and are presented to illustrate the order of magnitude of the cost of the stated alternatives. Alternatives could not be identified for all segments.

## SEGMENT 1, UPPER MISSISSIPPI RIVER, MINNEAPOLIS TO MOUTH OF ILLINOIS RIVER

Lock and Dam No. 22 is the most constraining lock in this segment, having a capacity under present conditions of 29,000,000 tons annually. Introduction of an N-up/-N-down lock operating policy and use of switchboats on a traveling kevil would increase the capacity at Lock and Dam No. 22 by about 25%. If minor structural improvements are found to be feasible in order to allow normal approach speeds at the lock, then combined with an N-up/N-down policy and full implementation of a Ready-to-Serve policy, capacity at Lock and Dam No. 22 could be increased by over 50%.

Providing 1200'x110' locks throughout the segment, with dual 600'x110' locks at Lock and Dam No. 1 would raise the capacity of the segment to over 60,000,000 tons annually (provided that improvements to the approaches and filling system of Lock and Dam No. 19 can be made to raise its capacity to a similar level).

Deepening of the Upper Mississippi to 12 feet could be accomplished by dredging at an estimated cost of about $220,000,000. However, all the locks on the segment would have to be replaced due to inadequate depths over the sills. Alternately, the existing pools could be raised by 3 feet to provide 12 foot depths or a combination of lock replacement and pool raising could be undertaken.

Improvements to provide year-round navigation on this segment include channel widening by excavation of rock in pools 15 and 18. The cost of year-round extension would be an estimated $45,000,000, half of which would be for rock excavation. It should be noted, however, that alternatives to extend the navigation season are prohibited by PL52-502 until the Upper Mississippi River Master Plan is completed.

## SEGMENT 2 - UPPER MISSISSIPPI RIVER, ALTON TO CAIRO, ILLINOIS

Locks and Dam No. 26 is the most constraining lock on this segment. It is currently authorized for replacement by a 1200'x110' lock which will increase its capacity from slightly over 60,000,000 tons to nearly 80,000,000 tons annually. Presently, full advantage is being taken on non-structural policy methods and minor structural methods (use of N-up/N-down policy, use of switchboats and extension of the guidewalls) to provide the present level of capacity.

Provision of a second 1200'x110' lock at Lock and Dam No. 26 would increase capacity to over 150,000,000 annually. A 12 foot channel already exists for most of the year in the subsegment north of the Missouri River. The cost of providing a 12 foot channel in the rest of this segment would cost an estimated $280,000,000 and would be accomplished by dredging and river training.

## SEGMENT 3 - LOWER MISSISSIPPI RIVER, CAIRO TO BATON ROUGE

This segment has an authorized depth of 12 feet. The estimated cost of the ongoing revetment program which will provide.12 foot minimum depth throughout the segment upon completion is approximately $79,000,000 per year. As there are no locks on this segment, actions aside from deepening and widening are inappropriate.

## SEGMENT 4 - LOWER MISSISSIPPI RIVER, BATON ROUGE TO GULF

Improvement alternatives for this segment are of two types. The first type is meant to improve access to the Mississippi River, the Port of Baton Rouge and the Port of New Orleans from the Gulf of Mexico, and vice versa. The second type is meant to increase the capacity of the Baton Rouge-Morgan City Bypass.

Deepening and widening of the Mississippi River-Gulf Outlet to 50'x750' (current dimensions are 36'x500') would cost an estimated $115,000,000, but would also require improvements to increase the capacity of Inner Harbor Lock (Segment 11) if traffic is expected to shift from the Head of Passes.

Dredging the Mississippi River to a 55 foot depth in the Port of New Orleans from mile 127 to the Gulf by way of Southwest Pass could be accomplished at an estimated cost of $206,000,000.

Provision of a 1200'x84' lock at Bayou Sorrell would increase the capacity of the segment from about 20,000,000 tons to nearly 30,000,000 tons annually. Subsequently, an increase in the percentage of multi-vessel lockages (which should occur naturally as traffic increases) and improvements to improve approach and entry times to normal levels at Port Allen Lock could increase capacity to over 35,000,000 tons annually.

## SEGMENT 5 - ILLINOIS WATERWAY

Marseilles Lock is the most constraining lock on this segment. Provision of switchboats or a traveling kevil and providing minor structural improvements at Marseilles could increase capacity from about 25,000,000 tons to approximately 30,000,000 tons annually.

Provision of duplicate locks on the segment was proposed in the River and Harbor Act of 1962. Provision of 1200'x110' locks throughout the segment (with elimination of Brandon Road Lock) would increase the capacity of the segment to nearly 80,000,000 tons annually.

Deepening of the Illinois River to 12 feet would require an initial investment estimated at about $174,000,000. This figure assumes that the duplicate locks would be constructed and would have an adequate depth over the sill.

## SEGMENT 7 - OHIO RIVER

This segment is composed of the following major sub-segments which will be discussed sequentially:

- the Ohio River.
- the Monongahela River.
- the Kanawha River.
- the Green River.

The two most constraining locks on the Ohio River are Emsworth and Gallipolis Locks. The capacity of Emsworth Lock could be increased from under 40,000,000 tons to about 45,000,000 tons annually by implementing a Ready-to-Serve operating policy and reducing chamber interference. The same measures could increase the capacity at Gallipolis Locks from about 50,000,000 tons to approximately 65,000,000 tons annually. Providing 1200'x110' locks at Emsworth, Dashield, Montgomery, and Gallipolis Locks and Lock and Dam No. 53 would provide a capacity of about 120,000,000 tons annually throughout the subsegment provided that minor structural and non-structural improvements can be made to the rest of the locks in the sub-segment to increase capacity to similar levels.

Locks on the Monongahela River are of a variety of sizes and capacities. Minor structural and non-structural alternatives would be of little value on this sub-segment. A minimum capacity on the sub-segment of 60,000,000 tons annually could be provided.

## SEGMENT 12 - TOMBIGBEE, ALABAMA, COOSA, BLACK WARRIOR RIVERS

Non-structural and minor structural improvements would provide little increase in capacity at the locks in this segment. Providing a 600'x110' lock at Oliver Lock would increase the capacity of the Black Warrior and Tombigbee Rivers from a little over 25,000,000 tons to over 30,000,000 tons annually. Providing dual 600'x110' locks at all sites on the Black Warrior and Tombigbee Rivers would increase capacity to about 60,000,000 tons annually.

## SEGMENT 14 - MIDDLE ATLANTIC COAST

Alternatives in this segment include deepening the Ports of Norfolk/Hampton Roads, Baltimore and Philadelphia.

Deepening of the Port of Norfolk/Hampton Roads by 5 to 10 feet (depths of 40, 45, 55 and 57 feet) would cost an estimated $250,000,000.

Deepening of the Port of Baltimore to 50 feet would cost an estimated $215,000,000.

## SEGMENT 18 - COLUMBIA-SNAKE WATERWAY

The use of switchboats at Bonneville Lock would increase its capacity from almost 10,000,000 tons to about 13,000,000 tons annually.

Providing a 675'x86' lock at Bonneville Lock would increase the capacity of the segment to over 25,000,000 tons annually.

Deepening the entrance bar to the Columbia River to 55 feet would cost an estimated $14,000,000 (approximately $30,000,000 to 60 feet) and would be incurred annually. Deepening the Lower Columbia River from the entrance bar to 55 feet to Astoria would cost an estimated $20,000,000.

## SEGMENT 19 - CALIFORNIA COAST

Deepening the Stockton Ship Channel (San Francisco Bay to Stockton) by 5 feet (to depths ranging from 30 to 50 feet) would cost an estimated $135,000,000.

# GLOSSARY

Agitation Disposal: A method of dredge disposal which resuspends sediment in the channel rather than transporting the material away from the dredge site.

Approach: Travel of a tow from the approach point, or from a point on the lock guidewall clear of the lock gates in the case of a turnback approach, to a point where the bow of the tow is abreast of the lock gates and the tow is parallel to the guidewall ready to enter the lock chamber.

Approach Point: The closest point to a lock at which one tow can safely pass another tow traveling in the opposite direction. Tows may not normally proceed beyond the designated approach point of a lock without the permission of the lockmaster.

Approach Speed: Rate of movement of tow during approach.

Approach Time: Time passed by the tow in the approach as above.

Authorized Depth: Depth of channel provided for by regulation.

Authorized Dimensions: Dimensions (width, depth) of channel provided for by regulation.

