USE OF PREDICTIVE MODELS IN AQUATIC HABITAT RESTORATION

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PREFACE

The work reported herein was conducted as part of the Evaluation of Environmental Investments Research program (EEIRP). The EEIRP is sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE). It is jointly assigned to the U.S. Army Engineers Water Resources Support Center (WRSC), Institute for Water Resources (IWR) and the U.S. Army Engineer Waterways Experiment Station (WES), Environmental Laboratory (EL). Mr. William J. Hansen of IWR is the Program Manager and Mr. H. Roger Hamilton is the WES Manager. Technical Monitors during this study were Mr. John W. Bellinger and Mr. K. Brad Fowler, HQUSACE. The Field Review group members that provide overall Program direction and their District or Division affiliations are: Mr. David Carney, New Orleans; Mr. Larry M. Kilgo, Lower Mississippi Valley; Mr. Richard Gorton, Omaha; Mr. Bruce D. Carlson, St. Paul; Mr. Glendon L. Coffee, Mobile; Ms. Susan E. Durden, Savannah; Mr. Scott Miner, San Francisco; Mr. Robert F. Scott, Fort Worth; Mr. Clifford J. Kidd, Baltimore; Mr. Edwin J. Woodruff, North Pacific; and Dr. Michael Passmore, WES, formerly of Walla Walla.

The work was performed under the Objectives and Outputs Work Unit for which Mr. John P. Titre, EL, was the Principal Investigator. The Co-Principal Investigator was Mr. Darrell G. Nolton, IWR. Prior to November 1995, the original Principal Investigator at WES was Dr. Pace Wilber (NOAA-CSC). Technical Reviews were provided by Dr. David J. Yozzo and Dr. Pace Wilber.

The report was prepared under the general supervison at IWR of Mr. Michael R. Krouse, Chief, TARD; Mr. Kyle E. Schilling, Director, IWR; and at WES, of Mr. H. Roger Hamilton, Chief, Resource Analysis Branch; Dr. Douglas Clark, Acting Chief, Coastal Ecology Branch; Dr. Robert M. Engler, Chief, Natural Resources Division; Dr. Conrad J. Kirby, Chief, Ecological Research Division,and Dr. John W. Keeley, Director, EL

At the time of publication of this report, Mr. Kyle E. Schilling was Acting Director, WRSC, and Dr. Robert W. Whalin was Director of WES. Commander of WES was COL Bruce K. Howard.

EXECUTIVE SUMMARY

This report provides an overview of the role of modeling in aquatic habitat restoration. Over 400 references were reviewed and listed in the Restoration Model (RESTMOD) database. Although the emphasis of the report is on hydrologic and biological/ecosystem models, other model types including planning/economic, water quality, sediment transport, and others are reviewed.

Chapter 1 includes an introduction to restoration analysis and management, and the potential importance of modeling as a planning tool. The organization of the RESTMOD database is outlined and its contents summarized

In Chapters 2 and 3, the use of modeling in the restoration planning process is emphasized, especially the role of modeling exercises in goal formulation and development of data collection/monitoring programs. The structure and functions of models are covered, along with recommendations for the selection and use of models in restoration planning. Case studies are presented as examples of model application.

Hydrologic models, including catchment, groundwater, channel and current models, are discussed in Chapter 4. Biological and ecosystem models, including avian, fisheries, instream flow, eutrophication, and Habitat Evaluation, Habitat Quality, and Habitat Suitability (HEP/HQI/HSI) models are reviewed in Chapter 5.

The RESTMOD database is available to interested users in electronic format.

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1 INTRODUCTION

To restore is the act or process of returning to an unimpaired or improved condition (Webster 1974).

The U.S. Army Corps of Engineers (Corps) is engaged in a program to establish criteria and procedures for aquatic environmental restoration projects. The Corps' view of aquatic restoration fits neatly within the broad context of Mr. Webster's; anything that may provide relief, even temporarily, from a bad situation. These types of programs may range from projects as simple as dredging nutrient-enriched sediments to minimize eutrophication in a lake, to complex marsh or stream restorations. Likewise, "aquatic habitats" are defined very broadly, and may range from small freshwater potholes, streams or rivers, to brackish or marine habitats.

The Corps' Evaluation of Environmental Investments Research Program (EEIRP) is designed to develop analytical methods and models for such issues as determining environmental objectives and measuring outputs and cost-effectiveness analysis (Feather and Capan, 1995). The broad goals of the EEIRP are to develop analytical tools to assist planners, managers and regulators in addressing the following two questions:

- Determining which of several alternatives is the recommended action based upon which is the most desirable in terms of the environmental objective being addressed.

- How to allocate limited resources among many "most desirable" environmental investment decisions.

Restoration of impaired, dysfunctional, or missing habitat is taking precedence over lengthy characterizations of the degradation processes, if for no other reason than budget limitations. Careful planning and evaluation of alternatives, and predictions about the probable outcomes lead to informed decisions and successful execution of restoration efforts. Modeling the environmental attributes that can lead to success, or failure, are an important part of that process.

This document is intended to provide practical information on the use of environmental models to plan and predict the outcome of aquatic restoration projects. It is written to provide basic information concerning model types, their uses and limitations, and to provide examples of their use.

Defining the Field

From a programmatic standpoint, successful pursuit of this initiative is enhanced by the ability to evaluate and predict the results associated with various restoration options, and an ability to set confidence limits about those predictions. There is a critical need for resource managers to be able to assess the probability of success of a restoration effort before expending public resources.

While the ultimate goal of any restoration project may be re-instituting a balanced ecosystem for a particular target species or assemblage of species, it is often not feasible to limit modeling exercises to ecological or biological models. Predicting restoration success usually involves defining numerous physical parameters *prior to* conducting ecological modeling. Most often restoration projects involve some form of engineering controls to physical parameters (e.g., hydraulic routing, point-source controls, physical habitat alterations) whose predicted effects themselves must be modeled before those inputs can be used in the ecological models.

A good example of the inputs of several models would be restoration of reproducing piscivorous avian populations by improving water quality in a eutrophic lake or embayment (Figure 1). In this example, engineering controls could include nutrient point/nonpoint source control, dredging of enriched sediments, or groundwater pump and treat systems. Each of these design considerations would require modeling, along with standard lake/bay hydraulic features, prior to running the eutrophication and subsequent biological models.

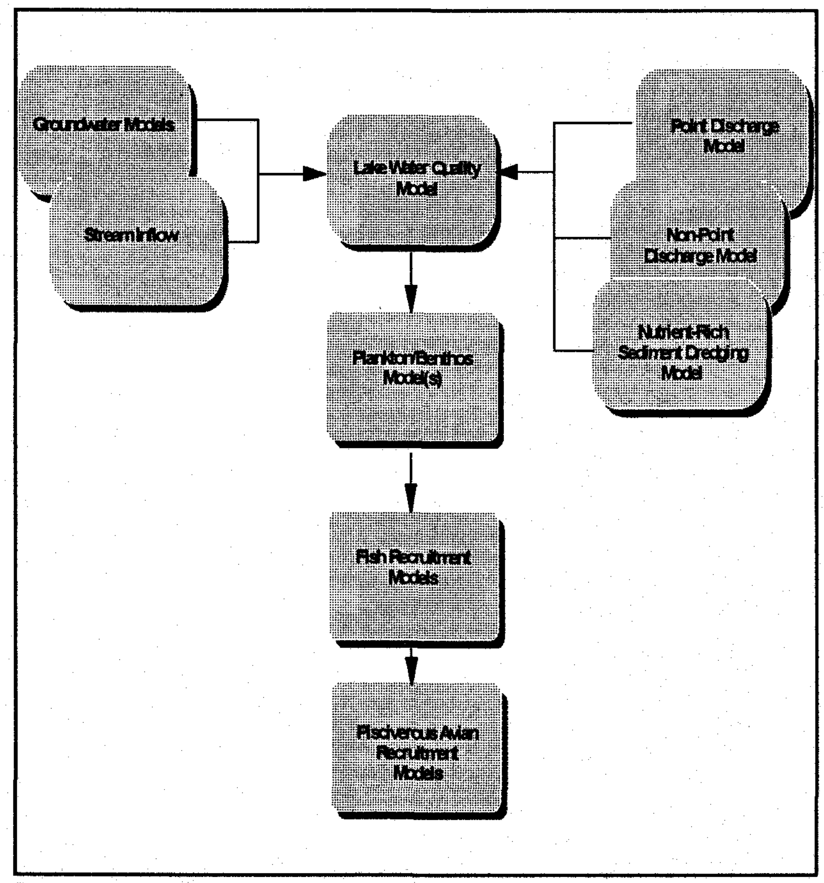

Figure 1. Flow diagram of an example restoration project showing multiple interactions of abiotic and biotic models.

Ideally, the overall approach to evaluating a restoration project should be structured to yield a probabilistic assessment of the likelihood of success relative to the amount of money/effort that will be expended on the project. Under ideal conditions, an example of this process might be as follows:

> A program is undertaken to improve populations of steelhead in its native areas of the Umquah River. Previous studies demonstrate that the population declines are due to increased siltation in traditional gravel spawning sites. Use of In-stream Flow Incremental Methodology, coupled with Habitat Suitability Index models indicate that site A is the most suited for remediation, with an 80% probability of success in increasing the steelhead population by 25% in 8 years. Those same models indicate that Site B is the second preferred site, with a reduced probability of success estimated at 60%. Due to logistical considerations (e.g., physical barriers restricting access to site), the cost of restoring site A is $8.4 million, whereas site B is set at $5.6 million. On a probabilistic basis then, the cost of both programs is equal at $9.3 million ($8.4 / 90% vs. $5.6 / 60%).

While hypothetical, the example demonstrates an ideal goal in restoration planning; to balance program cost with probable success. Resource managers and agencies are then given the tools with which to balance the amount of money available versus "acceptable" levels of risk in the restoration effort.

Probabilistic models have been the subject of increasing studies as resource managers look for tools to provide boundaries around environmental variability, especially as it influences the reliability of their predictions. Absent from the above example is a discussion of the confidence limits or uncertainty associated with either modeling prediction. Placing confidence boundaries around the assessment can play a pivotal role in the decision-making process. Resource managers, who are often not scientists, need to take into account the uncertainties associated with scientific information on which the restoration decision(s) will be made. In short, an analysis of the probability of restoration success, with confidence boundaries, would ideally be made prior to making the management decisions associated with implementing the restoration project.

Crockett (1994) defined three groups of people involved with models; the model developer, the model user, and the decision maker. We believe that this generalization is equally applicable to aquatic restoration planning and execution. As such, we are less interested in this document on providing lists of complex mathematical equations, and have chosen to focus on the needs of the model user and how the model outputs are used by the decision-maker. We have attempted to provide a framework in which the appropriate model(s) can be selected, evaluated, and applied to investigate a particular restoration problem. Furthermore, we provide examples of models and their use in restoration.

Restoration Analysis and Restoration Management.

The term "risk" was deliberately used in the example above. In many respects, the type of restoration assessment is similar to the paradigm/processes undertaken in an ecological risk assessment. Risk assessment begins with an environmental perturbation, and works toward quantifying the impact of the perturbation to the immediate or surrounding environment. Restoration assessment begins with planning a physical perturbation to an existing environment, and works forward toward assessing the probable outcome of that impact. The probability of impact or success is accompanied by the confidence or uncertainty of the assessment. The probability and uncertainty are co-utilized to determine clean-up levels or restoration levels.

This is not to say that a formal process of "risk assessment" for each restoration project is required, or even desirable . In a recent workshop conducted on reviewing restoration projects (Feather and Capan 1995), a group of national restoration experts generally supported the notion of uncertainty quantification, but indicated that formal processes are often great time and budget consumers. Many engineering "risks" could be evaluated informally during the design process. Models can be used to assist in project planning, assess economic impacts, and formally, or informally asses the probabilities of success or failure.

Given the analogies, we believe that the terms *"restoration analysis*", "*restoration success*", and "*restoration management*", are appropriate to add to the lexicon of environmental restoration. We define them as follows:

> *Restoration analysis* is the assignment of a probabilistic estimate, with defined uncertainties, that the stated success goals will be achieved.
>
> *Restoration success* is defined as the probability that a specified desirable effect will occur in response to the restoration effort. In the case of a graded response, it is the relationship between the magnitude of the response and the probability of occurrence.
>
> *Restoration management* uses the scientific estimates produced in the restoration analysis to make available the resources necessary to achieve restoration success.

Objectives and Organization

Document Objective

The goal of this document is to provide practical information of the use of environmental models to project managers in Corps' District offices as the intended audience. To that end we set the following objectives:

- Provide the most current information on environmental models in an easy-to-access format
- Define a process of restoration analysis based upon modeling predictions
- Provide examples of using models in actual restoration projects

We acknowledge here a bias towards ecological/biological models in this document. This not only reflects our Corps-directed mandate, but more importantly mirrors our perception that the biological endpoints are the most important, and difficult to predict, parameters in ecological restoration. Success is more often judged by presence or absence of a particular species, than by the attainment of a certain water depth, velocity and flow, or sedimentation load. This is not at all to say that physical parameters are not <u>critical</u> to success; they are. As such, we include in our review examples of physical models as they directly relate to restoration. Furthermore, there are better reviews and sources of information/direction on the use of for example hydrology models (Singh 1995) or water quality (Gobas and McCorquodale 1992; Buffle and DeVitre 1994). It is our intent here to discuss how to integrate those results with biological models.

Similarly, information on planning and economic models was only collected to provide context for the detailed discussion of the ecological/biological and physical models. Profiles of the planning and economic models reviewed are included in the RESTMOD database described in Chapter 2. A detailed discussion of such models, however, is beyond the scope of this report. The development and use of such models are more thoroughly addressed in other EEIRP work units and products.

Document Organization

To meet our project objectives, the remainder of Chapter 1 focuses on the model literature survey, how these models were classified based upon applications, and the construction of the database accompanying this document that allows easy access to the collected information. Chapters 2 and 3 are introductions to model selection and types of models. Chapter 2 provides more detail on the types and roles of models in restoration, and defines a process for using model predictions in restoration analysis. The functional classifications that we have selected are introduced, and a general overview of model structure is provided. Chapter 3 provides generic guidelines or criteria for selecting, calibrating, and validating environmental models. Chapters 4 and 5 provide examples of using models in restoration projects. Chapter 4 discusses the important role of hydrologic models, while Chapter 5 focuses on the numerous biological models that are available, and how they may be used for planning, predicting, and executing restoration.

All chapters make use of and reference articles that are listed within the Restoration Model (RESTMOD) database. Electronic copies of the database reside at the Waterways Experiment Station (WES) and are available upon request from: Chief, Resource Analysis Branch, US Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, ATTN: CEWES-EN-R. The organization and annotated review criteria for RESTMOD are described in more detail below.

Model Literature Review

The literature is rich with examples of environmental modeling. The types of documents include a monograph series on ecological modeling (Jørgenson, *Developments in Environmental Monitoring 1981 - 1992, volumes 1 - 12)*, an international journal (*Ecological Monitoring*), books or texts (e.g.,Mitsch and Gosselink 1993; Calow and Petts 1994), and innumerable articles in a myriad number of journals. Initially, a "broad brush" approach was taken in the review, examining any and all articles that might have relevance. A review article on modeling estuarine ecosystems also used to help further formulate the study design (STAC 1992). This aided in developing a conceptual approach to the problem, and refining the search to the models relevant to restoration analysis.

Having determined that the goal of the project was to define model use in restoration analyses and management, it became necessary to place boundaries around the types of models to be included in order to limit the number of articles procured. Step one was to always consider the intended audience and ask the question, "How will this assist a District planner in formulating a restoration decision?". The next step was to conceptualize the process of restoration planning: from conception to post-restoration measurements of success. While the process is defined in more detail in Chapter 2, briefly we identified the areas of hydrology, water quality, sediment transport/channel stability, and biology as the most important fields with which to structure the review.

Literature Search

Models which may be useful for restoration projects were initially identified using on-line literature searches. This included the Cambridge Abstract Service, the University of Washington's on-line library catalog service, and accessing the main headings from the Internet. When using the abstract/catalog services, key words or descriptors were chosen to identify models pertaining to ecosystems, habitats, water resources, restoration, and habitat engineering. General descriptors were initially used, and identified references copied onto diskette in files specific to the particular search.

In addition to the on-line searches various references listed in relevant articles and books were reviewed and selected. The articles identified from the on-line searches were also obtained and reviewed for additional appropriate references.

Once references were selected, the articles were obtained through universities, the Environmental Protection Agency, U.S. Army Corps of Engineers, U.S. Geological Service, U.S. Fish and Wildlife Service, and National Technology Information Service (NTIS), and a number of other federal, state, public and private sources. In addition, copies of computer projects for selected models described in the documents were requested from the sources. The copies acquired include disks of the specific model project and any documents associated with the functioning of the program.

Database Classification Scheme

As discussed previously, models may be classified by function or structure: i.e., what they do versus how they do it. For the purposes of this project, we elected to emphasize function over structure. More precisely, models were classified based upon the input/output, as opposed to the construction or mathematical type. The major justification for this approach is that resource managers are more likely to relate to a holistic system classification (e.g., estuarine, groundwater, habitat quality) as opposed to grouping models by structure (e.g., conceptual vs. simulation models, regression vs. stochastic models). The major model classes and subclasses are described in more detail in Chapter 2.

Review

After references were obtained, each journal article, document, or book was critically reviewed and classified according to the type of model presented in the paper. The model classification scheme used is presented in Table 1-1, and includes planning/economic, hydrologic, water quality, sediment transport/channel stability, biological, or other model classes, which were further divided into subclasses. Additional information such as the name of the model used (if applicable), any computer requirements, data needs, calibration, verification, output/predictions, and uncertainty was also recorded for each model (Table 1-2). Over 400 references were obtained and reviewed in compilation of this document.

TABLE 1-1. CLASSIFICATION SCHEME USED TO CATEGORIZE MODELS IN RESTMOD

Model Class	Model Subclass
Planning/Economic	Planning/Consensus Building
	Economic
	Recreational
Hydrologic	Catchment
	Groundwater
	Channel
	Current
Water Quality	Nutrient
	Dissolved Gasses
	Point/Non-Point Discharge
	Toxic Release
	Thermal
	Lake Restoration
Sediment Transport/Channel Stability	Beach Transport
	Siltation/Sedimentation Models
	Channel Stability
Biological	Ecosystem Models
	Eutrophication
	HEP/HQI/HSI
	Instream Flow
	Fisheries Models
	Avian Models
Other	Model Construction
	Reviews
	Other applicable models

TABLE 1-2. INFORMATION FIELDS FOR EACH RESTMOD ENTRY

FIELDS

TL	Title
AT	Author
CA	Corporate Author
SC	Source
SS	Secondary Source
PY	Publication Year
LT	Language of Text
LA	Language of Abstract
PT	Publication Type
ER	Environmental Regime
AB	Abstract
DE	Descriptors
IN	Identification Number

Model Class and Model Sub-Class	**Class**	**Subclass**
	Planning/Economic:	Planning/Consensus Building Economic Recreational
	Hydrologic:	Catchment Groundwater Channel Current
	Water Quality:	Nutrient Point/Non-Point Discharge Lake Restoration Toxic Release Dissolved Gases Thermal
	Sediment Transport/ Channel Stability:	Beach Transport Siltation/Sedimentation Models Channel Stability
	Biological:	Ecosystem Models HEP/HQI/HSI Avian Models Fisheries Models Instream Flow Eutrophication
	Other:	Model Construction Review Other Applicable Models

TABLE 1-2. (cont.)

Class Comment	Further specifies model type
Model Used	Model name
PC Requirements	Personal computer requirements
Data Needs	Data needed to run the model
Calibration	Calibration of the model
Verification	Information concerning verification or application of the model
Output	Model output/predictions
Uncertainty	Uncertainty of model predictions
Status	Reprint and/or computer model on file/not on file/model requested

2 ROLE OF MODELS IN RESTORATION MANAGEMENT

Models for Predicting Restoration Success

The goal of any conceptual or simulation model is the ability to predict an outcome from a given set of input parameters. Throughout this document we will make reference to a model's functional versus its structural class. Functional classification will refer to what a model is intended to examine: ecosystem models, groundwater models, and lake restoration models are examples of functional classification. Structure will refer to the mechanical form of the model; how it works. Examples of the types of structural models generally employed in environmental sciences include physical models (bench-scale reconstructions of the habitat), conceptual models (a concept or diagram of how a system works), statistical models (using statistics to derive generalizations), and mechanistic models (mathematically-based models with measurable inputs).

Conceptual Approach

Successful completion of a restoration project may involve a diverse number of disciplines, including planning, economics, law, engineering, hydrology and biology. Models may be used in any, or all of the stages of a restoration project. Models exist for conceptualizing, planning, allocating resources, predicting probable outcomes or choosing between a range of alternatives, and for setting goals for post-restoration monitoring.

A useful conceptual model upon which we based many of the ideas presented herein is that contained in the U.S. Fish and Wildlife Service's Instream Flow Incremental Methodology (IFIM). While developed specifically for examining multiple demands on out-flow from hydro-development sites, IFIM incorporates planning of water resource allocation(s) over time using water quality and hydraulic models, coupled with empirically derived habitat and flow functions. IFIM is structured so as to yield simulations of the quantity and quality of potential habitat resulting from proposed water development. It is specifically designed as a management tool, and provides an organizational framework for evaluating and formulating alternative water management scenarios (Stalnaker and Arnette 1976; Stalnaker 1994).

A paradigm envisioned for planning, implementing and measuring restoration success is given in Figure 2-1. All projects begin with a planning phase that examines the issues, sets and prioritizes goals, and determines what resources will be needed or available. Once the restoration conceptual framework is established, available data are compiled and used in the model simulations. The results of modeling may be used to justify going forward with the restoration project, or require re-setting of goals that have a higher probability of success. The modeling results can also be used to set the post-restoration expectations, and assist in measuring post-restoration success.

Model Functions

There are nearly as many ways to catagorize models, as there are models. As discussed previously, models may be classified by function or structure: i.e., what they do versus how they do it. For the purposes of this review, we elected to emphasize function over structure. More precisely, models were classified based upon the input/output, as opposed to the construction or mathematical type. The major justification for this approach is that resource managers are more likely to relate to a holistic system classification (e.g., estuarine, groundwater, habitat quality) as opposed to grouping models by structure (e.g., conceptual vs. simulation models, regression vs. stochastic models).

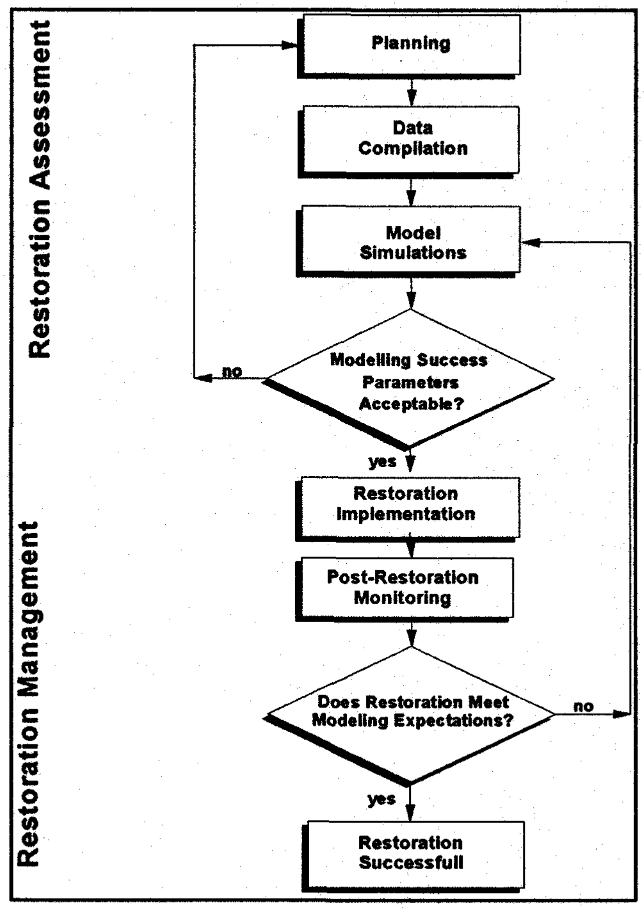

Figure 2-1. Conceptual flow diagram for conducting restoration analysis and management.

