US Army Corps
of Engineers
Hydrologic Engineering Center

Risk-based Analysis for Corps Flood Project Studies - A Status Report

19960719 110

Technical Paper No. 153

June 1996

Approved for Public Release. Distribution Unlimited.

DTIC QUALITY INSPECTED 4

Papers in this series have resulted from technical activities of the Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution within the Corps of Engineers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

RISK-BASED ANALYSIS FOR CORPS FLOOD PROJECT STUDIES - A STATUS REPORT

Earl E. Eiker and Darryl W. Davis[1]

ABSTRACT

The Corps of Engineers now requires risk-based analysis in the formulation of flood damage reduction projects. This policy is a major departure from past practices and is viewed as a significant step forward in improving the basis for Corps project development. The risk-based approach explicitly incorporates uncertainty of key parameters and functions into project benefit and performance analyses. Monte Carlo simulation is used to assess the impact of the uncertainty in the discharge-probability, elevation-discharge, and elevation-damage functions. This paper summarizes historical project development study methods, describes the risk-based analysis approach, presents application results, and discusses project design implications of the new policy.

INTRODUCTION

Studies involved in the development of flood damage reduction projects traditionally applied best estimates of key variables and other data elements in determining project benefits and performance. Benefit calculations involve discharge-probability, elevation-discharge (or rating),

---

[1]Chief Hydraulics and Hydrology Branch - Headquarters, US Army Corps of Engineers, Washington, D.C. and Director, Hydrologic Engineering Center, US Army Corps of Engineers, Davis CA.

and elevation-damage functions and costs associated with the proposed project over it's life. Historically, inherent errors and imprecisions in these data were acknowledged but not explicitly incorporated into the analysis or considered in the results. Uncertainty was normally addressed through sensitivity analysis, conservative parameter estimates, and addition of extra capacity such as freeboard for levees. Each has limitations in estimating the statistical implications of uncertainty.

Project performance traditionally considered level-of-protection as the primary performance indicator. It is the exceedance probability of the event that corresponds to the capacity of the project. The importance of this single indicator was often overemphasized, while ignoring other performance information needed to insure proper project comparisons in selecting the alternative to be recommended for implementation. Project selection and recommendations were generally based on maximizing net National Economic Development benefits.

RISK-BASED ANALYSIS APPROACH

Corps' policy now requires application of risk-based analysis in the formulation of flood damage reduction projects [1]. Risk-based analysis quantifies the uncertainty in discharge-probability, elevation-discharge, and elevation-damage relationships and explicitly incorporates this information into economic and performance analyses of alternatives. The process requires use of Monte Carlo simulation [2], a statistical sampling-analysis method that is used to compute the expected value of damage and damage reduced, while explicitly accounting for uncertainty.

The method for development of discharge-probability relationships depends on data availability. For gaged locations and where an analytical fit is appropriate, the method defined by Bulletin 17B [3] is applied. Uncertainties for discrete probabilities are represented by the non-central *t* distribution. For ungaged locations, the discharge-probability function is adopted from applying a variety of approaches [4]. When justified, curve fit statistics for the adopted function are computed. An equivalent record length is assigned based on the analysis and judgements about the quality of information used in adopting the function. Regulated discharge-probability, elevation-probability, and other non-analytical probability functions require different methods. An approach referred to as 'order statistics' [5] is applied to develop the probability function and associated uncertainty for these situations.

Elevation-discharge functions are developed for index

locations from measured data at gages or from computed water surface profiles. For gaged data, uncertainty is calculated from the deviations of observations from the best fit rating function. Computed profiles are required for ungaged locations and for proposed project conditions that are modified from that of historic observations. Where sufficient historic data exists, profile uncertainty is estimated based on the quality of the computation model calibration to the historic data. Where data are scant, or the hydraulics of flow complex, such as for high velocity flow, debris and ice jams, and flow bulked by entrained sediments, special analysis methods are needed. One approach is to perform sensitivity analysis of reasonable upper and lower bound profiles and use the results to estimate the standard deviation of the uncertainty in stage. Unless data indicate otherwise, the uncertainty distribution for flow-stage functions is taken to be Gaussian [6].

Elevation-damage functions are derived from inventory information about structures and other damageable property located in the flood plain. The functions are constructed at damage reach index locations where discharge-probability and elevation-discharge functions are also derived. Presently, separate uncertainty distributions for structure elevation, structure value, and content values are specified and used in a Monte Carlo analysis to develop the aggregated structure elevation-damage function and associated uncertainty. The uncertainty is represented as a standard deviation of error at each elevation coordinate used for defining the aggregated function at the index location.

