BAY-DELTA
Modeling Forum

Protocols for Water and Environmental Modeling

Bay-Delta Modeling Forum
Ad hoc Modeling Protocols Committee

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Bay-Delta Modeling Forum

The Forum is a statewide, non-profit, non-partisan, "consensus" organization whose mission is to increase the usefulness of models for analyzing California's water-related problems, with special emphasis in the San Francisco Bay, Sacramento-San Joaquin Delta, and Central Valley system. The Forum carries out this mission by:

- Providing a consensus-building atmosphere on California's water-related issues;
- Maintaining a modeling clearinghouse that provides an open forum for the exchange, improvement, and pooling of models, modeling information, and professional resources;
- Assisting in mediating technical disputes involving physical, chemical, biological, and economic modeling;
- Conducting impartial peer reviews of models in order to document strengths and weaknesses, suggest improvements, and identify appropriate applications;
- Seeking input from California water stakeholders and decision makers about their modeling needs; and
- Providing educational opportunities through technical conferences and workshops.

More information about the Bay-Delta Modeling Forum can be obtained at www.sfei.org/modelingforum/.

FOREWORD

This draft report presents modeling protocols that provide the water community with basic principles and guidelines for model development and use. This effort was spawned by discussion during the Bay-Delta Modeling Forum's (Forum) 1996 Annual Meeting & Workshop breakout session entitled "Should or Can Modeling Protocols/Conventions be Standardized?" At that session, the participants hypothesized that water stakeholders and decision-makers often lose confidence in models because of inconsistencies in model development and use. After much discussion, the participants concluded that the application of modeling protocols should result in better models and modeling studies and, thus, increase the confidence of stakeholders and decision-makers who use model results. The breakout participants unanimously agreed that modeling protocols can and should be standardized, and that the Forum should take the lead in this effort.

In March of 1997, the Forum formed an Ad hoc Modeling Protocols Committee to (1) develop modeling protocols that can become standards for model development and use and (2) prepare a written report of findings for Forum acceptance. As part of their effort, the Modeling Protocols Committee developed the following mission statement:

> The mission of the Modeling Protocols Committee is to develop modeling principles and guidelines (protocols) that provide guidance to water stakeholders and decision-makers, and their technical staff as models are developed and used to solve California's water and environmental problems.

The Forum "accepted" "Protocols for Water and Environmental Modeling" on January 21, 2000 and is assisting Forum members and other interested parties in implementing the modeling protocols. Since this report is a "living document," it will be updated periodically, as the need arises. As specified in the Forum bylaws, it should be noted that this report does not necessarily represent the views of the governing bodies of the represented organizations or the individual members of the Forum.

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Introduction

Mathematical computer models have become indispensable for planning and management of California's complex water systems. However, models can generate controversy in water management, particularly when the data, assumptions and mathematics of the model are not well documented or have not been generally accepted by the water community. This document presents general protocols and guidelines to better support the development and use of models in water and environmental planning and management. These protocols and guidelines reflect substantial contributions from a wide variety of academic and professional modelers and are intended to serve as guidelines for how computer models should be developed and used.

Adherence to modeling protocols and guidelines will result in better models and modeling studies by:

- Improving the development of models;
- Providing better documentation of models and modeling studies;
- Providing easier professional and public access to models and modeling studies;
- Making models and modeling studies more easily understood and amenable to examination; and
- Increasing stakeholder, decision-maker, and technical staff confidence in models and modeling studies.

Technical staff must obtain support from managers and supervisors of modeling activities to adequately implement these protocols and guidelines. This support comes in the forms of adequate budget and time for (1) proper model development and use and (2) management efforts to ensure that protocols and guidelines are followed in an efficient and effective way. While adherence to these protocols in the short-term may increase the budget and time requirements for an individual modeling study, these efforts should enhance the credibility and effectiveness of modeling work and reduce the effort needed to respond to technical controversies. The "bottom line" is that adherence to these protocols will reduce the overall, long-term costs for modeling, decision-making, and water management.

Solving Water Problems

Computer models do not resolve water conflicts; people do. However, modeling can assist in that role by:

- Furthering understanding of the problem.
- Defining solution objectives.
- Developing promising alternatives.
- Evaluating alternatives.

- Providing confidence in solutions.
- Providing a forum for negotiations.

Model Development Process

Table ES-1 presents a set of standardized steps that provide a general framework for model development. These steps are intended to ensure that the model (1) addresses the intended problem, (2) reasonably represents the system and (3) results are reasonably tested. In addition, the model development process helps ensure that the entire model development process is documented so that others will know what has been done and are clearly informed about the model's limitations for use.

Table ES1: Major Steps in Model Development

Step	Name	Purpose
1.	Problem Identification	Solving the right problem
2.	Define Modeling Objectives	Define use for model and standard of success
3.	Formulation of Model	Mathematical similarity to the problem system
4.	Selection and Study of Numerical Solution	Numerical similarity to the mathematical formulation of the problem
5.	Model Calibration	Set constants to represent system behavior and characteristics
6.	Model Verification	Test model based on model behavior
7.	Model Validation	Test model by comparison with field data
8.	Documentation of Model	Make model understandable to users
9.	Update and Support of Model	Maintain and improve the model's usefulness

Use of Models in Planning Studies

Aside from model development, the use of models for particular planning or policy problems should also follow a logical pattern combined with a logical planning process. This process, which is summarized in Table ES-2, is somewhat parallel to those of a classical planning study.

Table ES-2: Steps in Model Use for Planning and Policy Studies

1. Define study objectives.
2. Define how model outputs relate to the performance of alternatives.

3. Define a base case.
4. Define alternatives.
5. Identify model version and input data.
6. Model results.
7. Summarize and discuss the performance of each alternative.
8. Discuss study limitations.

Regulatory Aspects of Model Use in Planning Studies

Environmental impact analysis is an integral part of planning. Models are commonly used to evaluate project alternatives and the environmental impacts associated with those alternatives. The intent of the California Environmental Quality Act (CEQA) and the federal National Environmental Policy Act (NEPA) process is to make environmental documents a decision-aiding document rather than the primary decision-making report. Often, the environmental document and the decision-making report can be developed together. CEQA and NEPA environmental impact documents must describe the existing environmental setting from local and regional perspectives. When a proposed project is evaluated under CEQA, the analysis must use existing physical conditions as the baseline, not future projections. However, when the same project is evaluated under NEPA, the analysis must include the "no action" alternative, which includes predictable (future) actions by others.

Stakeholder and Public Review of Modeling Efforts

Providing stakeholders and the public with an early acquaintance of the model or modeling study can often reduce the technical controversies involved in modeling. A variety of methods are available to reduce the technical controversies involved in modeling and better integrate modeling activities into larger study activities, including the following:

- <u>Public Participation</u>—Proper planning requires adequate review and consultation with interested and affected stakeholders, agencies, organizations, and individuals. Efforts to secure public participation should be pursued through public workshop, meetings, and technical advisory and citizens committees.

- <u>Technical Advisory Committees</u>—Technical Advisory Committees are a common way to provide ongoing review for modeling and planning studies and typically come in two forms, as a committee of technical people representing stakeholders or a committee of recognized independent technical experts.

- <u>Shared Vision Modeling</u>—Shared Vision Modeling is the common development and/or use of a model, or set of models, by a group of diverse stakeholders and/or decision-makers. Its purpose is to remove as many technical disagreements as possible from the conflict so that efforts can focus on interpretation of the result, rather than arguments about the model. The development or use of shared vision modeling is usually a prelude to development and evaluation of alternatives as well as meaningful negotiations among stakeholders.

- Peer Review—Peer review is a method for reviewing models in a timely, open, fair, and helpful manner. All models require some level of peer review to assure that they are properly used. The Forum has developed a peer review process that is intended to inform stakeholders and decision-makers of (1) whether or not a given model is a suitable tool and (2) the limits on the use of the model. In 1997, enacted legislation (Senate Bill 1320) requires the California Environmental Protection Agency to conduct an external scientific peer review of the scientific basis, including modeling, for any water quality rule.

Public Access to Models and Data

Models and data used in public decision-making should be available for public scrutiny, like any other calculation or analysis presented in a public forum. For modeling studies used in public arenas, the model, model documentation and data sets used should be made available either through the services of agency staff, a consultant, or an Internet web site. If a "proprietary" model is used for public decision-making, enough information must be made available to enable stakeholders, decision makers and the public to determine the validity of the model.

Implementation of Modeling Protocols

The Forum "accepted" "Protocols for Water and Environmental Modeling" on January 21, 2000 and is assisting Forum members and other interested parties in implementing the modeling protocols. Since this report is a "living document," it will be updated periodically, as the need arises. As specified in the Forum bylaws, it should be noted that this report does not necessarily represent the views of the governing bodies of the represented organizations or the individual members of the Forum.

1. INTRODUCTION

Water stakeholders and decision-makers use models to help solve California's water and environmental problems. Numerous pressures have led to the use of models in varying stages of completion, documentation, public availability, testing, and evaluation. Often models are used with little foreknowledge of the confidence that can be placed in their predictive capabilities. Models are sometimes used in ways that violate the assumptions and boundary conditions that are built into them. Such deficiencies and differences in models have led to unnecessary conflicts among model users (ASTM, 1992).