Planning and Economic Models

Planning is often the most time-consuming, and potentially difficult phase to get through, especially if the project involves politically-sensitive and/or controversial issues. Evaluating the economic values of habitat versus alternative uses is often a critical component in determining the merits of restoration projects, or in evaluating proposed mitigation - replacing one habitat by restoring another marginal or creating *de novo* an alternative habitat. Economic models exist for quantifying wetland values. Economic models are also important in association with hydraulic power plants as water availability downstream of a dam is directly related to power generation needs.

Recreational concerns are not traditionally thought of as part of the restoration process, but as demonstrated in the IFIM example, are often critical considerations in restoring or altering certain habitats. Recreational models were included in the RESTMOD database when they might have some bearing upon restoration success (e.g., recreational fishing pressures, habitat use by recreational boaters).

As stated previously, the development and application of planning and economic models is addressed in considerable detail by other EEIRP work units and products.

Hydrologic Models

By definition, aquatic system habitats are more often than not controlled by hydrology. The quantity, speed and direction of water influences the shoreline and substrate stability, substrate type, dissolved gas content, nutrient availability, and other factors which in turn determine a site's biology. No restoration effort could be undertaken without first considering the pre- and post-restoration hydrology.

At the base of any aquatic restoration analysis is accounting: "water in / water out". For biological systems an important consideration is the ability to predict what will be the lowest level of inputs to the intended project. Two well-developed disciplines have evolved to account for and predict flow: catchment and groundwater simulations. Catchment models are used to predict the amount of water that will surface-flow into a system, and typically are large landscape-based projects. Groundwater models predict flows underground and are useful to restoration projects when those waters resurface and contribute to the overall water balance at the planned site. Groundwater models have also been more recently used to predict the mobilization and movement of contaminants from upland sites into aquatic ecosystems. These latter models may also influence restoration success and have been included.

Channel models are those that deal with the physical effect of water motion in rivers or streams. Velocity, pressure, and depth of water (i.e., hydraulics) are important variables in determining biotic communities. Current models are those that describe wind or tidally-induced motion in larger bodies of water (lakes, estuaries or marine systems). Current models are important in determining flow of nutrients in eutrophied systems, upwelling of nutrients or oxygen laden waters in lakes or offshore systems, or in determination of habitats suitable for transplant of sea grasses or kelp.

Water Quality Models

After the volumes and movement of water have been accounted for, the quality of the water in the habitat is the next important consideration in the determination of organisms in a habitat. Changes in water quality due to inputs of nutrients, changes in the dissolved gas content, temperature, or releases of toxic compounds all affect the organisms living in a habitat.

Nutrient models refer to those models that predict the physical fate and effects of nitrogen or phosphates to overall water quality. These may, or may not be incorporated into eutrophication models (defined as a separate sub-class under biological models).

Dissolved gas models refers to those that deal with increase/decrease in the dissolved content of oxygen, nitrogen, or carbon dioxide. Perhaps the best example of the importance of dissolved gas models is the occurrence of fish-kills associated with supersaturation of gasses from hydroelectric outfalls. An increase/decrease in dissolved gasses may also be a component of eutrophication models.

Point source and non-point source discharge models refer to the release of either nutrient or toxic chemical substances into aqueous bodies. These may range from diffusion/dilution models of known discharges from industries or municipal sewage, to area wide runoff (e.g., stormwater models) of mixed nutrients and contaminants. Examples of the importance of these models to restoration may lay in engineering controls of point sources, prevention of non-point runoffs into the restored site. Toxic release is used to categorize models relating to existing contaminated aquatic or upland sites (e.g.,PCBs at New Bedford Harbor, MA; PAHs at Eagle Harbor, WA). While the scope of this document is structured so as not to consider restoration of contaminated sites, it is impossible to ignore contaminant-related issues in any urban restoration project. In addition, there are emergent technologies, and associated models, that deal with controlling point or non-point pollution through the use of created or restored wetlands.

Thermal models were identified in the literature that dealt with the changes in temperature in rivers or streams associated with either changes in the catchment basin (e.g., logging) to physical alterations of the river (e.g., reservoir construction). The U.S. Fish and Wildlife Service's Stream Network Temperature Model is an example of modeling thermal effects on resident fish populations.

Lake restoration is a well-developed field unto itself, and as such models that deal with lake restoration were given special attention. These models may pertain to restoring eutrophied systems through source control (e.g., runoff control, dredging nutrient-rich sediments), or may deal with the problems and solutions associated with acidification.

Sediment Transport/Channel Stability Models

The Corps has been directly involved in the development of models that predict the accumulation or erosion of sediments in all aquatic systems. From bank stability to the behavior of dredged sediment released from hopper barges, numerous important models have been constructed to predict sediment behavior. Construction by the Corps of banks or jetties to stabilize navigation channels has had significant impacts upon fish and shellfish spawning and nursery habitats, eelgrass beds, and beaches. Accordingly, the literature reviews have included beach transport models.

Sediment transport is important to all types of aquatic habitats; including those in marine environments, and may involve a whole watershed in determinations about sediment load effects on planned restoration projects. Models are included in the review that examine the effects of logging on increasing suspended and bedload sediments in rivers and streams. Predicting the behavior of sediments released from dredging barges has been used to plan, implement, and monitor placement of material for marine restoration projects.

An important corollary to sediment transport are those models that attempt to predict the accumulation of sediment. Siltation models are important in all aquatic environments. Construction of a salmon redd must not only consider the amount of siltation carried within the spawning river, but predict whether the restored habitat will accumulate sediment over time - covering the gravel so necessary for successful juvenile salmonid development. Siltation models have been recently used to predict re-contamination rates for clean sediment caps placed over combined sewer outfall "hot spots" in urban embayments.

Channel stability refers specifically to those models that predict a river or stream's tendency to meander and cut away at natural or artificially-created banks or alter bed levels.

Biological Models

In using the term "restoration", a general initial expectation is the return of some desired biological component to a degraded or altered habitat. In fact, emphasis in the early part of this review on ecosystem models implied an overall importance to the biological components. Many models have been developed for predicting biological responses to abiotic factors, as well as managing fish and wildlife populations.

Ecosystem or community-level models are representations of one to several trophic levels, and are generally site-specific. In this classification scheme, ecosystem models may, or may not, include abiotic system components (e.g., light, substrate, nutrients) in addition to the population components. Examples of ecosystem models include plankton population dynamics, food web models, models of estuarine systems (e.g., Narragansett Bay model), and eelgrass or kelp bed community structures.

Eutrophication models are perhaps the most advanced modeling tools for restoration decisions, and as such have been given a unique sub-classification. Eutrophication affects rivers, lakes and estuaries receiving enrichment from urban sewage effluent and/or industrial discharges that have experienced massive phytoplankton blooms. Those blooms lead to secondary problems ranging from aesthetically unpleasant visuals and odor at the sites, to fish kills, or rendering drinking water supplies unsuitable. Urban economies are often associated with eutrophication, which has lead to the development of a number of good cost/benefit analysis models.

The U.S. Fish and Wildlife Service has been actively involved in the development of models for evaluating the characteristics of a habitat *vis-a-vis* life-cycle requirements of species of interest. These models have been formalized as habitat evaluation procedures

(HEP), habitat quality indices (HQI), and habitat suitability indices (HSI). HEP is essentially an ecological valuation technique that uses both quantitative and subjective valuations or weighting of environmental variables to arrive at an overall rating of a site as habitat for target species. This approach has been widely used as a means of evaluating resource management options, including mitigation or restoration.

Management of commercial and recreational fisheries through the use of mechanistic models has become a sophisticated science producing a number of well calibrated and verified models. As a management science, commercial fisheries offers many project elements that are applicable to restoration management. Models are used that incorporate abiotic factors, food chain interactions, perturbations, and other elements to produce an estimate of harvestable quantities with confidence limits and defined uncertainties. The resources are managed by comparing actual harvests to modeling predictions.

During the literature reviews, models were identified that linked marine or freshwater-dependent bird populations with abiotic and biotic factors in wetlands or marine environments. Since providing suitable habitat for avian populations may be a goal of some aquatic restoration projects, these models were included as a sub-class.

Additional Non-Category

"Other" was a class created for articles or references that may be of use to resource managers engaged in restoration analysis, but did not fit into any other classification. A number of interesting and pertinent articles were identified that dealt with the actual construction, of mechanistic models. For the ambitious resource manager that may chose to build his/her own models to describe unique environs, these reviews may be useful.

Review was reserved for articles that reviewed model techniques that were outside of other classes. As an example, an excellent review was found that relates how to incorporate data collected from airborne close-range sensing with modeling and environmental assessments. Another review dealt with assessing the effects of climate change on stream environments in the Columbia Basin.

Finally, a sub-class was created for articles we could not neatly put anywhere else, simply called "other" for articles or models applicable to the restoration analysis process. Examples included in this category are articles that dealt with management of large-scale environmental modeling projects, or a dynamic model for wave-induced light fluctuations in a kelp forest.

Model Structure

To facilitate discussions in subsequent chapters, some comments on model structure are warranted. Three general structure classifications are recognized: conceptual, physical, and mathematical. Conceptual models are those ideas or concepts that can be expressed in verbal or symbolic terms. Physical models are physical representations in the laboratory of the system to be studied. Mathematical models are single, or series of equations representing the actions of a systems elements. These are further defined, with examples of their application, below.

Conceptual Models

Frequently the first step in defining a restoration problem is its expression in verbal terms. Seeking the most precise verbal description that we can find of the problem forms the framework by which the problem is bounded. Indeed, some systems analysts explicitly recognize “word models” as an essential preliminary to the modeling phase (Jeffers 1978). We previously used a conceptual model to describe restoration analysis and management (Figure 2-1), and that framework serves as the skeleton upon which to construct this treatise.

The necessity of formulating conceptual models prior to embarking upon a restoration project cannot be overstated. It is generally the exception that two or three resource agencies involved in a restoration project will agree with each other’s descriptions of the important elements of the same system; disagreement on the particular elements of a system which contribute directly, or indirectly, to the problem is more likely. For larger groups with more complex problems, the disagreement may be both striking and difficult to resolve. Under those circumstances there is all the more reason to invest the time in an attempt to find an agreed upon conceptual model, even if that model contains some elements, expressed as alternatives, for which no agreement can be reached. Such a description may well help in the phases of definition and bounding of the extent of the problem and identification of the hierarchy of goals and objectives.

One example of the role of conceptual models in restoration is the use of the Delphi technique for developing Habitat Suitability Index Category I curves. HSI defines three levels of curves for use in habitat definition: Category I has the least amount of species-specific data; Category III has the greatest amount of data from which to formulate habitat preferences. Category I curves are used in the IFIM when little or no empirical data exists on a species habitat preferences. The Delphi technique is a strategic planning exercise, originated by the Air Force, that has been used to develop expert-opinion-based HSI curves for some fish species (Crance 1987).

Conceptual modeling has applications in virtually all aspects of restoration planning, design and execution. Berger (1991) describes a theory-based evaluation model used to assess large, complex, multi-attribute environmental restoration and conservation projects. Young and Gray (1985) used a conceptual component based on a “willingness to pay” concept to provide a formula for estimating direct economic benefits of state water development plans using input-output models. Vietinghoff *et al.* (1989) present a short list of restoration methods for eutrophied estuarine waters and describe 2 computer-based methods to assist in the decision process. Both conceptual and mathematical models were combined in order to identify the restoration method that shows best ecological results associated with a minimum of costs using scenario analyses and optimization techniques. Shields and Abt (1989) applied conceptual and mathematical modeling to stream cutoff bend management. Cutoff bends along modified, stabilized streams often constitute a valuable recreational, ecological, and aesthetic resource. However, the resource value rapidly declines as the bends fill with sediment, and new cutoff bends do not form to replace them in highly managed rivers. Using existing hydrographic data, these investigators provided modeling outcomes to predict the condition of cutoff bends under different management scenarios.

Physical Models

Physical representations of aquatic systems in the lab can yield important information concerning the behavior of a water body over time. Physical models have been constructed to examine such diverse problems as shoreline erosion (Bottin 1990), urban stormwater runoff (Borchardt and Statzner 1990), and turbine intake fish diversions (Odgaard *et al.* 1990). In a unique application relevant to a restoration problem, the extent of mature willow trees to be tolerated in the restoration of the river corridor along the River Enz in Germany was determined using a physical model (Larsen 1993). Larsen noted that the advantage of physical model tests for measuring resistance to river flow by natural vegetation is that the model reproduces the combined effects of channel curvature, branching channels, patches of vegetation, etc. Mathematical models cannot effectively account for the complexity involved in these types of systems.

Mathematical Models

Mathematical or numerical models are what generally comes to mind when the word "model" is mentioned in resource planning, and indeed embodies the bulk of the models that we discuss in this document. The utility of mathematical models is in their ability to define a system as a series of mathematical expressions. By following the various mathematical rules for manipulating the relationships, predictions of the changes that we may expect to occur in physical or ecological systems as various component values of these systems are changed can be derived. These predictions, in turn, enable us to make comparisons between our model systems and the real systems which they are intended to represent. Precise, well calibrated and verified models, along with the power of modern computers, allow modelers to provide the outcome associated with competing alternatives in a form that can be evaluated by the resource managers.

It will be repeatedly emphasized throughout this document that all models are only representations of our perception of reality. Mathematical models of any system can be considered valid only to the extent that the data, assumptions and equations describing the operation of the components of the model accurately describe the operations of the components of the real system. Model limitations will be described further below and in Chapter 3.

Statistical Models

Statistical models attempt to derive generalizations by using probability distributions, regression, principal components analysis, and other statistical techniques to summarize experimental or observational data (Suter 1993). A comprehensive review of the methods and techniques is beyond the scope of this discussion. Excellent references for conducting statistical analyses include Sokal and Rohlf (1984) and Zar (1984).

Probability distributions are a means to compare expected frequencies of an event or system with actual observations. Probabilistic phenomena for water resource managers include rainfall, evaporation, streamflows, and temperature. By fitting a probability distribution to the observations, frequency analyses can then be performed. Examples include frequency analyses for 25, 50, or 100 year flood events, examining patterns of rainfall distribution, or trends analyses for stream or river flow. Biological modelers may also use probability distributions to examine relations between expected and actual observations in community structure. Jackson *et al.* (1992) used probability estimates to relate fish communities in lakes from five regions of Ontario and determined that the observed assemblages were nonrandomly structured. Their models evaluated pairs of species according to departures from null or random co-occurrence expectations.

Regression techniques examine functional dependency between two or more variables; that is, the magnitude of one of the variables (dependent) is assumed to be determined by the magnitude of the second (independent) variables, whereas the reverse is not true (Zar 1984). Prediction of a system behavior or a species behavior is a frequent application of multiple regression. For example, predicting fish habitat preferences (Gibson 1993; Angermeier 1992; Boezek and Rahel 1992), patterns of wetland uses by species of birds (Gibbs *et al.* 1991), lake water quality associated with algal assemblages (Kemp *et al.* 1992), or to relate species richness of rare plants to measured habitat variables (Hill and Keddy 1992).

Where multiple variables may interact to define complex species assemblages or guilds, ordination techniques may be more appropriate than regression. Ordination techniques tend to be more descriptive than predictive, but can be useful for defining expected changes in biological communities in response to perturbations. For example, Hupp (1992) used binary-discriminant and ordination analyses to define distinctive riparian-species patterns reflecting a six-stage model of channel evolution and was used to infer channel stability and hydrogeomorphic conditions after channelization to West Tennessee streams.

Deterministic Models

Deterministic models are rigid models that given a certain starting point, the outcome of the modeled response is *determined* and is predicted by the mathematical relationship incorporated in the model. These models predict outcomes as single values, that is without variability.

Deterministic models have a role in restoration planning and management. Janse and Aldenberg (1990) describe a computer model, PCLoos, which is a dynamic, deterministic model written to simulate the phosphorus cycle and plankton growth in the shallow, hypertrophic Loosdrecht Lakes (The Netherlands) before and after restoration measures. Both the water and the upper sediment layer are modeled. The model comprises three algal groups, zooplankton, fish, detritus, zoobenthos and upper sediment (all modeled both in carbon and in phosphorus) besides inorganic phosphorus in both the surface water and the interstitial water.

Habitat quality indices (HQI) are deterministic models, which will be examined in detail in Chapter 5. A limitation of the HQI, is in the precision associated with the variables that feed into the model. Hoggle *et al.* (1993) assessed the precision of the HQI model II for rating habitat quality in trout streams and predicting fish standing stocks. Precision depends on the ability of observers to generate similar input values, and in evaluating three 50-m stream reaches by three teams per reach, among individual attributes, measurements of cover and eroding bank had the greatest variability.

Stochastic Models

Real environments are uncertain, or stochastic (May, 1974). Models which incorporate probabilities are known as stochastic models, and have particular value in simulating the variability of complex systems. Predicted values for stochastic models depend upon probability distributions.

Stochastic models have the greatest opportunity to meet the objectives of this document; that is to provide a probabilistic estimate of the success of a proposed restoration effort.

Adams and Berg-Andreassen (1989) used a stochastic model to examine the cost/benefit ratio, with range distribution, of a controversial channel project in the Vermillion Bay area of coastal Louisiana. A hydrodynamic and economic model study was undertaken to examine the environmental and economic issues with the ultimate goal of facilitating rational and objective management of available resources.

The above discussion should not be interpreted as implying that stochastic models alone can define success probabilities. In fact, many modeling efforts for resource management rely on all types of modeling. Basco (1988) provides an excellent review of how deterministic, analytical, physical or numerical models can be combined with stochastic methods to synthetically generate probability statistics for the dependent variables in a river-estuary-coast (REC) system. Defined as the "joint probability method", it has been utilized by coastal engineering firms to develop coastal flooding maps of most of the United States coastlines in recent years and can be used to provide computations of annual solids washoff and sediment budget in a watershed.

3 MODEL SELECTION PROCESS

Selection of an appropriate and suitable model(s) is perhaps the single most important decision the model user will make, generally at the early stage of planning a restoration process. Care must be taken to ensure that the model is appropriate for the task at hand, that the model provides output in a form that is useable in the decision process, and that the model has been both calibrated and validated.

While this document emphasizes the selection and use of existing environmental models, it may be more practical or important to write project/system-specific models. Jeffers (1978) cautions that "mathematical modeling is an intoxicating pursuit, so much so that it is relatively easy for the modeler to abandon the real world and to indulge him/herself in the use of mathematical languages for abstract art forms". There are numerous excellent general guides to model construction in the literature, including Thomann (1982), Orlob (1975), Hall and Day (1977), Jeffers (1978), Armour (1988), and Schroeder and Haire (1993).

In many ways, selecting a model is similar to the process of constructing a model. As shown in Figure 3-1, goals are first set for the project, the model processes are conceptualized, and then the constraints of time, space, and data are placed on the type of model that can be selected. All models should be calibrated and verified prior to application. Each of these model selection and application 'subtasks' will be discussed in more detail below.

Within the restoration modeling paradigm described previously in Chapter 2, the model selection and application procedures are a subset of the planning, data compilation, and model simulation steps. While Figure 3-1 suggests that the process represents discrete linear steps without feedback loops from subsequent steps, the subtask boundaries are in fact blurred, and there is often the potential for stepping backwards. Setting goals, objectives, and conceptualizing

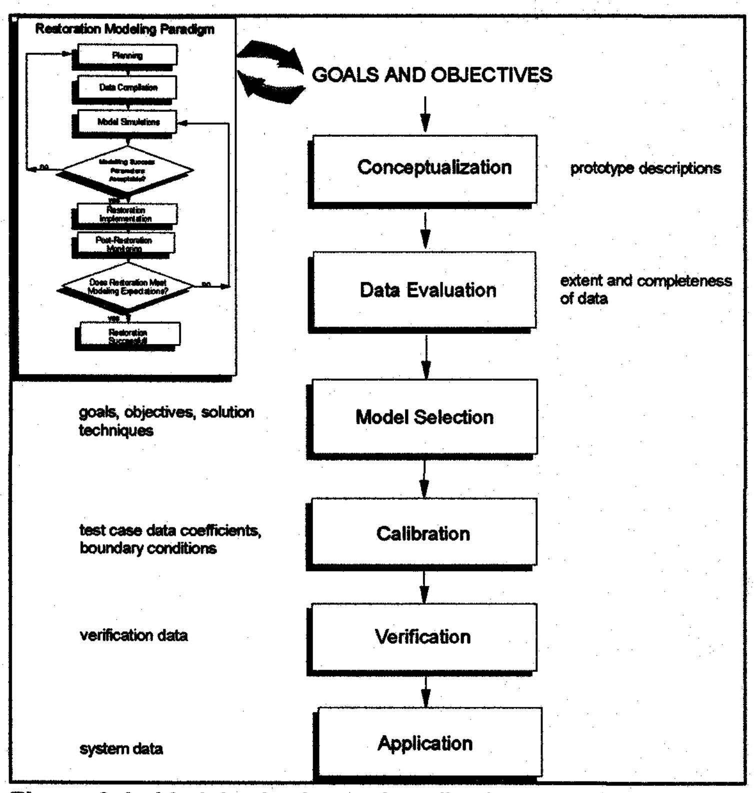

Figure 3-1. Model selection and application procedures

often are accomplished in tandem by resource planners and managers. Evaluation of the existing data sets will affect the model selection process, but also may require re-evaluation of the goals and objectives. The goal setting to model selection steps may proceed smoothly, but model failure during the calibration and/or verification steps could require examining any or all of the steps taken prior to model selection.

Goals, Objectives, and Conceptualization

In the model selection process, the first task should be to set the goals and objectives for the modeled system. A goal statement is usually what the model is to be used for rather than what explicit form it will take (Orlob 1975). Goals should be formulated in a fashion that can provide decision criteria to the restoration decision makers. For example:

> "The model output will provide cost/benefit ratios for evaluating construction of a salt marsh at Site A vs. Site B.

> "The model should provide information concerning the potential for flooding to occur in a constructed saltmarsh at Site A"

While these may seem trite to state, knowing what output is critical to the decision makers defines how a model selector/user proceeds. O'Neil (1975) has suggested that underestimation of the importance of objectives is a prime ingredient in the demise of modeling projects.

The model objective should be a more specific statement, formulated by the model user, that serves to define and bound the problem to be modeled. For statistical models, these are statements of the null hypothesis to be tested. For deterministic or stochastic models, these are commonly statements or definitions that describe what output will be required from the model. Suter (1993) calls these "operational definitions", and argues that without clearly stated operational definitions, the endpoints do not provide direction for testing and modeling, and the results of assessments tend to be as ambiguous as the endpoints.

Examples of problems associated with stating ambiguous, non-testable output for community-level habitat models are presented in a review by Schroeder and Haire (1993). They contrast the following two HSI output statements:

> "The guide evaluates the value of the wetland to fish and wildlife with wetlands capable of supporting a diversity of fish and wildlife species rating high."

> "An output of 1.0 represents a shelterbelt with the maximum year-round number of vertebrate wildlife species (wildlife species richness) to be expected for an individual shelterbelt, and outputs approaching 0 represent successively lower values of species richness."

In the first statement, what quantifies "diversity" is ambiguous. There are a number of important indices developed for expressing diversity; some representing the total number of species in an area ("species richness"), or others that attach relative importance to the species assemblage (e.g., the Shannon-Wiener index). In the second statement, the output as richness is clearly stated, and is thus testable.

Conceptualizing is the process of defining what are the important sub-units of the modeled system (Figure 3-2). This is typically a process engaged in by the model builders, but it may also be a useful exercise for a user who intends on selecting an existing model. Building the conceptual components model will be a function of the important components to be examined, and of the data available for the model. By constructing this conceptual model, the user can compare how his/her intended use compares to the model that has been selected, or at the very least provide a checklist of data input and output from the model.

