CHAPTER 1

Introduction

This chapter introduces surface water systems and the modeling of these systems. The contents of this book are also summarized here.

1.1 OVERVIEW

Surface water systems are waters naturally open to the atmosphere, such as rivers, lakes, reservoirs, estuaries, and coastal waters. The most common uses of surface waters include the followings:

1. Aquatic life support.
2. Water supply.
3. Recreation such as swimming, fishing, and boating.
4. Fisheries.
5. Transportation.

People rely on surface waters for recreation, water supply, and fish production. Surface waters are also critical for the survival of many species. Tens of thousands of birds, mammals, fishes, and other wildlife depend on surface waters as habitats to live, feed, and reproduce.

Rivers are naturally flowing waterbodies. They are a watershed's self-formed gutter system and usually empty into an ocean, lake, or another river. An example is the Illinois River watershed, located in Oklahoma and Arkansas (Fig. 1.1.1). The watershed acts as a collector of all kinds of water (and pollution) discharges. Lakes (and reservoirs) often act as receiving basins downstream from the surrounding watershed. Lakes modify these inflows from the watershed, serving both as filters and buffers. They retain water, sediment, toxics, and nutrients in response to in-lake hydrodynamic, chemical, and biological processes and dampen the extremes of discharges. Estuaries may also act as filters for the sediment and nutrients discharged from rivers and surface runoff.

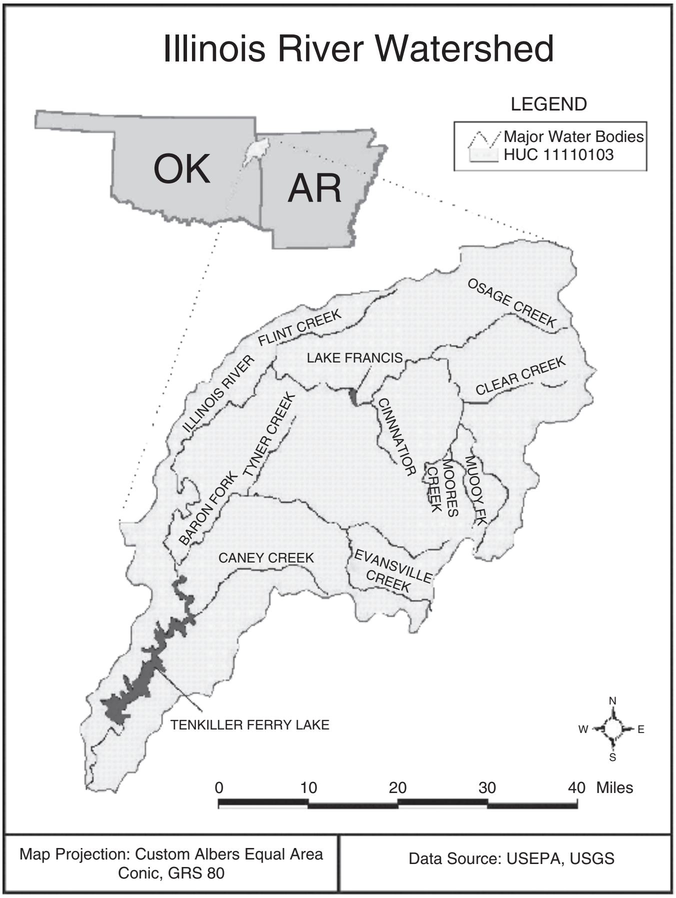

Fig. 1.1.1 Illinois River watershed, Lake Tenkiller drainage basin, the lake, and its main tributaries.

Surface waters are at once resilient and fragile. They are constantly changing as a result of both natural and human forces. The ecosystem of surface waters is an interactive system that includes hydrodynamic characteristics (e.g., water depth and flow velocity), chemical characteristics (e.g., solids, dissolved oxygen, and nutrients), and characteristics associated with the biological community of the water column and benthos. Large amounts of nutrients and contaminants enter into a variety of surface waters. Under siege from all directions, the ecosystems often face assault in the form of increasing populations; inadequately planned land use; and pollutants from farms, homes, and factories. Although every surface water system is unique, many face similar environmental problems: eutrophication, pathogen contamination, toxic chemicals, loss of habitat, and declines in fish and wildlife. These problems, in turn, can cause declines in water quality, living resources, and overall ecosystem health.

