Water Quality Models

In order to determine the impacts of a particular discharge on ambient water quality, it is usually necessary to model the diffusion and dispersion of the discharge in the relevant water body. The approach applies both to new discharges and to the upgrading of existing sources. This chapter provides guidance on models that may be applicable in the context of typical Bank projects.

Mathematical models can be used to predict changes in ambient water quality due to changes in discharges of wastewater. In Bank work, the models are typically used to establish priorities for reduction of existing wastewater discharges or to predict the impacts of a proposed new discharge. Although a range of parameters may be of interest, a modeling exercise typically focuses on a few, such as dissolved oxygen, coliform bacteria, or nutrients.

Predicting the water quality impacts of a single discharge can often be done quickly and sufficiently accurately with a simple model. Regional water quality planning usually requires a model with a broader geographic scale, more data, and a more complex model structure.

Model Classification

Water quality models are usually classified according to model complexity, type of receiving water, and the water quality parameters (dissolved oxygen, nutrients, etc.) that the model can predict.

The more complex the model is, the more difficult and expensive will be its application to a given situation. Model complexity is a function of four factors.

- *The number and type of water quality indicators*. In general, the more indicators that are included, the more complex the model will be. In addition, some indicators are more complicated to predict than others (see Table 1).
- *The level of spatial detail*. As the number of pollution sources and water quality monitoring points increase, so do the data required and the size of the model.
- *The level of temporal detail*. It is much easier to predict long-term static averages than short-term dynamic changes in water quality. Point estimates of water quality parameters are usually simpler than stochastic predictions of the probability distributions of those parameters.
- *The complexity of the water body* under analysis. Small lakes that "mix" completely are less complex than moderate-size rivers, which are less complex than large rivers, which are less complex than large lakes, estuaries, and coastal zones.

The level of detail required can vary tremendously across different management applications. At one extreme, managers may be interested in the long-term impact of a small industrial plant on dissolved oxygen in a small, well-mixed lake. This type of problem can be addressed with a simple spreadsheet and solved by a single analyst in a month or less. At the other extreme, if managers want to know the rate of change in heavy metal concentrations in the Black Sea that can be expected from industrial modernization in the lower Danube River, the task will probably require many person-years of effort with extremely complex models and may cost millions of dollars.

For indicators of aerobic status, such as biochemical oxygen demand (BOD), dissolved oxy-

Table 1. Criteria for Classification of Water Quality Models

Criterion	*Comment*
Single-plant or regional focus	Simpler models can usually be used for single-plant “marginal” effects. More complex models are needed for regional analyses.
Static or dynamic	Static (constant) or time-varying outputs.
Stochastic or deterministic	Stochastic models present outputs as probability distributions; deterministic models are point-estimates.
Type of receiving water (river, lake, or estuary)	Small lakes and rivers are usually easier to model. Large lakes, estuaries, and large river systems are more complex.
Water quality parameters	
Dissolved oxygen	Usually decreases as discharge increases. Used as a water quality indicator in most water quality models.
Biochemical oxygen demand (BOD)	A measure of oxygen-reducing potential for waterborne discharges. Used in most water quality models.
Temperature	Often increased by discharges, especially from electric power plants. Relatively easy to model.
Ammonia nitrogen	Reduces dissolved oxygen concentrations and adds nitrate to water. Can be predicted by most water quality models.
Algal concentration	Increases with pollution, especially nitrates and phosphates. Predicted by moderately complex models.
Coliform bacteria	An indicator of contamination from sewage and animal waste
Nitrates	A nutrient for algal growth and a health hazard at very high concentrations in drinking water. Predicted by moderately complex models.
Phosphates	Nutrient for algal growth. Predicted by moderately complex models.
Toxic organic compounds	A wide variety of organic (carbon-based) compounds can affect aquatic life and may be directly hazardous to humans. Usually very difficult to model.
Heavy metals	Substances containing lead, mercury, cadmium, and other metals can cause both ecological and human health problems. Difficult to model in detail.

gen, and temperature, simple, well-established models can be used to predict long-term average changes in rivers, streams, and moderate-size lakes. The behavior of these models is well understood and has been studied more intensively than have other parameters. Basic nutrient indicators such as ammonia, nitrate, and phosphate concentrations can also be predicted reasonably accurately, at least for simpler water bodies such as rivers and moderate-size lakes. Predicting algae concentrations accurately is somewhat more difficult but is commonly done in the United States and Europe, where eutrophication has become a concern in the past two decades. Toxic organic compounds and heavy metals are much more problematic. Although some of the models reviewed below do include these materials, their behavior in the environment is still an area of active research.