Auxiliary Chamber: A chamber of a multiple-chamber lock which is usually smaller and used less than the main chamber. Auxiliary chambers are normally used to pass small tows, light boats, and recreational vessels, and to maintain navigation during periods when the main chamber is shut down.

Barge: A non-self-propelled, usually flat-bottomed vessel, used for carrying freight on inland waterways.

Beam: The width of a vessel at its widest point.

Bed Load: The sediment carried by the river which propogates along the river bed.

Booster Pump: For pipeline dredge material transport, an auxiliary pump in addition to the dredge pump.

Block Coefficient: The ratio of the actual displacement of a vessel to the product of its length, beam, and draft.

Bulk Commodity: A good which is normally transported without the use of wrappers, cartons, containers, or other packaging.

Canal: A man-made waterway.

Canalization: Creation of a waterway by construction of locks and dams, river training works, new channels or canals, and combinations of these.

Capacity: The tonnage which can be put through a lock during a given period such as a year, under specified conditions.

CFS: Cubic feet per second, a measure of the rate of flow of water past a given point, such as a dam.

Chamber: The part of a lock enclosed by the walls, floor, sills, and gates; the part of a lock within which the water level is changed as vessels are raised or lowered. A lock may have more than one chamber, and they may be adjacent or laterally separated.

Chambering: That part of a lockage cycle starting at the end of the entry and ending when the exit gates are fully recessed, or when the bow of the exiting vessel crosses the lock sill, whichever is earlier. Chambering includes closing the entry gates, filling or emptying the lock chamber, and opening the exit gates.

Chambering Time: The time it takes to close the entry gates, fill or empty the chamber and open the exit gates.

Channel Maintenance: Dredging, lighting and other operations which assure or maintain the navigability of a channel.

Channelized River: A river which is deepened in parts in order to provide a navigable waterway.

Clamshell Dredge: Dredge equipment which utilizes two bucket edges, like opposing shovels, to lift dredge material.

Commodity Flow Pattern: The predictable routing of the movements of goods.

Confined Disposal: For dredged material, disposal in an area enclosed by dikes or levees.

Constraining Lock: The lock on a particular waterway or channel having the least capacity.

Controlling Depth: The minimum depth of a channel, which determines the maximum draft of the vessels utilizing the waterway.

Cut: A segment of a tow which is put through a lock separately from other segments of the tow.

Cutterhead Dredge: A dredge which utilizes a revolving head to bite and loosen bottom materials.

Dedicated Tow: A tow composed of a towboat and barges which always stay together and are operated as a unit.

Deep Draft Channel: A channel maintained for shipping purposes, which must be deeper than the normal 9 to 12 foot tow channels.

Delay Function: An equation defining the mathematical relationship between the traffic level at a point, such as a lock, and the resultant delay period.

Delay Time: The time elapsed from the arrival of a vessel at a lock to the start of its approach to a lock chamber; the time spent in queue awaiting lockage.

Demand: In economics, the amount of a particular commodity people are willing to buy at specified prices.

Dike: An embankment which is constructed to control or redirect flow in a channel.

Dipper Dredge: Utilizes a stationary single shovel as opposed to a clamshell dredge.

Double Lockage: The type of lockage performed when a tow passed through a lock chamber in two segments or "cuts."

Downtime: The time a lock is not operative.

Dragline Dredge: A dredging tool utilizing a single bucket pulled over dredge material toward a stationary crane.

Dredging: The process of excavating or cleaning out a channel for the purpose of providing a certain depth.

Draft: The depth of water displaced by a vessel.

Dustpan Dredge: A type of dredge which removes material with water jets, then transports the material through the pump and discharge line via suction.

Empty Backhaul: On the return voyage of a tow, the percentage of barges which are empty.

Entry: That part of a lockage cycle starting at the end of the approach and ending when the tow or cut is secured within the chamber and the gates are clear, or when the closing of the gates has been initiated, whichever is earlier.

Entry Time: The time taken from the end of approach (when the bow is over the sill) until the tow is secured in the chamber.

Exchange Approach: The type of approach executed when the vessel inbound to the chamber passes a vessel outbound from the chamber.

Exchange Exit: The type of exit executed when the vessel outbound from the chamber passes a vessel inbound to the chamber.

Exit: That part of a lockage cycle starting at the end of chambering and ending when the lock has completed service a vessel or cut and can be dedicated to another vessel or cut.

Exit Time: The time between the end of the chambering operation and when the tow is clear of the lock.

First Come - First Served: A lock operating policy in which vessels are selected for service in the order in which they arrived at the lock, irrespective of travel direction; often abbreviated FCFS.

First In - First Out: A location on a waterway where tows are assembled and disassembled, or where the configuration of a tow is altered.

Fleeting: Rearranging tows, usually to add or delete barges.

Fleeting Area: A location on a waterway where tows are assembled and disassembled, or where the configuration of a tow is altered.

Fleet Mix: The composition of all vessels and barges used on a waterway.

Flow Regulation: Controlling of the flow of the waterway by river training or scheduled release of water from reservoirs.

Fly Approach: The type of approach executed when the lock has been idle and the inbound vessel proceeds directly to the chamber.

Fly Exit: The type of exit executed when the lock will be idle following the departure of the outbound vessel, that is, when no vessels are awaiting lockage.

Free Flowing River: A river unregulated by a system of locks and dams.

GREAT: Great River Resource Management Study, undertaken in three parts by the Corps districts of St. Paul, Rock Island and St. Louis.

Hopper Dredge: Dredge which utilizes a draghead sliding over the bottom and forces material into hoppers of the vessel.

Hydraulic Cutterhead Dredge: A cutterhead dredge utilizing a centrifugal pump which moves a slurry of water and material from the bottom, transporting it to the point of discharge.

Hydrology: The science dealing with the properties, distributions and circulation of water.

INSA: Inland Navigations Systems Analysis.

Integrated Tow: A tow consisting of a lead barge with a raked bow and a square stern, a number of intermediate double squareended barges, and a trailing barge with a square bow and raked stern.

Intracoastal Waterway: Inland route paralleling the coast for inland craft.

Jacknife Lockage: A type of lockage in which the tow is rearranged, usually from two barges wide to three, by breaking the face coupling on at least one barge and knockout of the towboat.

Jumbo Barge: A barge 195 feet long and 35 feet wide.

Knockout Lockage: A type of lockage in which the towboat alone is separated from its barges and set alongside of them in the lock chamber.

Kort Nozzle: A funnel-shaped structure built around the propeller of a towboat to concentrate the flow of water to the propeller.

LASH: Lighter aboard ship; and international trade containerized cargo transportation system featuring shallow draft barges used for inland distribution which are carried in a ship over the oceans. Lash barges are 70 feet long and 31 feet wide.

Light Boat: A towboat which is not pushing any barges.

LOCALC: Lock Capacity Calculator, a computer model used for estimating lock capacity.

LOKCAP: Lock Capacity Function Generator.

Lock: A structure on a waterway equipped with gates so that the level of the water can be changed to raise or lower vessels from one level to another.

Lockage: Passage of a tow or other vessel through a lock. A normal lockage cycle consists of an approach, entry, chambering, and exit.

Lockage Time: The time elapsed from the start of approach of the first vessel or cut served by a lockage to the end of exit of the last vessel or cut served by a lockage. Includes the time required to disassemble and assemble multiple-cut tows and to rearrange setover tows, when such activities prevent the use of the lock by other vessels.

Morphology: Land form and structure.

Multiple-Cut Lockage: The type of lockage performed when a tow must be passed through the lock in two or more segments or "cuts."

Multiple-Vessel Lockage: A type of lockage in which more than one vessel or tow is served in a single lockage cycle.

Navigable Dam: A navigation dam which permits the passage of vessels without the use of a lock during periods of high water.

Navigable Pass: An operation whereby a vessel traverses a navigable dam without passing through a lock.

Navigation Season: That part of the year when the waterway is open to traffic.

N up/M down: A lock operating policy in which up to N upbound vessels are serviced, followed by up to M downbound vessels, where N and M are positive integers.

N up/N down: A commonly used special case of N-up/M-down, in which N and M are equal.

Non-Structural Measure: Proposed measure to improve navigation on a waterway or segment not involving building of a lock nor any structural modifications to the lock or waterway.

O & M: Operation and Maintenance.

One Way Reach: A reach narrow enough that two vessels may not pass simultaneously.