Unfortunately, stakeholders, decision-makers, and even their technical staffs, often lose confidence in models because of (1) an inadequate understanding of modeling principles and (2) inconsistencies in the way models are developed and used and (3) a lack of model and data upkeep. A good understanding of modeling and confidence in model results are essential for (1) stakeholders and decision-makers responsible for setting water quality standards, flow requirements and other regulations, and (2) planning and operating entities who use models to comply with such regulations. To address this problem, the Bay-Delta Modeling Forum (Forum) has developed modeling protocols, which are basic principles and guidelines for model development and use. Model developers, users of modeling services, and water stakeholders and decision-makers wishing to understand modeling and its consequences should find such protocols useful for improving quality control and quality assurance in modeling studies.

The objective of these modeling protocols is to provide guidance to water stakeholders and decision- makers, and their technical staff as models are developed and used to solve California's water and environmental problems. Adherence to modeling protocols by California's water community will result in better models and modeling studies by:

- Improving the development of models;
- Providing better documentation of models and modeling studies;
- Providing easier professional and public access to models and modeling studies;
- Making models and modeling studies more easily understood and amendable to examination; and
- Increasing stakeholder, decision-maker, and technical staff confidence in models and modeling studies.

A computer model consists of two basic parts: the computer code or software and the input data set. Computer models can be as simple as a mass balance equation, which can be performed on a calculator or spreadsheet, or as complex as multiple differential equations that require solution by highly specialized computers programs. According to the Forum bylaws, modeling includes, but is not limited to, applications to the following water-related topics (BDMF, 1997):

- Data gathering, storage, and access
- Economics

- Fisheries, aquatic biology, and habitat health
- Groundwater
- Hydrodynamics
- Hydrology, hydraulics, and irrigation
- System operations and real-time management
- Water quality
- Water resources planning

Modeling protocols and guidelines have been discussed since use of computer modeling became widespread in the 1960s. Substantial consensus exists regarding the broad outlines of proper development and use of computer models (ASTM, 1992, 1995a,b; Beck, 1983a, 1985; Gass and Thompson, 1980; James, 1993; Jacoby and Kowalik, 1980; Sargent, 1988). Some such protocols have been developed specifically for water resources modeling (ASTM, 1992, 1995a,b; Beck, 1983a, 1985; IAHR, 1994; Dee, 1995; Tsang, 1991). The guidelines developed here synthesize this thought with recent California modeling experiences.

This report explains in basic terms why models are important, how modeling efforts are reviewed, and how models should be developed and used. It prescribes basic modeling protocols that provide a commonly accepted and consistent framework to develop, use, and document computer models.

2. PURPOSES OF MODELING

Solving Water Problems

Models do not resolve water conflicts; people do. However, modeling can assist in that role by (Lund and Palmer, 1998):

- Furthering understanding of the problem.
- Defining solution objectives.
- Developing promising alternatives.
- Evaluating alternatives.
- Providing confidence in solutions.
- Providing a forum for negotiations.

The purpose of most models is to reproduce consistently the observable phenomena that are of significance for a particular problem. For example, the purpose of a salinity water quality model is to reproduce in time and space the distribution of salinity due to the effects of flows, diversions, tides, etc. Models can be used to support real-time decision-making or evaluate a physical or biological system under historical, present, and potential future conditions.

California resources planning increasingly depends on analytical methods and tools that can provide practical answers for immediate problems and significant direction for long-range plans (BDMF, 1995). Models are essential for analysis of issues arising in water rights, development of new water projects, and re-operation of existing projects. These models play an important role in developing environmental impact analyses of projects under the California Environmental Quality Act (CEQA) and the federal National Environmental Policy Act (NEPA).

California's water system is very complex in terms of its extent, diversity of water uses, surface and groundwater hydrology, and coordination of component operations. Planning and efficient operation of such large complex systems generally requires extensive data gathering and computer modeling analysis. For such complex systems, no simple method exists to reasonably understand and assess the likely performance and impacts of planning and operating alternatives. Field testing without prior modeling is too risky, expensive, and time-consuming from almost any point of view.

Historical Uses of Modeling

The use of mathematical models in water planning and management began in Europe in the 1700s, with the Chezy and related equations for flows in open channels. The success of such mathematical descriptions for planning, design, and operational purposes led to the steady improvement and wider application of mathematical models, continuing to the present day.

Beginning in the 1950s, the availability of computers greatly expanded the ability to apply mathematical models to real water problems, since actual computations could occur many times more quickly and with high reliability. The first uses of computers to simulate large regional water systems were by the U.S. Corps of Engineers for the Missouri River System in 1953 and by the British government for the Nile River in 1959. Since this time, the planning, operation, and management of almost every large water system in the world is coordinated and investigated using computer models.

In California, computer models are used to better understand and manage a wide variety of hydrodynamic, hydrologic, water quality, economic, and operational processes. The central and increasing roles of computer models in California water management has led to increasing scrutiny and sometimes controversy over model use and development. Water stakeholders and decision-makers use mathematical models to develop and test theories describing forces at work in the Bay-Delta estuary and to project consequences of proposals to use and protect the estuary's resources. Most Bay-Delta models are developed to deal with some kind of water transfer across the Delta from north to south, and many models attempt to describe the movement of water and the materials dissolved, suspended or otherwise entrained in it.

Appendix A summarizes some of the modeling efforts that have been undertaken to evaluate and solve Bay-Delta water problems over the past 70 years. Summary descriptions of “water” models commonly used in California are presented via the Bay-Delta Modeling Forum’s web site at **www.sfei.org/modelingforum/.**

3. STAKEHOLDER AND PUBLIC REVIEW OF MODELING EFFORTS

In the highly technical and political arenas of California water, it is important that models enjoy a wide base of support from stakeholders and decision-makers, technical staff, and even the public. Modeling of water systems is not just a technical exercise. The objectives of modeling are to aid in planning, policy or operational decisions. Thus, models must be developed and used in ways that (1) provide assurance to decision-makers that the analysis is reasonable, (2) can be trusted by reasonable parties, and (3) addresses major technical concerns for the system's performance. To help assure that a model achieves these objectives, stakeholder and public review of modeling efforts has become common, and in many cases is even expected.

Public Participation

Proper planning requires adequate review and consultation with interested and affected stakeholders, agencies, organizations, and individuals. These groups and individuals should be provided opportunities to participate throughout the planning process. Efforts to secure public participation should be pursued through public workshops, meetings, and technical advisory and citizens committees. (U.S. Water Resource Council, 1983)

As outlined in NEPA (USCEQ, 1981), planning should include an early and open process, termed "scoping," to identify both the likely significant issues to be addressed and the range of those issues. Scoping should be used throughout planning to ensure that all significant factors are addressed. Scoping may be used to narrow the number of plans under consideration so that meaningful and efficient analysis and choice among alternative plans can occur. Scoping should include consideration of all water problems and opportunities.

Sometimes water projects fail due to a lack of stakeholder and decision-maker communication as well as insufficient public participation in the water planning process. To help ensure that water planning succeeds, planning should be performed with considerable dialog, input and agreement (consensus, where possible). Fortunately, a wide variety of ways exist for agencies and consultants who conduct modeling studies to effectively communicate their modeling results and incorporate the ideas and comments of others into their work.

Technical Advisory Committees

Technical advisory committees (TACs) are a common way to provide ongoing review for modeling and planning studies. TACs typically come in two forms, as a committee of technical people representing stakeholders or a committee of recognized independent technical experts. It is often useful to maintain both types of TACs during a modeling study.

A TAC consisting of technical stakeholder representatives are usually formed to do the following:

- Ensure that local and diverse expertise is used to address the problem. Often, the entities involved in a problem have different special expertise relevant for a modeling study. Having technical representatives from each knowledgeable entity helps to make this expertise available for the development and application of models.

- Enhance communication. Enhanced communication allows TAC members to become familiar with the details of a modeling study, which should reduce stakeholder misunderstandings of the model and model results. Ultimately, this should help build stakeholder confidence in model and planning study results.

- Help model results be relevant for a wider range of interests and problems. A major model or modeling study will have implications and applications for many entities in a region. Thus, many entities will seek to use or modify the model to enhance their own understanding or for their own purposes. If a single model development exercise can support these broader interests, the regional interest is served.

- Provide local experts a structured opportunity to contribute ideas and concerns. This is a very local form of "peer-review," occurring early in the modeling process.

A committee of recognized independent technical experts can also have several uses. In most modeling exercises, some level of local technical controversy exists. An advisory panel independent of stakeholder interests can provide a form of technical arbitration on such issues and, often, can suggest additional approaches to address such controversial problems. In addition, scrutiny by such recognized independent experts can help support the credibility of model and planning study results.

Shared Vision Modeling

A very different form of stakeholder involvement is "shared vision" modeling. Shared vision modeling is the common development and use of a model or set of models by a group of diverse stakeholders and/or decision-makers. The fundamental concept is that those affected by water resource modeling should be provided the opportunity to participate in model design, development, evaluation, enhancement and use. Shared vision modeling is intended to take the technical decisions out from the political spotlight, and remove as many technical questions disagreements as possible from the conflict. A goal of this process is to provide all interested parties with a tool that can be used to increase their understanding of the problem and possible solutions. If participants can arrive at agreement on what is contained in the model, then later efforts can focus on interpretation of the results, rather than arguments about model content. The development or use of the shared vision model is usually a prelude to development and evaluation of alternatives as well as meaningful negations among stakeholders. In addition, this approach helps to create a technically based forum where the parties can negotiate (Lund and Palmer, 1998).

