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MODELING WATER QUALITY IN THE TUALATIN RIVER: ACHIEVEMENTS AND LIMITATIONS

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ABSTRACT: Many of today's water-quality models are adequate for the simulation of basic transport processes and simple chemical and biological reactions. They are good tools for helping us understand and quantify water-quality processes, but at some level of complexity these tools will fail. Such successes and failures are illustrated by a modeling study of the Tualatin River in northwestern Oregon. In this study, CE-QUAL-W2 was used successfully to assess the sources and transport of phosphorus, quantify the river's ammonia assimilative capacity, determine the relative importance of the sources and sinks of dissolved oxygen, quantify the factors that affect phytoplankton growth, and test the effects of potential management strategies. The model failed, however, to adequately predict pH or assess long-term sediment diagenesis. Improved models also are needed for simulating sediment transport and periphyton growth. These are some of the issues that must be addressed by the next generation of water-quality models.
KEY TERMS: water quality model; CE-QUAL-W2; Tualatin River; successes; limitations.

INTRODUCTION

For decades, water-quality models have been used as tools to assess the combined effects of advection, dispersion, reaeration, and selected chemical and biological reactions on stream water quality. These models tended to use steady-state representations of stream hydraulics and included only a small number of reactions. Recent advancements in computer technology, however, have allowed more complex and dynamic water-quality models to be built. As these tools have become more capable, their utility in helping scientists, regulators, and river managers understand stream processes also has increased. Models are now commonly used to assess pollutant transport, quantify source and sink processes, determine assimilative capacities, and design regulatory compliance schemes. In these endeavors, today's models are often sufficiently accurate to be useful, particularly when simulating advection/dispersion, water temperature, conservative transport, and simple eutrophication processes.

All models make simplifying assumptions in their mathematical representations of stream processes. For some modeled parameters, such as water temperature, the controlling processes (in this case, fluid dynamics and heat transfer processes) are well known and can be accurately represented by model algorithms. For other model constituents, such as dissolved oxygen and algal communities, the mathematics of the controlling processes are not as well known, and models must represent such processes with empirical or simplified equations. In many instances, such simplifications are acceptable and the model remains a useful tool. In other cases, the model will fail to represent stream processes with sufficient accuracy to be useful.

The potential successes and shortcomings of water-quality modeling today are well represented by a model of the Tualatin River developed by the U.S. Geological Survey (Rounds and others, 1999). This paper uses that study as an example of the utility of a well-calibrated water-quality model, as well as of the problems that remain to be addressed by the next generation of stream water-quality models.

Study Area

Located on the west side of the Portland, Oregon, metropolitan area, the 712-square-mile Tualatin River Basin (figure 1) is home to almost 400,000 people and supports a wide variety of agricultural, urban, and forest-derived activities. The population depends on the Tualatin River as a source of municipal, industrial,