TABLE 1.1.1 The Distribution of Water on Earth[a]

Region	Volume ($10^3 km^3$)	% of total
Oceans	1,350,000	94.12
Groundwater	60,000	4.18
Ice	24,000	1.67
Lakes	230	0.016
Soil moisture	82	0.006
Atmosphere	14	0.001
Rivers	1	—

[a]Based on Lvovich (1971).

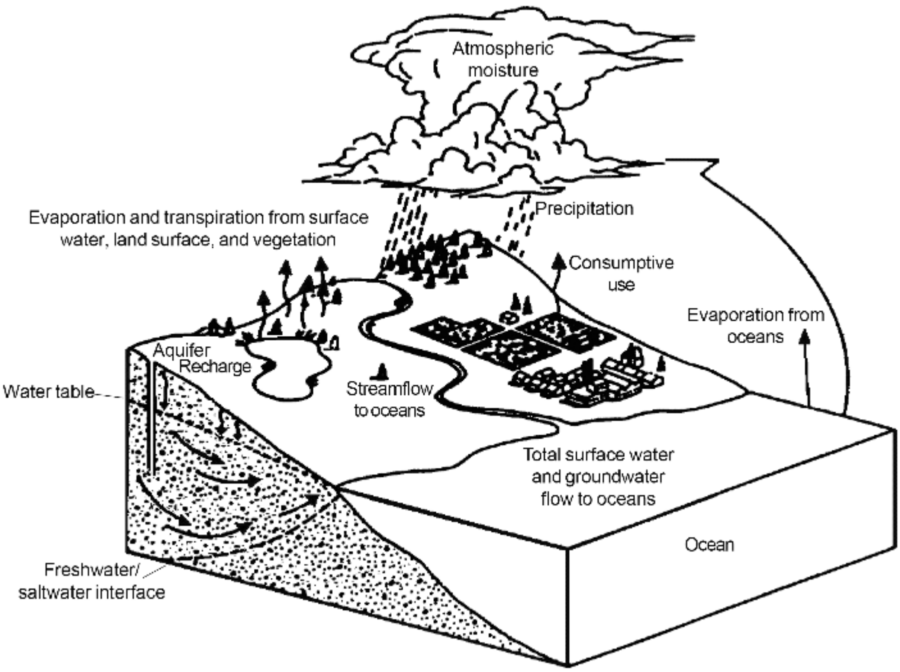

Fig. 1.1.2 Water's natural cycle (EHC, 1998).

Table 1.1.1 is a water budget showing the distribution of water over the earth (Lvovich, 1971). Rivers and lakes, though critical to civilization, contain a very small fraction of the total water budget. The water cycle (also known as the hydrologic cycle) represents the movement and endless recycling of water between the atmosphere, the land surface, and the ground. No matter what water quality problems that an ecosystem is associated with, its water cycle is often a key factor affecting the problems. From raging streams to the slow movement of water through the ground, as illustrated in Fig. 1.1.2, water is in constant motion. The water cycle begins with water evaporation from the earth's water surface, soil, and plants. The vast majority of evaporation occurs from the oceans. Once in the air, the water vapor is transported by winds and may later condense into clouds. A portion of the water vapor falls to the ground as precipitation in the form of rain or snow.

As the precipitation returns water to the land surface, a portion of it seeps into the ground and becomes groundwater. The remaining portion, which does not infiltrate the soil but flows over the surface of the ground to a stream, is called surface runoff. The water flowing through the ground can also return to the surface to supply water to rivers and lakes. All of the land that eventually drains to a common river or lake is considered to be in the same watershed. By a network of streams that flows into larger and larger streams, the water that is not evaporated back into the atmosphere eventually reaches the oceans. Therefore, land use activities in a watershed can affect the water quality of surface waters, such as rivers, lakes, and estuaries, as contaminants are carried by runoff and groundwater to these surface waters. To accurately estimate pollution loadings to a surface water system, the water cycle of the watershed must be considered accordingly.