Open Pass: Passage of a vessel through a lock with no lock hardware operation. This is possible only when the upper and lower pool levels are nearly equal, and occurs most frequently at tidal locks.

Orange Peel Dredge: Similar to clamshell dredge.

Plain Suction Dredge: Utilizes suction alone to remove and transport dredge material.

PMS: Performance Monitoring System. The Corps of Engineers system for keeping and producing statistics at locks.

Pool: The body of water impounded by a dam.

Practical Capacity: As opposed to the hypothetical capacity of a lock, the actual maximum possible throughput under extant conditions.

Processing Time: The sum of all times taken to process a given tow through a specific lock (entry time, exit time, etc.).

Recreational Lockage: A lockage of recreational craft.

Reach: A channel segment between two given points on a waterway.

Representative Lock: A lock designated as representative of locks of similar size.

Reliability: Refers to the percentage of time a facility is in use or able to be used.

Revetment: Material; either natural or artificial, used for bank protection.

River Stability: Measure of a river's ability to maintain its features over long periods of time.

River Mile: A number specifying the location of a point along a waterway, obtained as the distance from a reference point designated as mile zero.

River Training: Regulation of river flow utilizing dikes and revetments.

Scow: Large flat-bottomed vessel often pulled by a tug.

Seasonality: Fluctuations in conditions concurrent with the seasons of the year.

Seiches: Oscillations of the surface of a lake or landlocked sea that vary in a period from a few minutes to several hours.

Sensitivity Analysis: The analysis of multivariable functions holding one or more variables constant.

Service Time: The time taken to process a tow through a lock. Identical to processing time.

Setover Lockage: A lockage in which the towboat and one or more barges are separated as a unit from the remaining barges and set alongside of them in the lock chamber. The term is usually applied only to single lockages, but it could be used to describe any cut. The term is often used to refer to all types of single lockages requiring rearrangement of the tow.

Shoaling: Building up of sandbars through deposition of sediment.

Sidecasting Dredge: Utilizes a draghead sliding over the bottom, discharging dredged material over the side of the vessel back into the water.

Sill: A transverse structural element of a lock chamber upon which the lock gates rest when they are closed; the upstream or downstream boundary of a lock chamber.

Single Lockage: The type of lockage performed when the entire tow can fit into the lock chamber, with or without rearrangement, and hence requiring only one lock operating cycle.

Spillway: Overflow area of a dam.

Stage: Elevation of the water surface.

Standard Barge: A barge 175 feet long and 26 feet wide.

Straight Lockage: A lockage which does not require rearrangement of the tow in order for the tow to fit into the lock chamber. The term is usually applied only to single lockages, but it could be used to describe any cut.

Switchboat: A towboat used to assist tows requiring a multiple-cut lockage. A switchboat may be used to assist a tow in entering or exiting the lock chamber, or it may independently power a cut through the lock.

Technical Capacity: The maximum theoretical tonnage which can be put through a lock under specified circumstances.

Ton: A unit of weight equal to 2,000 pounds avoirdupuis (907.20 kilograms); short ton.

Ton-Mile: A unit of transportation production equal to the movement of one ton a distance of one statute mile.

Tow: A towboat and one or more barges which are temporarily fastened together and operated as a single unit.

Towboat: A shallow-draft commercial vessel used to push or pull barges.

Tow Configuration: Orientation of barges tied together to form a tow.

Training Works: Structures such as dikes or revetments placed along river channels to increase runoff capacity, prevent bank erosion, and stabilize the location of the channel.

Traffic Level: Volume of traffic.

Turnback: A lockage in which no vessels are served; a reversal of water level in a lock chamber with no vessels in the chamber. A turnback includes closing one set of gates, filling or emptying the chamber, and opening the other set of gates. Also called a "swingaround" or an "empty lockage."

Turnback Approach: The type of approach executed when the preceding event at the lock was a chamber turnback.

Turnback Exit: The type of exit executed when the next event is a lockage in the same direction, requiring a chamber turnback.

Watershed: A region or area bounded peripherally by water parting and draining to a particular body of water.

Waterway: Any body of water wide enough and deep enough to accommodate the passage of water craft, particularly commercial vessels.

# FOOTNOTES

1. CACI, Inc., *Freight Transportation Energy Use, Volume III, Freight Network and Operations Database*, October 1978.

2. Peat, Marwick, Mitchell & Co., *Implementation of the Performance Monitoring System*, March 1974.

3. Battelle, Inc., *Forecast of Future Ohio River Basin Waterway Traffic Based on Shipper Surveys*, September 1979.

4. United States Army Corps of Engineers, *Potential Nonstructural or Low Cost Waterways System Improvements*, by LTC F.M. Anklam, Waterways Experiment Station, January 1971.

5. Peat, Marwick, Mitchell & CO., *Evaluation of Operational Improvements at Locks and Dam No. 26.*, Mississippi River, July 1975.

6. United States Army Corps of Engineers, Technical Report H-78-6, *Capacity Studies of Gallipolis Locks, Ohio River, West Virginia*, by L. L. Daggett and R. W. McCarley, Waterways Experiment Station, May 1978.

7. United States Army Corps of Engineers, *Reconnaissance Investigation, Improvement of Navigation Conditions in the Lower Cumberland-Tennessee Rivers Below Barkley Canal*, November 1972.

8. Ibid.

9. Peat, Marwick, Mitchell & Co., *Evaluation of Operational Improvements at Locks and Dam No. 26, Mississippi River*.

10. G. M. Matlin, *Technical and Economic Assessment of Waterway Dimensions Transport*, Moscow, 1959.

11. United States Army Corps of Engineers, *Mississippi River-Illinois Waterway 12 Feet Channel Study, Phase I Report*, September 1972, Revised May 1973.

12. General Research Group, *Economic Analysis of Year Round Navigation on the Upper Mississippi River*, November 1979.

13. United States Army Corps of Engineers, *Mississippi River-Illinois Waterway 12 Feet Channel Study, Phase I Report*.

14. Peat, Marwick, Mitchell & Co., *Evaluation of Operational Improvements at Locks and Dam No. 26, Mississippi River*.

15. United States Army Corps of Engineers, *Mississippi River-Illinois Waterway 12 Feet Channel Study, Phase I Report*, September 1972, Revised May 1973.

16. Ibid.

17. United States Army Corps of Engineers, Technical Report H-78-6, *Capacity Studies of Gallipolis Locks, Ohio River, West Virginia*, by L. L. Daggett and R. W. McCarley, Waterways Experiment Station, May 1978.

18. United States Army Corps of Engineers, *Monongahela River, Pennsylvania and West Virginia, Final Environmental Statement on the Operation and Maintenance of the Navigation System*, October 1975.

19. United States Army Corps of Engineers, Miscellaneous Paper H-77-1, *Capacity Studies of Winfield Locks Kanawha River, West Virginia*, by L. L. Daggett and R. W. McCarley, Waterways Experiment Station, February 1977.

20. United States Army Corps of Engineers, *Feasibility Study for Bonneville Lock and Dam*, September 1978.

21. Anatoly B. Hochstein, *Optimum Dredged Depth in Inland Waterway*, Journal of the Waterways Harbors and Coastal Engineering Division, November 1975.

22. Ibid.

23. United States Army Corps of Engineers, *Coordination Report on Navigational Improvements for Apalachicola River Below Jim Woodruff Dam, Florida*, October 1978.

24. Mitre Corp., *Disposal of Dredged Material Within the New York District*, Volume 1, Present Practices and Candidate Alternatives.

25. Adolph W. Mohr, ASCE Journal of Waterways and Harbors, Development and Future of Dredging, May 1974.

26. Arthur D. Little, Inc., The National Dredging Study, 11 Volumes, 1974.

27. United States Army Corps of Engineers, The Dredged Material Research Program.

28. United States Army Corps of Engineers, Government Estimates and Hired Labor Estimates for Dredging, Engineer Regulation No. 1110-2-1300, February 15, 1980.

29. United States Army Corps of Engineers, The Dredged Material Research Program.

30. Arthur D. Little, Inc., The National Dredging Study, 11 Volumes, 1974.

31. United States Army Corps of Engineers, Projects on which Hopper and/ or Sidecasting Dredges may be Employed, March 1979.

32. Arthur D. Little, Inc., The National Dredging Study, 11 Volumes, 1974.

33. United States Army Corps of Engineers, Mississippi River-Illinois Waterway 12 Feet Channel Study, Phase I Report, September 1972, Revised May 1973.