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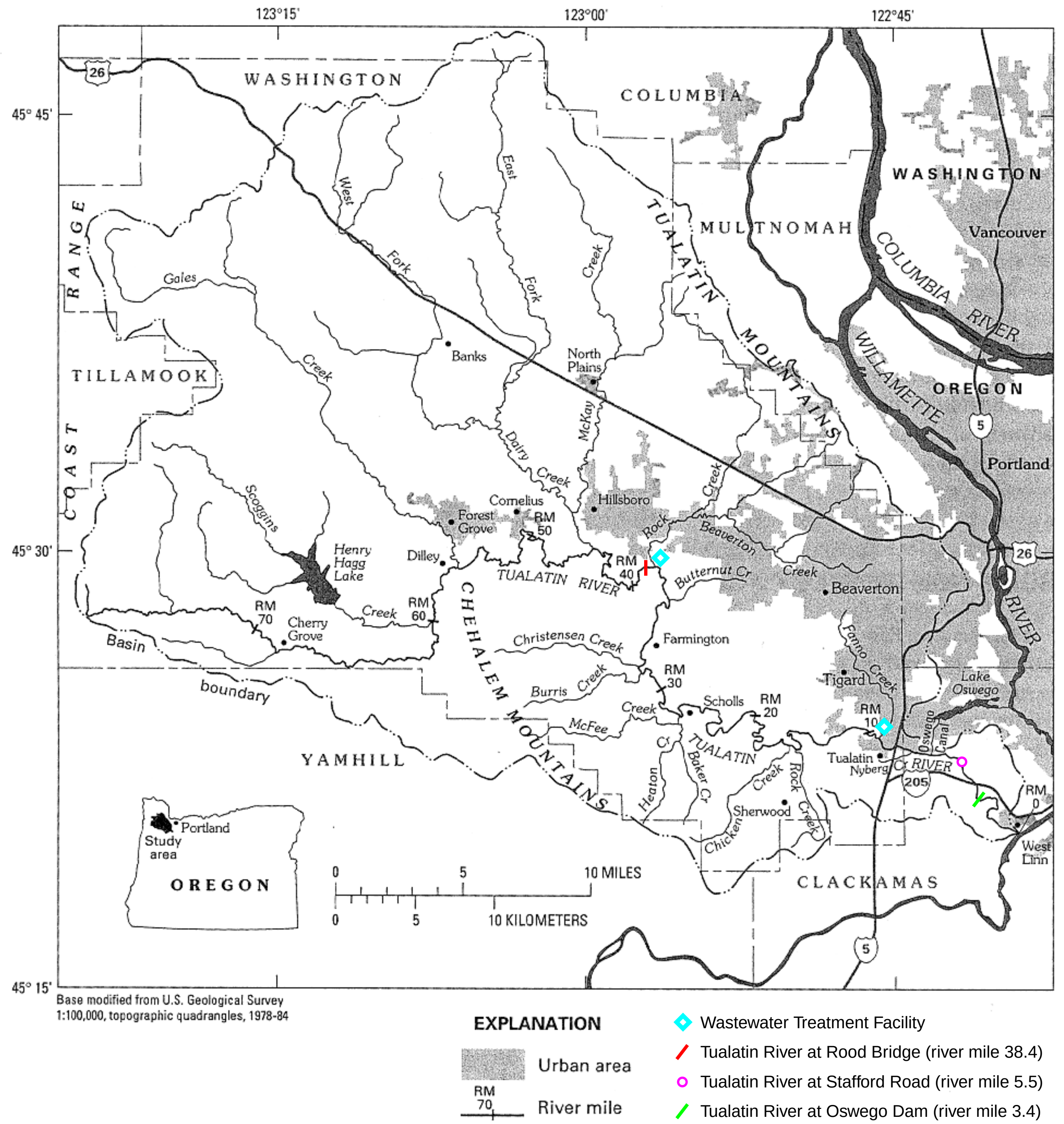

Figure 1. Map of the Tualatin River Basin, Oregon.

and irrigation water; habitat for fish and other wildlife; and a place to recreate. The river also receives and transports the urban population's treated wastewater. The Tualatin River is not a large stream by many measures, varying from 50 to 200 feet wide and 5 to 20 feet deep in most places. Streamflow varies with the seasonal precipitation, with the highest flows occurring in the winter. During the dry summer months of July through September, streamflow near the mouth of the river at West Linn typically ranges between 100 and 200 cubic feet per second; such flows are typically augmented with releases from an upstream reservoir.

The Tualatin River valley is relatively flat, which causes the river to meander. A low-head dam at river mile 3.4 causes the already placid river to back up for as much as 25 miles. This "reservoir" reach has many of the characteristics of a long, narrow lake, and most of the river's water-quality problems occur there. The river is turbid and deep enough that attached algae (periphyton) are not favored. Conditions are favorable, however, for unattached algae (phytoplankton) that drift with the river flow. Given the long residence times, warm water, ample nutrients (nitrogen and phosphorus), and plentiful solar energy typical of summer conditions in western Oregon, phytoplankton can thrive in the Tualatin River and degrade the river's water quality.

Historically, water-quality problems included pH values greater than the Oregon State standard of 8.5, dissolved oxygen concentrations less than the minimum standard of 6.0 (pre-1996) or 6.5 mg/L (post-1996), and chlorophyll-a concentrations greater than the Oregon nuisance phytoplankton growth criterion of 15 μg/L. The pH problems were known to be related to excessive algal growth; part of the dissolved oxygen problem was related to discharges of ammonia from the basin's two largest wastewater treatment facilities. Under the Clean Water Act, Total Maximum Daily Loads (TMDLs) of total phosphorus (to decrease algal growth) and ammonia (to decrease oxygen consumption) were established in 1988.

In 1990, the U.S. Geological Survey began an investigation of the sources and transport of nutrients (nitrogen and phosphorus), the dynamics of phytoplankton growth, and the sources and sinks of dissolved oxygen in the Tualatin River. Part of that effort involved the development and application of a water-quality model to synthesize our knowledge and test potential management options.