1.2 UNDERSTANDING SURFACE WATERS

Three important tools used in supporting water quality management are (1) observation, (2) theoretical analysis, and (3) numerical modeling. Although each tool has advantages, each has certain disadvantages. The appropriate way to apply these tools is to better understand and make use of them according to their properties (Ji, 2004). Also, in the end, the professional judgment of the engineers and the managers inevitably comes into play.

In terms of helping decision makers identifying the scope of the environmental problems, reliable measured data are invaluable. Observation is the only way to know the real characteristics of the ecosystem and to provide the basis for theoretical analysis and numerical modeling. Only after certain observations are made can theoretical analysis and numerical modeling help the understanding of hydrodynamic and water quality processes and produce reliable results for supporting decisionmaking. These processes, in many cases, cannot be described well in mathematical models before they are measured in real waterbodies.

But measured data alone are rarely sufficient to make informed decisions on water quality management plans, especially when it comes to large and complex waterbodies. Due to budget, time, and technical constraints, field measurements are often limited to certain small areas (or fixed locations) and within certain periods of time. Measured data can go only so far in pointing the direction toward sound water quality policies and practices. Further, data errors can result in ambiguous interpretation and misunderstanding of the real physical, chemical, and biological processes. In these cases, theoretical analysis and numerical modeling become important. Through calibration and verification, numerical models are capable of realistically representing the hydrodynamic, sediment, toxic, and water quality conditions of the waterbody. The models can then be used as tools to support decisionmaking.

Key parameters used to represent the hydrodynamic and water quality conditions of surface waters include: (1) water temperature, (2) salinity, (3) velocity, (4) sediment, (5) pathogens, (6) toxics, (7) dissolved oxygen (DO), (8) algae, and (9) nutrients.

Water temperature is an important parameter representing the conditions of a waterbody. It also affects when animals and plants feed, reproduce, and migrate. Periodic power plant discharges can cause sudden changes in temperature and be disruptive to a local ecosystem. If water temperature rises too high, the DO level deceases, directly threatening aquatic life and contributing to eutrophication. In estuaries and coastal waters, salinity is a key parameter representing the environmental conditions. Water velocity plays a key role in transporting and mixing water quality variables.

Sediments enter surface waters from many sources and can alter the habitat of benthic organisms once they settle. Sediments can cause siltation in harbors and navigation channels. Sediments cloud the water, making it difficult for plants, such as underwater grasses, to receive sufficient sunlight to survive. Sediments are also important carriers of pollutants. Sediment transport can move the pollutants far away from their sources.

Pathogens, toxic metals, and organic chemicals are often derived from wastewater, farms, and feedlots. They can be transported to beaches and recreational waters, causing direct human exposure and disease. Pathogens may also accumulate in aquatic biota, such as oysters, clams, and mussels, causing disease when consumed by humans.

Dissolved oxygen is one of the most important parameters of water quality and is used to measure the amount of oxygen available for biochemical activity in water. Adequate DO concentrations are a requirement for most aquatic animals. The natural balance of DO can be disrupted by excessive wastewater loads of nutrients. Nutrients can come from wastewater treatment plants, fertilizers, and atmospheric deposition. Nutrients are essential for plants and animals, but excessive nutrient loading can cause algae overproduction, disrupting the natural balance. When algae die and decay, they deplete the dissolved oxygen in water.

Water quality management needs information to identify and evaluate various alternatives for achieving economic and water quality goals. Economic goals are often to achieve cost effectiveness, whereas water quality goals are usually set to meet certain water quality standards. The effectiveness of management alternatives may be measured in terms of how well they accomplish these goals. To determine this effectiveness often requires an assessment of the current state of the waterbody and how it has changed over time. Information is needed about the likely response of the waterbody to the management alternatives, such as decreasing nutrient loads from specific sources or increasing water inflows to the ecosystem, which may require a significant amount of infrastructure investment. It is paramount to be able to predict the consequences and effectiveness of the alternatives as accurately as possible, thus incorporating this information into decisionmaking.