This approach is really an extension of classical engineering planning to more pluralistic decision-making circumstances (Werick and Whipple, 1994). The model is typically developed by a single, often neutral, entity with very close coordination by technical representatives from each stakeholder or stakeholder group. The model is then approved by the participants and can be used separately by each group, with a fixed model version and documentation (Lund and Palmer, 1998).

Shared vision modeling, like other consensus building processes, requires that strong motivation exists among the stakeholders to develop a consensus (Walters, 1997). Arriving at a consensus about a model is not easy. Model development will progress much more slowly than if performed by single group (Lund and Palmer, 1998). However, if the modeling and negotiation steps are considered as one extended process, shared vision modeling usually saves time in the long run.

Peer-Review

Peer review is a method for reviewing models in a timely, open, fair, and helpful manner. Peer review serves model developers and model users by (1) providing constructive feedback to model developers and (2) serving to further the model's acceptance and understanding by the user community, including stakeholders and decision-makers. Peer review of a model or model application usually occurs after the model has been developed and used. Because each water system is unique, all models require some level of peer review to assure that the model is not misused. Many forms of "peer review" exist. Generally, an independent party selects one or more reviewers from academic, consulting, and agency experts. These reviewers are presented with the products of the modeling study (data, reports, model documentation, etc.) and sometimes given oral presentations. The peer reviewers then return a written report of their findings.

The Forum has developed a peer review process for peer reviewing computer models process (BDMF, 1996). These peer reviews are not intended to be "stamps-of-approval" for particular models or to disapprove of models. Instead, they are intended to inform stakeholders and decision-makers of (1) whether or not a given model is a suitable tool, and (2) the temporal, geographic, or other limits on the use of the model. The Forum's model peer review steps are as follows:

1. Select Models
2. Select Reviewers
3. Obtain Funding
4. Assemble Model, Documentation, and Data
5. Scope the Review
6. Conduct Initial Review
7. Test Models
8. Prepare Draft Report
9. Conduct Review Workshops
10. Prepare Final Report

More information on the Forum's peer review process appears on the Forum's web page at www.sfei.org/modelingforum/.

External Review

In 1997, California enacted a “peer review” requirement for technical analyses performed by the California Environmental Protection Agency (Cal EPA), including its member agencies. This law, Senate Bill 1320 (Sher), requires all organizations within the Cal EPA, such as the State Water Resources Control Board, to conduct an external scientific peer review of the scientific basis for any water quality rule and prescribe procedures for conducting that scientific peer review (California Senate, 1997).

Under this law, Cal EPA organizations can enter into an agreement to perform the peer review with one or more of the following:

- National Academy of Sciences;
- University of California;
- California State University;
- Any similar institution of higher learning; or
- A scientist or group of scientists of comparable stature and qualifications that is recommended by the President of the University of California.

If the state organization disagrees with any aspect of the external scientific peer review, it must (1) explain why it disagrees in the adoption of the final rule, and (2) include this information as part of the rulemaking record. Senate Bill 1320 can be found on the Internet at www.leginfo.ca.gov.

Often, deciding on what forms of stakeholder and external review should be used is not easy. Each form of outside involvement imposes different financial and time commitments and provides different (and, at the outset, somewhat uncertain) benefits. These benefits include increased compliance with legal and regulatory mandates, comprehension and acceptance of results, and understanding of the problem and potential solutions.

4. MODEL DEVELOPMENT

> "Different types of models are appropriate for solving different kinds of problems; there is no universal model for solving all manner of problems; comprehensiveness and complexity in a simulation are no longer equated with accuracy; and there is a healthy mood of critical questioning of the validity and credibility of water quality models."
> M.B. Beck (1985)

Mathematical computer models represent a systematic organization of a system's knowledge developed for some kind of planning, engineering, or scientific purpose. This chapter is divided into three sections. The first section discusses how different forms of knowledge are represented in computer models. The second section presents a relatively accepted approach for computer model development that (1) emphasizes the use of a model for problem solving and (2) informs modelers and model users of general model strengths and limitations. The third section discusses modeling errors that originate in model development.

Knowledge Basis for Model Development

Models represent existing or hypothesized knowledge of how a system works. The two major origins of this knowledge are mechanistic and empirical. Mechanistic models are based on the fundamentals of physics and chemistry, while empirical models are based more directly on field or laboratory observations. These two bases for modeling are discussed frequently for water resource and environmental management models (Beck 1983a, 1985; Klemes 1982; Scavia and Chapra 1977). Since our knowledge of these systems is imperfect, probability is sometimes used in modeling to represent uncertainty. Models are often discussed in connection with adaptive management (Holling 1978), where models evolve with our management of it and help us learn with time.

<u>Mechanistic Models</u>
Often called causally or physically based models, mechanistic models rely on fundamental rules of logic and the laws of physics and chemistry. Some examples of mechanistic models include:

- Use of conservation of mass to derive models of the operation of river-reservoir systems;
- Use of conservation of mass, momentum, and energy with channel geometries and bed elevations for hydraulic routing;
- Use of principles of advection and dispersion for contaminant transport modeling; and
- Population dynamics models based on predator-prey and other demographic equations.

Mechanistic models commonly consist of a set of fundamental governing equations representing conservation of mass, energy, and momentum, reaction kinetics, demographics, etc. Often, these are differential equations. These governing equations have initial or boundary conditions, and can be solved by several numerical schemes.

Establishment of boundary conditions and parameter values often requires a great deal of empirical knowledge, especially with detailed spatial and temporal resolution. Also, many components of the governing equations are often empirical, such as use of Manning's equation for bed friction in hydraulic models and Fickian diffusion to represent dispersion in fate and transport models. The numerical solution techniques used to solve the large number of governing equations often involve some simplification of the system's geometry and dynamics, which can introduce errors into model results. Thus, it is difficult to have a purely mechanistic model.

<u>Empirical Models</u>
The equations and calibrations of empirically based models rely (more directly) on field or laboratory data, or empirical observations. Physical, chemical, biological, or socio-economic theory are less important than the accumulation of observations and data. Empirical models sometimes can "fit" current experiences well, but are often less reliable when the system is changed significantly from the behavior for which the model was developed (Klemes 1982). Nevertheless, empirical models are very commonly used when modeling biological, chemical, economic, and even many physical processes. Such models usually take the form of regression or other statistically-estimated equations.

<u>Mixed Models</u>
Most models used in water resources and environmental problem solving are mixtures of mechanistic and empirical models. The better-understood parts of the modeling problem (such as conservation of mass) are commonly mechanistic, whereas less well-understood processes, such as fluid friction, are modeled based on empirical relationships (such as Manning's n).

Quantified conceptual models are a common compromise between causally based and empirical models. Conceptual models often begin as a rough, relatively qualitative representation of how components of a model interact, based on theoretical, empirical, or hypothetical relationships. These "models" then can develop into quasi-mechanistic, quasi-empirical models. The Stanford Watershed Model of the 1970s is a fairly successful example of such a quantified conceptual model. Most “adaptive management” models are also of this mixed form (Holling 1978).

<u>Adaptive Management and Computer Models</u>
Adaptive management is a systematic process for continually improving management policies by learning from the outcomes of operational programs. It allows resource managers a way to proceed responsibly in the face of uncertainty instead of either "charging ahead blindly" or "being paralyzed by indecision," both of which can foreclose management options, and have social, economic and ecological impacts (Taylor, 1996). Adaptive management is a response to uncertainty about the system being managed. It also allows actions to be designed, at least in part, to provide new information about the system (Williams, 1998).

Much has been written about the role of computer models for improving the basis for management, even when little is known about the system being managed (Holling 1978). In these cases, models often are seen as a rigorous tool for (1) systematically identifying what is known and what is not, (2) estimating the importance of things imperfectly known and (3) providing an explicit technical basis for beginning to manage critical systems before they are completely understood. Models are both a distillate of past experience and a stimulus to the future development of experience (Beck 1985).

Model Development Process and Guidelines

Considerable consensus exists in the profession and academia that development of computer models should follow general guidelines, which are outlined below and summarized in Table 1. This process is designed to aid the user of the model and the users of model results by (1) providing assurances that the model works adequately and (2) identifying the limits of the model's capabilities. Additional discussion of this process can be found elsewhere (ASTM, 1992, 1995a,b; Beck, 1983a, 1985; Gass and Thompson, 1980; James, 1993; Jacoby and Kowalik, 1980; Sargent, 1988; IAHR, 1994; Dee, 1995; Tsang, 1991).

Table 1: Major Steps in Model Development

Step	Name	Purpose
1.	Problem Identification	Solving the right problem
2.	Define Modeling Objectives	Define use for model and standard of success
3.	Formulation of Model	Mathematical similarity to the problem system
4.	Selection and study of numerical solution	Numerical similarity to the mathematical formulation of the problem
5.	Model Calibration	Set constants to represent system behavior and characteristics
6.	Model Verification	Test model based on model behavior
7.	Model Validation	Test model by comparison with field data
8.	Documentation of Model	Make model understandable to users
9.	Update and Support of Model	Maintain and improve the model's usefulness

(Note: Some of the modeling terms in Table 1 are sometimes used interchangeably. The meaning of each term in this document is described below.)