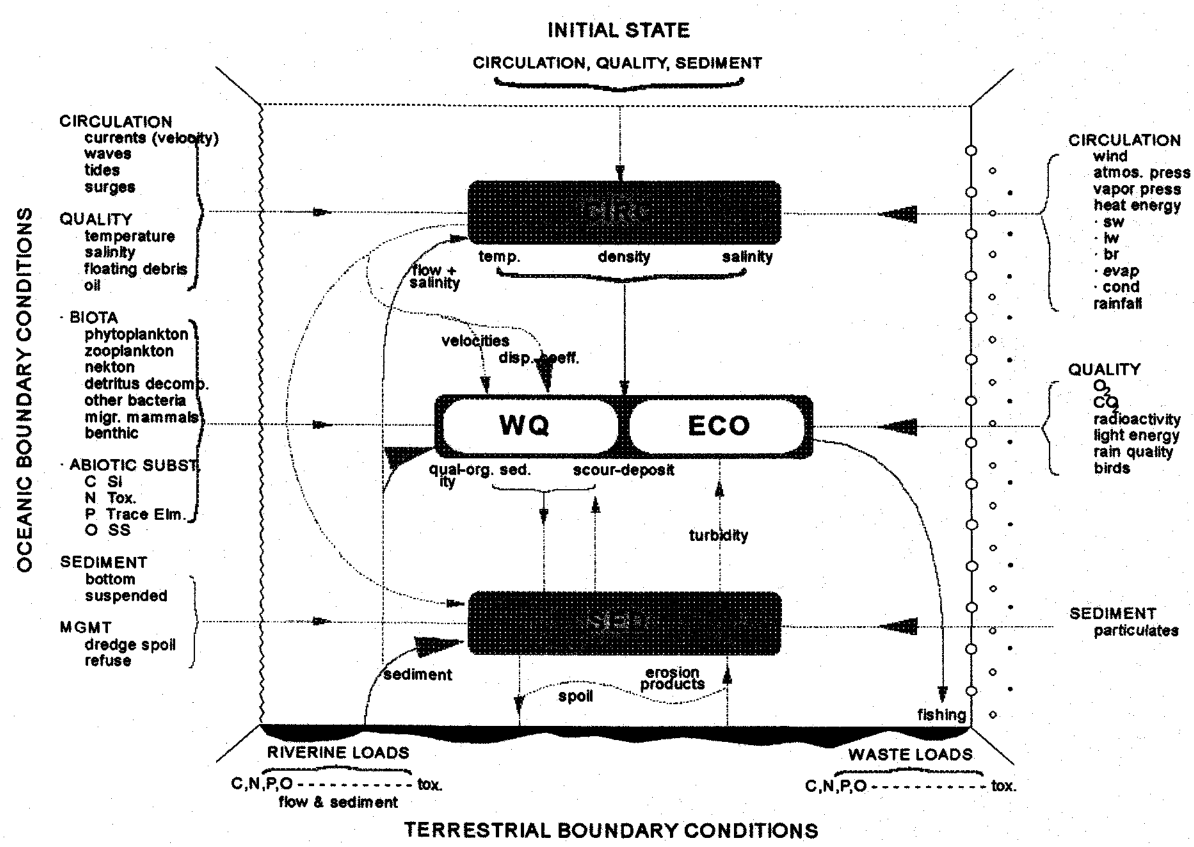

Figure 3-2. General conceptual model of a marine ecosystem (Orlob 1975).

Data Evaluation

The data available for the studied system will determine the selection of the model. Surprisingly, little attention is paid in the modeling literature to the importance of assessing the available data for both adequacy and accuracy. At least one author has stated that inadequate and insufficient data may be the most important factor influencing the utility and costs of using models (Gerber 1982).

Modelers are often faced with limited data, and hence are forced into large assumptions that increase the uncertainty of the output. However, concerted efforts can often lead to locating data in unlikely places. For example, during a review of sediment quality in the Gulf Coast states, we identified sources of data from EPA (Florida and Dallas), EPA's EMAP project, NOAA's Status and Trends, the USACE District offices as well as WES, state agencies, and the University of Texas, Austin. These were all evaluated and combined to form a single, large database. Many state and federal agencies now maintain databases on hydrologic conditions, physical rock or soil, biological communities, weather, recreational use, and a host of other topics that may be relevant to restoration monitoring.

With the advent of personal computers, and the diversity of sophisticated spreadsheet and database packages available, the data management and evaluation has become less the domain of university-related scientists with access to mainframe, sophisticated computers, and more accessible to resource managers and scientists. Powerful, user-friendly software such as Excel®[1], LOTUS®, or Quattro-Pro® provide ease of data entry, and contain statistical packages for basic data evaluation (e.g., F-tests, *t*-tests, heterogeneity of data), while more sophisticated database programs (e.g., Paradox®, Oracle®), or statistical programs (SYSTAT®, SPSS-X®, Statgraphics®, SAS®) allow for advanced data manipulation.

Where data are unavailable, it is common to apply assumptions concerning the numerical behavior of the components of the modeled system. Application of assumptions leads to less precision and confidence in the output from the model. However, making assumptions is frequently an unavoidable circumstance, and the only 'fault' that could be ascribed to a model user under these conditions is failure to adequately document where and why the assumptions were made in the model. Fully documented and justified assumptions may then be included in the uncertainty evaluation of the output by the decision makers.

[1]The spreadsheet and statistical packages named here are registered trademarks of their respective parent companies. Mention of trade-names is not intended as an endorsement of any single product.

Model Selection

Fawthrop (1994) notes that models are "tools of the trade" for many aquatic system scientists and decision makers, and like tools in any profession they must be robust, effective and easy to use.

A set of general guidelines for selection and application of water quality models, listed in Figure 3-3, was first proposed by Grimsrud *et al.* (1976), and then expanded by Crabtree *et al.* (1987). The bullets identified under item 1 are essentially equivalent to the discussions of goals, objectives, and data above. We would argue, however, that stating the required level or precision or confidence *a priori*, as bullet four suggest, places an undo burden on the selection process. While the model user should always maintain an awareness of precision and confidence in the model, an actual assessment will not be possible until after the selected model has been calibrated, and verified with the user's data sets. The elegance of this checklist is reflected in items 2 and 3. The message of 2 is that bigger is not better, and that the user should not get caught up in the modeler's elegant artistic expressions, as Jeffers cautioned. Item 3 is a reminder to always question the output, and to place limits on the interpretation of the output.

1. Define the problem and determine:
   - What questions need to be answered.
   - What information is required.
   - What information is readily available.
   - What is the required level of precision and accuracy or degree of confidence in the results.
   - Identify what modeling and control options are available.
2. Apply the simplest model that can provide the answers:
   - Select or develop a model that fits the problem, not a problem that fits the model.
   - Use the least sophisticated model that will provide the required level of accuracy.
   - Do not confuse model complexity with accuracy or precision.
   - Always question whether increased accuracy is worth the increased effort and cost.
   - Assess the model sensitivity.
3. Evaluate the results and implications of the predictions produced by the model:
   - Consider the implications of any modeling assumptions.
   - Consider the implications of the degree of confidence in the results.
   - Assess the value of the results.
   - Reassess, in the light of the results, the suitability and relative significance of the available options.
   - Do not read more significance into the simulation results than is actually there.
4. Make recommendations or decisions.

Figure 3-3. Guidelines for the Selection and Application of Models (adapted from Grimsrud *et al.* 1976 and Crabtree *et al.* 1987).

A similar checklist of desirable features for community-level habitat evaluation models was proposed by Schroeder and Haire (1993). Their list included:

1. *Clearly defined testable output:* the model output is clearly defined and can be tested against a specific community attribute.

2. *Model tested with empirical data:* some portions of the model have been, or there are opportunities, to adequately test the model.

3. *Documentation of sources of information:* the sources of information for development of the model hypotheses are clearly identified, adequate citations are provided for published sources, and that sources are provided to check unpublished data.

4. *Clearly stated assumptions and limitations:* the model must adequately describe the assumptions used to develop hypotheses and model relations, and should contain an adequate discussion of model limitations.

5. *Clearly defined variables:* for each variable included in the model, there should be an unambiguous definition such that measurements of the variable result in repeatable data.

6. *Adequate verification of model performance:* sample field setting data sets for the model should be available for evaluation. The model should provide reasonable outputs for the intended area of application.

7. *Multiple levels of resolution:* the model provides for more than one level of resolution, and the levels of resolution are meaningful for the intended applications and data availability.

Model Calibration and Validation

Both calibration and validation are tests of the applied model; data are used to generate output, which is then compared to actual field measurements of the modeled output. Calibration may be thought of as "tweaking" or "tuning up" the model to produce output that meets some defined acceptance criteria when compared to actual field output. While there is not a standard acceptance criterion, Thomann (1972) has proposed 10% as a goal for calibration. During calibration various model parameters or coefficients are adjusted, and the effect on output is examined. During this stage, a sensitivity analysis of the parameters can demonstrate what factors can have the greatest effect on model output.

Validation of the model proceeds with the calibrated model, and a different set of field values to produce output that theoretically should be predictive of actual conditions. To validate, the simulated model values can be compared with field data using graphical and/or statistical techniques (e.g., *t*-tests). The calibration and validation steps principally are used for simulation models, are less applicable to statistical or conceptual models, such as HSI.

Model Uses and Limitations

Models are *representations* of real systems, and never should be confused with reality itself. Real systems are too complex to model completely, so inevitably we make assumptions that simplify our mathematical evaluations. Even when well calibrated, models predictions are only "snapshots" of the historical data which have been used to generate the output, and thus cannot be thought of as completely predictive for all scenarios.

Fawthrop (1994) cautions that the reliability of model results depends upon a great many contributing factors. His list includes: the soundness of the underlying theory; the skills of the modeler in translating theory to a computer program; the quality of the input data; and the applicability of the technique to the issue in hand. When models are used as decision-making tools, then the users of the results are *de facto* decision makers.

It is a common problem of model users to read more significance in the modeling results than is actually there. For example, in using statistical models, it is important to remain aware that correlation does not necessarily imply causation. Rexstad *et al.* (1988) were able to show statistically significant relationships between deliberately selected disparate data sets (e.g., meat prices, student grades, telephone numbers, pitching earned run averages) using principal components analysis, canonical correlation analysis, and discriminant function analysis. If these multivariate techniques can lead to obviously erroneous correlations between pitching ERAs and hamburger prices, how do we interpret the results when the variables are less disparate. If variables are more closely related (logically or intuitively), it is more likely that the model user would believe the output. It is hard to provide guidance about what to believe and what not to believe, short of encouraging the user to ensure that the quantitative model is supported by a thoughtful conceptual model.

Despite the numeric output, there is still room for professional, scientific subjectivity in examining the output of any model. Models are not true or false; they merely possess different degrees of usefulness (O'Neill 1975). When thought of as maps of reality, then when the map functions as expected, we can proceed to build toward further understanding. When the system does not function as we expect, we may use the results to formulate questions concerning our beliefs on how the system is functioning. This is difficult because if the model reflects our view of reality, we are inclined to have confidence in it; on the other hand if the model outputs results we consider unrealistic, we may disbelieve it. The real value of the model is its usefulness as a tool for organizing thoughts, information, and for formulating questions.

Delete ?

4 HYDROLOGIC MODELS

Discussions of aquatic systems begins with a simple premise: water in, water out. But what that water does while it resides in the specific area of concern has been the subject of study since as early as ancient Mesopotamia, and has been commented on by the likes of Plato, Aristotle, and DeVinci (Chow *et al.* 1988). Models have been developed to predict how much water will move in and out of a system, how fast it moves within the system, the sediment carrying capacity, contaminant translocation and diffusion, how motion can be controlled and volumes contained, and the net effect of all of the above on organisms living within.

Hydrophysical processes dominate the discussion in this, and the next two chapters; water quality and sediment transport. Our focus in Chapter 4 is on the volumes and movement (force and velocity) of water, as these factors ultimately influence the biological communities. As has been the case throughout this document, it is not our intent to provide an in-depth discussion of hydrophysical modeling, but to provide a basic information to the lay person on the field, and then provide examples of the use in restoration projects. A detailed review of hydrophysical models in environmental management is given by Fisher (1983), Mays and Tung (1992), and Singh (1995).

Hydrologic Cycle

The basis of hydrology is the so-called hydrologic cycle, which is shown in Figure 4-1. While this cycle may seem elementary, the conceptualization of inputs and outputs is germane to model construction and application in hydrology. Atmospheric water represents the processes of precipitation, evaporation, interception and transpiration. The surface water system includes the overland flow, surface runoff, subsurface and groundwater outflow. Finally, the subsurface water includes the process of infiltration, groundwater recharge, subsurface flow, and groundwater flow. The sum of the inputs, minus losses to interception, transpiration and evaporation, represents the volume of water available to an aquatic system.

Each of the conceptual sub-units of the hydrologic cycle can and has been modeled, and is of some importance to freshwater and estuarine restoration projects. As a general statement, the hydrophysical process we are most interested in is the volume and movement of water in restoration projects -- i.e., how much is available and how will it proceed through the restored system. To that end, we will discuss catchment simulations, and stream/river models. While lakes and estuaries are also important, restoration in those bodies is often tied in with eutrophication models; those models are discussed in Chapter 5.

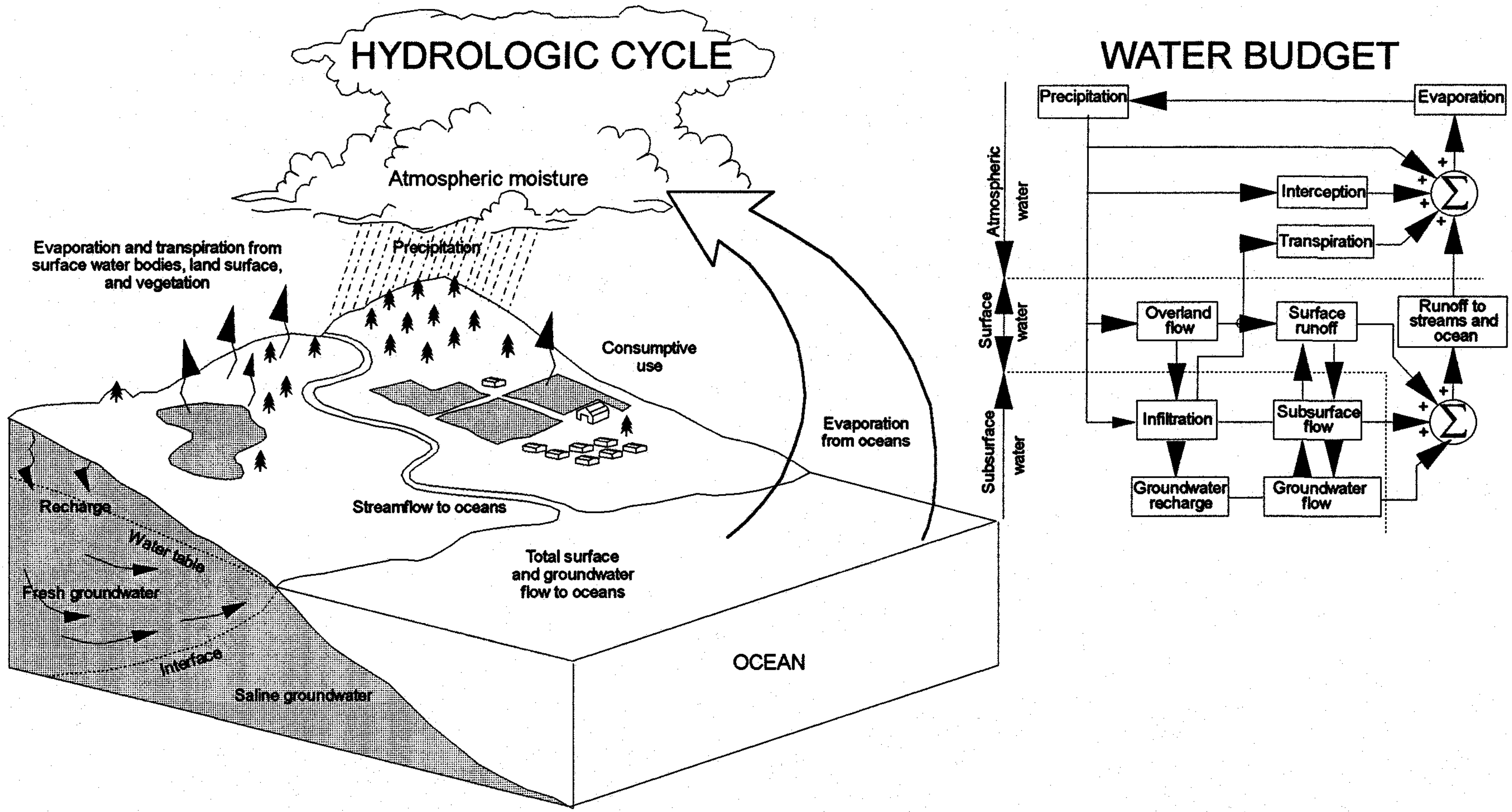

Figure 4-1. Diagrammatic representations showing the hydrologic cycle and water budget for an aquatic system. Water budget is from Chow *et al.* 1988.

Mathematics

Hydrophysical models are not recommended for the mathematically feint of heart. This is not to say that simple regression models or statistical analyses are not used in water management, they are. For example, regression equations of annual precipitation versus average annual streamflow, or water demand on a reservoir system versus annual population growth, can be used as a general tool for water resource management. However, the model sophistication escalates quickly into the realm of advanced differential calculus, linear and nonlinear dynamic projecting, matrix equations and probability functions which requires the skills of a trained professional. We recommend and endorse the consultation of water engineers in planning, executing, and interpreting hydrologic model results.

Catchment Simulations

The term *catchment* is used to describe a defined unit area that "catches" precipitation that contributes to the input of a specified water body. The term *watershed* is often a synonym with catchment. Catchment models simulate the land phase of the hydrological cycle, with the model output usually being a prediction of the balance of water into a reservoir, lake, groundwater, or river system.

Catchment models can operate independently, but more often are incorporated as a component of larger physical or ecological models. Catchment models are important modules in flood prediction/control models (Singh 1995), of reservoir system modeling (Wurbs 1993), storm water models (USEPA 1994), or pollution control (Boston *et al.* 1992). Newson (1994) describes four general objectives of catchment models:

- Predicting/forecasting the flow from a watershed
- Predicting spatial variability of response from localized precipitation
- Predicting the results of land-use change
- Predicting the movement of sediment/pollutants

For restoration purposes, catchment simulations are important in terms of predicting volumes of water; both during flood periods, and with low-flow periods. Models for small watersheds range from simple regression correlations of rain and outflow, to complex multi-compartment stochastic models that contain modules for all aspects of the hydrologic cycle.

With most of the major river systems in the United States being subject to some form of impoundment by dams, weirs, or otherwise, a discussion of catchments must necessarily include reservoir models. In a reservoir system, water-intensive restoration projects will compete with existing users for limited water supplies; several of the models discussed below have the capacity to predict not only the available water supply, but also determine the impacts on competing users within a watershed.

Habitat construction projects may need to consider the probability of a large flood event impacting, or eliminating, planned in-stream structures or modifications. The impacts of sediment transport, or pollution from watershed sources are covered in later chapters, but are important considerations in predicting success of a proposed restoration. Catchment simulations are especially important in eutrophication models.

Catchment Simulation Models

Virtually all federal agencies with a water concern have developed models of watershed hydrology (Singh 1995). This includes the U.S. Department of Agriculture, U.S. Army Corps of Engineers, EPA, U.S. Geological Survey, Bureau of Reclamation, National Weather Service, and the National Oceanic and Atmospheric Administration. Some of the more commonly used models are listed in Table 4-1. These projects tend to be generic in construction, and require tailoring, calibration, and validation for specific river/watershed systems. EPA's Hydrological Simulation Program - FORTRAN (HSPF) is an excellent example of a nationally-developed model which serves as the backbone for regionally-tailored modeling efforts. For example, the Kentucky Watershed Model is a continuous simulation model tailored to be more applicable to the climate and geography of Kentucky and other parts of the humid eastern portion of the United States. Additional examples of the utility of HSPF include the Texas Watershed Model, and the Fox River/Green Bay Mass Balance study (Wisconsin Department of Natural Resources 1994).

Reviews of watershed models are given by Fawthrop (1994), Mays and Tung (1992), Singh (1988; 1989; 1995), and Wurbs (1993). The comprehensive review of watershed hydrology by Singh is also accompanied by a compact disc containing some of the more commonly used watershed models (e.g., HEC-PRMS, HSPF, SSARR, and others). A brief discussion of some commonly used projects is given below.

One of the most comprehensive and commonly used/adapted models is HSPF, which is supported jointly by the EPA and the U.S. Geological Survey. The model was constructed to be able to simulate a continuous dynamic event, or steady-state behavior of both hydrologic/hydraulic and water quality processes in a watershed. Data such as the time history of rainfall, temperature, and solar radiation, along with land surface characteristics such as use patterns, soil properties and land management practices, are used to simulate the processes that occur in a watershed. The result of this simulation is a time history of the quantity and quality at any point in a watershed--the inflow to a lake, for example. Flow rate, sediment load, and nutrient or contaminant concentrations can also be predicted. Detailed information on the model structure is given in Bicknell *et al.* (1993), and an excellent overview of HSPF may be found in Donigian *et al.* (1995).

Applications and uses of the model include flood control planning and operations, river basin and watershed planning, water quality planning, soil erosion and sediment transport studies, and fate/transport of nutrients and toxic substances in a watershed. Modules have been added to the HSPF frame that allow for examination of a wider variety of functions. Module examples include a pre- and post-processing data management capability called ANNIE, a module that examines effects from acid mine drainage (ACIDPH), and a sediment-nutrient interaction module (RQUAL) that was developed for the Chesapeake Bay project. HSPF is a public domain product that can be obtained through EPA's office of Center for Exposure Assessment Modeling (CEAMS) (Table 4-1).

Reservoir-system simulation models are a well developed and tested discipline that incorporate catchment modules, but also generally include demand and/or optimization functions. Reservoir models generally incorporate some mechanism for making period-by-period release decisions within a framework of user-specified operating rules and/or criteria functions. Comprehensive reviews of reservoir models are given by Wurbs (1993). Catchment computations may be directly incorporated in the reservoir model, or more commonly are written as separate modules with the computed inflows being provided as input to the reservoir model.

Probably the world's foremost hydrologic model development laboratory is the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC). HEC has built a series of hydrologic system forecast models that range from flood prediction and control, to reservoir operational models and downstream control of water quantity and quality. Most relevant of the family of HEC projects to the catchment discussion is HEC-5, Simulation of Flood Control and Conservation Systems. HEC-5 simulates the sequential operation of reservoir systems for flood control and conservation purposes, at time intervals ranging from one minute to a month. Reservoir simulations can be run to evaluate input into the reservoir system, potential downstream flooding, evacuation needs for flood control storage in the reservoir, predict low flow requirements and diversions and meet hydropower requirements. A variant, HEC-5Q, incorporates a water quality prediction module. Water temperature, three conservative and three nonconservative constituents, dissolved oxygen and phytoplankton simulations can be conducted. Using HEC-5Q, water quality release requirements at both the site and downstream control points can be simulated. Multiple reservoirs on a system, and up to forty control points and any length of study period can be simulated on hourly, daily, or monthly intervals. Upstream inflow and quality are routed through the reservoir and the minimum allowable discharge for all downstream needs is computed. The discharge and all intervening local inflow (e.g., tributaries) are routed to all control points downstream of the reservoir (HEC 1995).

Other examples of HEC models relevant to this discussion include the Prescriptive Reservoir Model (HEC-PRM) program which represents reservoir operation as a network-flow programming problem with flow, release, and storage decision variables. Reservoir Yield (RESYLD) simulates operations for a single reservoir with controls at the reservoir and one downstream control point. Operation is for water supply, power, water quantity and water rights, taking account of flood control and other storage restrictions at the reservoir, quantity and quality of inflow to the reservoir, evaporation, quantity and quality of local inflows downstream and channel and outlet capacities, as well as project requirements (HEC, 1995).

The Streamflow Synthesis and Reservoir Regulation (SSARR) model is another USACE-developed program that has been widely applied to controlled river systems. Originally developed by the Corps' North Pacific Division for planning, design and management of the Columbia River system, the model has undergone refinements in conjunction with the Northwest River Forecast Center of the National Weather Service (Speers 1995). The model simulates precipitation inputs, has relatively simple mathematical routing and reservoir functions. The lack of mathematical complexity should not be interpreted as lack of utility -- this simple, elegant model has proved very useful for Columbia River planning, and in a wild rice restoration project in upper Minnesota (discussed further below).