Model Application

The Tualatin River was simulated using a modified version of the Corps of Engineers model CE-QUAL-W2 (Cole and Buchak, 1995; Rounds and others, 1999), or W2 for short. This model is a two-dimensional, laterally averaged flow and water-quality model designed for lakes and reservoirs where lateral differences in water quality are negligible and vertical variations can be important. Because the reservoir reach of the Tualatin River is essentially a long, narrow lake and several subreaches tend to stratify under low-flow summer conditions, W2 is an appropriate tool for this stream. In addition to simulating flow, velocities, water levels, and water temperature, this version of W2 simulates up to 22 water-quality constituents, including dissolved oxygen, ammonia, nitrate, orthophosphate, phytoplankton, zooplankton, dissolved solids, suspended solids, dissolved organic matter, particulate organic matter, bed-sediment organic matter, total inorganic carbon, alkalinity, pH, and a conservative tracer.

For the Tualatin River, W2 was applied to a 35-mile reach from river mile 38.4 (just upstream of Rock Creek and the discharge of one of the wastewater treatment plants) to the low-head dam at river mile 3.4 (figure 1). The model grid was discretized into 155 segments and 16 layers. Both treatment plants, as well as two major and eight minor tributaries were included in the model. The water budget also included precipitation, irrigation withdrawals and other diversions, evaporation, and groundwater discharge. The model was calibrated for the May 1 through October 31 period of the years 1991 through 1997.

RESULTS

The Tualatin River model was used in both diagnostic and prognostic modes. The model was used to better understand the budgets of nitrogen and phosphorus in the river, quantify the relative importance of the sources and sinks of dissolved oxygen, and determine the effects of algal growth on water quality. In a prognostic mode, the model was used to determine the river's assimilative capacity for ammonia, help determine the river's sensitivity to phosphorus loads, and chart future directions for river management.

Successes

Success in modeling depends on the goals of the modeling exercise. For some simulated constituents or properties, success is measured by strict accuracy in numerical predictions. For other constituents whose simulation is more complex, numerical accuracy is still desired, but success may be measured as the accurate prediction of certain trends and cycles. For the Tualatin River model, most of the modeling work was fairly successful, although the model's capabilities are still limited.

In particular, river discharge and stage were simulated well, as all of the aspects of the water budget were either measured or reasonably estimated. This is not unexpected, as the mathematics of fluid flow in rivers is well understood. Similarly, the physics of heat exchange and energy transport also are well understood and quantified, so it is not surprising that the Tualatin River model simulated water temperatures accurately. A comparison of simulated and measured quantities for the summer of 1996 are shown in figure 2 for a critical location in the Tualatin River (Stafford Road, river mile 5.5). It is clear from figure 2A that the model