Although fair consensus exists on the major steps of good model development, this procedure is not standardized to the degree found in many other technical fields, such as chemical analysis. Perhaps this lack of detailed standards reflects the difficulty and diversity of modeling problems. The model development steps in Table 1 are often iterative in nature. For example, if a model fails to calibrate well (step 5), the model developer often re-examinations the model's formulation (step 3). Model development is rarely a completed process, but rather evolves with continual improvement, adaptation, and updating.

Step 1. Problem Identification

It is impossible to model everything. The first and most important step in modeling is to identify the problem to be modeled, and, by implication, identifying the problems (or parts of the problem) that are not to be addressed. Considerable attention should be given to the role of the model in addressing the problem, both in the short and long terms, and who will be using the model.

Step 2. Define Modeling Objectives

Most computer modeling efforts can address only a few important aspects of a general problem. Thus, it is important early in the model development process to identify specific modeling objectives. Modeling objectives help the model development process by:

- Allowing the developers to focus on particular aspects of the problem and uses of the model;
- Providing specific criteria for evaluating the model (i.e., how well does the model's application satisfy the stated objectives?); and
- Indicating the intended model uses and potential users of the model and model results.

Modeling objectives should reflect a clear understanding of how the model is expected to be integrated into larger decision-making, scientific, or engineering problem-solving contexts.

Step 3. Formulation of a Model

Model formulation is the simplification (of our understanding) of the real problem into a mathematical form that is consistent with modeling objectives. Formulation involves the explicit specification of relationships thought to govern the behavior of the system (Beck 1983a). Model formulation typically begins with development of a conceptual model, which is a working understanding of how a system works. The conceptual model forms the basis for more detailed and explicit development of a mathematical model.

When formulating a model, the model developer will need to make various decisions, hopefully reflecting the problem, modeling objectives, and an understanding of the problem. In addition to formalizing the relationships that describe the system, the spatial and temporal aggregation and scale of the system need to be specified. Is the model to be steady-state or dynamic? Linear or non-linear? Deterministic or stochastic? If stochastic, which type of stochastic?

When solving ecological modeling problems, which species or classes of species will be represented and which environmental factors affecting them are to be included? For hydrodynamic modeling problems, should 1, 2, or 3 dimensional representations of the system be used, how coarse of a spatial grid should be used, what time-step should be used if the model is dynamic? For water quality modeling problems, which constituents should be included, and how should their sources, sinks, and reactions be represented?

More often than not, the "detailed" modeler will choose the more detailed solution (highly disaggregated in time and space, dynamic, stochastic, etc.). However, this is usually the wrong decision, or perhaps merely an impossible decision. Highly detailed models are typically unsupported by field or laboratory data of sufficient quality or quantity and may provide little predictive understanding of the problem. Also, complex models are not always needed to solve the problem and achieve the objective. Instead, simplified models can often work just as well if the modeler represents the most important parts of the problem, consistent with the available data and knowledge of the system. When solving problems, managers cannot wait for perfect knowledge of a system. Indeed, the formulation and testing of a model (as an active hypothesis) usually can accelerate our understanding of a system. As a practical matter, a need exists for a balance between the errors from simplification and the errors introduced by having additional uncertain parameters, inputs, and boundary conditions (Beck, 1985).

As model development proceeds to model calibration, testing and use, it is often necessary to revisit decisions made in model formulation, at least in part. Model development is usually an iterative process, which is healthy.

<u>Step 4. Selection and Study of Numerical Solution.</u>
Once the mathematical form of a model has been specified, the numerical method to solve the model equations must be found. Often, particularly for complex models, the solution method for the model equations will require testing to ensure that the numerical solutions are correct for the intended types of problems and modeling objectives. Sometimes, concerns about numerical solution are reduced or eliminated through the use of commonly accepted software capable of solving some common forms of mathematical equations. These commonly accepted software includes spreadsheets, commercial equation solvers (e.g., MATLAB, STELLA, LINDO, MINOS, etc.), and commercial subroutines (e.g., IBM's IMSL routines). Concerns about accuracy and stability can be addressed by comparing the numerical solutions with (1) analytical solutions available for special cases or (2) solutions from trusted numerical solution methods.

<u>Step 5. Model Calibration.</u>
Model calibration is the process of establishing specific values for parameters (constants) in the model's mathematical equations and algorithms. Typically, the purpose of calibration is to "fit" the model to the system being modeled, trying to "match" model and real output. The definition of a "good" fit or match between model and real output usually depends on the objectives and intended uses of the model. For example, when using a rainfall-runoff model, if flood periods are of greatest interest, the model's ability to correctly predict low flows might not be important.

Table 2 briefly describes several approaches to model calibration. Each method requires successively greater amounts of data from the real system.

Table 2: Approaches to Model Calibration

Approach	Description
Classical Physical Constants	Usually, these are physical constants, such as gravitational acceleration with known constant values. These parameters are typically set to these known values.
Literature Values	Often specific studies have been conducted elsewhere or at other times to estimate the value of parameters in specific model equations. These values are often useful for estimating reasonable parameter values for other models using the same model equation in similar conditions. A variation of this approach is to have an "expert" on a particular parameter provide an educated guess of what its value should be. This calibration approach is often used where data collection is impossible or to see if parameter values given by other approaches are "reasonable."
Field Measurements	Some model parameters, such as watershed area, are relatively deterministic, unchanging, and easily estimated. Field measurement or map measurement of such parameters can often give reasonable estimates.
Statistical	Very frequently, a model parameter can be measured, but might not have a constant value. This situation can arise because of measurement error or natural variation of the parameter over time or space. If a single parameter value is to be used, statistical methods can be used to estimate the "best" single value for the parameter. Through Monte Carlo modeling, it is possible to use many parameter values for a single parameter, if needed, yielding probabilistic model results.
By Manual Fit	One of the most common approaches to setting parameter values is to take one or more sets of input and output data from the real system and then make many runs of the model, iteratively adjusting parameter values until a "good" fit is achieved. This implies that the modeler has a firm idea of what constitutes a good fit. Taken to extremes, calibrating a model by fit treats the parameters as "fudge factors" to help make the model "fit" the real data. Often, graphical assessment is used to calibrate models.
Regression and Automated Fit	Regression is a more mathematically based approach to setting parameter values "by fit." In regression, varying parameter values optimizes an objective function (defining good fit). Common linear regression is the most typical objective where the parameters of the model are optimized to find the set of parameter values with the minimum sum of squared error. If much input and output data are available for the real system, and the model equations are amenable to optimization, regression methods can often yield statistics on the model's likely error and other quantitative estimates of goodness of fit. More sophisticated optimal parameter estimation techniques also are available (Beck 19893b).

In reality, several of the above methods are usually used to set values for model parameters. Picking the best combination is often something of an art.

From a different perspective, model calibration also is a form of model testing. If the model cannot be made to reasonably simulate known field observations by direct (and reasonable) modification of calibration parameters, then the model has, in some way, been tested and found to be empirically inadequate. Importantly, much can be learned from such failures, which are common in modeling. The ways that a model fails to "fit" a calibration data set also can be instructive in re-formulating the model (and in formulating empirical studies) by helping to identify specific processes or conditions that the model represents poorly (Beck, 1985).

If a model can be adequately calibrated, additional testing, in the form of verification and validation is desirable. However, if the number of adjustable model parameters is large compared to the size of the calibration data set, then a "good fit" is often meaningless since many sets of parameter values would likely give reasonable agreement with the relatively small calibration data set. Large models with many adjustable parameters, typically require much larger calibration data sets.

<u>Step 6. Model Verification.</u>

Model verification consists of several techniques that provide some test of the adequacy or reasonableness of a model for a particular purpose. Sometimes, model verification is defined as assessing if a model "behaves in the way the model builder wanted it to behave" (Beck, 1983a; Gass, 1983). Model verification and other model testing techniques are summarized in Table 3. Several such tests are typically used, with specific tests applied to test particular model components in addition to testing overall model behavior. The methods are listed generally in order of increasing rigor.

Many of the first four tests listed in Table 3, particularly the Turing test, can be aided through some form of data display to aid the user and experts in evaluating (1) the "reasonableness" of a large quantity of model results, (2) the behavior of overall model results and (3) the results of model components. A particular approach for the first four tests is "degenerate testing" (Sargent, 1988), where model inputs are skewed to attempt to create degenerate model behavior. This can be done either for extreme cases where actual system behavior is known (droughts drying reservoirs) or to induce numerical or other logical degeneracy in the model's computations (e.g., large transients in dynamic models).

Sensitivity analysis is commonly used in model development to test the reasonableness of a model's behavior. In essence, it is another form of model verification. It is also used to assess if particular components of the model need to be represented in more detail or can be suitably represented with less detail. In this second function, if a sensitivity analysis shows that model outputs are insensitive to a particular parameter in a subprocess, then perhaps the representation of this sub-process can be simplified reasonably. Thus, some sub-processes within a system may be "parameterized," or represented by a single constant parameter. Conversely, if a model cannot be made to "fit" reasonable observed data without making a particular "parameter" vary in time or space, then perhaps a more detailed representation is needed of the parameter representing that process. It is common for model verification to lead to improvements in model formulation.