34. United States Army Corps of Engineers, Duplicate Lock GDM Phase I, A Plan for Modernization of the Illinois Waterway, 1975.

35. United States Army Corps of Engineers, Mississippi River-Illinois Waterway 12 Feet Channel Study, Phase I Report, September 1972, Revised May 1973.

36. United States Army Corps of Engineers, Missouri River Bank Stabilization and Navigation Project, July 1978.

37. United States Army Corps of Engineers, Reconnaissance Report on Operation and Maintenance of Monongahela Navigation System, October 1975.

38. United States Army Corps of Engineers, "Reconnaissance Report on O & M Expenses of Allegheny River Navigation System," July 1979.

39. United States Army Corps of Engineers, Reconnaissance Investigation, Improvement of Navigation Conditions in the Lower Cumberland-Tennessee Rivers Below Barkley Canal, November 1972.

40. United States Army Corps of Engineers, Feasibility Report - White River Navigation to Batesville, Arkansas, May 1979.

41. United States Army Corps of Engineers, Coordination Report on Navigational Improvements for Apalachicola River Below Jim Woodruff Dam, Florida, October 1978.

42. United States Army Corps of Engineers, Tennessee-Tombigbee Waterway, Alabama and Mississippi, Supplement to the Project Costs and Benefits, Economic Reanalysis Summary, February 1976.

43. Ian Amos, Channel Non-Maintenance in the New York Harbor: An Economic Analysis, Port Authority of New York and New Jersey, September 1979.

44. United States Army Corps of Engineers, Tennessee-Tombigbee Waterway, Alabama and Mississippi, Supplement to the Project Costs and Benefits, Economic Reanalysis Summary, February 1976.

45. Hochstein, et al, Waterway Analysis, Inland Navigation Systems Analysis, July 1976.

46. United States Army Corps of Engineers, "Layout and Design of Shallow Draft Waterways," EM1110-216-1, 1979.

47. United States Department of Transportation, Coast Guard, Paramore, Dayton, Parricelli, and Willis, Human and Physical Factors Affecting Collisions, Rammings and Groundings on Western Rivers and Gulf Intracoastal Waterways, 1979.

48. United States Army Corps of Engineers, Vessel Characteristics Survey, Navigation Analysis Center, WRSC, June 1980.

49. Hochstein, et al, Waterway Analysis, Inland Navigation Systems Analysis, July 1976.

50. Marbury, Least Energy Operation of River Shipping, SNAME, Chesapeake Section, September 1977.

51. United States Department of Transportation, Coast Guard, *Projected United States Coast Guard Icebreaking & Icebreaker Requirements* 1975-2000, February 1975.

52. United States Army Corps of Engineers, "*Ice Engineering for Civil Works,*" by K. L. Carey, G. D. Ashton, and G. E. Frankenstein, August 1973.

53. United States Department of Transportation, *St. Lawrence Seaway Development Corps, St. Lawrence Seaway System Plan for All-Year Navigation*, July 1975.

54. United States Army Corps of Engineers, "*Ice Control at Navigation Locks,*" Engineer Technical Letter No. 110-2-237, December 1978.

55. General Research Group, *Economic Analysis of Year-Round Navigation on the Upper Mississippi River*, November 1979.

56. GL/SLS Winter Navigation Board, *Great Lakes - St. Lawrence Seaway Navigation Season Extension Demonstration Program*, Fourth Annual Report, 1976.

57. Hochstein and Patton, *Marine Technology for the Artic and Western Regions of Alaska*, Louis Berger & Associates, Inc., July 1979.

# BIBLIOGRAPHY

Adrian Volker Dredging Company Assessment of Certain European Dredging Practices and Dredged Material Containment and Reclamation Methods, December 1978.

Ameraport Council. Alabama-Mississippi Superport, (Preliminary Study).

American Association of Port Authorities. Ship Channel Capabilities for Merchant Vessels in United States Deepwater Seaports Through the Year 2000, Gulf Region AAPA Committee of Ship Channels and Harbors, June 1970.

American Association of Port Authorities. Ship Channel Capabilities for Merchant Vessels in United States Deepwater Seaports Through the Year 2000, North Atlantic Regions, June 1970.

American Association of Port Authorities. Ship Channel Capabilities for Merchant Vessels in United States Deepwater Seaports Through the Year 2000, Alaska, West Coast and Hawaii Regions, AAPA Committee on Ship Channels and Harbors, 1970.

American Association of Port Authorities. Survey of Channel Dimensions Required for Safe Navigation for United States Ports, AAPA-And the Dredging Committee, October 1979.

Amos, Ian. Channel Non-Maintenance in the New York Harbor: An Economic Analysis, Port Authority of New York and New Jersey, September 1979.

Arctec Inc. Great Lakes/St. Lawrence Seaway, Lock Capacity Analysis, Volume I, April 1979.

Arthur D. Little, Inc. The National Dredging Study, 11 Volumes, 1974.

Ashton, G. D. River Ice, American Scientist, January-February 1979.

Battelle, Inc. Forecast of Future Ohio River Basin Waterway Traffic Based on Shipper Surveys for the Huntington District, United States Army Corps of Engineers, September 1979.

Bottoms, E. E. Economic Location of Locks, Transportation Engineering Journal, ASCE, Volume 95, No. TE1 - February 1969.

Bruun, Per. Port Engineering, Gulf Publishing Company, 1976.

CACI, Inc., Freight Transportation Energy Use, Volume III Freight Network and Operations Database, for Department of Transportation, October 1976.

CACI, Inc. Improvement of the LOKCAP Model to Handle Double Chamber Queuing, Draft Report, for United States Army Corps of Engineers, Washington, D.C., July 1979.

Calton, J.R. Economic Analysis of Mississippi River Navigation, March 22, 1979.

Cooper, D. H. Some Aspects of a Study of the Locking of Ships with High Blockage Factors, British Transport, Board Research Station, Southall, United Kingdom for National Ports Council, London, United Kingdom.

Daggett, L. and Shows, J. Miscellaneous Paper, 24th International Navigation Congress, Leningrad - 1977.

Delft Hydraulics Laboratory. Description of Activities of the Delft Hydraulics Laboratory Concerning Weirs and Locks, September 1978.

Denning, Rick A. Assessing Hydraulic Dredging Costs and Operations, New York Transit Authority.

Eddinger, J. M. American Dredging: The Turning Point, The Military Engineer, December 1978.

Fominsky, L. Method of Drag Calculation for Flotilla Determination, Transport, Moscow, Union of Soviet Socialist Republics, 1972.

Gannett, Fleming, Corddry and Carpenter, Inc. A History of Navigation Improvements on the Monogahela River, May 1979.

Gelencser, G. J. Improving the Effective Capacity of a Navigation System, 24th International Navigation Congress, Leningrad - 1977.

General Research Corp. Dredged Material Transport Systems for Inland Disposal and/or Productive Use Concepts, June 1978.

General Research Group. Economic Analysis of Year Round Navigation on the Upper Mississippi River, November 1979.

GL/SLS Winter Navigation Board. Great Lakes - St. Lawrence Seaway Navigation Season Extension Demonstration Program, Fourth Annual Report, 1976.

Great River Environmental Action Team (GREAT I). Dredging Requirements Work Group, Draft Final Report, September 1979.

Hochstein, Anatoly B. Navigable Conditions on Canals for Composite Use, Transport, Moscow - 1972.

Hochstein, Anatoly B. Optimum Dredged Depth in Inland Waterways, Journal of the Waterways Harbors and Coastal Engineering Division, November 1975.

Hochstein, Anatoly B. "The Outlook for the Development of Water Transportation, Waterways and Waterway Management," Izdatel'stvo Transport, Moscow 1973, (English Translation, DAEN-CWP-5-75-6, Department of the Army, Office of the Chief of Engineers, April 1976).

Hochstein et al. Waterway Analysis, Inland Navigation Systems Analysis, Corps of Engineers, July 1976.

Hochstein and Patton. Marine Technology for the Artic and Western Regions of Alaska, Louis Berger & Associates, Inc., July 1979.

Howard Needles Tammen & Bergendoff for the United States Army Corps of Engineers, St. Paul District, Recreational Craft Locks Study Selected Alternatives, Upper Mississippi River, Minneapolis to Guttenberg, October 1978.

Huval, Carl. Surges and Tow Squat in Lock Approaches.