CHESTER CREEK EXAMPLE

Chester Creek is a 177 km^2 watershed located near Philadelphia, PA. In this example, simulated project studies are performed to determine feasibility of implementing several flood damage reduction plans. This includes comparison of the economic value, performance, and other factors for with- and without-proposed project conditions. Future conditions are projected to be similar to the base year of project implementation. Plans evaluated are 7 and 8 m. high levees, a channel modification configured with 15 m. bottom and 43 m. top widths, and a detention storage project of 5.5 million m^3 capacity.

Without-project condition discharge-probability is derived using Bulletin 17B [3] guidelines. The stream gage located in the basin has a 65 year record length. Confidence limits for the discharge probability function are computed based on the statistics of the gaged record and streamflow record length. The rating curve at the index location is developed from a computed water surface profile. Rating uncertainty is derived from study of calibration

results using high water marks and sensitivity analysis. The standard deviation of uncertainty error varies from zero at no discharge to one foot for .01 probability discharge and beyond. Uncertainty in damage is taken as the standard deviation value equal to 10% of the damage value. For with project conditions, revised functions and associated uncertainties are developed.

Monte Carlo simulations develop expected annual flood damage and performance information for with- and without-project conditions. A summary of economic results are shown in Table 1. The display format is similar to that used historically. The results are different from that which would be generated from traditional analysis - but not dramatically so. Inclusion of benefits other than damage reduction benefits shown here could alter the study conclusions to a small degree.

Any of the alternatives with positive net benefits is a candidate for recommendation for implementation. All but the detention storage alternative meets this test. The 8 m. high levee is identified as the plan that maximizes national economic development. It also provides the greatest benefits and is the most costly plan.

Table 1. Results of economic evaluation

Plan description	Annual with-project residual damage in $1,000	Annual with-project inundation reduction benefit in $1,000	Annual cost in $1,000	Annual net benefit in $1,000
W/out Project	78.1	0.0	0.0	0.0
7 m.levee	50.6	27.5	19.8	7.7
8 m.levee	18.4	59.7	37.1	22.6
Channel	41.2	56.9	25.0	11.9
Detention	44.1	34.0	35.8	-1.8

Performance information is shown on Table 2. Expected annual exceedance probability is similar to the traditional level-of-protection except that uncertainty in the discharge -probability and stage-flow rating is explicitly incorporated. The long term risk (probability of exceedance within the 50 year project life) is calculated directly from the expected annual exceedance probability using the binomial theorem. Event performance is the conditional probability of the project containing a specific event, should it occur. These values are a direct output of the risk-based analysis.

Inspection of performance results indicate only the 8 m. high levee affords a high level of performance. This is

both the expected annual exceedance and event performance through the chance of containing the .4 percent chance event. Since it also provides maximum net benefits it appears to be a logical choice from the federal perspective. Notice, however, it has a 14 percent chance of exceedance during its project life. Since the consequences of capacity exceedance vary for different types of projects it is an important consideration in plan selection. Capacity

Table 2. Results of performance evaluation

Plan description	Expected annual exceed. prob.	Prob. of exceed. in 50 yrs	Event Performance, as %-chance non-exceedance for specified event: .02 Prob. event	.01 Prob. event	.004 Prob. event
W/out project	0.075	0.92	2.3	0.0	0.0
7 meter levee	0.012	0.46	88.2	48.3	6.6
8 meter levee	0.003	0.14	99.7	97.5	76.3
Channel	0.031	0.79	24.8	1.9	0.0
Detention	0.038	0.86	20.5	4.0	0.3

exceedance for levees may cause sudden deep flooding that results in high risk to occupants and significant damage. Channels and detention basins do not normally make matters worse when the capacity is exceeded. These considerations as well as others, such as environmental and social impacts, are requisites for plan evaluation and selection. Economic and performance information derived from risk-based analysis enable better decisions for project selection.

PROJECT STUDIES RISK PERFORMANCE RESULTS

Questions often arise with regard to the relationship between the Corps historic levee studies, risk-based analysis results, and certification of Corps' levees for FEMA base flood protection. Table 3 summarizes the results from several on-going Corps levee project investigations. Note that the NED plan levee elevation, the project which is most often recommended for implementation, is not related to, nor dependent upon, the FEMA certification elevation.