Step 7. Model Validation.
Validation is the process of comparing model results to historical data. A model cannot completely duplicate historical data under all conditions for two reasons: (1) models are just mathematical representation of reality and (2) historical data contains problems with

Table 3. Methods for Model Testing (Verification and Validation)

Method	**Summary**
1. Sign Test	Do changes in model inputs lead to changes in model outputs in the "right" direction?
2. Ordinal Test	Do sequential changes in input values lead to output changes that are consistently in the "right" direction?
3. Sensitivity Analysis	Do changes in input and parameter values lead to "reasonable" changes in output values, both in magnitude and direction of change?
4. Turing Test	Can an "expert" in the subject of the simulation distinguish between the model's behavior and the behavior of the real system? Is model behavior "reasonable" to experts?
5. Comparison with Analytical Solutions	A test for numerical behavior, where rigorous analytical solutions exist for simple applications of the model, do analytical and simulation results agree?
6. Reproducibility or Comparison with Other Models	Do other studies and models find results similar to those found by the model in question? For selected model components, do model results agree with hand calculations?
7. Statistical Analysis	How much variation in the calibration data can be explained by the model? What is the statistical significance of the calibration of the model?
8. Independent Testing of Model Components	Confidence in the whole model is improved by testing of individual model components.
9. Independent Calibration and Validation	Using separate data sets to calibrate and test the model, how well does the calibrated model estimate outputs for the test data set? If several test data sets are available, what do these tests imply for the conditions that limit the model's effectiveness?
10. Deductive Proof	Can the model, or important parts of the model, be derived from fundamental information (e.g., conservation of mass, momentum, energy, and geometry)? Is the logic of the model correct and correctly implemented?

accuracy, precision, and completeness. Thus, validity is a matter of degree: it depends on the information available and is subject to the requirements established by the decision-maker. Despite this necessary level of subjectivity, models should not be used for assessments without examination of their validity (ASTM, 1992).

The term "validation" is used variously in the computer modeling literature (Beck 1983a, b; Gass 1983). Here, model validation is the testing of a calibrated model by comparing model results with one or more sets of independent field or laboratory data. The intent is to provide an independent field test of the model, preferably under a variety of field conditions (such as wet and dry years). This is the highest scientific hypothesis testing form of model test. In terms of strength and rigor, it is superseded only by deductive proof from first principles.

The comparison of model results and field data for model validation is often not a simple exercise, but requires some consideration of which comparative statistics are appropriate for the particular objectives of the model. Comparative statistics could include (ASTM 1993): comparative time-series of results (as tables or graphs) for specified locations, comparisons of maximum results (such as flood peaks), comparisons of duration above a water quality standard, or common statistical comparisons such as root mean squared error (RMSE), average absolute value of error, various types of correlation statistics, or statistical tests of the probability that model result distributions differ from the distribution of field data (which may contain measurement errors).

Model validation is almost always difficult, requiring a large amount of independent high quality data. There are some problems for which model validation is prohibitively difficult, impossible, or irrelevant. An example of where validation is irrelevant is a long-term water use forecasting model. By the time enough future data is accumulated to validate the model, the forecasting use of the model is likely to be mute. Models of complex processes, such as non-point source pollution or some complex operations problems also are difficult to validate, due to the difficulty of collecting spatially disaggregated data on a dynamic basis. Sediment transport models often are difficult to validate (as well as calibrate) because field data often are as prone to error as model results, making it difficult to compare model results and data (McAnally, 1989). Often, some sort of data validation is a desirable prelude to model validation. Where it is impossible practically to validate model results, the model may still have considerable use, although its detailed and quantitative results should not be viewed with the same confidence as results that closely correspond to accurate field data under a wide variety of conditions. If models are used for water management, validation is always problematic, since the model is intended to examine system behavior under circumstances for which validation data is inherently unavailable, such as conditions that significantly differ from present conditions (Gass, 1983; Thomann, 1987).

Gass (1983) presents a broader view of model validation, including evaluation of the "face validity" of a model; is the model and its behavior reasonable to those with field experience with the system? This is much like the Turing, sensitivity, sign, and ordinal tests discussed in Table 3. In a sense, these are tests of the model's ability to simulate behavior seen in the real world. Given data availability and our understanding of complex environmental problems, it is often impractical to expect that a model can be proven true; rather, it is more frequently only possible to not prove a model false (Holling, 1978).

<u>Step 8. Documentation of Model.</u>

> "The purpose of the model report is to communicate findings, to document the procedure and assumptions inherent in the study, and to provide general information for peer review. The report should be a complete document allowing reviewers and decision-makers to formulate their own opinions as to the credibility of the model." ASTM (1995a)

The three major forms of computer model documentation are (1) the computer interface with the user, (2) comment statements in the source code and (3) a manual or text, often in the form of user's and reference manuals. In practice, documentation usually involves combinations of all these forms in varying amounts. The writing of model documentation should generally parallel a model's development, with substantial "tidying-up" at the end.

Although documentation via the model's user interface seems attractive, almost all models require far more detailed documentation in the form of separate reference and user's manuals. These manuals are almost always the ultimate and authoritative forms of documentation. Comment statements in the source code (or notes in spreadsheets) are useful, but usually are only suitable for those who must review the model code and make changes. In essence, comment statements are directed to model programmers rather than model users.

The reference and user's manuals are texts that most users will refer to when running a model, preparing data and interpreting results. These manuals should describe the following (ASTM, 1992, 1995b; Gass, 1984):

- The particular objectives of the model and its range of applicability;
- The types and forms of data required and the computer capability needed;
- The conceptual approach of the model;
- The mathematical formulation used in the model, and the limitations of this formulation;
- The numerical solution algorithm, including the limitations of this solution method;
- The calibration of the model and its performance in various verification and/or validation tests;

In addition, these manuals should include the following:

- Instructions for the user on how to run the model;
- Instructions for preparation of any required data files, including numerical size limits in this version of the model;
- A series of test cases that demonstrate the performance of the model;
- An example that leads the user through all steps in executing the model; and
- Literature references that allow the user to follow-up on particular aspects of the model.

Model documentation should be written clearly and precisely, with little use of jargon. The objective is to aid users of the model and model results in interpreting model results. Model documentation is often left until the end of a model development project, where it is frequently neglected. Instead, it is often more efficient and effective to begin model documentation early in model development, documenting various modeling decisions and assumptions at the time these decisions are made. Substantial, though lesser, effort is then required to formalize the documentation towards the end of the project. Increasingly, model documentation is provided on-line to facilitate updating and access to relevant data and meta-data.

Because models are seldom fixed for long periods, the writer should establish a system for tracking version numbers. Whenever possible, the model should be structured at the beginning so that future updates and developments are easily understood by existing users and do not require re-entry of the input in a new format.

Step 9. Update and Support of Model.
Successful models require establishment of a means for updating and user support. This represents a substantial ongoing cost and commitment. Agency modeling groups, consultants, and academic applied research units are sometimes given this role. The approach chosen for updating and supporting the model should be consistent with the technical, decision-making, and institutional objectives of the model.

The purpose of specifying an explicit model development process is to increase the likelihood that a model will serve the modeling purposes discussed in Chapter 2. Just as we are more certain of the serviceability of a bridge if it is constructed from a well-analyzed and field-tested design and whose construction has been subject to inspection and component testing, a model that is methodically developed and implemented is far more likely to provide good service.

Errors in Model Development

When solving water-related problems, the model developer has to deal with systems that include two major, and quite distinct, types of components: the natural ones and the man-made ones. Man-made components are usually fairly well known because they were designed with specific criteria. For example, the developer is able to obtain the dimensions of a spillway and its rating curve for discharge versus elevation or those of a concrete canal that conveys water from one part of a state to the another. However, nature does not provide Manning's roughness coefficients for the innumerable river segments that crisscross the system, especially under extreme conditions of flood with overflowing banks, etc. Thus, the model developer must accept that water systems will be modeled imperfectly, which introduces an ever-present fundamental error. A key question for the developer is how to reach decisions in spite of the uncertain comprehension of the system.

Conceptual Errors in the Description of the System to be Modeled

Since reality is too complex to be modeled perfectly, the model developer must develop a simplified, schematic view of the system and its behavior. When conceptualizing and simplifying, an excellent understanding of the natural system behavior is needed to separate what is important and essential from what is secondary or tertiary. The developer must also conceptualize both the static description of the system and its dynamic characteristics.

When conceptualizing the static state of the system, the geometrical and topographic description (of say, a watershed) must be determined. For example, how long is the main river? Can we approximate it by a succession of highly straightened segments with sharp turns at the junctions or must we subdivide the river into a very large number of reaches to accommodate changes in width, slope, roughness, direction, etc? How do we know the error committed by not carrying out the greatest level of refinement in the description?

Dynamic characteristics include description of the physical laws that govern the system. These physical laws include Henry's law at the molecular scale, Fick's law at the microscopic scale, and Darcy's law at the punctual scale. However, modelers are usually not interested in such small scales because of the large areas that are usually modeled.

The following four approaches are available to model phenomena across small scales without overwhelming data and computation requirements:

- A simplified approximate process can be adopted, such as soil storage "reservoirs" representing soil moisture behavior;
- Extend the scale of the known small-scale process beyond its field applicability (i.e., to a larger scale) or known data (such as employing a single Green-Ampt infiltration model for a large area using aggregated parameter values and inputs);
- Integrate the small-scale process over time and space to develop an analytical solution for its large-scale behavior (which is difficult); and
- Omit the process, if it is understood or demonstrated to have a minor effect on model results.