Ingold, P.R. Physical Constraints on Waterway Use, Technical Report No. 3, Department of Geology, University of Michigan, November 1973.

Kearny Management Consultants. *GREAT II*, 1979.

Kolkman, P.A. and Slagter, J.C., Delft Hydraulics Laboratory and Rijkswaterstaat, *The Kreekrak Locks on the Scheldt-Rhine Connection*.

Kolkman, P.A. Delft Hydraulics Laboratory, *Low-head Navigation Locks Door Filling and Emptying Systems Developed by Hydraulic Investigations*, September 1973.

Kolkman, P.A. *Ships Meeting and Generating Currents*, Proceedings Symposium on Aspects of Navigability of Constraint Waterways, including Harbor Entrances, Delft - 1978.

Kooman, C. and De Bruijn, P.A. *Lock Capacity and Traffic Resistance of Locks*, Rijkswaterstaat Communications No. 22, 1975.

Kooman, C. and De Bruijn, P.A. *Navigation Locks for Push Tows*, Rijkswaterstaat Communications, 1973.

Koster, J. Push Towing on Canals, Public Notice 91, Delft Hydraulics Laboratory. *Suction Effect of Canal Banks on Ship Behaviour*, September 1971.

Koster, J. *Stopping Distances of V.L.C.C. in Umuiden*, March 1974.

Lower Mississippi Region Comprehensive Study Coordinating Committee. *Lower Mississippi River - Comprehensive Study*, 1974.

Makkaveyev, N.I., et. al. *Utilization of Reservoirs for Transportation*, 1972.

Marbury. *Least Energy Operation of River Shipping*. SNAME, Chesapeake Section, September 1977.

Matlin, G.M. *Technical and Economic Assessment of Waterway Dimensions* Transport, Moscow - 1959.

McNown. *Hydraulic Design Criteria for Inland Waterways*, Kansas Water Resource Research Institute PB-250 771, 1975.

Mississippi River Commission, Office of the President, Vicksburg, Mississippi. *Channel Improvement Feature Flood Control*, Mississippi River and Tributaries Project, July 1977.

Mississippi River Commission. *1975 National Water Assessment - Lower Mississippi Region, Specific Problem Analysis Summary Report*, Vicksburg, Mississippi, 1977.

Mitre, Corp. *Disposal of Dredged Material Within the New York District*, Volume 1, Present Practices and Candidate Alternatives.

Mohr, Adolph W. ASCE Journal of Waterways and Harbors, *Development and Future of Dredging*, May 1974.

Murden, William R., Jr. *The Development of New Dredging Procedures*, September 1978.

Northwestern University, Econometrics Center, Chicago, Illinois, for the United States Army Engineer Institute for Water Resources, Virginia-Volumes 1-3, *Cost-Benefit Analysis for Inland Navigation Improvements*, October 1970.

Operations Research, Inc. by Dayton, R.B. *Analysis of Bridge Collision Incidents*, December 1976.

Robert R. Nathan Associates and Coastal Zone Resources Corporation, for The Coastal Plains Regional Commission, *The Coastal Plaints Deepwater Terminal Study*.

Peat, Marwick, Mitchell & Co. for Office of the Chief of Engineers, United States Army Corps of Engineers, *Implementation of the Performance Monitoring System*, March 1974.

Peat, Marwick, Mitchell & Co. for Lower Mississippi Valley Division, United States Army Corps of Engineers, *Evaluation of Operational Improvements at Locks and Dam No. 26, Mississippi River*, July 1975.

Rochberg, Dr. Richard. *Analysis of Capacity of Locks*, DAEN-CWP-P, September 1979.

Souder, et al. *Draft Economic Analysis of Year-round Navigation on the Upper Mississippi River*, June 1979.

Task Committee on Hydromechanics of Ice, *River Ice Problems: A State-of-the-Art Survey and Assessment of Research Needs*, Journal of the Hydraulics Division, ASCE, January 1974.

Task Committee on Maintenance of Navigable Waters of the Committee on Waterways of the Waterway, Port, Coastal and Ocean Division. *Adequacy of Dredging Methods and Equipment in the United States for Maintenance of Navigable Waters*, Journal of the Waterway, Port, Coastal and Ocean Division, ASCE, WW3, August 1977.

Temple, Barker & Sloane, Inc. *Tow Haulage Feasibility Study McClellan-Kerr Arkansas Navigation Project for The Ozarks Regional Commission*, March 1979.

Turner. *Dredging: A Vital But Troubled Industry*, The Military Engineer, December 1978.

United States Army Corps of Engineers. *Allegheny River Pennsylvania (Mile 0 to Mile 72) Final Environmental, Statement on the Operation and Maintenance of the Navigation System*, Pittsburgh District, October 1975.

United States Army Corps of Engineers. *Analysis of Tow Entry, Locking and Exit Times at Lock and Dam 51, Ohio River* by Daggett, L.L., McCarley, R.W. and Stinehour, J.E., Waterways Experiment Station, March 1974.

United States Army Corps of Engineers. *Apalachicola River Below Jim Woodruff Dam, Florida - Coordination Report on Navigational Improvements*, Mobile District, October 1978.

United States Army Corps of Engineers. *Arkansas River Basin Coordinating Committee - Report on 1978 Activities:* Southwestern Division, January 1979.

United States Army Corps of Engineers, Tulsa, District. *Arkansas River Navigation Lock Filling Characteristics for Various Lifts*.

United States Army Corps of Engineers. *Barbers Point Harbor, Oahu, Hawaii, Design Memorandum No. 1, Phase II - Project Design*, Honolulu District, March 1977.

United States Army Corps of Engineers. *Barge Loading and Horse Power Trends*, Kansas City District, April 1971.

United States Army Corps of Engineers. *Channel Widths for Navigation in Bends*, Engineer Technical Letter No. 1110-2-225, July 1977.

United States Army Corps of Engineers. *Columbia River and Tributaries Review Study - Inventory of Problems and Areas of Concern* North Pacific Division, August 1974.

United States Army Corps of Engineers. *The Commercial Dredging Fleet in the United States*, NCD ADP Center, August 1979.

United States Army Corps of Engineers. *Consolidated Statements of Operations for Cutterhead and Dustpan Pipeline Dredges, Fiscal Years 1971 and 1974*, Office of the Chief of Engineers.

United States Army Corps of Engineers. *Coordination Report on Navigational Improvements for Apalachicola River Below Jim Woodruff Dam, Florida*; Mobile District, October 1978.

United States Army Corps of Engineers. *Design Memorandum No. 10, Navigation Lock, Lock and Dam No. 16, Webbers Falls Arkansas River, Oklahoma*, Tulsa District, November 1964.

United States Army Corps of Engineers. *Design Memorandum No. 14, Navigation Lock, Lock and Dam No. 15, Robert S. Kerr, Arkansas River, Oklahoma*, Tulsa District, May 1964.

United States Army Corps of Engineers. *Design Memorandum for Rehabilitation of Lock and Dam No. 1, Mississippi River*, St. Paul District, February 1978.

United States Army Corps of Engineers. *Design Memorandum, San Francisco Bay to Stockton, California*, Sacramento District, May 1979.

United States Army Corps of Engineers. *Development of Alluvial Streams for Navigation*, by Franco, John J., Waterways Experiment Station, January 1971.

United States Army Corps of Engineers. *Development of Navigation with Locks and Dams*, Franco, John J., Hydraulics Laboratory, Waterways Experiment Station, June 1976.

United States Army Corps of Engineers. Diked Dredged Material Disposal on the Great Lakes - Design Analysis for Diked Disposal Facility; St. Paul District, February 1977.

United States Army Corps of Engineers. Dismal Swamp Canal, Virginia and North Carolina, Dismal Swamp Study, Norfolk District, February 1974.

United States Army Corps of Engineers. Documentation of LMVD Dredging Activities - Work Package No. 8 - LMVD Potamology Program (T-1); Memphis District, August 1976.

United States Army Corps of Engineers. Draft Environmental Impact Statement Ohio River Navigation Project Operation and Maintenance, Ohio River Division.

United States Army Corps of Engineers. Draft Environmental Impact Statement Relating to Operation and Maintenance at Sheboygan Harbor, Wisconsin; Chicago District, March 1979.

United States Army Corps of Engineers. Draft Environmental Statement - Confined Disposal Facilities, Dredging, Structures, Repairs and Operations, Frankfort Harbor, Michigan; Detroit District, September 1977.