Assessing the water quality of a surface water system requires expertise from many disciplines. Although the various processes may be described independently, they interact in complex ways. Multiple disciplines (hydrodynamics, sediment transport, pathogens and toxics, eutrophication, etc.) interact with each other to address water quality objectives. The result is not simply the assemblage of multiple disciplines working independently on a problem. Physical, chemical, and biological processes also vary over a broad spectrum, both in time and space. Spatial variations largely depend on the topography of the waterbody and external loadings. Temporal variations may have long-term (yearly), seasonal (monthly), diurnal (hourly), and short-term (minutes) time scales.

Often water quality is defined in terms of concentrations of the various dissolved and suspended substances in the water, for example, temperature, salinity, DO, nutrients, phytoplankton, bacteria, and heavy metals. The distribution of these substances has to be calculated by the water quality model. Based on the principle of conservation of mass, the concentration change can be represented simply in a one-dimensional (1D) form (Ji, 2000a):

$$\frac{\partial C}{\partial t} = -U\frac{\partial C}{\partial x} + \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) + S + R + Q \tag{1.2.1}$$

where C = substance concentration, t = time, x = distance, U = advection velocity in x direction, D = mixing and dispersion coefficient, S = sources and sinks due to settling and resuspension, R = reactivity of chemical and biological processes, Q = external loadings to the aquatic system from point and nonpoint sources.

It would be an oversimplification to say that this book is all about Eq. (1.2.1), but it is safe to say that this equation includes the major elements of hydrodynamics, sediment, toxics, and eutrophication. Many discussions in this book can be related to this equation directly or indirectly.

The changes of concentration C in Eq. (1.2.1) are determined by the following:

1. The hydrodynamic processes control the water depth (D), the advection (represented by the U term), and mixing (represented by the D term), which will be described in Chapter 2.
2. The size and properties of sediment (or particular organic matter) affect the settling and resuspension (represented by the S term), which will be illustrated in Chapter 3.
3. The chemical and biological reactions of pathogens, toxics, and/or nutrients are represented by the R term, which will be presented in Chapters 4 and 5.

4. External loadings from point and nonpoint sources are included by the Q term, which will be elaborated in Chapter 6.

The applications of Eq. (1.2.1) (and its more complicated versions) to rivers, lakes, and estuaries are presented in Chapters 8–10, respectively.

1.3 MODELING OF SURFACE WATERS

"Modeling is a little like art in the words of Pablo Picasso. It is never completely realistic; it is never the truth. But it contains enough of the truth, hopefully, and enough realism to gain understanding about environment systems" (Schooner, 1996). The two primary reasons to conduct modeling are (1) to better understand physical, chemical, and biological processes and (2) to develop models capable of realistically representing surface waters, so that the models can be used to support water quality management and decisionmaking.

The modeling of surface waters is complex and evolving. Presently, the success of a modeling study, especially sophisticated three-dimensional (3D) and time-dependent modeling studies, still depends heavily on the experience of the modeler. There is not a complete agreement among the professionals regarding the "best" approach to modeling rivers, lakes, estuaries, and coastal waters.

Water quality management needs to understand key processes affecting environmental problems in order to evaluate management alternatives. Examples of such environmental problems include:

1. Thermal pollution due to power plant discharges.
2. Sedimentation in harbors causing siltation and high dredging costs.
3. Eutrophication due to excessive nutrient loadings.
4. Low DO conditions caused by waste water discharges.
5. Accumulation of toxic materials in the sediment bed.

Water quality management increasingly depend on accurate modeling. This dependency is further amplified by the adoption of the watershed-based approach to pollution control. Models enable decision-makers to select better, more scientifically defensible choices among alternatives for water quality management. In many cases, the models are used to evaluate which alternative will be most effective in solving a long-term water quality problem. The management decisions require the consideration of existing conditions, as well as the projection of anticipated future changes of the water system. In these applications, the models not only need to represent the existing conditions, but also have to be predictive and give conditions that do not yet exist. Models are also used to provide a basis for economic analysis, so that decision makers can use the model results to evaluate the environmental significance of a project, as well as the cost–benefit ratio.

Three key factors have contributed to the great progress in the modeling of surface waters:

1. Better understanding and mathematical descriptions of physical, chemical, and biological processes in rivers, lakes, estuaries, and coastal waters.
2. Availability of fast and efficient numerical schemes.
3. Progress in computer technology.