Selection Considerations for Catchment Models

Scale is a substantive issue in hydrological modeling; the user should consider the practical and analytical differences for catchment models designed for 10 km^2, 100 km^2, 10,000 km^2, and so on (Newson 1994). Furthermore, the importance of spatial variability should be considered. The user should pre-determine if a *lumped* representation of all the water sources into a single output is appropriate, or if a *distributed* representation of the spatial variety of rainfall, snowpack, soils, slopes, channels, etc., is more critical in determining a restoration project's possible success.

The type of model is an important consideration that the user should be aware of. Many of the simpler models are single event models (HEC-1, TR-20). Continuous simulation models (HSPF, SWMM) are used when a long-term accounting for all runoff components, including both surface flow and indirect runoff (interflow and groundwater flow), is required. These models account for the overall moisture balance of a watershed on a long term basis and therefore are suited for long term runoff-volume forecasting. If water quality predictions are important, then the model should incorporate these as modules.

Internet Resources for Catchment Simulations

An excellent resource for hydrologic catchment models is the Internet. The actual hydrographic models, supporting information, sources for data, examples of model use in environmental projects, and links to federal, state, local, and international agencies with an interest in hydrologic modeling can all be accessed via the personal computer. Table 4-2 provides some federal, state, and university-sponsored home pages that can be accessed for models and model applications, or may be accessed for further information or links to other water resources.

The Internet is also a source for information on development of new hydrological models, or applications of existing models. For example, NOAA's Great Lakes Environmental Research Laboratory is developing an ambitious Coupled Hydrosphere-Atmosphere Research Model (CHARM) from existing atmospheric and hydrologic models that will examine the interactions between the Great Lakes and regional weather patterns(www.glerl.noaa.gov). The Corps' Construction Engineering Research Laboratory (CERL) has a home page for the GIS-based Geographic Resources Analysis Support System (GRASS). GRASS integrates spatial interpolation with image processing and map production to produce 2-D, 3-D, or animated graphical support. The GRASS home page (*softail.cecer.army.mil/grass/GRASS.main.html*) provides links to examples of the integration of monitoring data and modeling from the Chesapeake Bay project, and the environmental restoration project on White Oak Creek and the Clinch River at Oak Ridge, TN (Fontaine 1991).

Examples of Catchment Simulations In Restoration Projects

Catchment models have an established history in the study, and restoration of, eutrophic lakes or reservoirs. The ability to track and to predict the volumes of water, along with the accompanying nutrients from a watershed system into small lake, reservoir, or estuary is essential to restoration processes.

As discussed previously, the Chesapeake Bay model, has been tailored and calibrated to the geographic and biological conditions of the Bay. The model is used to identify and quantify nutrient loads in the Chesapeake Bay basin in order to support the 40 percent reduction goal of the Bay Project.

Catchment models have been used to simulate what conditions were like in an impacted system prior to human intervention. This approach is a conceptual *Field of Dreams* -- if you build it they will come-- the justification is that when hydrologic conditions are returned to pre-restricted conditions, biological restoration will naturally follow. For example, Walters *et al.* (1992) used hydrological simulation models that were developed to reconstruct what conditions may have been like in the natural pre-drainage Everglades catchment. Their modeling objective was to define conditions for ecological restoration of nesting populations of wading birds and concentrated on re-establishing more natural seasonal hydro patterns in freshwater marsh areas now used extensively by the birds. The *Restoration of Dreams* approach to hydrologic simulation is also central to the Riverine Community Habitat Assessment and Restoration Concept as defined for the Missouri River system by Nestler *et al.* (1993).

In an interesting application of catchment data and flow prediction modules to restoration of salmonids to the Columbia River system, the USACE examined the possibility of constructing a new dam with the intended purpose of impounding sufficient water to augment downstream flows. The proposed Galloway Dam on the Weiser River in Idaho, would store water to augment flows on the Snake and Columbia rivers from Hells Canyon Dam to the Pacific Ocean to increase the downstream survival of juvenile salmon, *Oncorhynchus* spp., and steelhead *Oncorhynchus mykiss*. The Corps used a linear, multiplicative, computer model (FISHBEN) that incorporated fifty years of past flow data to predict future flow conditions. Juvenile fish populations and their survival through river reaches, reservoirs, dams, transportation, and in-river fish passage were predicted and used to estimate overall fish survival. Adult returns were predicted, and economic values based on potential harvest were used to estimate monetary fishery benefits.

The USDA Natural Resource Conservation Service (formerly Soil Conservation Service) used the Streamflow Synthesis and Reservoir Regulation (SSARR) hydrologic model to forecast a system of lake level control in the Upper Otter Tail River Basin, Minnesota to improve the wild rice growing environment at the White Earth Indian Reservation (SCS, 1990). The model prediction was used to control water levels through a series of manual control structures on the lakes.

Uncertainty in Catchment Simulations

Any discussion of uncertainty associated with output begins with an examination of the model structure and the ability to calibrate, validate, and conduct sensitivity analysis on the model and its inputs. Most of the models listed in Table 4-1 are well documented and have a long history of successful calibration and use. This is especially true of HSPF, and for any of the HEC models. For new or lesser-known models, procedures for calibrating watershed models is given in Sorooshian and Gupta (1995). Calibration and validation require data with which to conduct the checks; catchment simulations are generally in the unique position of having long-term stream or river flow data sets. Sources for data may be found by accessing some of the Internet address discussed above.

River/stream Channel Models

We move from the discussion of water into the system, to a discussion of how that water moves through rivers and streams. We distinguish hydrology as the study of volumes and how water moves through a system, and hydraulics as the physical force exerted by water and its effects in terms of velocity, depth, and substrate. Hydrologic modeling is an important component of determining whether a base streamflow is sufficient for maintaining acceptable fish habitat, and/or predicting the response of fish habitat to naturally occurring, or human-induced, changes in streamflow, temperature, sediment transport, or water chemistry (Stalnaker *et al.* 1994). Hydraulic modeling is an important predictor of effects of in-stream construction. Numerous models have been developed to predict the effects of construction/alteration of weirs, embankments, and flood channel control structures on aquatic habitats. As we will discuss in Chapter 5, Statzner *et al.* (1986; 1988) have developed the concept of "hydraulic stream ecology" - that the structure and function of most aquatic communities is tied to the stability or predictability of hydrological patterns and instream hydraulic conditions.

River/Stream Simulation Models

The precepts and concepts discussed for catchment simulations are also applicable to rivers and streams, and indeed the models discussed above double as river/stream models, or are important precursors to these simulations programs. HSPF or SSAR are examples.

The HEC has produced a number of hydrologic and hydraulic models that could be applied in river/stream restoration projects. A few of these are discussed briefly below, but we recommend a visit to the HEC Home Page on the Internet for a complete description of the many useful utilities offered by HEC.

HEC-2, the Water Surface Profile program, computes water surface profiles for one dimensional steady, gradually varied flow for rivers of any cross section. Separate subroutines are available for modifying input cross section data that may be useful for in-stream restoration; for example, for locating in-stream structures or inserting excavations on cross sections. The water surface profile through structures such as bridges, culverts and weirs can also be computed. Variable channel roughness and variable reach length between adjacent cross sections can be accommodated.

HEC-RAS, the River Analysis System, is a more complex system than HEC-2, that was principally designed for use in flood plain management and flood insurance studies to evaluate floodway encroachments. Like HEC-2, it is intended for calculating water surface profiles for steady gradually varied flow. However, HEC-RAS can compute output for a full network of channels, a dendritic system, or a single river reach under subcritical, supercritical, or mixed flow regime water surface profiles. The effects of various obstructions such as bridges, culverts, weirs, and structures in the flood plain may be considered in the computations. HEC-RAS could have restoration applicability for projects located within the flood plain; for example oxbow lakes. The model is described as an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.

TABLE 4-1. CATCHMENT MODELS

MODEL	OUTPUT	COMMENTS	SOURCE
Hydrologic Simulation Program - Fortran **(HSPF)**	• Flow regimes/runoff • Sediment transport • Water quality • Flood peaks/volumes	HSPF is a modular, stochastic, model that allows continuous simulation of complex watersheds, with multiple land uses, point and nonpoint contaminant sources, networked channels and drainage patterns, and lakes and reservoirs.	U.S. EPA. , Center for Exposure Assessment Modeling 960 College Station Rd. Athens, GA 30605-2720
Hydrologic Engineering Center - 5 **(HEC-5)**	• Water Supply	HEC-5 is a widely used reservoir model that simulates operation of a system of reservoirs in a river network for flood control, water supply, hydropower, and instream flow maintenance for water quality.	U.S. Army Corps of Engineers, Hydraulic Engineering Center 609 Second Street Davis, CA 95616
Precipitation-Runoff Modeling System **(PRMS)**	• Flow regimes • Flood peaks/volumes • Sediment yields • Groundwater recharge	PRMS is a modular-designed, distributed-parameter, physical process watershed model designed to evaluate various combinations of precipitation, climate, and land use on watershed response.	U.S. Geological Survey Water Resources Division MS 412, Denver Federal Center Lakewood CO 80225
Watershed Modeling System **(WMS)**	• Flow regimes • Sediment loads	WMS provides graphical tools for stream definition, automated delineation of watershed and sub basin boundaries, or can be used to delineate flood plains. Model is developed and maintained by the Engineering Computer Graphics Laboratory of Brigham Young University in cooperation with the USACE - WES.	Engineering Computer Graphics Laboratory Brigham Young University CB 300 Provo, Utah 84602
Streamflow Synthesis and Reservoir Regulation Model **(SSARR)**	• Rainfall-runoff • Storage routing • Streamflow Routing	SSARR simulates a river system from rain/snowmelt runoff to regulation of runoff through a river reservoir system. The model predicts response of a watershed to precipitation, actions of the river as the water flows through it, and the effects of engineering structures such as diversions and reservoirs.	US Army Corps of Engineers North Pacific Division Hydrologic Engineering Branch P.O. Box 2870 Portland, OR 97208-2870

TABLE 4-2. INTERNET SOURCES OF MODELS, DATA, AND GENERAL INFORMATION RELATING TO CATCHMENT STUDIES

INTERNET HOME PAGE	NET ADDRESS	HOST	RESOURCES
Hydrologic Engineering Center	wrc-hec.usace.army.mil/software/software.html	U.S. Army Corps of Engineers	• Hydrologic software • Data Storage Systems • Flood Planning analysis • Reservoirs • River Hydraulics • Statistical Hydrology • Surface Water Hydrology • Model descriptions and publications • Ordering information
Access EPA	epa.gov/Access/contents.html	U.S. Environmental Protection Agency	• Descriptions of EPA Scientific Models • HSPF • CORMIX1,2 • SWMM • WASP • Databases • ODES • STORET • Model Clearinghouses
Watershed Modeling System	http://www.et.byu.edu/~geos/software/wms/wms.html	Brigham Young University	Access to description, use and demo model of WMS.
WETnet	ingis.acn.purdue.edu:9999/wetnet.html	Purdue University	• Hydrographic Models • USGS Distributed Routing Rainfall-Runoff Model • KWM:Kentucky Watershed Model • SWM-IV: Stanford Watershed Model IV • TWM: Texas Watershed Model • Water resources search engines • Data sets (GIS, water quality, agricultural data)
SEIC Water Resources Page	seic.okstate.edu/water.html	Oklahoma State Univ.	• Links to federal water resource pages • USGS, NOAA, HEC, USACE-CERL • Links to state and other water resource pages • WATERnet, TWRI Texas Waternet, • National Institute for Water Resources
Universities Council on Water Resources	uwin.siu.edu:80/ucowr/index.html	Southern Illinois Univ.	• Links to water resource pages • USGS, WETnet, GLIN, Middle East Water Resources • List for sources of water resource data
Geographic Resources Analysis Support System	softail.cecer.army.mil/grass/GRASS.main.html	U.S. Army Corps of Engineers	• GRASS Software and Support software • Examples of spatial modeling and animated model output • Links to other GRASS-supported environmental projects • Links to other sources of water resource models and data

HEC-4, the Monthly Streamflow Simulation, will analyze monthly stream flows at a number of interrelated stations to determine their statistical characteristics and generate a sequence of hypothetical stream flows of any desired length having those characteristics. It has the capability to predict missing stream flows on the basis of concurrent flows observed at other locations. It will also use the generalized simulation model for generating monthly stream flows at ungaged locations based on regional studies.

A series of models has been developed by the Danish Hydraulic Institute that have been used extensively in Europe for water management. Called the MIKE series, MIKE 11 is a generalized, one-dimensional modeling system for the simulation of flows, sediment transport and water quality in rivers, estuaries, and other water bodies (Havnø *et al.* 1995). MIKE21 is a comprehensive modeling system for 2-dimensional free surface flows applicable to studies of lakes, reservoirs, estuaries, bays, coastal areas and seas. Finally MIKE SHE is a professional engineering software package for the simulation of all major hydrological processes occurring in the land phase of the hydrological cycle. MIKE SHE simulates water flow, water quality and sediment transport in rural catchments (Refsgaard and Storm 1995).

Internet Resources for Stream/River Models

Internet resources for stream and river modeling are presented in Table 4-3. Internet Resources for HEC, WES, or EPA were included in Table 4-2. Table 4-3 provides more examples of river models in use, as well as access points for the MIKE model series.

Examples of Stream/River Models In Restoration Projects

Harberg *et al* (1993) describe the restoration of a Missouri River chute that was cut off from the main channel by channelization. Their objective was to restore the physical habitat to conditions similar to those that existed in the chute. HEC-2 was used to estimate flow characteristics of the chute with different inlet and chute width sizes. The model output was used to determine the flow and velocities through the chute with various inlet and channel widths to determine the best design dimensions, that would be similar to what occurred historically. In theory, if physical habitat were restored, the historic functions of the chute would follow. These functions include spawning and rearing of various native fish species, feeding and nesting habitat of shorebirds, furbearer habitat, and waterfowl migratory habitat.

TABLE 4-3. INTERNET SOURCES OF MODELS, DATA, AND GENERAL INFORMATION RELATING TO RIVER/STREAM STUDIES

INTERNET HOME PAGE	NET ADDRESS	HOST	RESOURCES
USACE WES Hydraulic Laboratory	http://hlnet.wes.army.mil/	USACE Waterways Experiment Station	The TABS-MD numerical modeling system is a collection of generalized computer programs and utility codes. It is designed for studying multi-dimensional hydrodynamics in rivers, reservoirs, bays, and estuaries. These models can be used to study project impacts on flows, sedimentation, constituent transport, and salinity. The CH3-D model predicts temporal variation of sediment transport, erosion and deposition in three dimensions.
MIKE-SHE, MIKE 11	http://www.dhi.dk/mikeshe.htm	Danish Hydraulic Institute	Description of the theoretical underpinnings and utility of the MIKE-SHE model. Links provided for connection to other DHI software packages, including MIKE 11 and MIKE 21.
Model-Derived Surface Hydrology Data Set for Four River Basins	http://climate.gsfc.nasa.gov/~eos_hpc/mdshdsfrb.html	E. Wood, Princeton Univ.	Description of a water-balance model developed and applied to the Red-Arkansas, Missouri, Colorado River, and Appalachicola Rivers.
Enhanced Stream Water Quality Model (QUAL 2E)	http://www.epa.gov/docs/QUAL2E_WINDOWS/metadata.txt.html	U.S. Environmental Protection Agency	General description of the functions of QUAL 2E, computer requirements, and acquisition information.
Use of EPA's Qual-2E Model to Predict Water Quality in an Arkansas River System	http://twri.tamu.edu/~twri/twripubs/NewWaves/v7n1/abstract-2.html	J. Rogers, Univ. Houston, TX	Demonstration of the use and calibration of EPA's Qual-2E models for the North Fork Saline River (Arkansas) system.
Stream Assimilation Capacity for Waste Material	http://mmm.mbhs.edu/advweb/stream/contents.html		Provides an example of the use of STELLA in predicting the maximum waste flows that could be handled in a Maryland stream. The homepage is designed for a Maryland high school class project.

5 BIOLOGICAL MODELS

It all comes back to biology. After the rocks have been laid, the gravel placed and graded to the proper depth, area, and slope, delivery of clean water assured at a dependable volume and flow, if you build it will they come? Restoration is an on-going learning process. There are numerous examples of successful efforts that were designed by insightful individuals with a clear understanding of resource needs. Simultaneously, the restoration landscape is littered with attempts at habitat construction that failed. These generally were due to incomplete design for the target species requirements.

The models discussed thus far assist us in planning and predicting the social and abiotic factors that can influence the success or failure of a biological restoration project. If these models are working as predicted, what models are available to predict the ability of a specific species or community to thrive in this physically restored environment? That is precisely the focus of this chapter -- to examine the models that have been derived for predicting species or community adaptability to a specified range of physical systems. There are hundreds of biological models in the literature. They range from the simple and practical to the complex and esoteric. In keeping with our stated goals in Chapter 1 of presenting pragmatic information on model use to restoration managers, we have focused this presentation toward practical applications of biological models that have been or could be used in decision making.

Chapter 5 begins by focusing on models that deal with predicting plant, invertebrate, fish, or avian species or assemblages. Many restoration projects are small in scale and really need only to focus on the needs of one or two species; for example restoration of waterfowl habitat. Other projects are larger in scale and need to predict ecosystem level responses, such as the Everglades efforts discussed in Chapter 3. We have included discussion of ecosystem models for rivers and streams, wetlands, and estuaries. Eutrophication prediction is a unique subset of lake and estuarine ecosystem modeling, and is discussed separately below. The formal processes known as HEP and the IFIM are also discussed in this section. Finally, we include a listing of Internet links to net sites that have relevance to biological modeling; including models, data sets, or general information on restoration.

Specific Community Models

Frequently, restoration efforts are planned to encourage re-introduction of lost species, or to enhance habitat for specific species or guilds. For example, restoration of specific foraging habitat for the California least tern (*Sterna antillarum browni*) requires consideration of not only the physical characteristics of the preferred prey habitat (e.g., depth, water clarity, currents, sediment grain size), but also the ability to predict if suitable prey will colonize that habitat. Enhancement of trout populations in a stream is dependent upon the presence of suitable physical habitat (e.g., pool/riffle sequences) but also upon increases in prey populations. To that end, we examine predictive models for plant, benthos, fish, and avian species below. Prediction of phytoplankton communities is frequently the domain of eutrophication models, and is reserved for a later section.

Aquatic Vegetation Models

Aquatic macrophytic vegetation play a key-role at multiple ecological levels within wetlands, lakes and estuaries. For instance, aquatic vegetation can reduce nutrient or contaminant levels in the water (Mitsch and Gosselink 1993), provide food for herbivorous zooplankton and fish (de Nie 1987; Lee and Jones 1991), provide refuge or nurseries for a variety of invertebrates and fish (de Nie 1987), and prevent resuspension or displacement of sediment by current, wind or benthivorous fish (James and Barko 1994; Scheffer 1991).

It has been suggested that the principle role of revegetation in restoration is one of habitat stabilization (Scheffer 1991). While they may stabilize an environment, macrophytes cannot be expected to exist in an already disturbed environment, and restoration of a habitat might begin with the need to re-establish the macrophytes. Furthermore, a functioning macrophyte community can be essential to the success of restoration projects planned for other purposes. For example, wetlands are being created as part of pre-discharge water treatment for acid mine tailings (Mitsch and Gosselink 1993), and eelgrass beds (*Zostera marina*) are being planted for both mitigation and sediment stabilization (Merkel and Hoffman 1988).

Physical Predictors of Plant Distribution

Reliable prediction of the response of vegetation to different physical conditions such as light, substrate, or depth is important to determine an optimal restoration strategy. Generally, predicting growth of aquatic macrophyte vegetation is based upon light, depth, substrate (e.g., rock, sand, clay), and proper current speeds. A common tool for predicting distribution has been statistical models: simple regressions or multivariate analyses. Regression models have been useful to demonstrate correlations for depth distributions, relations between substrate type, or other environmental factors that may be intuitive, or unexpected.

Figure 5-1 shows a hypothetical regression of Secchi disk transparency vs. the lower limits of macrophyte distribution, while Figure 5-2 shows a probability plot based upon depth. While the relationship between light and depth appears intuitively obvious, factors affecting the irradiation at depth may be less so. Sediment resuspension, humic discoloration of the water, or phytoplankton blooms can influence light penetration. Multivariate statistical analysis can lead to improved inferences about where plants will exist. However, Scheffer (1991) points out that while statistical models appear attractive for predicting plant distribution, comparison of the predicted locations against actual data suggests that these relationships are useful for predicting where vegetation does not occur, but do not necessarily predict where vegetation will certainly grow.

Light attenuation is most frequently the limiting factor in macrophyte distribution, and a number of different models have been developed to predict depth of growth for aquatic angiosperms as well as seaweeds. Duarte (1991) developed a mathematical expression that predicts the depth limit of seagrass communities worldwide, and showed that seagrasses may extend from mean sea level down to a depth of 90 m. Differences in seagrass depth limit are largely attributable to differences in light attenuation, although

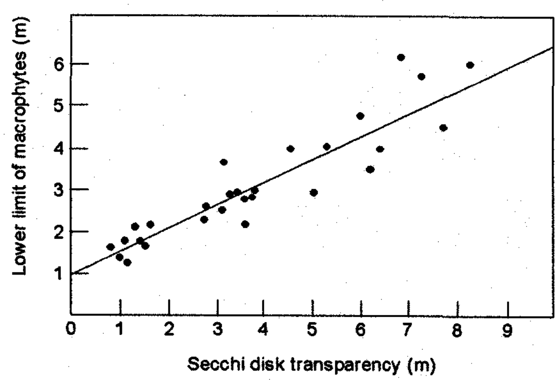

Figure 5-1. Hypothetical regression of limit of macrophyte distribution against transparency.

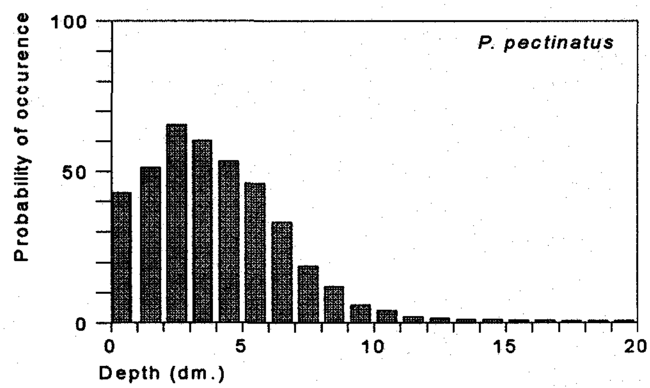

Figure 5-2. Probability of occurrence of *P. pectinatus* with increasing depth. (Adapted from Scheffer *et al.* 1992).

differences in seagrass growth strategy and architecture also appear to contribute to explain differences in their depth limits.

Another approach for predicting light requirements of aquatic angiosperms is the use of bioenergetic budgets; the lower limits of plant growth are then defined by balancing photosynthetic capacity with respiration requirements. For example, a bioenergetic budget for eelgrass (*Z. marina*) was developed by Zimmerman *et al.* (1988). These authors first developed a mass balance model that accounted for the amount of carbon reduced by photosynthesis against the amount of carbon oxidized by respiration. The model summarized respiration over 24 hours, and photosynthetic oxidation over the portion of the day in which irradiance was sufficient to saturate photosynthesis. Once the period of irradiance-saturated photosynthesis was determined, estimating the light availability at depth was expressed mathematically as a function of surface irradiance, photoperiod, and light attenuation. Critical assumptions in this approach relate to the estimated photosynthetic (shoot) and the respiring nonphotosynthetic (root) ratios, which are likely to be both seasonal and site specific variables. Again, this model may be capable of telling us where eelgrass will not exist, but not necessarily where it will grow.