United States Army Corps of Engineers. Draft Environmental Statement - Confined Disposal Facility and Maintenance Dredging of the Federal Navigation Channels, Les Cheneaux Islands, Michigan; Detroit, District, September 1977.

United States Army Corps of Engineers. Draft Survey Study for Great Lakes and St. Lawrence Seaway Navigation Season Extension, March 1979.

United States Army Corps of Engineers. The Dredged Material Research Program.

United States Army Corps of Engineers. Dredging the Nations Waterways: A Big Job for Industry and the Army Corps of Engineers, by McGinnis, Major General C.I., The Military Engineer, December 1978.

United States Army Corps of Engineers. Duplicate Locks GDM Phase I, A Plan for Modernization of the Illinois Waterway, 1975.

United States Army Corps of Engineers. Economic Analysis of Mississippi River Navigation to Evaluate the Feasibility of Maintenance Dredging, Lower Mississippi Valley Division.

United States Army Corps of Engineers. Effect of Depth on Dredging Frequency by Trawle, M.J. and Boyd Jr., J.A.. Technical Report No. H-78-5, Waterways Experiment Station.

United States Army Corps of Engineers. Engineering and Design, Channel Widths for Navigation in Bends, Office of the Chief of Engineers, July 1977.

United States Army Corps of Engineers. Engineering and Design, Ice Control at Navigation Locks, Office of the Chief of Engineers, December 1978.

United States Army Corps of Engineers. Engineering and Design Navigation Lock Sill Depths and Hydraulic Loads on Gates, Office of the Chief of Engineers, June 1977.

United States Army Corps of Engineers. Engineering and Design - Tidal Hydraulics, Office of the Chief of Engineers, August 1965.

United States Army Corps of Engineers. Estuarine Navigation Projects, Committee on Tidal Hydraulics, Washington, D.C., January 1971.

United States Army Corps of Engineers. Evaluation to Determine Operational Maintenance Costs in Support of Navigation and Bank Stabilization Features of Missouri River Project - Sioux City to the Mouth, Missouri River Division, January 1976.

United States Army Corps of Engineers. Evaluation of Ice Management Problems Associated with Operation of a Mechanical Ice Cutter on the Mississippi River, by Ashton, George D., Cold Regions Research and Engineering Laboratory for United States Department of Transportation, United States Coast Guard, October 1974.

United States Army Corps of Engineers. Feasibility Report Improvement Mississippi River, Phillips County (Helena Harbor) Arkansas, Memphis District, January 1978.

United States Army Corps of Engineers. Feasibility Report - White River Navigation to Batesville, Arkansas, Memphis District, May 1979.

United States Army Corps of Engineers. Feasibility Study for Bonneville Lock and Dam; Portland Division, September 1978.

United States Army Corps of Engineers. Filling and Emptying Characteristics of Barge Canal Lock, Sacramento River Deep-Water Ship Channel Project California, Waterways Experiment Station, August 1960.

United States Army Corps of Engineers. Final Composite Environmental Statement for Operation and Maintenance Work of Three Navigation Projects in the Lake Borgne Vicinity, New Orleans District, March 1976.

United States Army Corps of Engineers. Final Environmental Impact Statement, Duluth-Superior Harbor, Operation and Maintenance - Diked Dredge Disposal Facility; St. Paul District, July 1977.

United States Army Corps of Engineers. Final Environmental Impact Statement, Jacksonville Harbor, Maintenance Dredging, Office of the Chief of Engineers, April 1975.

United States Army Corps of Engineers. Final Environmental Impact Statement - Maintenance Dredging and Contained Disposal of Dredged Materials at Green Bay Harbor, Wisconsin; Chicago District, May 1976.

United States Army Corps of Engineers. Final Environmental Statement - Calumet Harbor and River, Illinois and Indiana - Maintenance Dredging and Disposal; Chicago District, Chicago, Illinois, October 1975.

United States Army Corps of Engineers. Final Environmental Statement Charleston Harbor Deepending Project, Charleston Harbor and Shipyard River, South Carolina, Charleston District, April 1976.

United States Army Corps of Engineers. Final Environmental Statement, Confined Disposal Facility for Bolles Harbor, Michigan, Detroit District, April 1975.

United States Army Corps of Engineers. Final Environmental Statement, Confined Disposal Facility at Pointe Mouille for Detroit and Rouge Rivers, Detroit District, March 1974.

United States Army Corps of Engineers. Final Environmental Statement, Illinois Waterway, Calumet-Sag Navigation Project, Illinois, Maintenance Dredging and Disposal, Chicago District, January 1975.

United States Army Corps of Engineers. Final Environmental Statement Maintenance Dredging of Atlantic Intracoastal Waterway, South Carolina, Charleston District, April 1976.

United States Army Corps of Engineers. Final Environmental Statement Operation and Maintenance of Baltimore Harbor and Associated Channels, Maryland and Virginia, Baltimore District, October 1974.

United States Army Corps of Engineers. Final Environmental Statement Operation and Maintenance of Navigation Project, Savannah River Below Augusta Including the New Savannah Bluff Lock and Dam, Georgia and South Carolina, Savannah District, September 1976.

United States Army Corps of Engineers. Final Environmental Statement Operation and Maintenance of a Nine-Foot Channel in the Illinois Waterway From the Junction of the Calumet-Sag Channel and the Chicago Sanitary and Ship Canal to the La Grange Lock and Dam, Chicago District, February 1975.

United States Army Corps of Engineers. Final Environmental Statement, Sebewaing River, Michigan, Operation and Maintenance, Confined Disposal Facility and Flood Control Facilities, Detroit District, April 1978.

United States Army Corps of Engineers. Final Report Great Lakes/St. Lawrence Seaway Lock Capacity Analysis Volumes I & II by Kotas, T., Kim, J., and Jacobi, J., North Central Division, April 1979.

United States Army Corps of Engineers. *Fiscal Year 1977 Annual Report of the Chief of Engineers on Civil Works Activities*, Office of the Chief of Engineers, Washington, D.C., 1977.

United States Army Corps of Engineers. *Fiscal Year 1978 Annual Report of the Chief of Engineers on Civil Works Activities*, 1978.

United States Army Corps of Engineers. *Gallipolis Lock and Dam Replacement Study, Ohio River, Plan of Study, Phase I*, August 1977.

United States Army Corps of Engineers. *Government Estimates and Hired Labor Estimates for Dredging*, Engineering Regulation No. 1110-2-1300, 15, February 1978.

United States Army Corps of Engineers. *"Grays Landing Lock and Dam and Point Marion Lock", Monongahela River, General Design Memorandum, Phase I, Plan Formulation*, Pittsburgh District, September 1975.

United States Army Corps of Engineers. *Green and Barren Rivers, Kentucky Navigation Study*, Louisville District, February 1979.

United States Army Corps of Engineers. *Great Lakes - St. Lawrence Seaway Lock Cost Estimate Study* by Rock Island District for North Central Division, October 1977.

United States Army Corps of Engineers. *Great River Environmental Action Team I - Final Report*, St. Paul District, Sediment and Erosion Work Group, May 1979.

United States Army Corps of Engineers. *Great River Resource Management Study, Great III, Preliminary Reconnaissance Report, Mississippi River (Saverton, Missouri to Cairo, Illinois)*, St. Louis District, June 1979.

United States Army Corps of Engineers. *Guidelines for the Industry Capability Program*, Regulation No. 1125-2-15, Office of the Chief of Engineers.

United States Army Corps of Engineers. *Gulf Intracoastal Waterway, Louisiana - Texas Section, Reconnaissance Report*, New Orleans District, January 1979.

United States Army Corps of Engineers. *Gulf Intracoastal Waterway (Louisiana Section), Vermilion Lock Replacement*, New Orleans District.

United States Army Corps of Engineers. *Harbor Maintenance Dredging Final Environmental Statement in the State of Hawaii*, Honolulu District, September 1975.

United States Army Corps of Engineers. *Honolulu Harbor, Oahu, Hawaii, Design Memorandum No. 1, Phase II - Project Design*, Honolulu District, February 1977.

United States Army Corps of Engineers. *"Ice Control at Navigation Locks,"* Engineer Technical Letter No. 110-2-237, Office of the Chief of Engineers, December 1978.

United States Army Corps of Engineers. *"Ice Engineering for Civil Works,"*, by Carey, K.L., Ashton, G.D., and Frankenstein, G.E., for Directorate of Civil Works Office of the Chief of Engineers, August 1973.