Models can cover only a limited number of pollutants. In selecting parameters for the model, care should be taken to choose pollutants that are a concern in themselves and are also representative of the broader set of substances which cannot all be modeled in detail.

Data Requirements

As one might expect, the data requirements for different models increase with the complexity and scope of application. As shown in Table 2, all models require data on flows and water tem-

Table 2. Data Requirements for Water Quality Models

Data requirements	*Comment*
Water flows	Needed by all water quality models. Average flows needed by simpler models; detailed, dynamic information needed for more complex models.
Temperatures	Average temperatures required for simple models; detailed time-series required for complex models.
Dissolved oxygen concentrations	Base-case concentrations required by all models predicting dissolved oxygen impacts of a management alternative.
Biochemical oxygen demand (BOD)	Base-case concentrations and loads required by all models predicting dissolved oxygen impacts of a management alternative.
Ammonia, nitrates, phosphates, organic compounds, heavy metals	Base-case concentrations and loads required by all models predicting ammonia, nitrate, and other impacts of a management alternative.

peratures. Static, deterministic models require point estimates of these data and often use worst-case "design flow" estimates to capture the behavior of pollutants under the worst plausible circumstances. For most management purposes, the worst case will be high summer temperatures, which exacerbate problems with dissolved oxygen and algal growth, and low flows, which lead to high concentrations of BOD and other pollutants. Dynamic models will need time-series data on flows, temperatures, and other parameters.

In addition to hydraulic data, models require base-case concentrations of the water quality parameters of interest (dissolved oxygen, mercury, and so on). These are required both to calibrate the models to existing conditions and to provide a base against which to assess the effects of management alternatives. The models also need discharges or loads of the pollutants under consideration from the sources (e.g., industrial plants) being studied. The types and amounts of data needed for a given application are specific to the management question at hand.

Examples of Water Quality Models

Table 3 contains information on five representative water quality models, using the criteria in Table 1; Table 4 contains a textual description of each model. A large number of water quality models have been developed for particular watersheds, project-specific analyses, and other specialized purposes. In many cases, models are developed and used only once, for a particular project. In other cases, models are available only as proprietary, commercial software packages.

The list of models in Table 3 is not intended to be exhaustive, and the inclusion of a model should not be viewed as an endorsement or recommendation by the World Bank. The models were selected because they have been applied in a wide variety of management analyses and because public domain versions of the software are readily available. The list should be viewed as a representative sample of models that might be applied to a particular management problem. Sources of additional information on the models discussed here and on comprehensive surveys of water quality modeling are given at the end of the chapter.

The models shown in Table 4 vary from simple analytical models suitable for approximating the effects on water quality of individual industrial plants (WQAM) to complex models that include a wide variety of pollutants and pollution sources (WASP). Of the five models, WASP is the only one that is potentially capable of handling all types of water bodies, management analyses, and water quality parameters under consideration. The others may well be sufficient for a problem where WASP's complexity is not needed.

It is extremely important to recognize that the models or software packages only provide a framework for the analyses. Data specific to the watershed, industrial plants, and management scenarios will need to be gathered on site to make any model operational. An economic analogue might be the use of input-output analysis of a

Table 3. Water Quality Models for Management Analyses and Receiving Water Types

Management analysis	*WQAM*	*QUAL2E*	*WASP*	*CE-QUAL-RIV1*	*HEC-5Q*
Receiving waters					
Rivers and streams	x	x	x	x	x
Lakes and reservoirs	x	x	x		x
Estuaries and coastal areas	x		x		
Single-plant effects	x	x	x	x	x
Multiplant regional effects		x	x	x	x
Static	x	x	x		
Dynamic			x	x	x
Deterministic	x	x	x	x	x
Stochastic		x	x	x	x
Quality parameters					
Dissolved oxygen	x	x	x	x	x
Biochemical oxygen demand (BOD)	x	x	x	x	x
Temperature	x	x	x	x	x
Ammonia nitrogen	x	x	x	x	x
Coliform bacteria		x	x	x	
Algal concentrations	x	x	x	x	x
Nitrates		x	x	x	x
Phosphates		x	x	x	x
Toxic organic compounds			x		
Heavy metals			x		
Reference	Mills et al. 1985	Brown and Barnwell 1987	Ambrose, Wool, and Connolly 1988	USACE 1990	USACE 1986

regional economy. Although the framework (input-output tables arranged by economic sector, etc.) is the same regardless of the region or management question being analyzed, the data required will be specific to the problem at hand. To carry the analogy a bit further, both water quality and input-output models often require some customization when applied to localized problems. In the case of input-output models, particular economic sectors may be analyzed in more detail than others. Similarly, some water bodies and water quality constituents will receive more attention than others, depending on the problem at hand.