The powerful, yet affordable computers in combination with fast numerical algorithms have enabled the development of sophisticated 3D hydrodynamic and water quality models. These advanced models contain very few simplifying approximations to the governing equations.

Personal computers (PCs) have evolved rapidly to become the standard platform for most engineering applications (with the exception of very large-scale problems). The PCs represent the most widely used computer platform today. Models developed on a PC can be transformed to other PCs without much difficulty. The relatively low prices of PCs also make modeling more cost effective. Due to the rapid advances in computer technology, PCs are now widely used in surface water modeling studies. As a matter of fact, all of the case studies presented in this book are conducted on PCs.

Models play a critical role in advancing the state-of-the-art of hydrodynamics, sediment transport, and water quality, and of water resources management. Because of their requirements for precise and accurate data, models also ultimately contribute to the design of field data collection and serve to identify data gaps in characterizing waterbodies. Models are used to analyze the impact of different management alternatives and to select the ones that result in the least adverse impact to the environment.

Models are often used to improve the scientific basis for theory development, to make and test predictions, and to clarify cause-and-effect relationships between pollutant loadings and the receiving waterbody. Reliable predictions stand out as a salient requirement for models, because decisions can have costly social and economic consequences on businesses, municipalities, and even entire states. Models are often used to evaluate and test potentially expensive water quality management alternatives prior to their implementation. The cost of a hydrodynamic and water quality modeling study is usually a small fraction of the implementation cost. Models can simulate changes in an ecosystem due to changes in internal and/or external conditions, such as water elevation variations or increased external pollutants. These simulations predict positive or negative changes within the ecosystem due to the management actions, such as improved sewage treatment or reduced agricultural runoff. These simulations are obviously far more cost effective than testing expensive management actions on a trial-and-error basis, thus making models a useful tool for water quality management. Since huge financial investment is at stake, accurate model results are imperative to support the costly implementation.

In the past decades, hydrodynamic and water quality models have evolved from simplified 1D, steady-state models, such as the legendary QUAL2E model (Brown and Barnwell, 1987), to complex 3D, time-dependant models of hydrodynamics, sediment, toxics, and eutrophication. Three-dimensional modeling has matured from a research subject to a practical engineering tool. Over this same period, computational requirements for realistic 3D modeling have changed from supercomputers, to high-end workstations, and then to PCs.

These advanced 3D and time-dependant models, which can also be readily applied for 1D- and two-dimensional (2D) problem settings, provide a powerful computational tool for sediment transport, water quality, eutrophication, and toxic chemical fate and transport modeling studies. Their hydrodynamic submodel provides: (1) flow field, (2) water depth, (3) temperature and salinity, (4) mixing, and (5) bottom stress.

The flow field, water depth, and mixing are used to determine mass transport of solids, toxics and other constituents. Bottom stress is used to estimate the exchange between the water column and sediment bed as a result of sediment deposition and resuspension. Since the mid-1980s, these models (e.g., Blumberg and Mellor, 1987; Hamrick, 1992; Sheng, 1986) have successfully transformed from academic research to practical tools for managing surface water systems.

Numerous models have been developed in the past decades. Many of them are actually based on similar theories and numerical schemes, even though the input and output formats of these models may look very different. For example, the Estuarine, Coastal and Ocean Model (ECOM) (HydroQual, 1991a, 1995a) and the Environmental Fluid Dynamics Code (EFDC) (Hamrick, 1992) both have hydrodynamic theories similar to the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987). The POM, ECOM, EFDC, and CH3D (Sheng, 1986) models all use the sigma coordinate in the vertical and a curvilinear grid in the horizontal. The CE-QUAL-ICM model (Cerco and Cole, 1994), the WASP model (Wool et al., 2002), and the EFDC model have the eutrophication theories similar to the RCA model (HydroQual, 2004). The Chesapeake Bay sediment flux model (Di Toro and Fitzpatrick, 1993) and its modified versions have almost become the "standard" sediment diagenesis model in eutrophication modeling.

These advanced models often include several coupled submodels for different physical, chemical, biological processes in surface waters, such as (1) the hydrodynamic, (2) the wind wave, (3) the sediment, (4) the toxic, (5) the eutrophication, (6) the sediment diagenesis, and (7) the submerged aquatic vegetation (SAV) model.