United States Army Corps of Engineers. *Illinois Waterway Duplicate Locks GDM Phase I*, Chicago District, April 1975.

United States Army Corps of Engineers. *"Improvement of the Lower Mississippi River and Tributaries 1931-1972,"* 1972.

United States Army Corps of Engineers. *Improvement of Navigation Channel Design Memorandum No. 1, James River Basin, Virginia, James River Below Richmond Project Economics and Formulation*, Norfolk District, April 1972.

United States Army Corps of Engineers. *Inland Navigation Simulation Model: Verification and Evaluation*, by Wilson, Lengyel B., Pittsburgh District.

United States Army Corps of Engineers. *Interim Report To Congress, The Streambank Erosion Control Evaluation and Demonstration Act of 1974*, September 1978.

United States Army Corps of Engineers. *"John H. Overton Lock and Dam," Design Memorandum No. 7*, St. Louis District, November 1977.

United States Army Corps of Engineers. "Layout and Design of Shallow-Draft Waterways," EM1110-2-1611, December 1980.

United States Army Corps of Engineers. Lock and Dam Design Information, Portfolio, McClellan-Kerr, Arkansas River Navigation System, Southwestern Division.

United States Army Corps of Engineers. Lock and Dam No. 26, Replacement Upper Mississippi River Basin, Mississippi River-Alton Illinois, St. Louis District.

United States Army Corps of Engineers. Locks and Dams 52-53, Kentucky and Illinois, Major Rehabilitation, Louisville District.

United States Army Corps of Engineers. "Lock Design, Sidewall Port Filling and Emptying System," by Waterways Experiment Station for the Office of the Chief Engineers, July 1975.

United States Army Corps of Engineers. Los Angeles Harbor Deepening Project GDM, Los Angeles District, November 1979.

United States Army Corps of Engineers. Los Angeles and Long Beach Harbors Model Study, Report 2, Observations of Ship Mooring and Movement, by Crosby, Leroy G., Durham, Donald L., Waterways Experiment Station, January 1975.

United States Army Corps of Engineers. Lower Granite Design Memorandum No. 20, Navigation Facilities, North Pacific Division.

United States Army Corps of Engineers. Lower Monongahela River Navigation System, Locks and Dam 2, 3, and 4, Replacement Study-Phase I. Pittsburgh District, February 1976.

United States Army Corps of Engineers. "The Lower Ohio River Navigation Study," A Public Information Brochure, Louisville District, May 1979.

United States Army Corps of Engineers. Maintenance Dredging, Existing Navigation Projects, San Francisco Bay Region, California, Final Composite Environmental Statement Volume I, San Francisco District, December 1975.

United States Army Corps of Engineers. Major Rehabilitation of Dresden Island Lock and Dam, Illinois Waterway, Rock Island District, August 1977.

United States Army Corps of Engineers. Maximum Ship Size Study, Draft, Great Lakes - St. Lawrence Seaway, North Central Division, December 1977.

United States Army Corps of Engineers. McClellan-Kerr Arkansas River Navigation System "Lock and Dam Design Information Portfolio," Southwestern Division.

United States Army Corps of Engineers. Minutes of the Symposium on Design of Groins and Dikes at the Waterways Experiment Station on March 14 and 15 1978.

United States Army Corps of Engineers. Miscellaneous Paper H-77-1, Capacity Studies of Winfield Locks Kanawha River, West Virginia, by Daggett, L.L. and MacCarley, R.W., Waterways Experiment Station, February 1977.

United States Army Corps of Engineers. Mississippi River-Cairo, Illinois to Baton Rouge, Louisiana Draft Reconnaissance Report, Vicksburg District, October 1979.

United States Army Corps of Engineers. Mississippi River-Illinois Waterway 12 Feet Channel Study, Phase I Report, Chicago District, September 1972, Revised May 1973.

United States Army Corps of Engineers. Mississippi River Old Lock 14, LeClaire, Iowa, Rock Island District, March 1978.

United States Army Corps of Engineers. Mississippi River and Tributaries, Mississippi River Levees and Channel Improvements Final Environmental Impact Statement Vicksburg District, February 1976.

United States Army Corps of Engineers. Mississippi River and Tributaries Project, Problems Relating to Changes in Hydraulic Capacity of the Mississippi River, by Madden, Edward B., Committee on Channel Stabilization, Army Engineers Waterways Experiment Station, August 1974.

United States Army Corps of Engineers. Mississippi Sound and Adjacent Areas Reconnaissance Report Dredging Activities, Mobile District, March 1979.

United States Army Corps of Engineers. Mississippi Sound and Adjacent Areas Reconnaissance Report Dredging Equipment and Dredged Material Transportation and Disposal, Mobile District, March 1979.

United States Army Corps of Engineers. Missouri River Annual Operating Plan 1978-1979, Missouri River Division, Reservoir Control Center, August 1978.

United States Army Corps of Engineers. Missouri River Bank Stabilization and Navigation Project, Missouri River Division, July 1978.

United States Army Corps of Engineers. Mississippi River and Tributaries Project, Problems Relating to Changes in Hydraulic Capacity of the Mississippi River, by Madden, Edward B., Committee on Channel Stabilization, Army Engineers Waterways Experiment Station, August 1974.

United States Army Corps of Engineers. Mississippi Sound and Adjacent Areas Reconnaissance Report Dredging Activities, Mobile District, March 1979.

United States Army Corps of Engineers. Mississippi Sound and Adjacent Areas Reconnaissance Report Dredging Equipment and Dredged Material Transportation and Disposal, Mobile District, March 1979.

United States Army Corps of Engineers. Missouri River Annual Operating Plan 1978-1979, Missouri River Division, Reservoir Control Center, August 1978.

United States Army Corps of Engineers. Missouri River Bank Stabilization and Navigation Project, Missouri River Division, July 1978.

United States Army Corps of Engineers. *Missouri River Bank Stabilization and Navigation Project, Projected Status of Navigation Channel in 1981*, Missouri River Division, June 1979.

United States Army Corps of Engineers. *Missouri River Hydrographic Survey, Omaha, Nebraska*, Omaha District, 1976.

United States Army Corps of Engineers. *Mobile Bay Model Study, Report I, Effects of Proposed Theodore Ship Channel and Disposal Areas on Tides, Currents, Salinities, and Dye Dispersion,* by Lawing, Raymond J., Boland, Robert A., and Bobb, William H., Waterways Experiment Station, September 1975.

United States Army Corps of Engineers. *Model Studies of Navigation Improvements, Columbia River Estuary, Report 2, Entrance Studies, Section IV, Jetty A. Rehabilitation, Jetty B, and Outer Bar Channel Relocation*, by Herman, Jr., F.A., Waterways Experiment Station, July 1974.

United States Army Corps of Engineers. *Monongahela River Navigation System Investigation, Stage I Work Plan,* Pittsburgh District, September 1978.

United States Army Corps of Engineers. *Monongahela River, Pennsylvania and West Virginia, Final Environmental Statement on the Operation and Maintenance of the Navigation System*, Pittsburgh District, October 1975.

United States Army Corps of Engineers. *Movement of Freight Over Inland Waterways*, Draft, by Olson, Howard E., Institute for Water Resources, 1975.

United States Army Corps of Engineers. *"NTP Inland Waterway Study,"* Inland Navigation Simulation, 1975.

United States Army Corps of Engineers. *"Ohio River Basin Lock Capacity Analysis Preliminary Documentation,"* Louisville District, November 1978.

United States Army Corps of Engineers. Phase I, *Advanced Engineering and Design Report, Southern Branch of Elizabeth River, Chesapeake, Virginia, Channel Deepening for Navigation*, Norfolk District, June 1978.

United States Army Corps of Engineers. Phase II, Advanced Engineering and Design Report, Southern Branch, Elizabeth River, Chesapeake, Virginia, 35 Foot Channel Extension, Norfolk District, May 1978.

United States Army Corps of Engineers. Physical Characteristics of Inland Waterways, Inland Navigation Systems Analysis, Office of the Chief of Engineers, December 1975.

United States Army Corps of Engineers. Potential Nonstructural or Low Cost Waterways System Improvements, by Anklam, LTC F.M., Waterways Experiment Station, January 1971.

United States Army Corps of Engineers. Projects On Which Hopper and/or Sidecasting Dredges May Be Employed, March 1979.