The next sections give three hypothetical examples of applications of various models and one actual case.

Hypothetical Examples

1. Modernization of a petroleum refinery in a severely degraded river basin

A Latin American government has applied for a loan to upgrade processing technology at a large oil refinery. The improvements are expected to decrease waterborne discharges of BOD and phenols by 50 percent. Use of a simple model (WQAM) shows that this reduction will slightly improve downstream dissolved oxygen levels. It also predicts that under the 10-year, 7-day design flow (the lowest flow for a 1-week period in 10 years), dissolved oxygen levels will increase from 2 parts per million (ppm) to 2.5 ppm. Although WQAM cannot analyze phenol concentrations, ambient levels are already very low because of a high dilution by flow in the river. Managers then use WQAM to assess the effects of added end-of-pipe treatment, which would increase dissolved oxygen levels from 2.5 ppm to 3.0 ppm. They concluded that further improvements will not significantly affect water quality because of high levels of discharge from other sources. The analysis takes 1 to 2 person-months, assuming that the requisite data on water flow and quality are readily available, and costs approximately US$10,000.

Table 4. Descriptions of Selected Models

Model	*Comment*
WQAM	Set of methods or mathematical tools used for preliminary analysis of changes in water quality due to changes in loadings. Unlike the other examples, WQAM is not a computer model per se but a collection of simple methods and procedures.
QUAL2E	Steady-state model for simulating well-mixed rivers and streams. Commonly used for assessing the impact of changes in point-source discharges on water quality. Especially suited for analyzing the effects of nutrients on algal concentration and dissolved oxygen. Widely applied in the United States and elsewhere.
WASP	Flexible, compartmental modeling structure for analysis of a wide variety of pollutants in almost any type of water body. The most powerful and complex of the models discussed here, it also requires more data and expertise for successful application. Extensively applied to water quality assessments in rivers and streams.
CE-QUAL-RIV1	Intended primarily for simulating the dynamics of highly unsteady stream flows, such as those occurring during flood events. Consists of a module for water quantity linked to one for water quality. Although the quantity module has seen numerous applications, the quality module is less widely applied than WQAM, QUAL2E, or WASP.
HEC-5Q	Developed primarily for analyzing water flows and water quality in reservoirs and associated downstream river reaches. It can perform detailed simulations of reservoir operations, such as regulating outflows through gates and turbines, and vertical temperature gradients in reservoirs.

2. New food-processing plant in a moderately polluted coastal estuary

A new vegetable-canning plant is planned for a moderately polluted tropical estuary. Use of a simple model (WQAM) shows that the mill's discharges may have a significant effect on the estuary's dissolved oxygen and nutrient levels. If the plant is brought on line, dissolved oxygen would decrease from 4.5 ppm to 3 ppm, which could cause problems for aquatic life. Phosphorus concentrations could increase from 0.5 ppm to 2.0 ppm, which, according to local experts, could lead to algal blooms and affect the local fishery. Next, a more complex model (WASP) is used to obtain a more detailed assessment, and it too shows effects that are deemed unacceptable. Since the plant is new and is projected to have state-of-the-art pollution abatement equipment in place, it is found to be more cost-effective to improve water quality by upgrading a nearby municipal sewage treatment plant. Projected discharge reductions in the municipal plant are found to give acceptable water quality when analyzed with WASP. The analysis takes 10 to 12 person-months, assuming that the requisite data on water flow and quality are readily available, and costs approximately US$100,000.

3. Regional water quality enhancement plan for a moderate-size river basin

A Central European government has received a loan to perform long-term investment planning for industrial and municipal sewage treatment for a river basin of 20,000 square kilometers. The basin contains approximately 100 point sources, one quarter of which are industrial treatment plants. Increased user fees are expected to pay for primary sewage treatment for all municipalities within 10 years. In addition, increases in emissions fees should induce all industrial sources to install and operate primary sewage treatment plants within the same time frame. The central government has agreed that it will finance more advanced treatment facilities for a subset of municipalities out of general revenues. In addition, it will use the emissions fees levied on industrial dischargers to finance advanced treatment works for some sources. Because of a shortage of investment capital, the government wishes to get as much improvement in water quality per amount invested as possible.