As an example, Fig. 1.3.1 illustrates the major components of the EFDC model. In addition to computational modules, these advanced models tend to

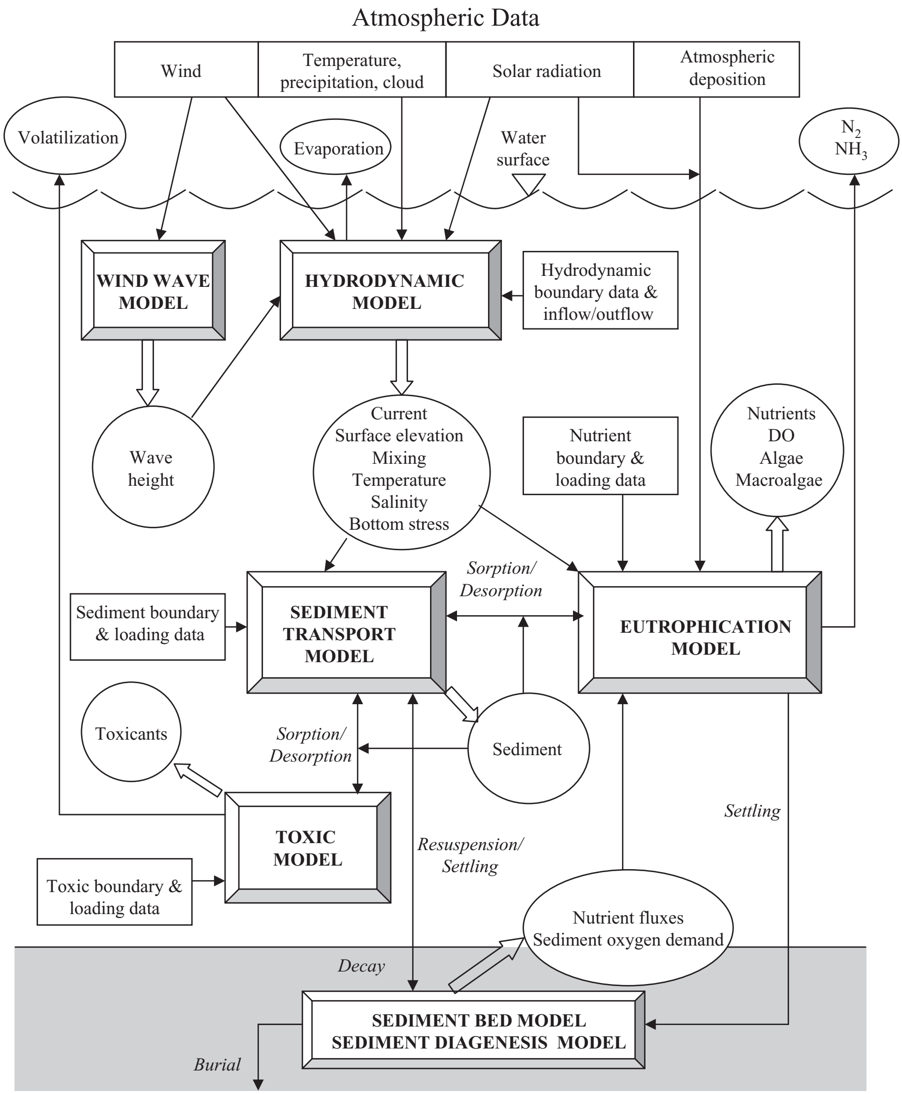

Fig. 1.3.1 Major components (submodels) of the EFDC model.

evolve into complex software systems, comprising many tools and sources of information. They may contain components for grid generation, data analysis, preprocessing, postprocessing, statistical analysis, graphics, and other utilities. Examples of these modeling packages include EFDC, ECOM, MIKE 3 (DHI, 2001) and TRIM (Casulli and Cheng, 1992).

Whereas the basic theories of the aforementioned models (and other models) might have been universally agreed upon, choosing the "best" model for a particular application is the subject of considerable controversy. It is beyond the scope of this book to get into the subtleties of this controversy. This book does not review models and does not recommend the so-called "best" model for surface water modeling. There are dedicated reports covering particular aspects of model review and model selection (e.g., Tetra Tech, 2001; Imhoff et al., 2004; HydroGeoLogic, 1999).