RISK-BASED ANALYSIS AND THE DESIGN PROCESS

A Risk-based Analysis is only one component of a much larger process in a flood damage reduction study. While this analysis provides a wealth of information that was not previously available, it is not a substitute for good engineering practice, nor is it intended to be. The

Table 3. Corps levee project risk-based analysis results

General Information		Risk-based Analysis Results				
(1) Levee Project	(3) FEMA Cert. Elev. (Ft.)	(4) NED Plan Elev. (Ft.)	(5) NED Levee Expected Prob.	(6) 1% Chance Expected Elev. (Ft.)	(7) Conditional % Chance Non-exceedance	
					FEMA (Col. 3)	NED (Col. 4)
1. Pearl R., Jackson, MS	44.6	47.0	0.0013	41.8	97.6	99.8
2. American R., CA	49.1	52.0	0.0046	47.1	83.0	93.4
3. West Sacramento, CA	32.2	33.5	0.0006	29.8	99.9	99.9
4. Portage, WS	798.3	797.0	0.0001	795.6	99.9	99.6
5. Grand Forks, ND	834.4	NA	NA	831.5	90.8	NA
6. Hamburg, IA	912.2	911.5	0.0011	909.8	99.9	99.2
7. Pender, NE	1329.3	1330.0	0.0026	1327.8	76.3	83.6
8. Muscatine, IA	560.8	561.5	0.003	558.8	90.1	94.4
9. Cedar Falls, IA	864.7	866.0	0.0028	862.6	90.0	94.0
10. Guadalupe R. TX	57.9	56.5	0.01	56.5	87.2	73.6
11. White R. IN	715.0	713.2	0.004	712.3	98.0	86.1

Column Definitions: (3) 1% chance median discharge + 3.0 feet. (4) The NED plan levee elevation. (5) The expected annual exceedance probability of the NED levee elevation. (7) The % chance non-exceedance of a levee with the top elevation equal to that corresponding to the column noted given the 1% chance median annual event occurs.

risk-based analysis discussed in this paper is used to formulate the type and size of the optimal structural (or non-structural) plan that will meet the study objectives. Corps' policy requires that this plan be identified in every flood damage reduction study it conducts. This plan, referred to as the National Economic Development Plan (NED), is the one that maximizes the net economic benefits of all the alternatives evaluated. It may or may not be the recommended plan based on additional considerations.

The first step in a flood damage reduction study is to conduct the risk-based analysis. This analysis identifies the NED Plan and provides a starting point for the design process. Output from the analysis includes data on stage exceedence probabilities and expected project performance at index locations along the stream.

A residual risk analysis for the NED Plan is next performed to determine the consequences of a capacity exceedence. We know that for a flood damage reduction project, the question is not **IF** the capacity will be exceeded, but what are the impacts **WHEN** that capacity is exceeded, in terms of both economics and the threat to human life! If the project induced and/or residual risk is unacceptable, and a design to reduce the risk cannot be developed, other alternatives must be further analyzed. Either a larger project, that will assure sufficient time for evacuation, or a different type of project, with less residual risk, should be selected to reduce the threat to life and property.

When the type and size of the project have been selected, we are ready to begin the detailed design. To attain the confidence that the outputs envisioned in the formulation of the selected project will be realized, specific design requirements are developed. For a levee, increments of height are calculated to provide for embankment settlement and consolidation, allow for construction tolerances, and permit the building of a road along the crown for maintenance and access during flood fights. For a channel project, super-elevation, if required to contain the design water surface profile, is determined. For a reservoir, allowances to accommodate the Inflow Design Flood without endangering the structure and to account for wind and wave action are estimated. A similar thought process is also used for upstream diversion projects. These specific requirements must be included in the design.

The design must also include measures to minimize the adverse impacts of a capacity exceedence. For levees, the final grade is set so that initial overtopping will occur at the least hazardous location along the line of protection. This location is usually at the downstream end of the levee, so the protected area will fill in a gradual manner. This

same approach is taken in the final design of channel projects. For reservoirs, a plan is developed so that as the point of capacity exceedence is approached, there is a gradual increase in outflow from the project to provide time to initiate emergency measures downstream. Upstream diversions are also configured to allow a gradual increase in flow during a capacity exceedence. These design efforts notwithstanding, it is normal practice to include a flood warning system in the final plan as a last measure for risk reduction.