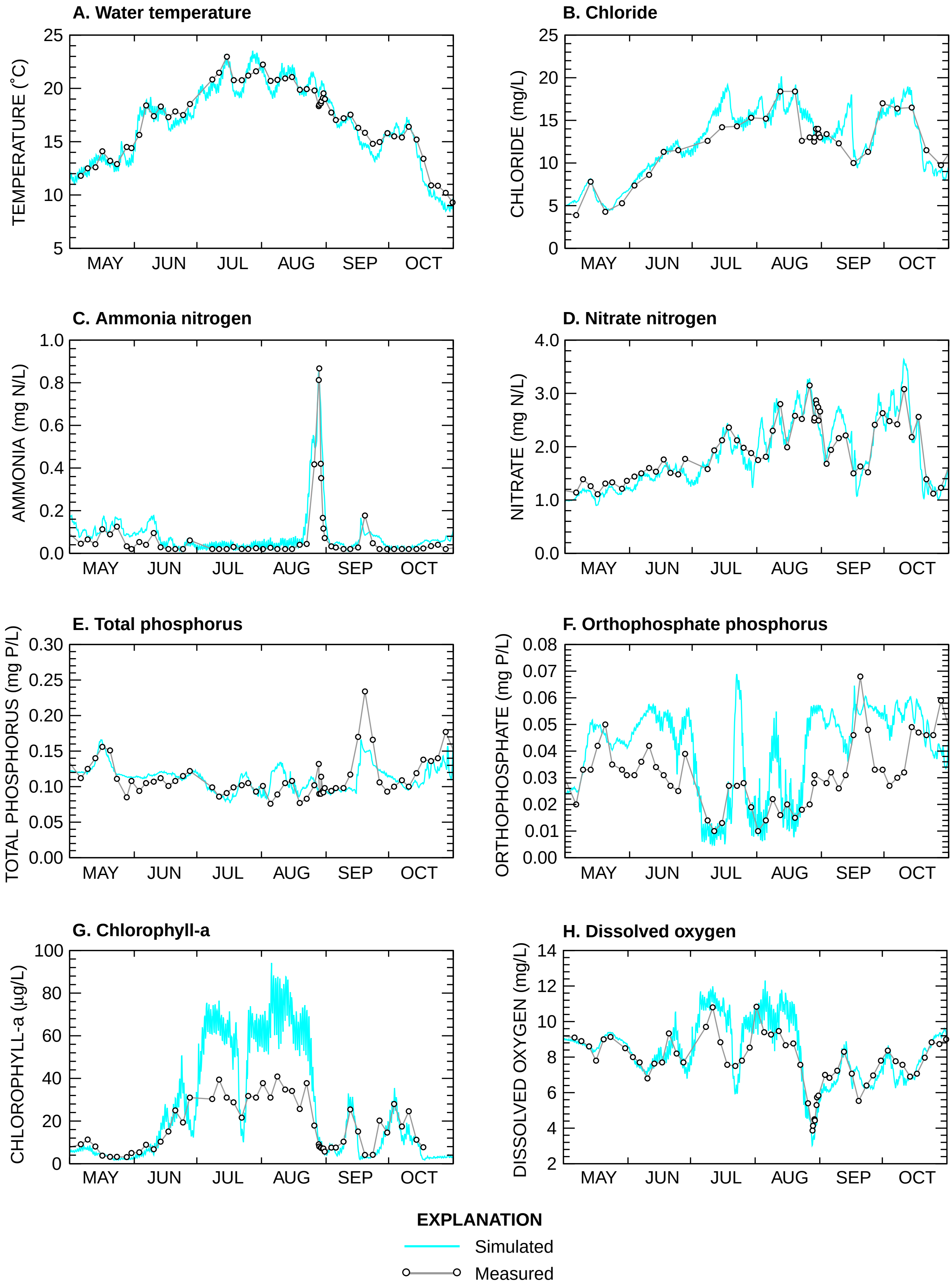

Figure 2. Comparison of simulated and measured temperature and water-quality constituent concentrations in the Tualatin River at Stafford Road (river mile 5.5) during 1996.

simulates the seasonal trends in water temperature closely. In terms of numerical accuracy, the mean absolute error in the simulated water temperature at this site is only 0.7 ˚C (table 1). It is a reasonable expectation that today's water-quality models should simulate water temperature with less than a 1 ˚C error, and the simulation of water temperature within 0.5 ˚C is outstanding.

Table 1. Goodness-of-fit statistics for the model results.

Fit statistic	Temper-ature (˚C)	Chloride (mg/L)	Ammonia (mg N/L)	Nitrate (mg N/L)	Total phos-phorus (mg P/L)	Ortho-phos-phate (mg P/L)	Chloro-phyll-a (μg/L)	Dissolved oxygen (mg/L)
Mean absolute error (in indicated units)	0.71	1.0	0.036	0.15	0.015	0.013	12	0.69
Coefficient of determination (no units)	0.98	0.96	0.87	0.95	0.68	0.64	0.92	0.84

Figure 2 and table 1 also show very good results for chloride (a conservative tracer), ammonia, nitrate, and total phosphorus. The chloride results (figure 2B) indicate that no important sources or sinks for this constituent were omitted by the model and that the basic transport processes in the river are accurately simulated. The results for ammonia and nitrate (figures 2C and 2D) indicate that the microbially mediated reactions affecting these constituents, despite their representation as simple first order processes in the model, are adequately modeled: trends and absolute concentrations for these nitrogen species are accurately simulated. The sources, sinks, and transport of total phosphorus appear to be adequately simulated by the model (figure 2E): a mean absolute error of 0.015 mg P/L is acceptable for this application.

The simulated trends and size of the algal population were captured relatively well by the model (figure 2G), although the model clearly overestimated the size of the algal population in the July-August period. Obviously, the model's representation of the algal community as a single species is not fully predictive; fortunately, the algal assemblage in the Tualatin River is dominated by only one or two species of diatoms and no distinct algal succession occurs. The model's predictions for dissolved oxygen (figure 2H) were very good, with a mean absolute error of less than 0.7 mg/L (table 1). Given the fact that the dissolved oxygen concentration is the result of boundary inflows, reaeration, algal photosynthesis, ammonia nitrification, and the decomposition of organic matter in the water column and the sediments, and the fact that most of these processes are represented in the model with simple or empirical relations, the results for dissolved oxygen are surprisingly accurate. The greatest errors in the simulated dissolved oxygen concentration are directly attributable to errors in the size of the simulated phytoplankton population.