Model Equation Errors

After conceptualizing the static and dynamic characteristics of a system, the model developer expresses that knowledge as a system of equations and logical statements. The equations can be written in differential, integral and/or algebraic forms. Naturally, if the conceptualization was severely in error or omitted significant processes, the mathematical equations will not correct the analysis.

Physical Parameter Estimation Errors

Sometimes, physical parameters appearing in equations can be measured directly, such as the width of a river. However, parameters usually have to be estimated indirectly through a calibration procedure, which is always circumstantial and conditional. Errors enter into the model because (1) assumptions may be unreasonable for the given system or (2) the selected criterion to obtain the best match is not appropriate, or (3) the match is fortuitous and only applies under the actual conditions. Such estimations are usually conditional and circumstantial.

Data Errors

Model developers must be aware of data errors. Unfortunately, even measurements without errors will never cover the entire domain under investigation.

Compounding of Errors

One of the most troublesome problems when determining the magnitude of one sort of error versus another is that the errors end up being compounded. For example, if a finite difference model with coarse space and time increments is used to calibrate transmissivities based on observations, the parameters are conditional on the spacing. The same groundwater model used with a very fine grid (even ignoring problems of interpolation) may give poor predictions. A wrong model with the wrong type of parameters when calibrated on good data may perform reasonably well, but it cannot be used reliably under conditions different from its calibration.

Interpretation Errors

It is very easy when using automatic calibration procedures to obtain a decent model fit for the wrong reasons. Different models describing different mechanisms may lead to similar good matches with proper adjustment of their parameters.

5. USE OF MODELS IN PLANNING STUDIES

> "All mathematical models are based on a set of simplifying assumptions, that affect their use for certain problems. ... To avoid applying an otherwise valid model to an inappropriate field situation, knowledge of all of the assumptions that form the basis of the model and consideration of their applicability to the site and problem under evaluations is very important." ASTM (1995a)

Modeling Protocols for Planning Studies

Principles for the use of a model in a planning study are somewhat different from those for model development. A model-based planning study typically has a narrower set of objectives, a tighter time frame, and can rely on much of the documentation and understanding derived during model development. Principles that guide the use of models in a planning study should be aimed at improving the quality of the planning study. Thus, the principles offered here somewhat parallel those of a classical planning study (IWR, 1997) and are consistent with Federal water resources planning guidelines (WRC, 1983) and NEPA and CEQA requirements for EIR/EIS documents (USCEQ, 1981) (CEQA, 1999). Consequently, the documentation of a model's application can be either integrated or parallel with that of the larger planning study. For a model developed for a specific planning application, much of the following information will appear in the original model development documentation. The use of models in a planning study might follow the following steps.

1. Define Study Objectives.
The planning study's objectives should affect the type of models chosen and the way models are used for planning. Not all models are appropriate for all objectives, and models often are run differently depending on the study objectives. For example, a study of water quality operations in the Delta, requiring close absolute matches of salinity time-series in real time might require use of a detailed hydrodynamic-contaminant transport models with a great deal of real-time data. However, a planning study for an upstream storage facility might require only relative comparison of water quality statistics for different alternative plans, allowing use of a model with fewer computational and data demands.

2. Define How Model Outputs Relate to the Performance of Alternatives.
How do model outputs indicate how well a proposed plan would perform on specific planning objectives? How close is the correspondence between model output and likely field accomplishment of planning objectives.

3. Define a Base Case.
Planning studies are typically more understandable (and often less expensive) if alternative plans are developed from a base case. The "base case" can be defined as:

- Existing conditions;
- Existing conditions projected to some future year; or
- A "No Action" alternative (sometimes the same as above)
- A standard set of modifications to existing conditions (sometimes with projections into the future) to reflect changes and activities currently underway or to reflect agreed-upon new activities (as might be contained in a baseline consensus).

<u>4. Define Alternatives.</u>
Alternatives are the competing plans whose performance is to be compared. The definitions of alternatives should include (1) conceptual descriptions (usually as departures from the base case) and (2) detailed descriptions sufficient to allow replication (perhaps in an appendix). A wide range of alternatives are often useful and appropriate.

<u>5. Identify Model Version and Input Data.</u>
The model version and input data sets should be identified in the study documentation. Modifications made to the basic model, data, and related assumptions should be identified. If a planning study is intended for use in a public forum, the model and data should be available. Input data (and meta-data regarding the origins and confidence in the data) should be available online.

<u>6. Model Results.</u>
Modeling results for each alternative should be provided and discussed as appropriate to the planning study.

<u>7. Summarize and Discuss Performance of each Alternative.</u>
Summarizing the performance of each alternative on each planning objective should be part of a planning study.

<u>8. Discuss Study Limitations.</u>
The major limitations of the study results should be identified, and the implications for interpreting the results should be discussed.

Regulatory Aspects of Model Use in Planning Studies

Environmental impact analysis is an integral part of planning. Models are commonly used to evaluate project alternatives and the environmental impacts associated with those alternatives. The intent of California’s CEQA and the federal NEPA process is to make Environmental Impact Reports (EIR) and/or Environmental Impact Statements (EIS) a decision-aiding document rather than the primary decision-making report. The environmental document should be integrated within the broader plan formulation/evaluation steps of the typical project planning process (Stakhiv, 1989)

An EIR is a detailed informational document that analyzes a project’s significant effects and identifies mitigation measure and reasonable alternatives. An EIR must describe the existing environmental setting from local and regional perspectives. When a proposed project is compared to an adopted plan, the analysis must examine existing physical conditions (CEQA Guidelines Sec. 15121-15125, 15362). The EIR must always analyze the no-project alternative. The no-project alternative must describe maintenance of existing environmental conditions as a baseline for comparing the impacts of the alternatives (Dusek v. Redevelopment Agency (1986) 173 Cal.App.3d 1029). An EIR must include a description of the physical environmental conditions, as they exist at the time the notice of preparation is published, or if no notice of preparation is published, at the time environmental analysis is commenced. This environmental setting will normally constitute the baseline physical conditions (CEQA, 1999). For general plan amendments, however, it may be appropriate to analyze two no-project scenarios: maintenance of existing environmental conditions and future buildout under the existing general plan. These two approaches were used in the development of the draft State Water Resources Control Board (SWRCB) Decision 1630 (SWRCB, 1992). Draft Decision 1630 used (1) the average annual historical export rates from 1984 through 1989 to evaluate existing conditions for beneficial uses of Bay-Delta waters and (2) estimated future demand for water supply planning purposes.

NEPA requires the alternatives analysis in the EIS to include a “no action” alternative, which has two distinct interpretations depending on the nature of the proposal being evaluated. In the first situation, “no action” means "no change" from current management direction, such as when updating a management plan. The "no action" alternative, in this case, is the continuation of the present course of action until that action is changed. Consequently, projected impacts of alternative management schemes would be compared in the EIS to those impacts projected for the existing plan. In the second case, "no action” means the proposed activity would not take place, and the resulting environmental effects from taking no action would be compared with the effects of permitting the proposed activity or an alternative activity to go forward. If “no action” results in predictable actions by others, the consequences should be evaluated. For example, if denial of permission to build a water facility would lead to construction of a different facility, the EIS should analyze this consequence of the "no action" alternative (USCEQ, 1981).

Documentation and Access to the Modeling Study

Model studies (as well as model development) need to be documented and archived to ensure quality assurance. The American Society for Testing and Materials (ASTM) has developed a framework for documenting and archiving a groundwater flow model application that can be tailored for Forum use (ASTM, 1995b).

Model study documentation includes written and graphical presentations of model assumptions and objectives, the conceptual model, code description, model construction, model calibration, predictive simulations, and conclusions. Model archives consist of a file or set of files that contains logs of the calibration, sensitivity and predictive simulations, supplemental calculations, model documentation, a copy of the model source code(s) or executable files(s) used, or both, and input and output data sets for significant model simulations.

A model archive should consist of sufficient information generated during the modeling effort that a third party could adequately perform a post-modeling audit and such that future reuse of the model is possible. Table 4 shows a recommended simulation log for archiving each significant model run. Model users should archive an electronic copy of the log, data, and model (executable and/or source) code so that it is accessible via the Internet. Each log should include the modeler's name, simulation date, project name/number, simulation number, the code used (and version), the purpose of the run, the input file names, comments on the input data, the output file names, and comments on the results.

The above should be available in the form of study documentation. For modeling studies used in public arenas, this documentation, the model, and the data sets used should be made available either through the services of agency staff, a consultant, or a web site. Models of unusual long-term importance should be archived, both physically and on a web site. The agency or firm supporting the study should maintain such web sites.

Public Access to Models

Models used in public decision-making should be available for public scrutiny, like any other calculation or analysis presented in a public forum. The answer to the question: "How did you get that number?," must be available, and preferably reproducible and transparent, if the analysis is to be persuasive. Model documentation is the most fundamental way to provide explanation of model results. However, in many cases, even where documentation is reasonably complete and well-written, access to the model and data itself will be required to understand (1) the details of model results and (2) the stability and sensitivity of these results to small changes in input data and assumptions.