Design of a flood damage reduction project places a special responsibility on the engineer because of the potentially catastrophic consequences of a capacity exceedence. Of the types of structural projects usually considered in a flood damage reduction study, a levee is by far the most dangerous due to the severe consequences that may result from overtopping. If a levee cannot be designed to assure gradual filling of the protected area when the capacity is exceeded, then it simply should not be built. Reservoirs, channels and upstream diversions are generally better structural choices than levees. They provide some measure of protection even after their capacity is exceeded, and, they are better suited to minimize the adverse impacts of a capacity exceedence because they can be designed and/or operated to effect a gradual increase in flows and inundation in the protected areas.

REFERENCES

[1] US Army Corps of Engineers (USACE), "Risk-based Analysis for Evaluation of Hydrology/Hydraulics and Economics in Flood Damage Reduction Studies." Engineer Regulation 1105-2-101. USACE, Washington D.C.(1996)

[2] Benjamin, J. R., and A. C. Cornell, Probability, Statistics, and Decision for Civil Engineers. McGraw-Hill Book Co., New York, NY.(1970)

[3] Interagency Advisory Committee of Water Data. "Guidelines for Determining Flood Flow Frequency." Bulletin 17B U. S. Department of the Interior, U. S. Geological Survey, Office of Water Data Coordination, Reston, VA.(1982)

[4] Water Resources Council. "Estimating Peak Flow Frequency for National Ungaged Watersheds - A Proposed Nationwide Test." U. S. Government Printing Office, Washington, D.C.(1981)

[5] Morgan, M. Granger, and M. Hendron. Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press.(1990)

[6] US Army Corps of Engineers (USACE), "Risk-based Analysis for Flood Damage Reduction Studies." Engineer Manual 1110-2-1619. USACE, Washington D.C.(1996)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the date needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
JUNE 1996

3. REPORT TYPE AND DATES COVERED
FINAL

4. TITLE AND SUBTITLE

Risk-based Analysis for Corps Flood Project Studies - A Status Report

5. FUNDING NUMBERS

6. AUTHOR(S)

Earl E. Eiker, Darryl W. Davis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Hydrologic Engineering Center
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Paper 153 (TP-153)

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

HQUS ARMY COE (CECW-EH)
20 Massachusetts Avenue, NW
Washington, DC 20314-1000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION IS UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Corps of Engineers now requires risk-based analysis in the formulation of flood damage reduction projects. This policy is a major departure from past practices and is viewed as a significant step forward in improving the basis for Corps project development. The risk-based approach explicitly incorporates uncertainty of key parameters and functions into project benefit and performance analyses. Monte Carlo simulation is used to assess the impact of the uncertainty in the discharge-probability, elevation-discharge, and elevation-damage functions. This paper summarizes historical project development study methods, describes the risk-based approach, presents application results, and discusses project design implications of the new policy.