The government has decided to focus its water quality control efforts on dissolved oxygen and nutrients. It plans to tackle toxic pollutants (a problem in some heavily industrialized areas) at a later date, when the economy is projected to improve. A survey of existing water quality data shows that dissolved oxygen is especially problematic downstream from two major cities and that nutrient concentrations are of particular concern just below an industrial complex. Because of the large number of pollution sources, a simple approach using WQAM is rejected, but a model as complex as WASP is thought to be too expensive to calibrate and run for such a large area. In any case, since the government is formulating a long-term investment plan, it believes that the dynamic information provided by WASP or HEC-5Q is not required. Therefore, the government plans to use QUAL2E to project the effects on water quality of different investment strategies.

QUAL2E can assess whether a particular combination of treatment plants will meet a set of water quality goals. In addition to a water quality model, a simple optimization model will also be required to assess which combination will meet the goals at least cost. The government decides on a simple spreadsheet model with a commercial optimization add-on. The results show that significant savings can be achieved, in comparison with a strategy that requires all plants to have the same level of treatment. Assuming that the requisite data on water flow and quality are readily available, the analysis takes 100 to 150 person-months and costs approximately US$1,000,000.

A Real-Life Example: The Nitra River

An example demonstrating the savings that can be identified by a modeling exercise is a study of the Nitra River, a tributary of the Danube River. Current dissolved oxygen levels could be raised to a minimum of 4 milligrams per liter (mg/l), at a cost of about US$13 million, by using a mix of treatment systems for the major different discharges. To raise this value to a minimum of 6 mg/l would cost about US$26 million, with higher treatment requirements for most of the discharges. To bring all the discharges up to EU standards would cost about US$65 million; dissolved oxygen levels would be about 7 mg/l, and nutrient levels in the river would also be reduced. Despite some uncertainty in the results because of data shortcomings, the study concluded that the results "strongly suggest that substantial cost savings are possible using a least-cost control policy."

Management Objectives and Applications

A point often overlooked in the real-world application of water quality models is that they are a means of achieving a set of management objectives, not an end in themselves. In many cases, it may not be necessary to use a water quality model at all, even when it is known in advance that a project will affect water quality. Suppose that in hypothetical example 1 the local water quality was acceptable to local environmental authorities prior to upgrading the plant. Given that the plant upgrade will reduce discharges and so improve water quality, there is no need for model results that will assess the projected water quality improvement. To deal with the problem at hand, it may be enough to know that water quality will not become worse.

It should also be kept in mind that the motivations of project managers and those of water quality modelers may not be in concert. If environmental regulations focus on long-term averages for dissolved oxygen and BOD, there may be little, if any, need for advanced water quality modeling that can predict concentrations of heavy metals and toxic organic compounds. Water quality analysts, however, may be interested in performing complex analyses on metals and organic compounds because of the technical challenge.

Managers should remember that the accuracy of model projections is severely constrained by the quality and quantity of the available data used to calibrate and test the models. The hypothetical examples given above explicitly assume that these data are readily available, but this will often not be the case in practice. Although data on water quantity are often collected for larger water bodies, water quality information may be collected sporadically or not at all. This is especially true of information on algae and other biological indicators, heavy metals, and toxic organic compounds, since scientific interest in these data is relatively new.

Lack of data can create three problems. First, a model cannot be calibrated and tested until a monitoring system has been designed and operated for a considerable length of time. Second, water sample collection and analysis may be considerably more expensive than the modeling effort that it is designed to support. Finally, design of a monitoring system may fall prey to the same types of problems that can affect water quality modeling, including a lack of clear connections to management objectives and a tendency to excessive complexity.

Models are only an abstraction from the reality of a situation, and the improper use or misinterpretation of outputs from a model can lead to imprecise or incorrect results. Any conclusions reached on the basis of a model should therefore always be checked for realism and common sense.

In summary, managers should be cautious about underwriting the development and application of water quality models. They should be clear about their management goals, and model application should support those goals. In some settings, models may not be needed at all, while in others, simple models may suffice. Any model will require a substantial amount of supporting data, which may not be immediately available.

Sources of Additional Information

Although many textbooks and journal articles have surveyed water quality model development and application, most surveys are not readily accessible to nonspecialists. Among the less technically oriented materials available, Wurbs (1995) provides an up-to-date survey of modeling techniques for water management, covering both quality and quantity, and contains a useful guide to software packages. Novotny and Capodaglio (1995) provide a survey of the concepts used in water quality modeling and an overview of available models. Thomann and Mueller (1987) and Orlob (1982) are standard texts on the principles of water quality modeling.

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