Ideally, computer models should be readily available to all users for independent evaluation prior to formal use in public decision-making. The burden of explaining and substantiating model results is clearly eased if adequate and readable documentation is available, and if the model has been systematically developed and tested. Model developers should archive an electronic copy of the model in a form accessible via the Internet.   Each log should include the model developer's name, the (executable and/or source) code, and user's and reference manuals. However, some models used for public decision-making are copyrighted or "proprietary" and may not be easily available for public scrutiny. Typically, copyrighted models can be purchased at rates that differ depending upon whether the model is intended for commercial or academic use, but cannot be copied. The details of proprietary models, on the other hand, may be kept secret and the code may not be available even to the agency funding the modeling studies. Even if a model is copyrighted or proprietary, sufficient information must be made available to enable stakeholders decision makers and the public to determine the validity of the model.

Table 4

MODEL SIMULATION LOG

By: ____ Date: __________________

E-mail: ____ Phone: (____)____________

==

Project Title and No.: ____

Simulation Title and No.: ____

Code Used/Version No.: ____

Purpose of Simulation: ____

____

____

Names of Input Files: ____

____

Comments on Input Data: ____

____

Names of Output Files: ____

____

Comments on Results: ____

____

____

General Comments: ____

____

Errors in Model Applications

Several types of errors can arise when using a model for an application.

Wrong Choice of Model

The first task for a water manager is to choose a model that is appropriate for the problem to be solved. A wise model user should be leery of using a rainfall-runoff model for a desert environment that was developed in a precipitation-rich environment. If such a model is used either the basis for the model must be thoroughly scrutinized and deemed applicable or another model must be selected. Thorough model documentation must be available to adequately scrutinize the model. A poorly documented model should not be used even if the documentation claims it can do the job.

Wrong Choice of Time-Step

As discussed in Chapter 4, use of the choice of the incorrect time-step for running a model can result in errors. Using a small time-step can (1) greatly increase computation costs, (2) raise problems of computational accuracy (in some cases), and (3) greatly increase the need for high-quality data, which significantly increases the cost.

Wrong Calibration and Verification Procedures

At some stage in the study process, the model user will need to calibrate the model's parameters for the particular study. The model user must understand clearly the structure of the model to proceed with the calibration. It is not possible to calibrate reliably a model without a good understanding of (1) the phenomena and (2) the specific model structure that will be used to represent the phenomena. When calibrating a model's parameters, the model user should not use all the data. Instead, the user should select some of the years for calibration and some for validation. The years selected for calibration should not exhibit extreme behaviors. Partitioning the data record in this manner will (1) demonstrate the model's ability to extrapolate and (2) provide a quantification of the errors that are likely to be encountered for the more extreme situations, since many modeling studies extrapolate to situations that have not been encountered in the historical record.

Delimiting Error Significance (Sensitivity Analysis)

A model user needs to quantify the intrinsic model errors (say, in predicting runoff) as a function of seasons (e.g., dormant versus growing season) or flow conditions (e.g., during floods or recessions). A model user also needs to study the impact of an error in estimating certain parameters on the particular parameters of interest, such as instantaneous discharges or seasonal cumulative values. Once this is completed, the next step is to study the impact of an error in estimating certain parameters on a management decision. Whereas the intrinsic error can be determined by running the model, the "derived" errors for a particular study will depend on the objective of the study. An investigation is required for each individual study.

Characteristics of Useful Models

Model results may be useful, despite being wrong, when its quantified intrinsic error is comparable with the acceptable accuracy of a management decision that relied on the model results. For example, if a relatively large error in predicting runoff during dry weather seasons leads to a relatively narrow distribution in the needed size of a low flow augmentation dam, then the model is useful. However, if the reverse holds, then the model, in its present form, is not useful. To make the model useful, the intrinsic error must be reduced by better calibration or by a change in structure or a combination of the two. Even if the intrinsic error results in an unacceptable level of error for the management decisions that rely on the model, the model may be useful in a relative sense if the effectiveness of different management strategies are compared. However, the model user must be sure that the model properly incorporates the different responses between strategies. For example, if the water manager is concerned about the effects on a downstream surface water right holder of a pumping well near a river, the groundwater model should not treat the river as a constant head boundary. In addition, it is important that the model account for the dynamic flow and for the associated fluctuating river stage.

6. CONCLUSIONS

Computer modeling has become indispensable for managing water in California. Only through the use of computers, can the large amounts of data and the complex interactions involving water in California be adequately understood and predicted. This dependence on California's water models raises unavoidable, but healthy questions of quality control among the diverse water stakeholders and decision-makers in California. Over the past decades, such technical issues have had a significant role "in muddying the waters" of an already difficult decision-making process for managing the State's water resources.

This report proposes protocols and guidelines for the development and use of models for water planning and management in California. These protocols and guidelines represent a broad consensus from the California water modeling community. In addition, the protocol and guidelines have wide acceptance in the literature on computational modeling for water and environmental problems, as well as for business, industrial, and military purposes as developed over several decades. The Forum believes that acceptance and implementation of modeling protocols by California's water community will result in better models and modeling studies by:

- Improving the construction of models;
- Providing better documentation of models and modeling studies;
- Providing easier professional and public access to models and modeling studies;
- Making models and modeling studies more easily understood and amendable to examination; and
- Increasing stakeholder, decision-maker, and technical staff confidence in models and modeling studies.

Adherence to these protocols is likely to modestly increase the short-term costs of many modeling studies. However, in the long-term, the overall costs for modeling, decision-making, and water management will be reduced in more than compensating amounts due to (1) a need to produce fewer modeling studies and (2) those studies improving the quality of water management decisions.

While these modeling protocols are generally accepted in the modeling community, a need exists for regulatory agencies and public forums that use modeling results to expect adherence to higher modeling standards. Without specific expectations from users of modeling results, improvement is likely to be slow. Hopefully, these modeling protocols will help raise the expectations of modeling work.

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APPENDIX A

Historical Uses of Bay-Delta Models

Bulletin 27 Salinity Intrusion Model
In 1931, the California Division of Water Resources released Bulletin 27, "Variation and Control of Salinity", the first published description of a model dealing with Bay-Delta resources. Bulletin 27 presented a method for estimating the flows required to control seawater intrusion in the Delta. The procedure yields results in terms of "steady-state", or equilibrium relationships between flow and salinity. The model played a central role in estimating the remaining water supplies available for distribution south of the Delta by the Central Valley Project and, later, the State Water Project. Validation of the Bulletin 27 model was not assessed until the early 1960's. Evaluations at that time showed that the model could not successfully reproduce data collected subsequent to its formulation, and it was not used further. Nevertheless, the Bulletin 27 model retains historical importance because of its role in planning water projects whose operations continue today (CDWR, 1931).

U.S. Corps of Engineers Hydraulic Model
After World War II, water interests promoted the Reber Plan, a multi-purpose system of dikes enclosing much of the shallow water portion of San Francisco Bay. The Reber Plan physically separated the salty Bay's water from the fresher Delta water to prevent seawater intrusion and ensure fresh water for the Delta and diversions to the southern California.

To evaluate this plan, the U. S. Corps of Engineers constructed a scale model of the Bay in a warehouse at Sausalito, California. Initially, the model represented the Bay system from the ocean upstream to the vicinity of Chipps Island, the western limit of the Delta. A later expansion extended the model's boundaries to include the Delta, and a Peripheral Canal project. The physical model included a system of pumps and valves to generate tides at the model's ocean boundary, maintenance of appropriate ocean salinity at that boundary, and the introduction of fresh water to represent river inflows at the upstream boundaries. The model's was used to study the Reber Plan and other proposed navigation projects on water quality in the Bay-Delta estuary. The model is no longer used extensively for technical evaluation of Bay-Delta issues. However, it remains open for public visits and tours conducted by the National Park Service (Water Resources Engineers, Inc, 1966, 1968).

Seven-Reach Salinity Intrusion Model
In the early 1960's, analysts at the California Department of Water Resources (DWR) used newly available analog computer equipment to develop a salinity intrusion model to replace the Bulletin 27 model. The new model solved a differential equation that described transport due to tidally-averaged flow and tidal dispersion in a series of seven connected segments representing the estuary from the ocean to Junction Point, which is

on the Sacramento River just upstream of Rio Vista. Like the Bulletin 27 model,, the Seven-Reach model was used to derive equilibrium relationships between flow and salinity at stations in the Delta and Suisun Bay regions. The Seven-Reach model was used to plan Delta facilities for the State Water Project (SWP).

Delta Facilities Planning – Salt Routing Models

While planning Delta facilities for the SWP, DWR developed and used a series of procedures that used relatively simple blending calculations to estimate the transport of dissolved salts within the Delta channels. These models used estimated flow divisions at major Delta channel bifurcations and salinity estimates at Delta boundaries, including the downstream boundary at the western end of the Delta. The water quality arriving at key stations was estimated by blending the flows from the appropriate source locations.

The earliest salt routing models, which was had no formal name, was run as a hand calculation procedure before the availability of modern computers. Its principal purpose was to estimate the Delta outflows required to control salinity at the pumping facilities of the SWP in the southern Delta. It incorporated a rough form of “carriage water”, which is defined as the Delta outflow necessary to counteract the seawater intrusion caused by water diversions in the southern Delta. The DWR presented an updated version of the model’s theory and calculation procedure (Exhibit DWR-262) during the State Water Resources Control Board’s (SWRCB) Bay-Delta proceedings in 1987. The model was used by DWR in Delta planning studies until 1997 when it was replaced by another procedure after it was determined that the model’s theory does not correspond well with field experience (CDWR, 1987a, 1987b).