Scheffer *et al.* (1992) examined the distribution of submerged vegetation in a chain of six shallow, eutrophic lakes and analyzed its dynamics over 20 years using a series of vegetation maps. The responses of the two dominant species, *Potamogeton pectinatus* and *Potamogeton perfoliatus*, to water quality, depth, exposure, sediment type and meteorological conditions were examined with the use of multiple logistic regression models (Figure 5-3). The resulting models explained about half the variance in the vegetated surface percentage of the examined lakes. The presence of both species is predominantly related to rooting depth and water transparency. Additional positive relationships to wave exposure and spring water temperature were found for *P. pectinatus*. The yearly change in vegetation abundance is considerable in these lakes. On average, the vegetated area of a lake in two successive years differed by 50%. On a local scale, dynamics were even higher. Large vegetation stands disappeared from one year to another whereas in the same lake new areas were colonized.

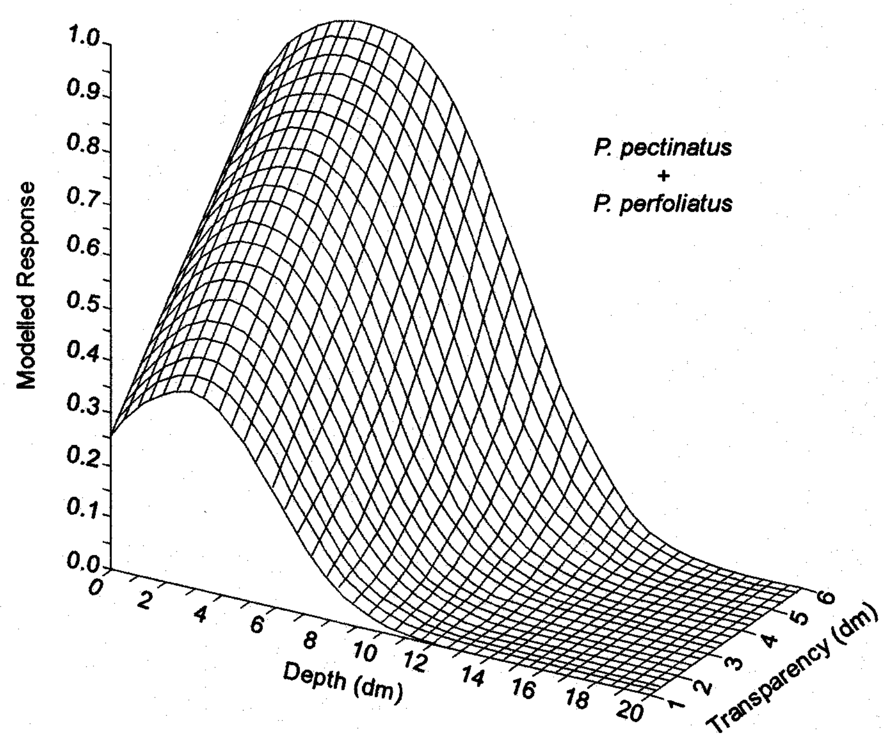

Figure 5-3. Predicted probability of occurrence of either *Potamogeton pectinatus* or *P. perfoliatus* at varying depth and transparency (Adapted from Scheffer *et al.* 1992).

Community Succession

Plant community succession is a well established axiom in the ecological literature, and planned plantings in restoration must be concerned with the successional abilities of a target species under specific environmental conditions. An example of a model developed specifically to predict succession of salt marsh plants on a created sediment shelf in the Chesapeake Bay is provided by Zieman and Odum (1977). Their model considered growth and succession of three species of plants (*Spartina alterniflora, S. patens*, *Distichlis spicata*), and had as principal variables solar radiation, temperature, salinity, and tidal inundation. Seagrass communities under varying environmental conditions have been modeled by Fong and Harwell (1994). Their model predicts which of three seagrass species, *Thalassia testudinum*, *Halodule wrightii*, or *Syringodium filiforme,* and associated communities, will dominate under multiple environmental factors. These variables include light temperature, salinity, sediment nutrients, and water-column nutrient concentrations in tropical and subtropical bays and estuaries.

Water Quality Enhancement

Finally, aquatic vegetation is playing an increasingly important role in reclamation of mining sites, and in water quality enhancement from mine drainage, tertiary treatment of municipal wastewater, and for storm water or nonpoint agriculture drainage. Odum *et al.* (1990) describe research they conducted on the ecological processes associated with wetland and marsh creation following cessation of phosphate mining in central Florida, and on a series of computer simulation models that were developed to predict seedling transplant success and plant community succession.

Rogers and Dunn (1992) present a modeling approach for evaluating the capability of constructed, restored, and natural wetlands to assimilate and process pesticides associated with agricultural runoff from croplands. The approach is unique in that the authors provide criteria for selection of "model" pesticides that includes use patterns and amounts as well as intrinsic characteristics of the pesticide. Their model design for constructed wetland cells included water flow and depth control, clay liners to prevent infiltration, and wetland vegetation as variables. The aim was to provide recommendations for pesticides that are compatible with wetlands as well as design characteristics for constructed wetlands to be used with specific crop-pesticide combinations.

Benthic/Epibenthic Models

Predictive models of benthic or epibenthic invertebrate community structure have been sought since the publications of G. Thorson and H.L. Sanders in the 1950's and 1960's. There are hundreds of publications describing benthic community development. An understanding of the evolution of ecological theory on this subject can be obtained from five papers. They are Sanders (1969), Johnson (1972), Pearson and Rosenberg (1978), Rhoads and Germano (1986), and Warwick (1986). Collectively, these papers describe basic patterns in the temporal and spatial development of estuarine and marine benthos, and offer generic models describing benthic community responses to physical and chemical environmental alterations.

From a restoration perspective, the importance of benthic communities is in their basis as prey items for a target fish or avian species. Alternatively, infaunal analyses may be used to assess whether a physically restored habitat is functionally equivalent to a natural habitat.

There are very few examples of predictive models for benthic infaunal communities. Most of the mathematical techniques developed compare communities from multiple sites, and attempt to correlate the specific community with the physical habitat. Application of these models has principally been to correlate disturbance (e.g., pollution impacts) with community impacts. An early conceptual model that associates species abundance with a gradient of organic enrichment is that of Pearson and Rosenberg (1978), show in Figure 5-4. While not quantitative, the model has been used to formulate municipal treatment facility outfall zone remediation goals.

A large portion of the benthic literature focuses on the development of community metrics. These metrics are mathematical expressions of the numbers of species, the diversity of species present, and biomass. Most often, relationships between communities and their environment are developed using multivariate statistical techniques. A review of these metrics and applicable statistical techniques can by found in Elliott (1977) and Gray (1981).

There is at least one commercially available software package designed to analyze benthic data. The Community Analysis System (CAS) (Bloom, 1995) package includes modules to calculate total species, total individuals, and a variety of diversity and richness indices, as well as ordination techniques to compare different sampling locations. The CAS Web site address is included in the Internet resources section at the end of this chapter.

One example of using benthic community metrics to predict both impacts of proposed river engineering, and restoration of riffle-pool runs on a river section is that of Smith *et al.* (1989). Benthic community metrics were determined from riffles, pools and runs of the Welland River in England. Correlative analyses were conducted that related family richness and total biomass in riffles, pools, and runs separately and then related to the frequency of these physical parameters. The correlations were then used to demonstrate that the effect of channelization on benthic macroinvertebrates was to reduce family richness by approximately 50%, and biomass by 80%. Their models further predicted that restoration of a riffle-pool sequence on a canalized stretch would result in a doubling of family richness, and a five-fold increase in biomass.

The River Invertebrate Prediction And Classification System (RIVPACS) has been developed in England for the prediction of benthic macroinvertabrate assemblages from known environmental features (Armitage 1994; Moss *et al.* 1987; Wright 1995; Wright *et al.* 1994). RIVPACS is a software package that has as its database infaunal analyses on 438 sites and 81 unpolluted river systems, which is coupled with associated physical, chemical, and seasonal (spring, summer, autumn) parameters. The software uses multivariate analysis to predict the probability of encountering specific macroinvertebrate species at new sites.

To date, there has been no satisfactory mathematical model that generally predicts trends in the establishment of benthic communities in the US. The use of models for prediction of benthic invertebrate communities in rivers and streams has been reviewed by Gore (1987, 1989). However, the models discussed are largely theoretical and have not been widely applied.

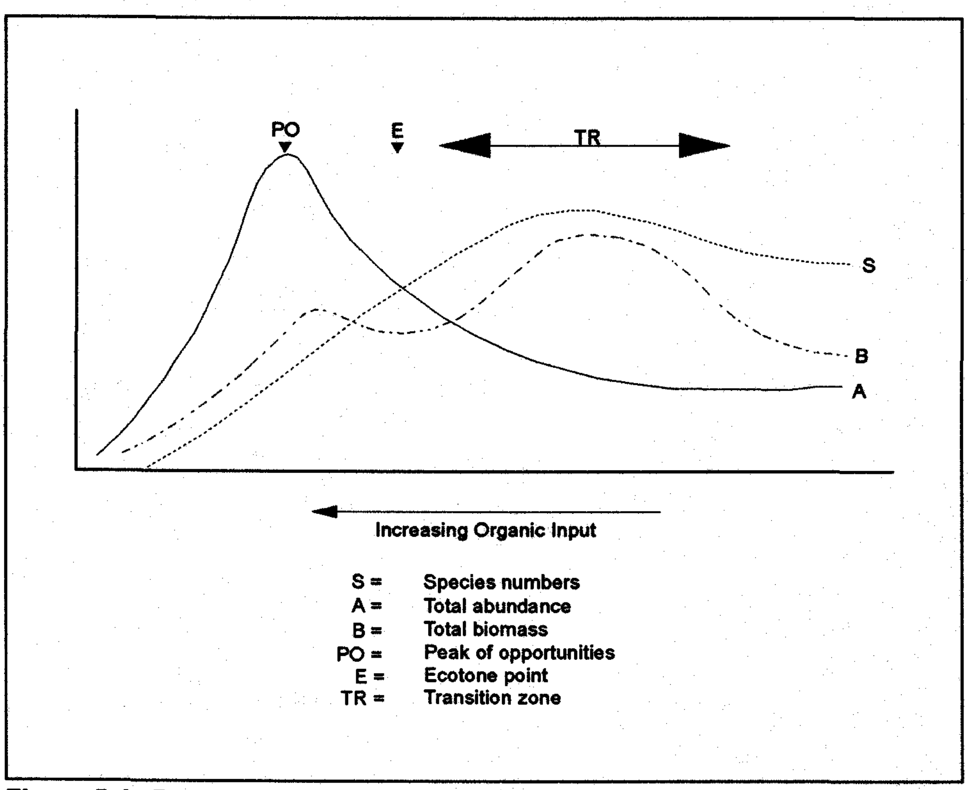

Figure 5-4. Pearson and Rosenberg (1978) conceptual model of benthic species, abundance and biomass changes along a gradient of organic enrichment..

Fish Models

Due to their importance to man as both a food item, and for recreation, a large number of models have been developed to predict fish communities, stocks and populations based upon a variety of biotic and abiotic parameters for multiple life stages. For restoration, we are most interested in those models that can predict changes in fish populations based upon manipulation of their physical or biological habitat. Restoration efforts for fish have included both non-structural (e.g., flow regulation) and/or structural (e.g., fish passageways) methods (NRC 1992). Non-structural applications are based upon the assumption that changes in physical parameters such as flow, depth, or water chemistry will result in positive effects upon the desired species or community. Structural modifications include the creation of habitats in streams or rivers using channel reconstruction, fish passageways, screens, logs, weirs, or other similar in-water methods.

In this section we will discuss models that predict suitable fish habitat from physical parameters, models that predict how constructed alterations to a habitat change fish populations or structure, predation models, and stock recruitment models that are outside of the IFIM, HQI or HEP process.

Physical Habitat Models

We define these as models that attempt to predict fish populations and/or structure from physical habitat variables. Examples of physical variables include many of those discussed in previous chapters such as catchment attributes (altitude, area, total flow), hydrology (flow, volume), water chemistry (pH, total dissolved solids), or site attributes (width, depth, coverage). Community structures or species distributions have often been correlated with three principle variables; depth, velocity, and substrate (Latka *et al.* 1993). Other variables also have been shown to be equally important including sedimentation rates, cessation of organic matter and sediment transport due to dam construction, presence of contaminants, and reduction of natural water temperature because of deep release of cold water from large reservoirs (Hesse *et al.* 1993).

Physical factor requirements or preferences can change with different life stages of fish. For example, Gibson (1993) provides a review of different freshwater habitat requirements for Atlantic salmon (*Salmo salar*), where multiple linear regression models were used to identify key physical parameters for each life stage. Spawning habitat usually occurs in rapid water at the tail of pools on the upstream edge of a gravel bar, with depths about 25 cm, in mean water velocities of about 30-45 cm/s, with maximum velocities about 2 body lengths/s, and with a substrate of irregularly shaped stones of cobble, pebble, and gravel. Underyearling salmon are most common in shallow pebbly riffles, whereas older and larger parr are usually in riffles deeper than 20 cm with a coarse substrate. Depth preference increases with size. Regression models quantifying parr habitat identified substrate as an important variable, with a positive relationship to an index of coarseness. Negative relationships were found with mean stream width, range of discharge, and overhanging cover. Water chemistry, especially alkalinity, nitrates, and phosphates, are important regulators of production.

Shirvell (1989) provides a review of six predictive habitat models and the adequacy of their predictive capabilities to infer habitat effects on stock size. Models reviewed included the Morphoedaphic Index (Ryder 1965), the Physical Habitat Simulation (PHABSIM) model developed under the IFIM (Stalnaker 1979), and the HQI and HEP procedures. Shirvell examined 40 physical variables that are commonly viewed as potentially determining fish population size, and found that only 15 habitat variables were found by one or more of the models to have significant correlations with the fish population (Table 5-1). The most frequently correlated variable was water depth, followed by velocity, substrate, cover, width, and total dissolved solids. The author concludes that no single habitat variable or group of variables universally regulates fish production, and that different populations were limited by different characteristics.

Habitat Alterations

Restoration of fish habitat often involves the physical addition, or removal, of specific structures. In rivers and streams, these structures can be placed to reduce bank erosion, increase habitat diversity by the creation of riffles and pools, provide cover, or improve substrate suitable for spawning (Marcus *et al.* 1990). In lakes or estuaries, placement of artificial reefs is intended to increase vertical substrate over soft bottoms and thereby increase habitat diversity for target species (Buckley 1989).

Restoration of fish communities can begin with the creation of a suitable spawning environment. With Pacific salmon, suitable spawning habitat (redds) involves predicting the sedimentation rates, dissolved oxygen, temperature, and flow. Havis *et al.* (1993) discuss development of a simulation model -- the Salmonid Spawning Analysis Model (SSAM) -- that can be used to predict the relative impacts of stream sediment load and water temperature on salmonid egg survival. SSAM combines several publicly available software packages (USFWS Instream Water Temperature, SNTEMP model, USACE Scour and Deposition in Rivers and Reservoirs, HEC-6 model, version 3.2 USDA-ARS Sediment Intrusion Dissolved Oxygen SIDO model), that are linked to simulate water temperature and water and sediment routing in gravel-bed rivers.

TABLE 5-1. ENVIRONMENTAL VARIABLES MOST FREQUENTLY USED BY HABITAT MODELS TO PREDICT STREAM AND RIVER FISH ABUNDANCE OR BIOMASS. HABITAT VARIABLES IN ITALICS HAVE BEEN SHOWN TO HAVE MATHEMATICALLY SIGNIFICANT CORRELATIONS WITH FISH BIOMASS OR ABUNDANCE (FROM SHIRVELL 1989)

Catchment Attributes		
Geomorphological Features	**Hydrological Features**	**Water Chemistry Features**
Altitude	Average daily flow	pH
Geology	Average seasonal flow	*Hardness TDS*
Catchment Area	Flow pattern	Alkalinity
Total channel length	*Extreme flow variations*	*Nitrogen (NO_2)*
Drainage density	Stability of flow	Phosphorous
Mean basin length	Precipitation	Dissolved Solids
Mean basin slope	*Water yield*	Conductivity
Forest ratio		*Temperature*
		Turbidity
		Oxygen
Site Attributes		
Width		*Bank Erosion*
Depth		Water Surface Area
Substrate composition		Volume
Sinuosity		Riffle:pool ratio
Flow type		Gradient
Velocity		*Fish food abundance*
Instream cover - debris, rocks, macrophytes		
Bankside cover - undercut, banks, log jams		
Fish food diversity		

Placement of physical structures or alterations in streams or rivers to improve fish habitat is a common restoration tool. Modeling of the hydraulic effects of structures is discussed by Heiner (1991), who developed scour and discharge equations for such common habitat structures as log weirs, flow deflectors, digger logs, and presents predictive equations for a new structure called a digger weir. Heiner's equations predict water depths and velocities, which can be used to predict quantities of habitat created or lost when structures are installed in streams, and aid in proper placement of structures in streams. In a related study, Cullen (1991) used a physical stream model to examine the effects of geometrically different model fishrocks to induce scour. Fishrocks were defined as boulders placed in streams to improve fish habitat, and create habitat in streams by increasing local water velocities near the substrate, increasing the local drag and lift forces that scour the stream bottom.

Artificial reefs placed in lakes or estuaries are sometimes called fish aggregating devices (FAD). While there is no question that substrate placement attracts fish, there is still no definitive study that demonstrates that FADs mimic true reefs or natural substrate that contribute to overall fish population increases. At least one study provides a method on predicting the increase in fish numbers due to FAD placement (Matsumiya *et al.* 1991). While this paper is largely devoted to the theoretical derivation of the model equations, the resultant predictive equation for maximum sustainable catch from an FAD may be useful in defining the maximum effect of an artificial reef on a fish population.

Prey and Predation Models

Restoration of a specific fish species can be a function of available prey and/or the ability to avoid serious predation pressures. Bioenergetic models have been used to predict the wet-mass energy density of zooplankton or benthic prey required for maintenance of a specific fish species. While it has been argued that fish distribution is a function of velocity, depth and substrate, some models of microhabitat use demonstrate that prey capture success dictates use of certain environments. For example, Hill and Grossman (1993) describe an energetic model of microhabitat use for rainbow trout and rosyside dace (*Clinostomus funduloides*), which they validated for a small stream in North Carolina. Their model output compared the net energy gained by holding a position at a specific current velocity with the bioenergetic costs of occupying that velocity and predicted that fishes would occupy velocities at which net energy gain was maximized.

Predation risk must be considered as part of the overall predictive exercise. For example, predation related mortality of juvenile salmonids at hydroelectric facilities on the Columbia River are suggested as canceling out positive benefits of expensive bypass systems built to reduce turbine mortality (Poe and Shively, 1994). Northern squawfish consume large numbers of juvenile salmonids after they pass through the bypass. Modeling and verifying the squawfish's reduced ability to forage at elevated water velocities provided additional evidence that restoration of threatened salmonids on the Columbia may be enhanced by increased flow from reservoirs during out-migration.

On a smaller scale, some authors suggest that fish use of a habitat is a function of both prey availability, and mortality pressures. Gilliam and Fraser (1987) present and test a model that specifies the choice of foraging area ("habitats") that would minimize total mortality risk while allowing collection of some arbitrary net energy gain. Using juvenile creek chubs (*Semotilus atromaculatus*), the authors predicted and then experimentally manipulated two use areas that varied in resource densities; one area had limited food resources (*Tubifex* spp. worms in sediments) but no mortality hazard (adult creek chubs), while the second area had high food resources and high mortality hazards. For the case tested, the model specified a simple rule: "use the refuge plus the site with the lowest ratio of mortality rate (u) to gross foraging rate (f)," i.e., "minimize uf." Independent prior measurements of mortality hazard (as a function of predator density) and gross foraging rate (as a function of resource density) allowed for the prediction of the resource level in the more hazardous foraging site that should induce a shift from the safer to the more hazardous site. The chubs' preferences in subsequent choice experiments agreed well with the theoretical predictions.

Predation effects are also mitigated by depth and the relative amounts of cover provided in the habitat. Angermeir (1992) examined the effects of water depth and habitat complexity on predation rates by adult rock bass (*Ambloplites rupestris*) on juvenile central stoneroller (*Campostoma anomalum*), pumpkinseed (*Lepomis gibbosus*), and fantail darter, (*Etheostoma flabellare*). Regression models were developed to examine the effects of depth, cover, and light on both predation rate and prey activity. Not surprising, the results suggest that effects of habitat features (e.g., depth, cover) on predator-prey interactions vary according to the natural history and behavior of particular prey and predators. Angermeir recommends that habitat-specific responses of prey to predation risk should be integrated into habitat models.

Fish Stock Models

The ability to predict standing fish crops is an integral component of resource management in a number of important commercial fish stocks. Fish stock assessment is a discipline unto itself with numerous well documented and validated computer models. For those interested in predictive methods for commercial fish stocks, we recommend the recent review by Gallucci *et al.* (1995).

Restoration of a fish species can involve restricting or prohibiting commercial or sport catch. The recent restrictions on international commercial fishing on the western Atlantic bank off Newfoundland by the Canadian government, severe restrictions placed on commercial salmon fishermen in Oregon, Washington and British Columbia, or sport fishing limitations placed on western streams and rivers (e.g., catch-and-release only) are all restoration efforts based upon modeled assessments of fish stocks.

Predictive models of fish stocks can also be used to determine effects of human activities on fish populations in rivers and estuaries. While it is often easiest to point to fishermen as the "culprits" in reducing fish stocks, often overlooked (or ignored) is the effect of urban and industrial inputs on fish recruitment. Rose and colleagues demonstrate the use of categorical time series regression models to examine the effects of hydrographic and anthropogenic influences on a number of important eastern fish stocks (Rose *et al.* 1986; Rose and Summers 1992). For the striped bass (*Morone saxatilis*) and American shad (*Alosa sapidissima*), historical stock recruitment was shown to be less related to changes in hydrographic conditions, as they were to changes brought about by anthropogenic influences such as increased nutrient loading, pollutants, and pesticides (Summers and Rose 1992). In an ambitious attempt to examine the role of hydrographic variables and gross pollution indicators on fishing stocks, Rose and Summers (1992) used historical catch data for 55 fish stocks over 46 years in the Potomac, Hudson, Narragansett, Delaware, and Connecticut estuaries. While the modeling approach was solid and previously validated, the study was inconclusive due to the lack of high quality historical data.

Fish recruitment models can also be applied to smaller stream populations. Elliott (1994) presents a review of density dependence and stock-recruitment models applied to brown trout (*Salmo trutta*) in England. This is an excellent and comprehensive treatise on the subject, and is recommended reading.

Community Structure Models

Predicting fish assemblages in a given stream or river reach has also been the subject of statistical modeling. Capone and Kushlan (1991) examined the fish assemblages in 40 dry-season pools in a hydrologically variable river drainage in northeast Texas. Using cluster analyses, the authors demonstrated three specific assemblages each dominated by mosquitofish, black bullhead, and sunfish-shiner-mosquitofish, respectively. Factor analysis showed that pool depth, pool persistence, channel size, canopy cover, pool substrate, and pH were adequate predictors of the given assemblages.

Avian Models

We noted earlier in Chapter 1 that improved bird habitat is often a principle objective, and often an inevitable consequence of aquatic restoration. Feather and Capan (1995) reviewed a number of aquatic restoration projects, and found that almost every project attributed part of its environmental significance to the North American Waterfowl Management Plan. Improved water quality, increased wetlands, expanded food resources (plants, invertebrates or fish), all increase the opportunities for birds.

We are interested in those bird species that rely on water bodies either as immediate habitat, or for forage. While much of the literature focuses on waterfowl, the field includes species that forage on fish (e.g., eagles, heron, osprey, kingfishers) or smaller birds that prey on aquatic insects (tree-swallow, red-winged blackbird). Biologists/ecologists in North America lead the way in developing avian mitigation/restoration methods. The U.S. Fish and Wildlife Service especially has been actively identifying variables that limit avian populations, modeling those habitat parameters, and providing the methods necessary to optimize those limiting factors. Some of those models have been done using HEP methodology, but a number have been developed independently. We examine a few selected models below.