Because the model was able to simulate streamflow, temperature, ammonia, and nitrate with high accuracy and dissolved oxygen with an acceptable level of error, the model was used extensively to quantify the river's ability to assimilate loads of ammonia from the Tualatin River Basin's two major wastewater treatment plants (Rounds and Wood, 1998). This modeling work has since been used as the basis for the revision of the ammonia TMDL for the Tualatin River.

The model also was used successfully to quantify (a) the effects of minimum levels of flow augmentation on dissolved oxygen levels, (b) the effects of reductions in sediment oxygen demand on dissolved oxygen levels, (c) the effects of various phosphorus levels on the size of the algal population, (d) the potential effects of increased wastewater discharges due to population growth, and (e) the effects of increased riparian shading on stream temperature, among other scenarios. In all of these exercises, the model was able to provide insights regarding the effects of each of these management strategies.

Continuing Challenges

Although the model was used successfully in many ways, not all of the Tualatin River modeling was successful, and the capabilities of the model are still limited in several important areas.

W2 has a good set of algorithms for simulating pH, tied to the transport of its alkalinity and total inorganic carbon constituents. For the Tualatin River model, an attempt was made to simulate pH for the summer of 1993, one of the few summers for which all of the necessary alkalinity boundary condition data were available. The results were good (within 0.2 pH units) for selected periods of the summer, but poor (error of 1.0 pH unit or more) for others. Essentially, the simulation of pH was only accurate when the simulation of the algal population size also was accurate. If the phytoplankton population was significantly overestimated, then the simulated pH could be more than 1.0 pH unit greater the measured pH and the prediction of pH values greater than 8.5 (the Oregon State maximum pH standard) was unreliable. These efforts to model pH, therefore, were classified as a failure. Part of the problem is that the model has no algorithms to estimate the pH buffering effects of dissolved organic matter. To accurately simulate pH, however, the model must first do a better job of simulating the size of the algal population.

The version of W2 used in the Tualatin River study can simulate only one type of phytoplankton. In rivers like the Tualatin where the water quality is so significantly influenced by algal activity, a more predictive set of algorithms for phytoplankton is needed. A good first step is to expand the number of simulated phytoplankton species, providing each with their own growth, respiration, and mortality rates as well as their own preferences for optimal light, nutrient, and temperature levels; version 3.0 of W2 implements this step. Going further, in rivers like the Tualatin where no clear species succession is evident, the algal community still responds to seasonal changes in streamflow, temperature, and length of day. More research is needed to add these subtleties to the next generation of water-quality models.

One of the more important oxygen consumption processes in the Tualatin River is sediment oxygen demand. The model represents this process as either a zero order or first order reaction—the choice is up to the model user. Although the model can keep track of bed-sediment organic matter, the model lacks detailed algorithms for short- and long-term chemical reactions in the sediments. Furthermore, the lack of a scour algorithm severely limits the model's ability to predict the fate of sediments. As a result, long-term (decadal) predictions of changes in sediment oxygen demand are not possible with this model.

The model results shown in figure 2F for orthophosphate are typical of model performance with this constituent. Although some of the general trends are well represented, and the levels of available orthophosphate during algal blooms are fairly accurate, the mean absolute error associated with this constituent are significant. Part of the problem is the lack of a good sorption algorithm in this version of W2; some of this has been addressed in version 3.0. In addition, some of the phosphorus in the Tualatin River exists as an iron-silicon-coprecipitate in colloidal-sized particles (Mayer, 1995). These complexities are not addressed by the model and in this case limit the model's ability to accurately predict the available concentration of orthophosphate.

Although periphyton (attached algae) are not prevalent in the Tualatin River, the water quality of many river systems is greatly influenced by the photosynthesis and respiration of these algae. Few models today have any ability to simulate the growth and effects of periphyton, even at the simplest level. The next generation of water-quality models should address this need.

SUMMARY

The field of water-quality modeling has advanced greatly in the past 10 years. Today's models are much more capable than their predecessors. Despite these advancements, however, many processes such as periphytic algal growth, algal succession, phytoplankton/zooplankton interactions, sediment scour and transport, sediment diagenesis, and sorption processes still need to be refined. The next generation of water-quality models must address some of these shortcomings.

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