Note that models are rarely either right or wrong: they either lead the modelers to proper conclusions or to improper conclusions. Thus how to use and interpret model results are as important as the model results themselves. In this light, models are similar to other tools in engineering: they can either be productively used or abused. The experience of the modeler plays a vital role in a successful modeling application. This primary reason is why modeling is also called an "art".

1.4 ABOUT THIS BOOK

This book is about processes, their modeling, and how to use models to support decisionmaking. Instead of addressing models, this book is focused on theories, mathematical representations, and numerical modeling of processes in surface waters. Through case studies, the modeling of rivers, lakes, estuaries, and coastal waters is illustrated.

Chapters 2–5 are dedicated to four important subjects, respectively, (1) hydrodynamics (Chapter 2), (2) sediment transport (Chapter 3), (3) pathogens and toxics (Chapter 4), and (4) water quality and eutrophication (Chapter 5).

After external sources and total daily maximum load (TMDL) are discussed in Chapter 6, and mathematical modeling and statistical analyses are described in Chapter 7, the rest of book is focused on different types of surface waterbodies: (1) rivers (Chapter 8), (2) lakes and reservoirs (Chapter 9), and (3) estuaries and coastal waters (Chapter 10).

Each chapter (after Chapter 1) introduces concepts, processes, and mathematical representations at a level sufficient to meet the modeling needs, but elementary enough to allow the readers to have a good understanding of the topic. The organization of each chapter is similar: it begins by introducing basic concepts, proceeds to the discussions of physical, chemical, and/or biological processes and their mathematical representations, and concludes the chapter with case studies.

The best way to understand theories is via examples and case studies. This book (Chapters 2–10) presents a range of applications designed to be representative of surface water systems, including rivers, lakes, and estuaries. Each chapter typically includes two case studies on two different waterbodies. The case studies are useful for understanding the theories and processes presented in the previous sections of that chapter. They detail key features of surface water systems and exhibit varying levels of complexity. They provide real-world examples of how models can be set up on a practical level, used to

TABLE 1.4.1 Waterbodies Discussed in This Book as Case Studies and Examples

Waterbody Name	Waterbody Type	Physical Feature	Major Problems	Chapters
Blackstone River, MA	Small river	Shallow (<1 m) Narrow (<20 m)	Sedimentation, Toxic metals	3, 8
Susquehanna River, PA	Deep river	Deep (>10 m)	Thermal pollution	8
Lake Okeechobee, FL	Lake	Large (1730 km^2) Shallow (3.2 m)	Phosphorus, Eutrophication	2, 3, 5, 7, 9
Lake Tenkiller, OK	Reservoir	Long (48 km) Deep (>45 m)	Eutrophication	9
Rockford Lake, NE	Reservoir	Small (0.6 km^2) Shallow (3.7 m)	Pathogens	4
St. Lucie Estuary and Indian River Lagoon, FL	Estuary-lagoon	Small (29 km^2) Shallow (2.4 m)	Salinity intrusion, Eutrophication	2, 4, 5, 10
Morro Bay, CA	Estuary	Small (8.5 km^2) Shallow (<2.5 m)	Sedimentation Pathogen	10

simulate surface waters, and applied to support decisionmaking. A primary objective of presenting these case studies is that the modeling approaches, the analysis methods, and the discussions on processes in these case studies are useful for readers to conduct their own modeling studies on similar waterbodies.

The case studies are carefully selected, so that they represent different types of waterbodies. All of the case studies originated from real engineering projects. None of them is just an "idealized" exercise. The contents of these case studies are based on either published journal papers or technical reports. Physical features of these waterbodies and major problems addressed in the cases studies are summarized in Table 1.4.1. Electronic files of two case studies are included in the modeling package:

1. Lake Okeechobee: Shows the modeling and applications of hydrodynamics, wind wave, sediment transport, water quality, and SAV.
2. St. Lucie Estuary and Indian River Lagoon: Presents the applications of hydrodynamics, sediment transport, toxic metal, and water quality.

Sample input files and output files of these studies are included in the modeling package. Readers can use these input files as templates for their own applications and avoid developing the entire input files from scratch.