Habitat

While fish and invertebrate models often focus on the physical characteristics of the aquatic habitat such as current, depth, substrate and velocity, avian habitat models may incorporate physical, ecosystem, and/or anthropogenic parameters. Gibbs *et al.* (1991) utilized extensive field observations at 87 palustrine and lacustrine wetlands on nongame water birds in central and eastern Maine to develop predictive models of habitat use for each species. Wetlands used by 15 species of water birds (Figure 5-5) were defined according to habitat variables that included the degree of development in an area and the distance to roads (Table 5-2). The models were able to demonstrate a number of valuable restoration/habitat parameters. For example, many of the species had large area-requirements (pied-billed grebe, common loon, herring gull, double-crested cormorant, bald eagle) or preferred to use wetlands near other wetlands (common loon, herring gull, great blue heron, spotted sandpiper, osprey, bald eagle). Furthermore, wetlands with intermediate amounts (33-66%) of emergent vegetation supported more species than closed (> 66%) or open (< 33%) wetlands. Low pH typified wetlands used by large-bodied piscivores (common loon, cormorant, osprey). This excellent resource provides bird use and habitat information from 87 wetlands, and models of habitat selection for each species.

Species	Latin Name
Common loon	*Gavia immer*
Pied-billed grebe	*Podilymbus podiceps*
Double-crested cormorant	*Phalacrocorax auritus*
American bittern	*Botaurus lentiginosus*
Great blue heron	*Ardea herodias*
Green-backed heron	*Butorides striatus*
Osprey	*Pandion haliaetus*
Bald eagle	*Haliaeetus leucocephalus*
Northern harrier	*Circus cyaneus*
Virginia rail	*Rallus limicola*
Sora	*Porzana carolina*
Spotted sandpiper	*Actitis macularia*
Common snipe	*Gallinago gallinago*
Herring gull	*Larus argentatus*
Belted kingfisher	*Ceryle alcyon*

Figure 5-5. Species modeled for wetlands used by Gibbs *et al.* (1991).

Other models have used limnological variables to predict use and abundance of bird species. Heglund *et al.* (1994) used statistical models to evaluate habitat parameters for Pacific loons (*Gavia pacifica*) and horned grebes (*Podiceps auritus*) in wetlands of the Yukon Flats National Wildlife Refuge, Alaska. Using logistic regression analyses, they defined significant associations between the probability of wetland use and limnological characteristics such as shoreline length, pH, calcium, total phosphorus, and chlorophyl. Using abundance data, they further attempted to define relationships between population

TABLE 5-2. VARIABLES USED BY GIBBS *ET AL.* (1991) TO DESCRIBE THE PHYSICAL CHARACTERISTICS OF WETLANDS FOR MODELING

Variable	Description
Wetland Area	Area (hectares) covered by water ≥ 0.1 m depth
Shoreline Development	Linear distance around perimeter of water (m)
Surface water, open	Percentage and area (ha.) of surface water that is unvegetated (open)
Surface water, aquatic bed	Percentage and area of surface water in submergent and floating-leaved vegetation (e.g., *Potamogeton, Nuphar*)
Surface water, emergent	Percentage and area of surface water in emergent vegetation (e.g., *Carex, Typha*)
Surface water, ericaceous	Percentage and area of surface water in ericacous (heath) vegetation
Surface water, alder-willow	Percentage and area of surface water in alder-willow
Surface water, flooded timber	Percentage and area of surface water in flooded timer (e.g., *Abies, Acer*)
Life-form diversity	An index of life-from diversity based on information theory.
Surface water irregularity Index	The ratio of the surface water perimeter to the perimeter of a circle with an area equal to that of the surface water
Interwetland distance	Linear distance between the edge of one wetland and the closest neighboring wetland
Distance to road	Linear distance between a wetland and the nearest actively traveled road.

numbers and these same use variables. An interesting finding was that while Pacific loon abundance could be adequately predicted by these same parameters, the horned grebe could not. This finding reemphasizes a point made in Chapter 2: models are often specific to certain systems or species in their use. Validation is required before the model can be used to predict, in this case, habitat parameters for different species.

Population Models

Much of the focus of waterfowl models is in predicting how the habitat variables discussed above influence breeding success. Carlson *et al.* (1993) discuss the development of stochastic computer model to simulate productivity of the northern pintail (*Anas acuta*). Adapting a mallard (*A. platyrhynchos*) model originally developed at the Northern Prairie Wildlife Research Center of the U.S. Fish and Wildlife Service, the model compares productivity parameters (e.g., initial body weights, weight loss during laying and incubation, incubation time, clutch size, nest site selection characteristics) and predicts nest initiation in response to changes in upland and wetland habitat conditions in central North Dakota. The model makes point predictions concerning number of nests per hen, hatch rate, success rate, and average clutch size, without providing confidence intervals surrounding those predictions. While the model point predictions of successful nests did not differ from observed values during wet ($p=0.35$), average ($p=0.94$), and dry ($p=0.88$) conditions, predictions of nest initiations during wet and average conditions were approximately three times the observed values. Incorporation of some estimate of variability could greatly enhance the utility of this model.

Models of bird populations can be complex and require the use of a programmer to translate the biologists notion of how a system works into mathematical equations. However, some population parameters can be modeled fairly simply using computer spreadsheets, as demonstrated in the Great Bustard (*Otis tarda*) model (Silvert 1989). Silvert describes how spreadsheets for management models of bird populations can be built not only to carry out simulations, but also to facilitate sensitivity analysis and the evaluation of numerous distinct scenarios. This is a fairly simplistic model, with few variables and it lacks the ability to establish confidence intervals on predictions. In its simplicity, however, may lie its attraction. Resource managers or field biologists often have an intuitive understanding of how their species may respond, and simple spreadsheets allow them to try "what if" scenarios. In the example of the Great Bustard, hunting restrictions are applied to predict population increases.

Use of Avian Models in Restoration

An example of a simulation model used to aid decisions in mallard (*Anas platyrhynchos*) management is given by Cowardin *et al.* (1988). Using the mallard model similar to that described above for Northern pintails, the authors linked habitat and nest data bases with mating pair-wetland regression models and the mallard productivity model. The models were run to predict the effects six separate management options (e.g., installation of nest baskets, nesting island construction) on increases in mallard ducks. The overall simulated management system is shown in Figure 5-6. The model simulations provided predictions on the percent increase in mallard production associated with each of the six management options. The output was structured in a fashion that allowed for economic analysis and ranking the management options on a mallard-per-unit expenditure of phosphorus and nitrogen.

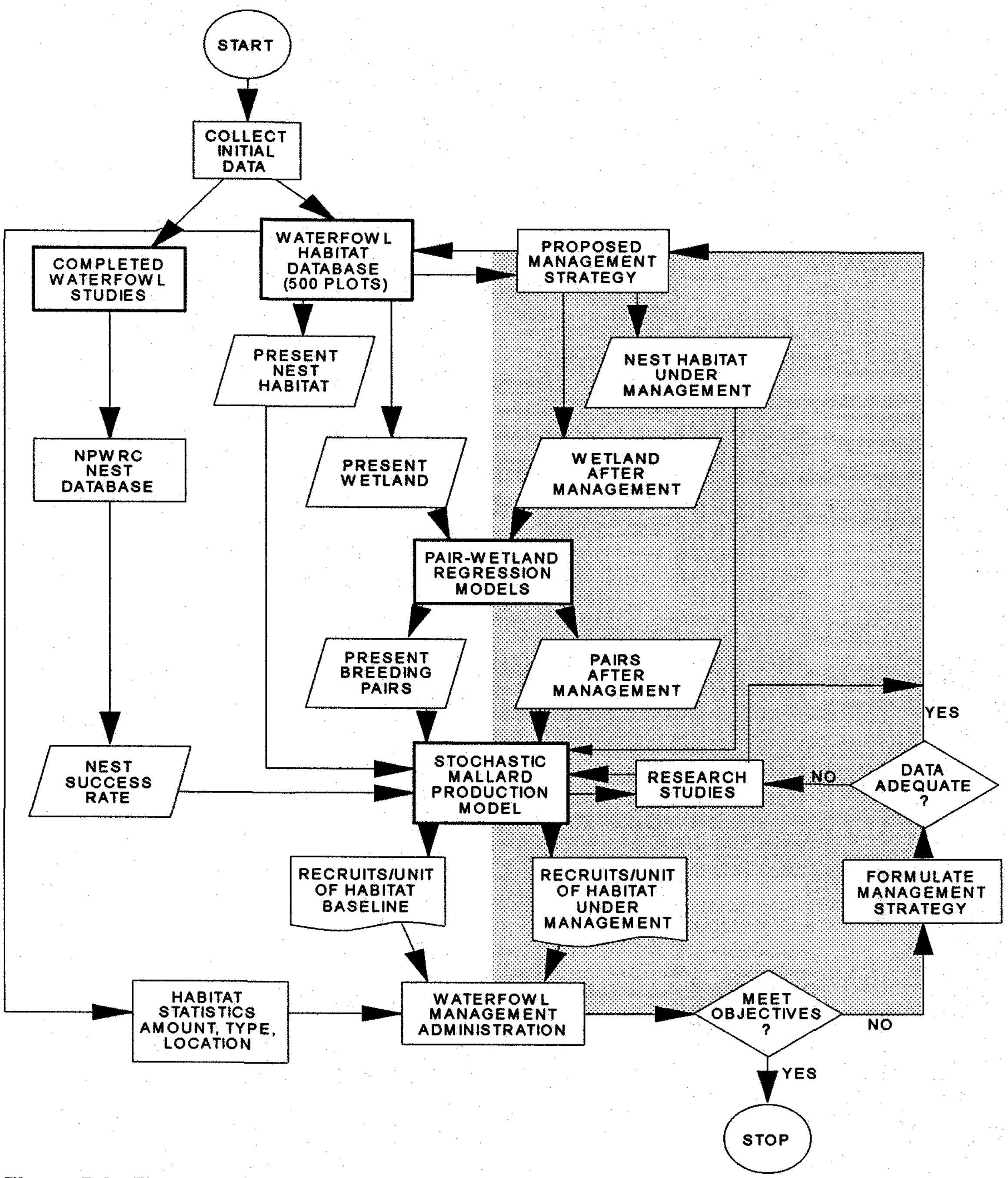

Figure 5-6. Flowchart illustrating the system for evaluating mallard management options. Shaded area denotes simulated management.

Ecosystem Models

Ecosystem models in this discussion pertain to system-wide relations between abiotic and biotic factors. The physical interactions that control the flow of nutrients and energy between biological components are linked by mathematical equations to define the entire system. We have grouped these as river/stream, lakes, wetlands, and estuarine ecosystem models. Eutrophication, which effects all of these ecosystems, is reserved for a separate discussion in the following section.

Stream/River Ecosystem Models

Streams and rivers have probably received far more physical manipulations than other systems. Dams, levees, channelization, irrigation drawdowns, reduced flow, and dredging all combine to drastically impact pre-construction ecosystems. These physical factors, coupled with point and non-point runoff from agriculture, industry, or urban streets, further impair the aquatic biota. Ecosystem restoration in streams or rivers can include improvements in water quality, changes in flow/velocity, decreasing/increasing sediment loads, construction to increase suitable species habitat (e.g., pools and riffles), and bank revegetation/devegetation, to name a few.

River management is an old discipline and as a result there have been many models developed to aid in resource allocations and more recently, restoration. We have provided a few select models below, but recommend referencing *The Rivers Handbook* (Callow and Petts 1994) and *Restoration of Aquatic Ecosystems* (NRC 1992) for further information.

Physical Functions

As discussed earlier under fish community models, one school of restoration thought is that the physical functions of rivers or streams can be used to predict ecosystems or communities. An example of this is the Riverine Community Habitat Assessment and Restoration Concept (RCHARC) (Nestler *et al.* 1993a; Nestler *et al.* 1993b; Latka et al. 1993). RCHARC was developed by the Corps as a tool to assist in evaluation of alternative water management scenarios for dams in conjunction with the restoration of aquatic habitat along the Missouri and Mississippi Rivers. The fundamental underlying assumption of RCHARC is that depth, velocity and flow patterns define endemic fish communities, and that modifications to these variables would, over time, change the structure of the fish community (Latka *et al.* 1993a, 1993b).

In RCHARC, use is made of a comparison standard river system (CSRS) which is assumed to represent the ideal habitat conditions in terms of channel configuration and seasonally varying flow characteristics for the aquatic community in the project river system. The CSRS can be based upon professional consensus, reference (unimpacted) river sections, or pre-impact conditions if data are available. Habitat value is then defined as similarities of depth and velocity distributions between the reference and project alternatives, on a monthly basis. Pearson product-moment correlation analysis is used to compare similarities between reference and project alternatives. The closer the correlations are to 1.0 (perfect correlation), the higher the assigned value.

Like any model system, RCHARC has advantages and disadvantages. RCHARC's frequency analyses feature allows for an examination of relatively few variables that impact many species. The authors point out that for a large warmwater river system that can have up to 100 species in several life stages, building models that focus on all species and habitat variables is cumbersome, and at best a daunting task (Nestler *et al.* 1993a, 1993b). They argue that a more feasible approach is to find a reach of river that contains a healthy community to use as a standard for analysis. RCHARC's primary assumption is enormous, and is an excellent example of the "if you build it they will come" restoration approach. The ideal or suitable habitat is not a numerically defined variable, but is based upon professional judgement of scientists and resource agencies. RCHARC is further limited in that it is not probabilistic; habitat suitability is defined by a single number, the correlation coefficient.

Water Quality

Water quality affects individual species and whole ecosystems. Stream, rivers, lakes and estuaries all are repositories of both direct effluent discharge (point source), and runoff from urban, industrial, and agricultural (non-point) sources.

Despite the dynamics of dilution operating in river systems, a recurring water quality problem is associated with conventional parameters such as ammonia, nitrogen and phosphorus. Oxley and Wallis (1974) demonstrate the use of simple multiple regression models to predict suitable ammonia levels in the Thames River. Output from the physical modeling were coupled with economic models to optimize treatment.

The EPA has developed the Enhanced Stream Water Quality Model (QUAL2E) as a steady state model for conventional pollutants in branching streams and well mixed lakes. This model includes the major interactions of the nutrient cycles, algal production, benthic and carbonaceous oxygen demand, atmospheric re-aeration, and their effect on the dissolved oxygen balance. It also includes a heat balance for the computation of temperature and mass balance for conservative minerals, coliform bacteria, and nonconservative constituents. The model can be used to examine the impact of both point and non-point waste loads on instream water quality.

QUAL2E has a long history of use and validation. The model originated in the late 1960s by work done by the Texas Water Development Board, a model called QUAL-1. EPA began a program to provide water quality models in the early 1970s for major river basins and specified that QUAL-1 be used as the basis for developing new, more advanced, basin-specific models. In the mid-1970s, a version for the Southeast Michigan Council of Government, an area-wide wastewater planning agency for the Detroit metropolitan area received widespread use. Another version revised for the National Council of the Paper Industry for Air and Stream Improvement has been used by the USGS on several rivers across the United States, as well as in England, Greece, Belgium, Spain, South America, South Korea, Thailand and the People's Republic of China.

Ecosystem water quality effects can also include changes to aquatic habitat brought about by changes in upland land use. For example, Hostetler (1991) conducted a modeling analysis of long-term stream temperatures on the Steamboat Creek Basin, Oregon. The Steamboat Creek basin serves both as an important source of timber, and as spawning and rearing habitat for anadromous steelhead trout (*Oncorhynchus mykiss*). Stream temperatures on Steamboat Creek are near the upper limit of tolerance for the survival of juvenile steelhead, a long-term effect of clear-cut logging. Hostetler demonstrates the utility of this model as both a restoration or management tool in defining upland resource use impacts on fish populations.

Wetland Models

Wetlands occupy a unique niche in the discussion of modeling for aquatic restoration in that they are at times entirely inundated with water, and at other times drained and function more as terrestrial ecosystems. Wetlands are discussed here in Chapter 5 as an ecosystem, with special focus on the processes that directly affect the species or assemblages that comprise the wetland community.

While wetland modeling is a relatively new discipline, already models have been developed to assess the environmental impacts due to water management practices, to describe the patterns of energy and nutrient dynamics, to estimate hydrologic conditions and storage capacity, and the use of wetlands for water purification (Mitsch 1983; Mitsch and Gosselink 1993). Three excellent resources for wetland modeling are *Wetland Modeling* (Mitsch *et al.* 1988), *Wetlands* (Mitsch and Gosselink 1993), and *Environmental and Ecological Modeling* (Jørgensen *et al.*, 1996). This section will briefly discuss some example projects and resources applicable to predicting restoration success.

Wetland simulation models have been developed to predict (1) the effects of changes in physical functions (e.g., hydrology, salinity) on wetlands, (2) ecosystem-level natural oscillations and trends through time (3) changes in assemblages of plants, animals and microorganisms (e.g. competition, grazing); and (4) changes in dissolved or particulate nutrients (e.g., nitrogen, phosphorus) or metals in wetlands.

Physical Functions

All of the hydrological principals discussed in Chapter 4 influence wetland community structure, and many of the hydrological models discussed are applicable to wetlands. Surface flows, recharge/discharge, groundwater, nutrient inputs, tides, salinity -- all contribute to determining the type of biological community that can be predicted. For example, in cooperation with the South Florida Water Management District, the USACE is investigating methods of combining the capabilities of ground-water and surface-water models to study the effects of water-management alternatives in ecologically sensitive wetlands that commonly are in direct connection with the ground-water system. Hydrologic data collected in Dade County will be used to construct and calibrate models of the Biscayne aquifer that will include simulations of the interactions between surface water, ground water, and wetlands. The intent of the modeling exercise is to increase the understanding of the hydrologic relations in the South Florida Everglades area, and to provide improved analytical tools to the water-resources community.

Tomasello and Ortel (1989) model changes in the discharges of the Cocohatchee River in Florida to estuarine tidal waters of the Gulf of Mexico. The Cocohatchee drains some of the most important ecological wetland assets to southwest Florida, including Corkscrew Swamp. The system is unique in that the river basin has been substantially altered by man-made drainage works, but development is relatively sparse. The model includes two dimensional routing routines for wetland regimes, hydrologic/hydraulic analyses of the agricultural and suburban land uses, and the dynamic wave channel routing. The models were calibrated and verified to existing hydrologic and hydraulic conditions with the intent to evaluate future proposed water management alternatives.

Ecosystem level trends

Models that predict large-scale changes in ecosystems over space and time are often referred to as landscape models. An example of a large complex landscape model that has been used to predict gross changes in marsh community structure is the Coastal Ecological Landscape Spatial Simulation Model (CELSS) (Costanza *et al.* 1989). CELSS is an integrated spatial simulation model that tracks 2,479 interconnected 1 km^2 cells that predict land loss and marsh succession for the Atchafalaya/Terrebonne, Louisiana coastal marsh and estuarine complex. All cells are interconnected, and the model tracks variables such as habitat type, water level and flow, sediment levels and sedimentation, subsidence, salinity, primary production, nutrient levels, and elevation. While CELSS will produce hard data output on each of the system variables, it's most useful function is the habitat maps which demonstrate changing patterns of land, hardwood swamp, as well as freshwater, brackish, and salt marshes.

Extreme conditions in wetlands often means the loss of water, or reduction in the amount of wetland acreage. Gibbs (1993) simulated loss of small, legally unprotected freshwater wetlands in a 600 km^2 area of Maine to examine how loss of small wetlands altered the geometry of the wetland mosaic and thereby might affect the dynamics of populations of birds, amphibians and small mammals. The modeling showed that the loss of small wetlands resulted in total wetland area declining by 19% (from 2032 to 1655 ha), total wetland number declining by 62% (from 354 to 136 wetlands), and average inter-wetland distance increasing by 67% (from 0.6 to 1.0 km). Also, average upland-wetland proximity decreased by 50% (0.5 to 1.0 km), such that just 54% of the landscape was within the maximum migration distance (1000 m) of terrestrial-dwelling and aquatic-breeding amphibians after loss of small wetlands, versus 90% before loss. A spatially-structured demographic model revealed that local populations of turtles, small birds, and small mammals, stable under conditions of no wetland loss, faced a significant risk of extinction after loss of small wetlands. No change in metapopulation extinction risk was evident for salamanders or frogs, largely because high rates of population increase buffered these taxa against local extinction. These results suggest that small wetlands play a greater role in the metapopulation dynamics of certain taxa of wetland animals than the modest area comprised by small wetlands might imply.

Aquatic Biota

In contrast to the ecosystem level models discussed above, some models have their utility in predicting success of individual species, or groups of species within altered wetlands. For example, Haukos and Smith (1993) focused modeling efforts on the ability to predict plant species compositions for 8 playa lakes on the Southern High Plains of Texas. The authors first conducted an assessment of seed banks in the lakes, and then used a seedling-emergence technique to gather data on the species composition in 2 environmental moisture regimes (drawdown and submerged). The model was then used to predict field vegetation from floristic composition of the seed bank in each playa lake. Although seedling densities differed among playas, the model adequately predicted the composition of vegetation in the playas. As environmental variability increased (more annual wet-dry fluctuations), the model became less reliable.

Hill and Keddy (1992) describe the use of models relating species richness of rare plants to measured habitat variables for the shoreline vegetation of lakes in southwestern Nova Scotia. Using multiple regression models derived from data collected at the Nova Scotian lakeshores, the authors report that richness of rare coastal plain herbs was easier to predict than richness of the "background flora" of wide-ranging species from noncoastal plain elements. The multiple-regression models using habitat variables accounted for 83% of the variability in species richness of rare coastal plain species but only 45% of that for the background flora. Richness was best correlated with the two inter-related variables, watershed area and shoreline width. The mechanism underlying this pattern appears to be that flooding kills woody plants, thereby reducing competition from shrubs and creating open expanses of shoreline.

Mitsch (1983) describe an energy/nutrient model for a Florida cypress dome ecosystem. The model was constructed in a fashion to be able to address a number of management questions, such as tree harvesting, drainage, fire, and disposal of sewage wastes.

Water Quality

The cycling of nitrogen and phosphorus both within natural wetland cycles, and from external sources such as urban runoff have been an active area of wetland modeling. For natural cycling within the wetland system, Childers *et al.* (1987) discuss three nitrogen cycling models that were each calibrated for three estuarine salinity zones (freshwater, brackish, saltwater) using data from the Barataria Basin, Louisiana. Accurate simulations of nitrogen cycling in estuarine ecosystems are particularly important to management applications as nitrogen is often the limiting nutrient in these environments.

Wetlands are increasingly being constructed to assist in water quality enhancement as filters for sediments, suspended particulates, or dissolved chemicals of concern for mines, agricultural runoff, municipal wastewater, or non-point pollution sources (Fields 1992; Hammer 1992; Mitsch 1992). Baker *et al.* (1991) describe the development of a simulation model that predicts the efficiency and economics of using wetlands to receive and treat coal mine drainage, specifically valent iron removal. Using STELLA, a series of simultaneous time-dependent differential equations and associated algebraic equations were created and calibrated comparing output to field data from the Simco Wetland in Coshocton County, Ohio. The chemical aspects of the model were further validated by comparing Tennessee Valley Authority actual field data for ten wetland sites to model outputs. An economic module was also developed to compare wetland cost with conventional treatment, based on unit costs obtained from various sources in the coal mining industry. The model demonstrated that iron removal was closely tied to loading rates and that the cost of wetland treatment was less than that of conventional treatment for iron loading rates of 20-25 g Fe^{++}/m^2/day and removal efficiencies < 85%. Conversely, the model predicted that at higher loading rates and where higher efficiencies are required, wetland systems are more costly than conventional treatment methods.

Examples of Wetland Models in Restoration Projects

Many of the models used to discuss and plan wetland restoration have principally dealt with water management. The example discussed in Chapter 4 for the Florida Everglades is typical. There are few examples of wetland models that deal strictly with the restoration process. However, there are numerous examples of projects developed for other purposes that can be adapted to the predictive process. For example, while CELSS was created to evaluate cumulative impacts from the numerous dredging projects and development projects in the Atchafalaya system, this type of spatial modeling can be used to evaluate potential mitigation/restoration projects. The FRAGSTAT landscape model has been used in an assessment of potential mitigation/restoration sites under a Natural Resource Damage Assessment settlement in the Puyallup River watershed and Commencement Bay, WA.

Odum *et al.* (1990) describe the development of a series of simulation models to assist in predicting ecological processes that affect the development of wetland ecosystems following phosphate mining, and how some of these processes might be accelerated. A computer simulation model was developed that related water levels and types of vegetation. In that study, which was field-validated, the model predicted willows, cypress, or floodplain-type hardwoods depending on the water levels and availability and success of seedling.