United States Army Corps of Engineers. Project Operation - Dredging Policies and Practices, Regulation No. 1130-2-307, Office of the Chief of Engineers, October 31, 1968.

United States Army Corps of Engineers. Public-Involvement in Planning Civil Works Study, Black Warrior-Tombigbee Waterway, Mobile District, September 1977.

United States Army Corps of Engineers. Robert S. Kerr Lock and Dam and Reservoir, Arkansas River, Report on Final Cost Allocation, Tulsa District, December 1977.

United States Army Corps of Engineers. Reconnaissance Investigation, Improvement of Navigation Conditions in the Lower Cumberland-Tennessee Rivers Below Barkley Canal, November 1972.

United States Army Corps of Engineers. Reconnaissance Report, Gulf Intracoastal Waterway, Louisiana-Texas Section, January 1979.

United States Army Corps of Engineers. Reconnaissance Report for Major Rehabilitation, Emsworth, Pittsburgh District, August 1977.

United States Army Corps of Engineers. Reconnaissance Report for Major Rehabilitation, Montgomery Lock and Dam, Ohio River, Pennsylvania, Pittsburgh District, February 1976.

United States Army Corps of Engineers. *Reconnaissance Report on Operation and Maintenance of Monongahela Navigation System*, Pittsburgh District, October 1975.

United States Army Corps of Engineers. *"Reconnaisssance Report on O & M Expenses of Allegheny River Navigation System,"* Pittsburgh District, July 1979.

United States Army Corps of Engineers. *Replacement of Federal Highway Bridges in Virginia and North Carolina*, Norfolk District, January 1977.

United States Army Corps of Engineers. *Resistance of Barge Tows*, Ohio River Division, June 1963.

United States Army Corps of Engineers. *Report of Operations-Hopper and Pipeline Dredges*, South Atlantic Division, October 1979.

United States Army Corps of Engineers. *Report on Gulf Coast Deep Water Port Facilities, Texas, Louisiana, Mississippi, Alabama and Florida*, Lower Mississippi Valley Division, June 1973.

United States Army Corps of Engineers. *Report on Replacement Emsworth, Dashields and Montgomery Lock and Dam, Ohio River/Pennsylvania*, Pittsburgh District, April 1971.

United States Army Corps of Engineers. *Restudy on Coosa River, Navigation Project, Alabama, Georgia*, Mobile District, Revised September 1977.

United States Army Corps of Engineers. *"River Ice,"* by Ashton, George D., Cold Regions Research and Engineering Laboratory, 1978.

United States Army Corps of Engineers. *Robert S. Kerr Report on Final Cost Allocation*, December 1977.

United States Army Corps of Engineers. *Rock Island Hydraulic Data*, Rock Island District, November 1976.

United States Army Corps of Engineers. *St. Lawrence Seaway New York - Feasibility Study for Additional Locks and Other Navigation Improvements Plan, of Study, Draft*, Buffalo District, June 1978.

United States Army Corps of Engineers. "*Sensitivity of Base Data in the Analysis of Lock Capacity*," A case study of Lock and Dam 26, Mississippi River, Waterway Experiment Station, July 1979.

United States Army Corps of Engineers. *Siuslaw River and Bar, Oregon*, Portland District, June 1976.

United States Army Corps of Engineers. *Study of Alternatives for Rehabilitation of Lock and Dam No. 1, Mississippi River, Minneapolis, Minnesota*, Volume IV, St. Paul District, April 1976.

United States Army Corps of Engineers. *Survey Study for Great Lakes and St. Lawrence Seaway, Navigation Season Extension, Draft Main Report and Environmental Statement*, Detroit District, March 1979.

United States Army Corps of Engineers. Technical Report H-78-6, *Capacity Studies of Gallipolis Locks, Ohio River*, West Virginia, by Daggett, L.L. and McCarley, R.W., Waterways Experiment Station, May 1978.

United States Army Corps of Engineers. Technical Report H-79, *The Effect of Depth on Dredging Frequency, Report 2, Methods of Shoaling Analysis*, by Trawle, Michael J., *Hydraulics Laboratory*, United States Army Engineer, Waterways Experiment Station, 1979.

United States Army Corps of Engineers. *Tennessee-Tombigbee Waterway, Alabama and Mississippi, Supplement to the Project Costs and Benefits, Economic Reanalysis Summary*, Mobile District, February 1976.

United States Army Corps of Engineers. *Tennessee-Tombigbee Waterway, Alabama and Mississippi, Columbus Lake, Design Memorandum No. 16, Navigation Channel*, Mobile District, June 1974.

United States Army Corps of Engineers. *Tennessee-Tombigbee Waterway, Mississippi and Alabama Feature Design Memorandum No. N-2A, Dredging Yellow Creek Embayment*, Nashville District, November 1973.

United States Army Corps of Engineers. *Tow Resistance Study for Missouri River Conditions*, Omaha District, June 1971.

United States Army Corps of Engineers. "*Towboats and Barges Operating Costs on the Mississippi River System*," Directorate of Civil Works Letter, Shwaiko, May 1979.

United States Army Corps of Engineers. *Trinity River Project, Texas General Design Memorandum*, Fort Worth District.

United States Army Corps of Engineers. *United States and Foreign Flag Deep Draft Vessel Operating Cost*, Directorate of Civil Works, April 1979.

United States Army Corps of Engineers. *Use of Tow Sequencing Procedures to Increase the Capacity of Existing Lock Facilities*, Waterways Experiment Station, Daggett, L., June 1974.

United States Army Corps of Engineers. *Vancouver to the Dalles, Columbia River Channel Maintenance, Final Environmental Impact Statement*, Portland District, May 1977.

United States Army Corps of Engineers. "*Vessel Characteristics Survey*," St. Louis District, June 1980.

United States Army Corps of Engineers. *Vermilion Lock, Louisiana Replacement, Design Memorandum No. 1, General Design*, New Orleans District, May 1976.

United States Army Corps of Engineers. *Webbers Falls Lock and Dam, Arkansas River, Report on Final Cost Allocation*, Tulsa District, September 1977.

United States Army Corps of Engineers. *Wilmington Harbor, Northeast, Cape Fear River, Wilmington, North Carolina, Final EIS, Plan of Improvement for Navigation and Environmental Quality*, Wilmington District, December 1977, Revised February 1979.

United States Department of Commerce. *The Economics of Deepwater Terminals*.

United States Department of Commerce, Maritime Administration. *The Effect of Federal Standards on United States Public Port Development*.

United States Department of Commerce. "Inland Waterway Reports and Issues," Transportation Research Board, Washington, D.C., 1976.

United States Department of Commerce, Maritime Administration. Mid-America Ports Study.

United States Department of Commerce, Maritime Administration. Planning Criteria for United States Port Development.

United States Department of Transportation, Coast Guard. Bridges Over Navigable Waterways of the United States, CG-425-2, 1975.

United States Department of Transportation, Coast Guard, Paramore, Dayton, Parricelli and Willis, Human and Physical Factors Affecting Collisions, Rammings and Groundings on Western Rivers and Gulf Intracoastal Waterways, January 1979.

United States Department of Transportation, Coast Guard. Projected United States Coast Guard Icebreaking and Icebreaker Requirements 1975-2000, February 1975.

United States Department of Transportation. National Transportation Trends and Choices (to the year 2000). January 1977.

United States Department of Transportation St. Lawrence Seaway Development Corp. St. Lawrence Seaway System Plan for All-Year Navigation, July 1975.

United States General Accounting Office. American Seaports - Changes Affecting Operations and Development, Report to the Congress, by the Comptroller General, CED-80-8, November 1979.

United States Great Lakes, Seaway Port Development and Shippers Conference. Final Report of Working Panels at First Review Meeting, Cleveland, Ohio, October 1977.

University of Michigan. Resistance of Barge Tows, Department of Naval Architecture and Marine Engineering.

Van de Kaa. *Power and Speed of Push Tows in Canals*, Proceedings Symposium on Aspects of Navigability of Constraint Waterways, Including Harbor Entrances, Delft, 1978.

Water and Environment Consultants, Inc. "*Relationship Between Calculated Hydraulic Parameters and Physical Features of the Channel*," for the United States Army Engineer District, Omaha, April 1976.

Water and Environment Consultants, Inc. "*A Study of the Shift in the Stage, Discharge Relationship of the Missouri River at Sioux City, Iowa*," for the United States Army Engineer District, Omaha, May 1976.