14. SUBJECT TERMS
risk analysis, flood control, levees, flood projects performance

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT

TECHNICAL PAPER SERIES

TP-1 Use of Interrelated Records to Simulate Streamflow
TP-2 Optimization Techniques for Hydrologic Engineering
TP-3 Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs
TP-4 Functional Evaluation of a Water Resources System
TP-5 Streamflow Synthesis for Ungaged Rivers
TP-6 Simulation of Daily Streamflow
TP-7 Pilot Study for Storage Requirements for Low Flow Augmentation
TP-8 Worth of Streamflow Data for Project Design - A Pilot Study
TP-9 Economic Evaluation of Reservoir System Accomplishments
TP-10 Hydrologic Simulation in Water-Yield Analysis
TP-11 Survey of Programs for Water Surface Profiles
TP-12 Hypothetical Flood Computation for a Stream System
TP-13 Maximum Utilization of Scarce Data in Hydrologic Design
TP-14 Techniques for Evaluating Long-Term Reservoir Yields
TP-15 Hydrostatistics - Principles of Application
TP-16 A Hydrologic Water Resource System Modeling Techniques
TP-17 Hydrologic Engineering Techniques for Regional Water Resources Planning
TP-18 Estimating Monthly Streamflows Within a Region
TP-19 Suspended Sediment Discharge in Streams
TP-20 Computer Determination of Flow Through Bridges
TP-21 An Approach to Reservoir Temperature Analysis
TP-22 A Finite Difference Method for Analyzing Liquid Flow in Variably Saturated Porous Media
TP-23 Uses of Simulation in River Basin Planning
TP-24 Hydroelectric Power Analysis in Reservoir Systems
TP-25 Status of Water Resource Systems Analysis
TP-26 System Relationships for Panama Canal Water Supply
TP-27 System Analysis of the Panama Canal Water Supply
TP-28 Digital Simulation of an Existing Water Resources System
TP-29 Computer Applications in Continuing Education
TP-30 Drought Severity and Water Supply Dependability
TP-31 Development of System Operation Rules for an Existing System by Simulation
TP-32 Alternative Approaches to Water Resource System Simulation
TP-33 System Simulation for Integrated Use of Hydroelectric and Thermal Power Generation
TP-34 Optimizing Flood Control Allocation for a Multipurpose Reservoir
TP-35 Computer Models for Rainfall-Runoff and River Hydraulic Analysis
TP-36 Evaluation of Drought Effects at Lake Atitlan
TP-37 Downstream Effects of the Levee Overtopping at Wilkes-Barre, PA, During Tropical Storm Agnes
TP-38 Water Quality Evaluation of Aquatic Systems
TP-39 A Method for Analyzing Effects of Dam Failures in Design Studies
TP-40 Storm Drainage and Urban Region Flood Control Planning
TP-41 HEC-5C, A Simulation Model for System Formulation and Evaluation
TP-42 Optimal Sizing of Urban Flood Control Systems
TP-43 Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems
TP-44 Sizing Flood Control Reservoir Systems by Systems Analysis
TP-45 Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin
TP-46 Spatial Data Analysis of Nonstructural Measures
TP-47 Comprehensive Flood Plain Studies Using Spatial Data Management Techniques
TP-48 Direct Runoff Hydrograph Parameters Versus Urbanization
TP-49 Experience of HEC in Disseminating Information on Hydrological Models
TP-50 Effects of Dam Removal: An Approach to Sedimentation
TP-51 Design of Flood Control Improvements by Systems Analysis: A Case Study
TP-52 Potential Use of Digital Computer Ground Water Models
TP-53 Development of Generalized Free Surface Flow Models Using Finite Element Techniques
TP-54 Adjustment of Peak Discharge Rates for Urbanization
TP-55 The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers
TP-56 Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models
TP-57 Flood Damage Assessments Using Spatial Data Management Techniques
TP-58 A Model for Evaluating Runoff-Quality in Metropolitan Master Planning
TP-59 Testing of Several Runoff Models on an Urban Watershed
TP-60 Operational Simulation of a Reservoir System with Pumped Storage
TP-61 Technical Factors in Small Hydropower Planning
TP-62 Flood Hydrograph and Peak Flow Frequency Analysis
TP-63 HEC Contribution to Reservoir System Operation
TP-64 Determining Peak-Discharge Frequencies in an Urbanizing Watershed: A Case Study
TP-65 Feasibility Analysis in Small Hydropower Planning
TP-66 Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems
TP-67 Hydrologic Land Use Classification Using LANDSAT
TP-68 Interactive Nonstructural Flood-Control Planning
TP-69 Critical Water Surface by Minimum Specific Energy Using the Parabolic Method
TP-70 Corps of Engineers Experience with Automatic Calibration of a Precipitation-Runoff Model
TP-71 Determination of Land Use from Satellite Imagery for Input to Hydrologic Models
TP-72 Application of the Finite Element Method to Vertically Stratified Hydrodynamic Flow and Water Quality