Continuing needs for wetland restoration are models that improve wetland restoration/creation efforts, to determine the degree to which constructed systems can replace lost functions, and to determine the potential for persistence of restored and constructed wetlands (Zedler and Weller 1990). Best *et al.* (1993) called for a research project that would focus on understanding the underlying ecological processes in natural and man-dominated wetland systems to prescribe conservation, rehabilitation and management strategies that would enhance the sustainability of these systems. Within this framework special attention should be directed to studies (1) of ecosystem parameters, on which the impact of disturbances are quantified. These studies, in which simulation models are used as tools for interpretation, can provide the basis for extrapolations in space and time; (2) on adaptation capacity and mechanisms of (groups of) species to extreme environmental conditions; (3) on (mutual) relationships between plants, animals and microorganisms (e.g. competition, grazing and mineralization); and (4) on dispersion between small wetlands.

Lake Models

Lake ecosystem models generally begin with primary production - defining the controlling temperatures, light and nutrient limiting conditions for phytoplankton. Energy gains and losses through trophic levels are defined in terms of grazing, respiration, feeding and assimilation efficiencies. Nutrient cycling includes excretion, transformation, sediment/water interactions, and "sinking" constants for dead organisms, excreta, and nutrients. Table 5-3 is a generic listing of these processes, controlling parameters, and some of the coefficient constants that ecosystem modelers use to define those processes (Scavia 1979). As a good general reference on lake ecosystem modeling, the series of articles in *Perspectives on Lake Ecosystem Modeling* (Scavia and Robertson 1979) is recommended.

In practice, the principal application of these complex lake ecosystem models for restoration purposes is related to water quality issues (e.g., eutrophication, contaminant trophic transfer). The National Research Council identified the most widespread problem facing lakes and reservoirs as being from point and non-point runoff of nutrients and pollutants (NRC1992). As lakes are unable to 'cleanse' themselves, they are contaminant sinks doomed to continually recycle the contaminants. The restoration modeling literature reflects this position; virtually all models we encountered dealt with effects of nutrients (nitrogen, phosphorus), contaminant (metals and organic chemicals), or changes in pH (e.g., acid rain) on lake ecosystems.

Physical Functions

The decreases in pH of lakes in the Northeastern U.S. and Canada due to acid rain effects have brought about a number of restoration studies. One restoration alternative for acid lakes is the addition of lime to bring the pH back to within acceptable limits. However, not all effects associated with acid lakes are simply due to inhospitable pH levels to aquatic organisms. One distinguishing feature of low pH water is its clarity due to decreases in dissolved organic carbon and phytoplankton production. Changes in transparency result in altered thermal characteristics of the lake which also has the capacity to affect organisms.

Schofield *et al.* (1993) examined the thermal degradation of brook trout (*Salvelinus fontinalis*) habitat in Adirondack lakes effected by acidification. Beginning with the hypothesis that acidification-induced reductions in the thermal stability of sensitive Adirondack lakes could lead to degradation of potential brook trout habitat, they further hypothesized, on the basis of energetic considerations, that brook trout growth and average size at age would be sensitive indicators of differences in the extent and availability of preferred summer habitat in lakes with different thermal structures. Both limed and unlimed lakes were included in the analyses to compare fish distributions.

To examine these effects, several models were used. Stratification boundaries for the lakes were predicted using the UFILS1 model that had previously been developed by USFWS (Driscoll *et al.* 1990) . Once the boundaries were determined, a multinomial logistic regression model was applied that provided a probabilistic estimate of stratification class based upon transparency and depth. Finally, a bioenergetic growth model was developed for sensitivity analysis of temperature effects on simulated growth of brook trout populations inhabiting lakes with different thermal structures.

TABLE 5-3. IMPORTANT LAKE ECOSYSTEM PROCESSES, THE CONTROLLING PARAMETERS OF THOSE PROCESSES, AND THE MODEL VARIABLES THAT DEFINE THE CONTROL PARAMETERS (ADAPTED FROM SCAVIA 1979)

PROCESS	CONTROL PARAMETERS	MODEL VARIABLES
Primary Production and/or Nutrient Uptake	Temperature	Optimum temperature Upper lethal temperature Q_{10} value
	Nutrients	Half saturation constant Maximum growth rate Maximum uptake rate
	Light	Saturation light intensity
	Functional groups	All coefficients
Respiration	Temperature	(as above)
	Primary production	Proportionality constant
	Zooplankton consumption	Proportionality constant
Grazing	Temperature	(as above)
	Total food	Half-saturation coefficients
	Food types	Selectivity coefficients
	Functional groups	All coefficients
Feeding and Assimilation Efficiencies	Temperature	(as above)
	Total food	Half saturation constant
	Functional groups	Maximum efficiency
	Food types	
Nitrogen Uptake	Forms of nitrogen available	Preference constants
Excretion	Temperature	(as above)
	Respiration	Proportionality/stoichiometry constants
Nutrient Transformation (water column and sediments)	Temperature	(as above)
	Organic components	First-order decay constants
Sinking	Physiological state	Proportionality Constant

The model output can be used in determining which lakes are most greatly affected, and where restoration (liming) can have the greatest impact. Shallow, high transparency lakes were found to be the most sensitive to changes in thermal stratification induced by changes in water color or light attenuation. Furthermore, the model output shows that liming significantly increases the available and volumetric extent of preferred brook trout habitat as a result of decreased transparency and increased thermal stability in these shallow lakes.

Ecosystem Level Trends

We have emphasized that the role of models in restoration is to aid in decision making, but at times those decisions must incorporate local interests, including recreational opportunities. An example of a model used to aid in local lake restoration decision making based upon an ecological approach is the Minnesota Lake Eutrophication Analysis procedure (MINLEAP)(Wilson and Walker 1989). MINLEAP formulates water and phosphorus balances and uses a network of empirical models to predict lake phosphorus, chlorophyll-a, and transparency values. This is a screening model designed to estimate local lake conditions with minimal input data and is run to identify "nuisance frequencies" of algal blooms. The output from MINLEAP include (1) statistical comparisons of observed and predicted phosphorus, chlorophyll-a and transparency values; (2) uncertainty estimates; and (3) estimates of chlorophyll-a interval frequencies, for observed and predicted conditions. The output of lake condition may be calibrated to citizen preferences using observer surveys to define swimmable and nonswimmable conditions in a locally meaningful manner.

Changes in lake water levels can have positive and/or negative effects on lake biota. This can include loss of habitat, changes in prey populations, or in the case of Mono Lake, changes in salinity which effects the entire ecosystem. Wiens *et al.* (1993) discuss the use of water-balance models by the National Academy of Sciences (NAS) and the Community and Organization Research Institute (CORI) of the University of Santa Barbara to predict changes in salinity, and the resultant changes in algal, brine shrimp, and avian populations (Figure 5-7). The models showed that as lake level declined, salinity increased. Mineral precipitate from the water column form a highly saline layer near the lake bottom. In this chemically stratified system, brine shrimp cysts sink and become entrapped in the lower levels. Increasing salinity translates into biological losses. Exposure of lake shoreline results in increased erosion.

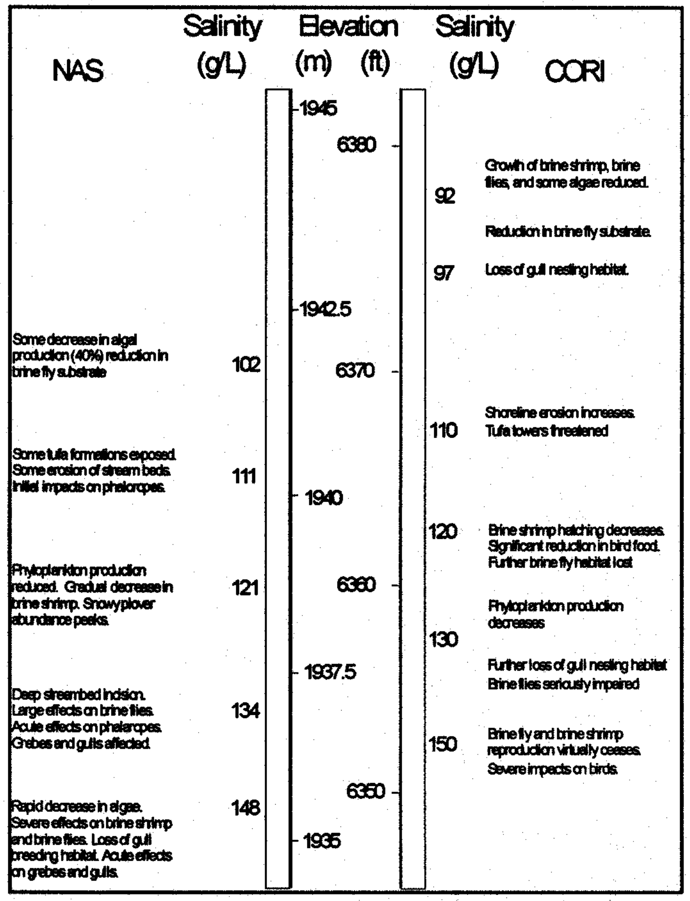

Figure 5-7. Modeled comparison of lake elevations above sea level at which various impacts on the Mono Lake ecosystem are likely to occur. Adapted from Wiens *et al.* 1993).

Aquatic Biota

Most of the species and ecosystem models discussed to this point are also applicable to lake systems. This is especially true of the plant community models (e.g., Scheffer *et al.* 1992), fish models (Shirvell 1989), avian models (Gibbs *et al.* 1991), and wetland models (Mitsch and Gosselink 1993). Furthermore, many of the eutrophication models we will discuss in the next section pertain to lakes.

One lake ecosystem type we have not discussed so far is reservoirs. Reservoirs are a permanent part of the American landscape, and over time have developed their own ecosystems. Reservoirs essentially function as lakes, although they tend to have a greater degree of management than do natural lakes. There are frequent alterations in organic loading and water levels, depending upon the inputs and demands on the reservoir system. As a result of these changing conditions, coupled with their recreational importance, reservoirs frequently require manipulation or restoration of certain functions (e.g., fisheries) within the system.

Cole and Deitner (1991) describe the use of a management planning model RIOFISH that simulates dynamics of reservoir fisheries, including fishery responses to environmental fluctuation, stocking, habitat modification and other model-user modifiable factors. An application example of RIOFISH is given that measures the sensitivity of a simulated bass-bluegill fishery to the effects of fluctuating water level and organic loading on modeled Lake Summer in New Mexico. Factors such as annual variation in organic loading negatively influenced fish biomass, density, catch rate, production and young-of-year recruitment independently of water level, reflecting model trophic effects. Severe water level fluctuation in certain modeled years also reduces or eliminates spawning success. The modeled bass-bluegill fisheries that were limited by fluctuating conditions positively responded to water level management and fingerling stocking.

Water Quality

We have made the point that most of the lake ecosystem models deal with water quality, and will discuss additional examples of eutrophication models in a later section. One water quality-related issue that we have not discussed is that of uptake of contaminants from water or sediments into primary consumers, and the transfer of those contaminants through multiple trophic levels. Most often, the contaminants of interest in these systems are mercury, polychlorinated biphenyls (PCBs), and pesticides (e.g., DDT). While this is generally the domain of the ecotoxicologist, restoration ecologists also have an interest in understanding what are ecologically "safe " levels of chemicals of concern, and how those numbers are derived. As such, a few trophic transfer models are worth mentioning here.

Most of the trophic transfer models are similar in terms of contaminant uptake and trophic transfers. In water-only uptake models, dissolved contaminants are taken up at all levels by both direct absorption (e.g., gill uptake in fishes) and through food-chain transfers. The models will vary in terms of uptake constants, kinetics, complexity of the food chain, and contaminant metabolism. Excellent examples of these types of models may be found in Thomann and Connolly (1984), and Thomann (1989).

A simple computer program for estimating contaminant trophic transfer is available for the personal computer. Gobas (1993) provides a model that can be used for estimating concentrations of hydrophobic organic substances in various organisms of aquatic food-webs from chemical concentrations in water and sediments. The model has been applied to the Lake Ontario food-web and shown to be in satisfactory agreement with field data. The model has been written to run under Microsoft Windows©, contains "fill-in-the blank" variable fields, and provides options to determine model confidence using Monte-Carlo simulation.

Examples of Lake Models in Restoration Projects

The examples we have chosen to discuss are eutrophication models, and are discussed under that section below.

Estuaries

While we have compiled a number of estuarine ecological articles, we have elected not to review them here. Instead, we defer to the excellent state-of-the-art review of estuarine modeling processes given in the summary paper written from the Estuarine Ecosystem Resource Workshop held in 1992 by the Chesapeake Bay Project (STAC 1992). The review is a compilation of presentations and discussions by selected estuarine scientists and managers. The conference objective was to discuss a variety of issues relevant to modeling estuarine ecosystem processes in Chesapeake Bay. While focused on the Chesapeake Bay, the three-day workshop brought together leading researchers and modelers from across the United States to investigate and to compare a range of numerical ecosystem approaches and to evaluate relevant applications for managing all estuarine resources. The STAC review discusses state-of-the-art methodologies and technologies used in several important areas, including: ecosystem process models, water quality models, spatially explicit fish bioenergetic models, individual-based fishery management models (IBFMs), ecosystem regression models, ecosystem network analysis models, and landscape spatial models.

Eutrophication Models

Eutrophication is the biological response in water due to increased enrichment by nutrients, primarily phosphorus and nitrogen, and can occur under natural or manmade conditions. Agricultural runoff, urban runoff, leaking septic systems, sewage discharges, eroded streambanks, and similar sources enhance the flow of nutrients and organic substances into water bodies, resulting in increased fertility of affected lakes, reservoirs, slow-flowing rivers and certain coastal waters. These increases in nutrients stimulate plant growth, which manifests as algal blooms, heavy growth of rooted aquatic plants (macrophytes), and algal mats, which subsequently leads to deoxygenation and, in some cases, unpleasant odors. Eutrophication often affects most of the vital uses of the water such as water supply, recreation, fisheries (both commercial and recreational), or aesthetics. In addition, lakes become unattractive for bathing, boating and other water oriented recreation. Most often economically and socially important species, such as salmonids decline or disappear and are replaced by coarser fish of reduced economic/social value.

Eutrophication models in this document are those models that predict the impacts of anthropogenic nutrients (i.e., phosphorus and nitrogen) on biota in rivers, lakes, or estuaries. Eutrophication models are often hybrids of hydrologic, hydraulic, nutrient cycling, and ecosystem models. Because of their importance to urban lakes and estuaries, eutrophication models have achieved a level of sophistication that warrants separate discussion from these other models. In fact, many of the lake and estuarine ecosystem models are written to predict conditions under which eutrophication exists, the probabilities of occurrence under a set of known conditions, and can be used to plan restoration goals. As a result of its direct influence on human activities, the processes contributing to eutrophication have been well studied, and well modeled. Many of the models and mathematical expressions used in lake ecosystem modeling also find their way into the eutrophication models. The main difference between the models is the natural recycling of nutrients predicted by the former, and the extreme responses to external nutrient inputs predicted by the latter.

Of all the types of models discussed thus far, eutrophication models come closest to meeting the criteria for planning restoration efforts that were discussed in Chapters 1 and 2. Eutrophication models are well documented, calibrated and validated. They often have probability functions, using Monte Carlo or similar functions to simulate the studied water bodies. In the paragraphs below we provide examples of the major eutrophication models and their applications.

Examples of Major Eutrophication Models

Perhaps the most well known and documented eutrophication model in the U.S. is the Watershed Model of the Chesapeake Bay. The Watershed Model of the Chesapeake Bay is a joint project of several state agencies and the federal government, and was originally derived from the Hydrological Simulation Program - Fortran (HSPF) discussed in Chapter 4. HSPF model parameters were modified to represent the geographic and biological conditions of the Chesapeake Bay.

The purpose of this model is to identify and quantify nutrient loads in the Chesapeake Bay basin in order to support nutrient reductions required by the Bay Program's 40 percent reduction goal. This is a large and sophisticated model, with inputs that include wind, precipitation, snowfall, solar radiation, temperature, dew point, soil types, vegetation type, crop type, land slope, soil characteristics, land use, river geometry, and water quality data. The model provides as output nutrient loading reports, along with statistical analyses and graphical representations. The model's structure allows for "what if" hypothetical situations, in order to examine and predict the level by which nutrients must be reduced based on the amount and rate at which nutrients are presently entering the Chesapeake.

EPA's Water Quality Simulation Analysis Program (WASP4 model) principally is used to simulate contaminant fate in surface waters, but can be applied to eutrophication simulation. A separate module, EUTRO4, has been developed to include prediction of dissolved oxygen, biochemical oxygen demand, phytoplankton, carbon, chlorophyll, ammonia, nitrate, organic nitrogen, and ortho-phosphate in the bed and overlying waters.

PCLoos is a fairly complex, yet comprehensive deterministic eutrophication model that simulates the phosphorus cycle and plankton growth in the shallow, hypertrophic

Loosdrecht Lakes (The Netherlands) before and after restoration measures (Janse and Aldengerg 1990). The model includes three algal groups, zooplankton, fish, detritus, zoobenthos and upper sediment (all modeled both in carbon and in phosphorus) besides inorganic phosphorus (SRP) in both the surface water and the interstitial water.

Eutrophication and Aquatic Biota

Eutrophication affects all levels within an ecosystem, but not all models predict effects on aquatic biota outside of phytoplankton. Effects on aquatic biota are often inferred based upon low oxygen, decreased light transmittance, or reduction in prey. Other models explicitly consider effects on species or assemblages; some of these we discuss here.

Eutrophication can affect vascular plants through changes in oxygen, competition for nutrients, or decrease in light attenuation. Bach (1993) describes a submodel of a larger eutrophication model that predicts the seasonal variations in growth and distribution of eelgrass (*Zostera marina*). The eutrophication model describes the growth of phytoplankton and zooplankton in relation to nutrient dynamics. The important factors controlling eelgrass growth and distribution included in the model were water transparency, water temperature, and water depth/topography of the eelgrass bed. Since water transparency depends on the phytoplankton (chlorophyll-a) concentration, the phytoplankton and eelgrass submodels interrelate, especially at the point of water transparency. The eelgrass submodel output describes seasonal and regional variations in production and biomass of above and below ground parts.

Zooplankton communities are effected by changes in oxygen conditions, temperature, and phytoplankton concentrations. One interesting application of food-web manipulation as a restoration tool for a hypertrophic stratified lake is given by Kasprezak *et al.* (1988). Lake Haussee in Germany had become eutrophied as a result of increased nutrients from a municipal waste-water treatment. While external sources of nutrients into the lake were halted in 1980, the lake remained in the state of hypertrophy because of the amount of accumulated nutrients. Modeling investigations of the hydrology, chemistry and food-web showed that the potential for self-purification is low. As an alternative, the effect of food-web manipulation using the ecological lake model SALMO was investigated. Output showed that by decreasing zooplankton mortality, a drastic reduction of phytoplankton biomass occurred.

Eutrophication of a water body can have a significant impact on the fishery resources. Lee and Jones (1991) provide a general discussion of the effects of eutrophication on fisheries resources, and introduce an approach for estimating the fish yield that could be sustained in a water body. The model, which is described as the Vollenweider-OECD eutrophication model, examines the change in fish yield that could be expected to result from eutrophication management practices involving phosphorus load reduction. Types of management practices that are discussed include input load reduction, aeration, nutrient removal (e.g., aluminum sulfate addition), aquatic plant harvesting, herbicide application, biological control, dredging and water level management.

Publicly Available Eutrophication Software Programs

The HSPF program, discussed in Chapter 4, has been adapted for a number of eutrophication related purposes, including the Chesapeake Bay Model described above. The Water Analysis Simulation Program (WASP) was also discussed in Chapter 4 as a generalized modeling framework that simulates contaminant fate in surface waters. Based on the flexible compartment modeling approach, WASP4 can be applied in one, two, or three dimensions. WASP4 is designed to permit easy substitution of user-written routines into the program structure. Eutrophication WASP4 combines a kinetic structure adapted from the Potomac Eutrophication Model with the WASP4 transport structure. EUTRO4 predicts dissolved oxygen, carbonaceous biochemical oxygen demand, phytoplankton, carbon, chlorophyll, ammonia, nitrate, organic nitrogen, and ortho-phosphate in the bed and overlying waters.

An interesting set of publicly available total phosphorus models developed for use on Excel 5.0 spreadsheets has been developed by the Soil and Water Conservation Society of Metro Halifax, Canada., and can be downloaded from the Internet (http://ccn.cs.dal.ca/Science/SWCS/SWCS.html). Developed to assist in evaluating and planning restoration of significant watersheds within the four Metro Halifax municipalities, to date the program has conducted phosphorus estimates on over 325 lakes. The modeling utilizes the data and structure developed by the Ontario Ministry of Environment and Energy as well as some work by the USEPA Clean Lakes Program affiliates. The results of the modeling are being translated and plotted on the `OECD management model which is a derivation of the international leading OECD studies.

The spreadsheet model (on Excel 5.0 software) is described as user-friendly and flexible, i.e., can be altered to vary any of the inputs at ease and derive answers to questions like "what if?". Each file is in the MS Excel 5.0 format and the books contain the following bound sheets: an introduction sheet (Intro), a flow chart (Flow-), a control spreadsheet (Control SS), a master spreadsheet (Master SS), and a runoff sheet (Runoff). The Master SS is the workhorse and consists of various land use data, scenarios, etc. The Control SS is a summary of the Master SS and extracts the data from the Master SS. The Control SS is the one to be utilized in order to obtain answers to ""what if"". The Control SS has a group of columns titled "Experimental Theoretical analysis" which can be used to vary the inputs and the resultant mean whole-lake total phosphorus concentration, the trophic status (based on the OECD Fixed Boundary), and the Carlson TSI(TP) are predicted.

Applications of Eutrophication Models to Restoration

In the discussion below we present a few of the models developed for eutrophication, and discuss how they may be used in a restoration context. An excellent resource for eutrophication models and their application is the National Technical Information Service (NTIS 1989). NTIS compiled a bibliography containing over 290 citations concerning eutrophication analysis, assessment, and effects. The application of mathematical models for eutrophication control is discussed.

A frequent use of eutrophication models is to determine what are the attainable loading limits for nutrients in a watershed, and then to develop water quality policy that ensures the attainment of those goals. Another use of eutrophication models is to rank restoration potential among different watersheds as a means of prioritizing the restoration effort. For example, loading models were used to develop an evaluation procedure that prioritized the restoration potential of 19 eutrophied reservoirs in Ohio (Fulmer and Cooke 1990). Each watershed had unique characteristics that dictated the practical lower or attainable limits of stream nutrient concentrations that could be achieved. The reservoirs that exceeded predicted attainable concentrations by the greatest amounts were considered to have the greatest potential for restoration. These were not reservoirs with the worst trophic states. The authors present arguments for the use of this method to establish water quality standards, provide a rational way to establish a priority project for lake restoration, and develop lake improvement and protection goals.

An example of the application of lake eutrophication models as a restoration tool is given by Souza *et al.* (1988). The authors examined twenty-five lakes as part of the New Jersey Lakes Management Project to assess the accuracy of trophic state models in predicting the lakes' existing condition and projecting post-restoration/management improvements. To assess the model's utility, the nutrient loading of each lake was first quantified, and based upon those data spring total phosphorus and summer chlorophyll-a concentrations were predicted. When predicted and observed data were compared, good agreement (defined as greater than or equal to 80%) was achieved for only 7 of the 25 lakes. The discrepancies between predicted and observed results were attributable primarily to rapid hydraulic flushing, unaccounted nutrient sources, and macrophyte colonization in small, urbanized lakes where the models were judged to be inadequate. The authors did conclude that the models were generally useful in projecting the decrease in nutrient loading required to improve trophic state and in prioritizing the control of various nutrient sources.

Habitat Evaluation Procedures

HEP and HSI Models are formal procedures established by the USFWS for determining suitability of an environment for a specific species or guild. HEP is based upon the assumption that the quality of an area as wildlife habitat can be described by a single number, the HSI. The HSI ranges from 0.0 to of 1.0, with 1.0 representing optimum habitat.