In 1967, DWR prepared a new salt-routing model, PCSTAGE, to estimate the consequences on the SWP supplies if the proposed Peripheral Canal was not constructed. PCSTAGE was used with SWP operation studies to estimate when the SWP would not be able to meet its water supply objectives without a Peripheral Canal. No detailed description of PCSTAGE is available. In 1974, DWR published a Draft Environmental Impact Report on the proposed Peripheral Canal Project. In the report, the Seven-Reach model described above and a new model, FLOSALT, was used with operation studies results to describe Delta seawater intrusion and to project the effects of Peripheral Canal operation on the control of land-derived salts in the Delta.

FLOSALT estimated flows in all of the major Delta waterways westward to the Chipps Island region and included exchanges of water and salt between the waterways and adjacent agricultural lands. FLOSALT used a one-month time step and tidally averaged flows. It also assumed that flow in each Delta waterway could be described as the sum of linear functions of the various Delta inflows. Salinity variations were calculated using a simple blending technique without dispersion. Delta agricultural lands were assumed to behave as completely mixed reactors. Calculations were conducted in parallel with seawater intrusion modeling, but were not combined with them. Due to its design, FLOSALT use was limited to modeling Delta configurations with a Peripheral Canal. Consequently, its results could not be compared with field experience. The model was not used extensively after preparation of the 1974 Draft EIR (CDWR, 1974).

The DAYFLOW Model and QWEST

Because of the importance of Delta flows, DWR developed DAYFLOW, a simple mass balance model that used observed or calculated daily flows in Delta waterways. DAYFLOW listings for water years since 1956 are now distributed using the Internet at http://iep.water.ca.gov/dayflow/. DAYFLOW includes values of interior Delta flows that are estimated, rather than measured directly. These include QWEST, an estimate of tidally averaged flow in the San Joaquin River at Jersey Point. When QWEST is negative, flow at Jersey Point is upstream, indicating a condition called "reverse flow". The concept of reverse flow was central to the carriage water theory summarized above and, accordingly, played an important role in Delta water quality control planning for many years. Reverse flow came to be considered important in transporting fish toward the SWP and federal Central Valley Project (CVP) pumping plants in the southern Delta. Standards expressed in terms of QWEST were proposed at one time for inclusion in the SWRCB's Bay-Delta Plan. However, other controls considered more effective were eventually adopted.

The Link-Node Models

In the mid-1960's, the SWRCB sponsored a study on control of water pollution in the Bay-Delta estuary. The work included development of a set of mathematical models often referred to as the "link-node" models. These new models extended earlier work by describing flows and quality in a network of nodes and connecting channels representing all of San Francisco Bay and the Delta. The models were comprised of three principal computer parts: DYNFLOW, DYNQUAL, and a steady-state version of DYNQUAL. DYNFLO solved differential equations to calculate intratidal flows and water surface elevations in Delta. DYNQUAL used results from the DYNFLOW to calculate the transport of dissolved materials using a simple blending algorithm. The third program also utilized DYNFLO results to calculate "steady-state" pollutant concentrations throughout the Delta. The link-node models were used in the SWRCB's study to evaluate pollutant distributions and seawater intrusion. However, DYNQUAL was later found not to correspond well with field observations due to the simplicity of its transport algorithm and, as such, was not widely used. The two programs were subsequently refined and adapted by others for an array of purposes. In particular, the link-node models formed an important foundation for today's hydrodynamic models (Kaiser Engineers, 1969).

TVRK – An Extension of the Link-Node Transport Model

In 1982, DWR published a report describing TVRK, an intertidal transport model using a differential equation that accounts for tidal dispersion in a manner similar to the Seven-Reach model described above. TVRK used input flows from a new version of DYNFLO and was based on the same network developed for the link-node models. However, at about the time TVRK was completed, the Fischer Delta Model became available and TVRK was not used extensively for Delta analysis (CDWR, 1982).

The Fischer Delta Model

In May 1982, the late Hugo B. Fischer reported on the initial development of DELFLO and DELSAL programs that eventually became known collectively as the Fischer Delta Model. Fischer's early work was sponsored by the U. S. Bureau of Reclamation to evaluate alternatives for discharge to the Delta of agricultural drainage collected from the San Joaquin Valley. Like the link-node models described above, the Fischer Delta Model uses two programs, one to calculate flow distributions in a channel network (DELFLO) and the second to calculate transport of dissolved materials (DELSAL). The most important conceptual difference between the two sets of models is their respective approaches to calculating transport. The link-node models, including TVRK, used a network of volume elements that are fixed in time and space. Moreover, TVRK based its quality calculations on tidally averaged flows with an additional term representing tidal dispersion. Fischer, on the other hand, adopted a system of moving volume elements to develop a transport algorithm that accounted for flows within the tidal cycle. This new algorithm minimized the numerical errors that had accompanied previous efforts at intratidal transport modeling (Fischer, 1982).

Work on the San Joaquin Valley drainage program was discontinued for technical and policy reasons unrelated to the modeling. However, the model or procedures derived from it were chosen for a variety of uses by a number of agencies. For example, the Contra Costa Water District (CCWD) used the model extensively in planning its Los Vaqueros Project. The DWR used a variant of the model to conduct studies for the SWRCB analyzing salinity associated with alternatives for implementing a Water Quality Control Plan based on the Bay-Delta accord of December 1994.

Water Project Operations Models

The models discussed above model flows and salinity transport within the Bay-Delta estuary. Another important, but separate, category of California water modeling deals with the operation of water resources projects dependent on the Delta, but whose effects are felt over a much greater geographic region. The principal examples of such models are DWRSIM, a program representing operations of the SWP and CVP, with emphasis on the State facilities in northern and southern California, and, PROSIM, a conceptually similar model that emphasizes operations of the CVP. The models are used for planning purposes to compare alternative proposals for future operations. For example, PROSIM was used by the Bureau of Reclamation to assess alternatives for implementation of the Federal Central Valley Project Improvement Act. The DWR has used DWRSIM for many purposes including analysis of alternatives for implementing a Bay-Delta Water Quality Control Plan. The DWR is cooperatively working with the USBR on the new water project model, CALSIM, which is intended to replace both DWRSIM and PROSIM.

Both models simulate operation of reservoirs, pumps and aqueducts during hydrologic cycles lasting several decades. Both model the effects of regulatory constraints and requirements in the Bay-Delta on project operations. For the latter purpose, the models express Bay-Delta water quality controls in terms of flow requirements, and use techniques and results from detailed Delta models. Results from the operations models are often used as inputs to detailed models such as the Fischer Delta model to conduct long-term projections of project impacts on flows and water quality in the Bay-Delta.

During the course of planning its future, the CCWD developed a model simulating operation of the Los Vaqueros Project, the Los Vaqueros Operations Model. This project is supplied in part under the CCWD's water supply contract with the CVP. It was designed primarily to stabilize the District's water quality, and its operations schedule is dependent on water quality conditions at its Delta diversion point.

Recent Flow/Salinity Models

The models discussed above are arranged in approximate sequence according to the time of their development. They also represent a progression of increasing computational complexity, made possible in no small part by the continuing availability of more powerful, less expensive computer equipment. However, two recently developed models play a significant role in Bay-Delta planning efforts even though they are not unusually demanding from a computational viewpoint.

The Kimmerer-Monismith equation expresses the location in the estuary where salinity at the channel bed has a total dissolved concentration of two parts per thousand. The location, usually called the position of X2, is given as a function of a recent antecedent location and Delta outflow. The equation played a central role in achieving the agreement expressed in the 1994 Bay-Delta accord and in the development of key standards adopted in the SWRCB's 1995 Bay-Delta Water Quality Control Plan. It is currently used in the DWRSIM program to calculate flow requirements for water quality control at stations in the Suisun Bay region (SWRCB, 1995).

The "G-Model," which was developed by CCWD staff, is a relatively simple formulation that expresses the relationship between Delta outflow and seawater intrusion at several western Delta stations as a function of antecedent Delta outflow. Unlike earlier equations, the G-Model does not require consideration of reverse flow in the San Joaquin River and so does not model a "carriage water" requirement. The model has been incorporated in the DWRSIM operations program and was used by DWR to evaluate alternatives for implementing the 1995 Bay-Delta Water Quality Control Plan. More recently, the G-Model was used to evaluate Delta alternatives proposed under the joint CALFED program (Denton, 1993).

Closing Notes

The history summarized above discusses some of the models that have been developed to assist in more complete understanding of issues in the Bay-Delta estuary. Two points present themselves for consideration. First, the history of Bay-Delta modeling is that people continue to strive for better models and, in the process, models once considered important and useful are set aside to make way for newer procedures. Second, the importance of simplicity is not to be underestimated. Modeling is often thought of as an activity carried on using the ever more powerful computers. However, the discussion above begins and ends by summarizing important, yet relatively simple, (and in certain respects similar) approaches to solving the same problem, even though work on the

Bulletin 27 Model was separated from work on the Kimmerer-Monismith Equation and the G-Model by about 70 years. The circumstance is not intentional, but it is not entirely coincidental.