TP-73 Flood Mitigation Planning Using HEC-SAM
TP-74 Hydrographs by Single Linear Reservoir Model
TP-75 HEC Activities in Reservoir Analysis
TP-76 Institutional Support of Water Resource Models
TP-77 Investigation of Soil Conservation Service Urban Hydrology Techniques
TP-78 Potential for Increasing the Output of Existing Hydroelectric Plants
TP-79 Potential Energy and Capacity Gains from Flood Control Storage Reallocation at Existing U. S. Hydropower Reservoirs
TP-80 Use of Non-Sequential Techniques in the Analysis of Power Potential at Storage Projects
TP-81 Data Management Systems for Water Resources Planning
TP-82 The New HEC-1 Flood Hydrograph Package
TP-83 River and Reservoir Systems Water Quality Modeling Capability
TP-84 Generalized Real-Time Flood Control System Model
TP-85 Operation Policy Analysis: Sam Rayburn Reservoir
TP-86 Training the Practitioner: The Hydrologic Engineering Center Program
TP-87 Documentation Needs for Water Resources Models
TP-88 Reservoir System Regulation for Water Quality Control
TP-89 A Software System to Aid in Making Real-Time Water Control Decisions
TP-90 Calibration, Verification and Application of a Two-Dimensional Flow Model
TP-91 HEC Software Development and Support
TP-92 Hydrologic Engineering Center Planning Models
TP-93 Flood Routing Through a Flat, Complex Flood Plain Using a One-Dimensional Unsteady Flow Computer Program
TP-94 Dredged-Material Disposal Management Model
TP-95 Infiltration and Soil Moisture Redistribution in HEC-1
TP-96 The Hydrologic Engineering Center Experience in Nonstructural Planning
TP-97 Prediction of the Effects of a Flood Control Project on a Meandering Stream
TP-98 Evolution in Computer Programs Causes Evolution in Training Needs: The Hydrologic Engineering Center Experience
TP-99 Reservoir System Analysis for Water Quality
TP-100 Probable Maximum Flood Estimation - Eastern United States
TP-101 Use of Computer Program HEC-5 for Water Supply Analysis
TP-102 Role of Calibration in the Application of HEC-6
TP-103 Engineering and Economic Considerations in Formulating
TP-104 Modeling Water Resources Systems for Water Quality
TP-105 Use of a Two-Dimensional Flow Model to Quantify Aquatic Habitat
TP-106 Flood-Runoff Forecasting with HEC-1F
TP-107 Dredged-Material Disposal System Capacity Expansion
TP-108 Role of Small Computers in Two-Dimensional Flow Modeling
TP-109 One-Dimensional Model For Mud Flows
TP-110 Subdivision Froude Number
TP-111 HEC-5Q: System Water Quality Modeling
TP-112 New Developments in HEC Programs for Flood Control
TP-113 Modeling and Managing Water Resource Systems for Water Quality
TP-114 Accuracy of Computed Water Surface Profiles - Executive Summary
TP-115 Application of Spatial-Data Management Techniques in Corps Planning
TP-116 The HEC's Activities in Watershed Modeling
TP-117 HEC-1 and HEC-2 Applications on the MicroComputer
TP-118 Real-Time Snow Simulation Model for the Monongahela River Basin
TP-119 Multi-Purpose, Multi-Reservoir Simulation on a PC
TP-120 Technology Transfer of Corps' Hydrologic Models
TP-121 Development, Calibration and Application of Runoff Forecasting Models for the Allegheny River Basin
TP-122 The Estimation of Rainfall for Flood Forecasting Using Radar and Rain Gage Data
TP-123 Developing and Managing a Comprehensive Reservoir Analysis Model
TP-124 Review of the U.S. Army Corps of Engineering Involvement With Alluvial Fan Flooding Problems
TP-125 An Integrated Software Package for Flood Damage Analysis
TP-126 The Value and Depreciation of Existing Facilities: The Case of Reservoirs
TP-127 Floodplain-Management Plan Enumeration
TP-128 Two-Dimensional Floodplain Modeling
TP-129 Status and New Capabilities of Computer Program HEC-6: "Scour and Deposition in Rivers and Reservoirs"
TP-130 Estimating Sediment Delivery and Yield on Alluvial Fans
TP-131 Hydrologic Aspects of Flood Warning - Preparedness Programs
TP-132 Twenty-five Years of Developing, Distributing, and Supporting Hydrologic Engineering Computer Programs
TP-133 Predicting Deposition Patterns in Small Basins
TP-134 Annual Extreme Lake Elevations by Total Probability Theorem
TP-135 A Muskingum-Cunge Channel Flow Routing Method for Drainage Networks
TP-136 Prescriptive Reservoir System Analysis Model - Missouri River System Application
TP-137 A Generalized Simulation Model for Reservoir System Analysis
TP-138 The HEC NexGen Software Development Project
TP-139 Issues for Applications Developers
TP-140 HEC-2 Water Surface Profiles Program
TP-141 HEC Models for Urban Hydrologic Analysis
TP-142 Systems Analysis Applications at the Hydrologic Engineering Center
TP-143 Runoff Prediction Uncertainty for Ungauged Agricultural Watersheds
TP-144 Review of GIS Applications in Hydrologic Modeling
TP-145 Application of Rainfall-Runoff Simulation for Flood Forecasting
TP-146 Application of the HEC Prescriptive Reservoir Model in the Columbia River System
TP-147 HEC River Analysis System (HEC-RAS)
TP-148 HEC-6: Reservoir Sediment Control Applications
TP-149 The Hydrologic Modeling System (HEC-HMS): Design and Development Issues
TP-150 The HEC Hydrologic Modeling System
TP-151 Bridge Hydraulic Analysis with HEC-RAS
TP-152 Use of Land Surface Erosion Techniques with Stream Channel Sediment Models
TP-153 Risk-based Analysis for Corps Flood Project Studies - a Status Report