These are not formal predictive models *per se*, but focus on what abiotic and biotic variables are required to support specific target species. The general process begins by identification of critical habitat variables for the species and life stage of interest. The variables are scored on the 0 - 1 scale by specialists, field biologists, and resource managers. Individual suitability indices are developed for each variable through the use of a suitability index graph. The individual suitability indices are combined into an aggregate HSI. An example of the process is given in Figure 5-8.

There is a significant element of "best professional judgement" built into the models as assumptions. For example, in the development of the mallard HSI in Figure 5-8 (Allan 1987), assumptions such as "optimum foraging opportunities for mallards will be facilitated by providing water depths of < 40 cm" are qualitative and based upon subjective evaluation by avian biologists. There is no basis for evaluating probabilities with this type of approach.

Species Specific HSI

The Fish and Wildlife Service has published a number of HSI documents for specific fish, birds, and mammals, some of which are listed in Table 5-4. Some of the published HSI models are generic to the species of interest. For example, Rice (1984) describes an HSI model that considers food and reproductive habitat requirements as indices of overall habitat suitability for dabbling ducks (*Anas* species). Habitat variables of water depth, percent submerged vegetation in open water, percent cover, percent open water, and presence of islands are compared with amount of forage, reproduction and cover to produce the index.

Other documents are narrow in scope to specific species in a defined region at a defined time of year. Allen (1987) discusses the winter habitat requirements for mallards in the lower Mississippi valley. The HSI model is restricted to *Anas platyrhynchos* overwintering within a narrow geographic band from Cape Girardeau, Missouri to Louisiana, excluding the coastal marshes of the Gulf of Mexico. The winter is defined as a 120-day period between November 1 and February 28.

Community Level HSI

HSI can also be applied at the community level to define a particular habitat in terms of species or guild richness, biomass, or trophic structure (Schroeder and Haire 1993). Community models are used when there is a need to more holistically define a community or ecosystem. General guidelines for these community levels HSIs are given by Schroeder and Haire (1993), which were discussed earlier in Chapter 3.

One additional reason for examining communities can be in minimizing the number of variables that need to be examined when there is an interest in multiple species. Miller *et al.* (1987) argue that most of the published habitat suitability index models for warmwater fishes were cumbersome due to the need for so many variable measurements. They applied a community level assessment by grouping closely related fish, and then only examining five variables for each group: percent pools, average current velocity, percent cover, pH, and dissolved oxygen. The models were found to predict reasonably well the fish groups in field studies in the Little Cypress Basin, Texas, and the Yazoo River, Mississippi.

Schroeder and Allen (1992) developed an HSI model to evaluate wildlife communities along the Snake River, near Jackson, Wyoming. This model is unique in that it evaluates percent cover for each plant type, channel configuration, presence of islands, overbank flooding, spring-fed creeks, shoreline complexity, pool-riffle ratio, percent of river subject to human disturbance, and estimates the richness of vertebrate species which depend on the riparian vegetation and physical conditions. Many of the variables can be measured by remote sensing, and combined with a geographic information system analysis.

Limits to the HSI Models

We have already noted that the HSI process is subject to a large number of assumptions, the variability around which cannot be quantified. Likewise, the output is a single number that cannot predict the probability of habitat quality for a specific species and/or life stage.

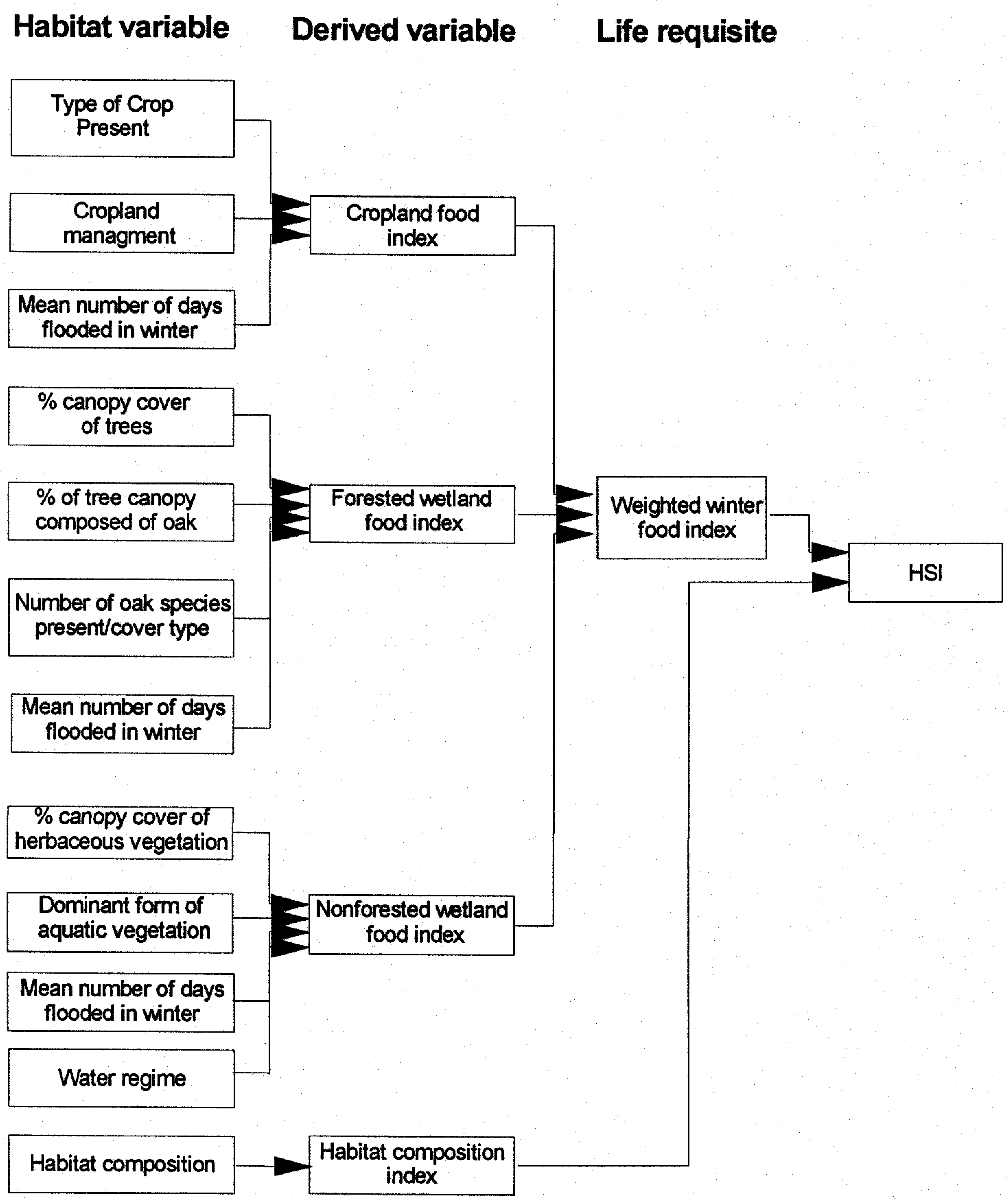

Figure 5-8. Example of development of an HSI by defining relationships between habitat variables, derived variables, and life requisites. Examples is from Allan (1987) for mallard winter habitat in the lower Mississippi valley.

TABLE 5-4. SELECTED HSI REPORTS FOR ALGAL, INVERTEBRATE, FISH, AVIAN, AND MAMMAL SPECIES

SPECIES	SCIENTIFIC NAME	AUTHORS
Algae		
Benthic microalgae		Pickney and Zingmark, 1993
Invertebrates		
Pink Shrimp	*Penaeus duorarum*	Mulholland, 1984
Hard Clam	*Mercenaria mercenaria* *M. campechiensis*	Mulholland, 1984
Fish		
Rainbow Trout Rosyside Dace	*Oncorhynchus mykiss* *Clinostomus funduloides*	Hill and Grossmand, 1993
Colorado River Cutthroat Trout	*Oncorhynchus clarki pleuriticus*	Bozek and Rahel, 1992
Brown Trout	*Salmo trutta*	Beard and Carline, 1991 Raleigh and Zukerman ,1986
Chinook Salmon	*Oncorhynchus tshawytscha*	Raleigh *et al.* ,1986
Coho Salmon	*Oncorhychus kitsutch*	McMahon, 1983
Brook Trout	*Salvelinus fontinalis*	Schmitt *et al.*, 1993
Paddlefish	*Polyodon spathula*	Moen *et al.* ,1992
Redbreast Sunfish	*Lepomis auritus*	Helfrich *et al.*, 1991
Smallmouth Bass	*Micropterus dolomieu*	Edwards *et al.* ,1983
Gizzard Shad	*Dorosoma cepedianum*	Williamson and Nelson, 1985
American Shad	*Alosa sapidissima*	Ross *et al.* ,1993
Southern Flounder Gulf Flounder	*Paralichthys lethostigma* *P. albigutta*	Engle and Mulholland, 1985
Avian		
Great Blue Heron	*Ardea herodias*	Short and Cooper, 1985
Dabbling Ducks	*Anas* species	Rice, 1984
Bald Eagles	*Haliaeetus leucocephalus*	Peterson, 1986
Mallard	*Anas platyrhynchos*	Allen, 1987
Osprey	*Pandion haliaetus*	Vana-Miller, 1987
Western Grebe	*Aechmophorus occidentalis*	Short, 1984
Mammals		
Beaver	*Castor canadensis*	McComb *et al.* ,1990
Moose	*Alces alces*	Allen *et al.* ,1987

Instream Flow Incremental Methodology

Perhaps the most well known, and documented procedure for conducting systematic planning for water resources is the IFIM. Developed principally by the U.S. Fish and Wildlife Service, the IFIM methodology is an attempt to integrate the planning concepts of water supply, hydraulic time series and analytical models from hydraulic and water quality engineering, with empirically derived habitat vs. flow functions (Stalnaker *et al.* 1995).

Like HEP, IFIM is also a formal procedure of habitat evaluation, originally written to evaluate flow impacts from dams on fish species in the regulated river system. IFIM in and of itself is not a model; rather it is a methodology, coupled with modeling, for assessing the environmental impacts of water management on biological resources. The recent publication of the IFIM "primer" by Stalnaker *et al.* (1995) provides an overview of the intent and functioning of the methodology.

A number of predictive models of fish community structure have been written for application in the IFIM (Nestler *et al.* 1989), which are used not only on regulated rivers, but have been applied in some instances to mitigation and restoration. Figure 5-9 shows the generic model links in the modeling process. These instream flow and habitat models strive to predict standing crops and/or other measures of biological productivity, based upon a set of habitat variables. The critical underlying assumption in these models is the premise that there are lower and upper boundaries for stream flow, beyond which conditions become unsuitable for fisheries.

It is not our intention to provide an in-depth view of IFIM; rather we will focus the remainder of this section on the models used to predict species use in a stream reach, and discuss applications of those models. For more information on the overall process, refer to the articles by Stalnaker *et al.* and Nestler *et al.* cited above. An additional overview of the process is given in Stalnaker (1994). Detailed information concerning data gathering and information processing for stream resource flow requirements is given in Stalnaker and Arnette (1976).

PHABSIM

At the heart of the IFIM process is PHABSIM - the Physical Habitat Simulation System. The purpose of PHABSIM is to simulate a relationship between streamflow and physical habitat for various life stages of a species of fish, or a recreational activity (Milhous *et al.* 1989). Like RCHARC described earlier, PHABSIM assumes that the production of "benefits" (e.g., fish, recreation) is limited by the availability of physical habitat. It differs from RCHARC in that PHABSIM attempts to define habitat requirements of the target species.

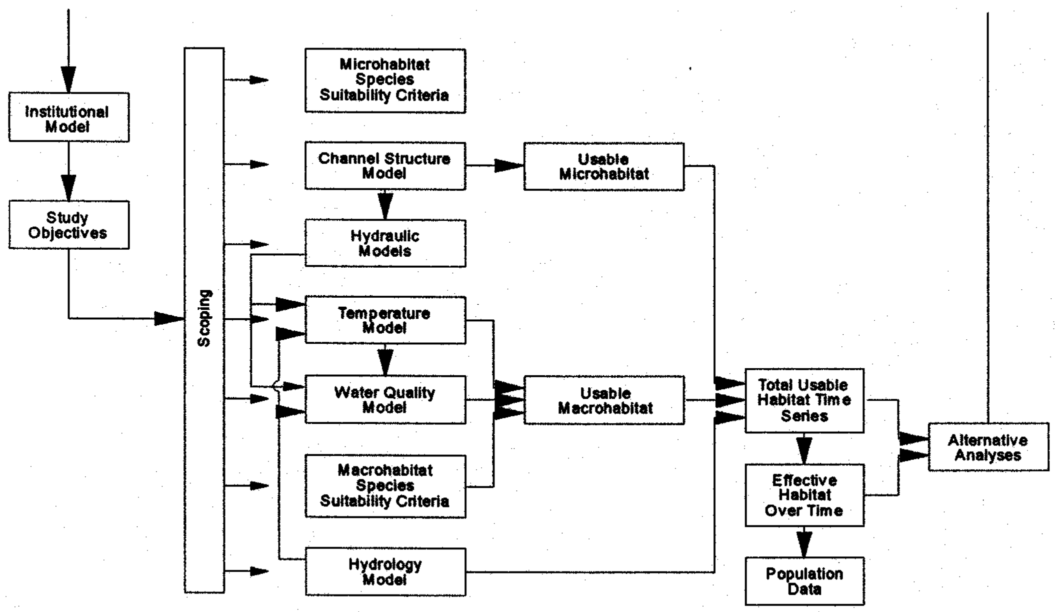

Figure 5-9. Schematic representation of model linkages in the IFIM showing input points for biological criteria. (Adapted from Bovee 1986).

Within PHABSIM are the hydraulic and habitat simulations of a stream reach utilizing defined hydraulic parameters and habitat suitability criteria. Data inputs include detailed hydraulic information (velocity, stage, slope, discharge), physical data (substrate type, cover, channel geometry) and the preferences of each life history stage of a fish species for a range of depths, velocities and substrate type (habitat suitability criteria). Output of the model is the Weighted Usable Area of the stream segment for the species of interest.

Applications of the IFIM

There are numerous examples of applications of the IFIM referenced in the RESTMOD database. Most often these are associated with regulated rivers, and fisheries "enhancement" is discussed instead of fisheries restoration. We view the terms not necessarily synonymous, but having similar goals in increasing target fish populations.

Use of IFIM as a restoration tool is demonstrated in on-going work for increasing chinook salmon production on the Trinity River, CA (Williamson *et al.* 1993). Limitations on salmonid stocks on the Trinity River were identified as insufficient stream flow, excessive sediment loading and stream bed sedimentation, and an inadequately regulated harvest.

PHABSIM was used to identify the physical habitat limitations for salmonids on the Trinity, while new models are being developed that examine habitat-induced limitations and capacity, temperature models for growth and early life development, and fish population and production models. These will be used to help formulate management options for reservoir release. Optimization of pre-smolt salmonid conditions on the river, coupled with fisheries and forestry management (to reduce sediment load), is the planned restoration strategy.

Cheslak and Jacobson (1990) integrate PHABSIM with a network hydrological model (NETWORK) and the IFIM stream temperature model (SNTEMP). Coupled with field fishery studies to evaluate the potential effects of temporal changes in carrying capacities on fishery resources, they demonstrate the model's overall utility in predicting rainbow trout (*Oncorhynchus mykiss*) populations downstream of a proposed hydroelectric project. Their analysis showed that the model performance was reasonable for each life stage and reach in the model structure. The model was used to compare population dynamics under natural and post-project conditions, and it indicated that a substantial enhancement in the fishery resource could be expected from instream flows proposed for the project.

Application of the IFIM has extended beyond the U.S., and has been adapted for both large and small studies throughout the world. Cubillo (1991) describes the use of the IFIM procedure, along with the USACE's reservoir water quality model QUAL-R1 and river water quality model (QUAL-2E) to plan flow regimes for both drinking water supply and habitat restoration in the water system that supplies Madrid, Spain.

IFIM was developed principally to characterize fish habitat, but has been applied to a number of other species as well. For example, Jowett *et al.* (1991) used IFIM to examine the microhabitat preferences of 12 benthic invertebrate taxa in 4 New Zealand rivers, and developed velocity, depth, and substrate suitability curves. Hearne *et al.* (1994) applied a modification to PHABSIM that relates changes in plant biomass to stream flow in South Africa.

Limits to the Application of IFIM Models and Methodology.

IFIM is a complicated, time and resource intensive process that has its limitations. Furthermore, like all models, PHABSIM has not been found applicable to all species or streams. In a comparison of the WUA prediction from PHABSIM and HQI on standing crops of trout (*Salvelinus* spp., *Salmo* spp.) in Wyoming streams, Conder and Annear (1987) found HQI to be a better predictor during low-flow. In contrast, there were no significant correlations found between WUA and the measured standing crops.

Loar (1985) evaluated the validity of physical habitat indices for predicting the response of trout populations to changes in stream-flow. Because the use of habitat indices is based on the assumption that fish abundance or biomass is positively correlated with the value of the habitat index, the study focused on an analysis of fish-to-habitat relationships. The study examined eight study sites on cold water streams with naturally reproducing populations of brown and rainbow trout. Fish biomass, abundance, and production were estimated, using electrofishing and mark-recapture techniques. Physical habitat was quantified, using the IFIM's PHABSIM system at each site. In comparisons of sites and actual populations with predicted habitat condition, the habitat condition alone was not sufficient to explain differences in rainbow trout abundance.

Scott and Shirvell (1987) provide a critical review of the underlying assumptions of PHABSIM, and discuss applicability of IFIM to rivers and streams in New Zealand. They evaluated studies in New Zealand that used IFIM, and determined that IFIM is not invariably more efficient than simpler methods. They conclude by recommending that IFIM be regarded as part of a framework that is still being developed.

Internet Resources for Biological Models

With the advent of the Internet, there are tremendous opportunities for information, data, and model acquisition. Many of the models we have discussed in Chapter 5 can be acquired by direct download, or ordered through government or private sources. For example, copies of HEP Ver. 2.2, HSI Ver 2.1, In-stream Flow Models PHABSIM, LIAM, and the Blossom Statistical Package can be downloaded and/or ordered. Documented information on these models is also available. There are a good number of European ecological models on the World Wide Web that we did not discuss, nor include in our current database. We have provided in Table 5-5 below a listing of practical and interesting web sites pertaining to modeling and restoration.

TABLE 5-5. INTERNET RESOURCES OF MODELS, DATA, AND GENERAL INFORMATION RELATING TO AQUATIC BIOLOGICAL MODELS

INTERNET HOME PAGE	NET ADDRESS	HOST	RESOURCES
Web Sites for Models			
Midcontinent Ecological Science Center	http://www.nbs.gov/mesc/swprods.html	National Biological Service	Source for obtaining copies of HEP Ver. 2.2, HSI Ver 2.1; In-stream Flow Models PHABSIM, LIAM, and the Blossom Statistical Package. LIAM is available as an MS Windows 3.1 version.
WWW-Server for Ecological Modeling .	http://dino.wiz.uni-kassel.de/ecobas.html	University of Kassel, Germany	This is an excellent source of information about a large number of terrestrial and aquatic ecological models. Both U.S. and European models are covered. The web site describes simulation models, the simulation-software, contacts for model acquisition/use, and literature
Distributed Modular Spatial Ecosystem Modeling	http://kabir.umd.edu/SMP/MVD/index.html#TOC	T. Maxwell and R. Costanza, Univ. of Maryland	This page describes the development of a Spatio-Temporal Ecosystem Modeling approach using the STELLA engine. The program is explained, and then provides example applications ecosystem models of Barataria Basin in Southern Louisiana, and the Everglades in Florida.
Soil & Water Conservation Society of Metro Halifax- Home Page	http://ccn.cs.dal.ca/Science/SWCS/SWCS.html	Soil & Water Conservation Society of Metro Halifax	Home page provides with links to demonstrated applications of lake modeling, Ontario lake data, and TP Predictive Models (in Excel 5.0 format).

TABLE 5-5. (cont.)

ADE-4 on the Web	http://biomserv.univ-lyon1.fr/Whatis.html	University of Lyon, France	ADE-4 is a multivariate analysis and graphical display software package for Macintosh micro-computers. It is made of stand-alone 42 modules; 28 of them are computation modules, and 14 are graphic modules. ADE-4 can be downloaded from this home page.
NetMul	http://biomserv.univ-lyon1.fr/base.html	University of Lyon, France	NetMul is an online multivariate analysis system. It provides a Web interface to the ADE-4 multivariate analysis software, which allows to use it from Mac, PC and Unix workstations
Columbia/Snake River Interagency Technical Management Team	http://etd.pnl.gov:2080/TMT/tools/intro.htm		A source of information, data, and models relating to salmonid stocks in the Columbia/Snake River Basin. These include the following models. • Columbia River Smolt Passage (CRiSP) Model • RealTime Forecaster • SURvival under Proportional Hazards (SURPH) • Empirical Life Cycle Model (ELCM) • Fish Leaving Under Several Hypotheses (FLUSH) • Passage Analysis Model (PAM) • Stochastic Life Cycle Model (SLCMc) • System Planning Model (SPM)
Wetlands Home Page	http://gnv.ifas.ufl.edu/~rsm/wetlands.htm	University of Florida	WETLANDS is a model designed to study water quality, groundwater contamination, remediation, waste disposal, groundwater recharge, drainage, subirrigation, transport into and from bodies of water, pond-soil-plant interactions, phytoremediation, and management practices.
CAS Home Page	http://gnv.ifas.ufl.edu/~sab/Cas-ver5.htm	Ecological Data Consultants	The Community Analysis System is a program for analysis of benthic or fish population data. The program includes a number of multivariate analysis techniques, and community indices.

TABLE 5-5. (cont.)

Restoration Web Sites

Society for Ecological Restoration Home Page (SER)	http://nabalu.flas.ufl.edu/ser/SERhome.html	Society for Ecological Restoration	Source page to the aims and programs of SER. Information on the journal *Ecological Restoration*, and links to other ecological resource sites.
Constructed Wetlands Bibliography	http://www.inform.umd.edu:8080/EdRes/Topic/AgrEnv/Water/Constructed_Wetlands_all	U.S. Department of Agriculture	Information and resources on the construction of wetlands .
Evaluation of Artificial Wetlands for Filtering of Agricultural Waste Waters Annotated Bibliography	http://gus.nsac.ns.ca/~piinfo/resman/wetlands/anno/annobib.html	Nova Scotia Department of Agriculture and Marketing	This is an additional annotated bibliography on the use of wetlands to treat municipal, storm water, industrial, and agricultural wastes.
List of WWW Sites of Interest to Ecologists	http://meena.cc.uregina.ca/~liushus/bio/ecology.html	University of Lyon, France	Links to a number of interesting ecological resources on the Net.
Ecological Society of America Home Page	http://www.sdsc.edu/1/SDSC/Research/Comp_Bio/ESA/ESA.html	Ecological Society of America	ESA publishes the journals *Ecology, Ecological Monographs*, and *Ecological Applications*. Special publications and work continues on habitat alteration and destruction, natural resource management, ecosystem management, and ecological restoration.

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ABSTRACT

This report provides an overview of the role of modeling in aquatic habitat restoration. Over 400 references were reviewed and listed in the Restoration Model (RESTMOD) database. Although the emphasis of the report is on hydrologic and biological/ecosystem models, other model types including planning/economic, water quality, sediment transport, and others are reviewed. Chapter 1 includes an introduction to restoration analysis and management, and the potential importance of modeling as a planning tool. The organization of the RESTMOD database is outlined and its contents summarized. In Chapters 2 and 3, the use of modeling in the restoration planning process is emphasized, especially the role of modeling exercises in goal formulation and development of data collection/monitoring programs. The structure and functions of models are covered, along with recommendations for the selection and use of models in restoration planning. Case studies are presented as examples of model application. Hydrologic models, including catchment, groundwater, channel and current models, are discussed in Chapter 4. Biological and ecosystem models, including avian, fisheries, instream flow, eutrophication, and HEP/HQI/HSI models are reviewed in Chapter 5. The RESTMOD database is available to interested users in electronic format.

KEYWORDS:

aquatic habitats, environmental restoration, predictive models, environmental planning

IMAGEWORLD

Use of Predictive Models in Aquatic Habitat Restoration

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