USING CE-QUAL-W2 TO ASSESS THE EFFECT OF REDUCED PHOSPHORUS LOADS ON CHLOROPHYLL-a AND DISSOLVED OXYGEN IN THE TUALATIN RIVER, OREGON

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INTRODUCTION

The Tualatin River drains a 712 square-mile basin on the west side of the Portland metropolitan area in northwestern Oregon. The basin supports a growing population of more than 320,000 people and a wide range of urban, agricultural, and forest-derived activities. The people who live in the Tualatin River Basin depend heavily on the Tualatin River for drinking water, irrigation water, recreation, and assimilation and transport of wastes. The economic prosperity currently enjoyed within the basin depends on the proper management of this surface water resource and the maintenance of its quality.

The streamflow of the Tualatin River reflects the seasonal rainfall, and the contribution of snowmelt is minimal. Most of the annual precipitation falls between November and June; seasonal streamflow is typically highest from December through April and lowest from July through October. The low-flow summer period is defined as May 1st through October 31st. Since January of 1975, Tualatin River streamflow has been augmented during this low-flow period with water releases from a man-made reservoir.

The reach of the river that is of primary concern meanders for approximately 30 miles over the floor of the basin, from river mile (RM) 38.4 to RM 3.4. This reach is characterized by a low slope (approximately 0.08 ft/mi) and backwater created by a low-head dam at RM 3.4. The river widens to 150 ft or more, exposing much of its surface to direct sunlight. In the summer, large populations of phytoplankton thrive in the warm, slow-moving water in which nutrients are usually abundant. The algal blooms and subsequent population crashes have historically contributed to violations of the State of Oregon minimum dissolved-oxygen standard (6.0 mg/L, pre-1996) and the maximum pH standard of 8.5. Several sites on the main stem also exceeded the 15 μg/L chlorophyll-a action level for nuisance phytoplankton growth.

In response to the Federal Clean Water Act (CWA) of 1972, the Oregon Department of Environmental Quality (ODEQ) in 1984 and 1986 listed the Tualatin River as a "water-quality limited" stream because of low dissolved-oxygen concentrations and nuisance levels of algae. One of the designated beneficial uses of the river, aesthetics, was listed as impaired by algal blooms. As required by the CWA, total maximum daily loads (TMDLs) were established for phosphorus and ammonia in order to limit algal blooms.

The establishment of TMDLs in the Tualatin River Basin prompted local and State agencies to be proactive in meeting their wasteload and load allocations. The urban area is served by four wastewater treatment plants (WWTPs), all of which are operated by the Unified Sewerage Agency of Washington County (USA). In 1990, the U.S. Geological Survey entered into a cooperative agreement with the USA to assess the water-quality conditions of the Tualatin River. One objective of that project was to construct and use a mechanistically based, process-oriented model of nutrients and dissolved oxygen for the main stem during the low-flow, high-temperature, summer period. The model was to be used as both a diagnostic tool to better understand nutrient and dissolved-oxygen dynamics, fate, and transport, and to assess the relative importance of various processes, and as a prognostic tool to evaluate the relative water-quality benefits of various management alternatives for the Tualatin River.

RESULTS OF MODEL CALIBRATION

A modified version of the U.S. Army Corps of Engineers model CE-QUAL-W2 was calibrated using data obtained during the May 1 to October 31 period of 1991, 1992, and 1993. These 3 years exhibited a wide range of hydrologic conditions, from very dry in 1992 to fairly wet in 1993. Because the water quality of the Tualatin River is closely coupled to its streamflow, the summers of 1991-1993 also exhibited a wide range of water-quality conditions, which allowed a robust model of the Tualatin River to be created when all three of the datasets were used for calibration. The calibration parameters represent the best fit of the model to a wide range of observed conditions.

Chlorophyll-a

The factors that control algal growth in the Tualatin River are well understood. When several days of bright sunlight are coupled with warm water, sufficiently-long travel times, and ample nutrients, an algal bloom occurs. The first step in model calibration, therefore, was to make sure that the model simulated both the streamflow and the water temperature in the river well in all 3 years (S. A. Rounds, U.S. Geological Survey, unpub. data, 1997). Once that was accomplished, the calibration of the algal growth in the river was accomplished by adjusting four rates— algal growth, algal respiration, algal excretion, and zooplankton grazing.

Rapid algal growth is typically observed as far upstream as a sampling site at RM 16.2. Blooms usually continue to expand, or may be eroded by zooplankton grazing, downstream to the dam at RM 3.4, but the results at RM 16.2 are representative and only those are presented in this paper. Simulated and observed concentrations of chlorophyll-a at RM 16.2 are shown in figure 1. The basic cycle in algal growth is captured by the model in all 3 years, even in 1992, which is characterized not so much by a succession of blooms as by an initial bloom followed by sustained, high concentrations of chlorophyll-a through the rest of the season. Model performance is degraded during time periods when zooplankton grazing is important (for example, during early August in 1991 and mid to late August in 1993).

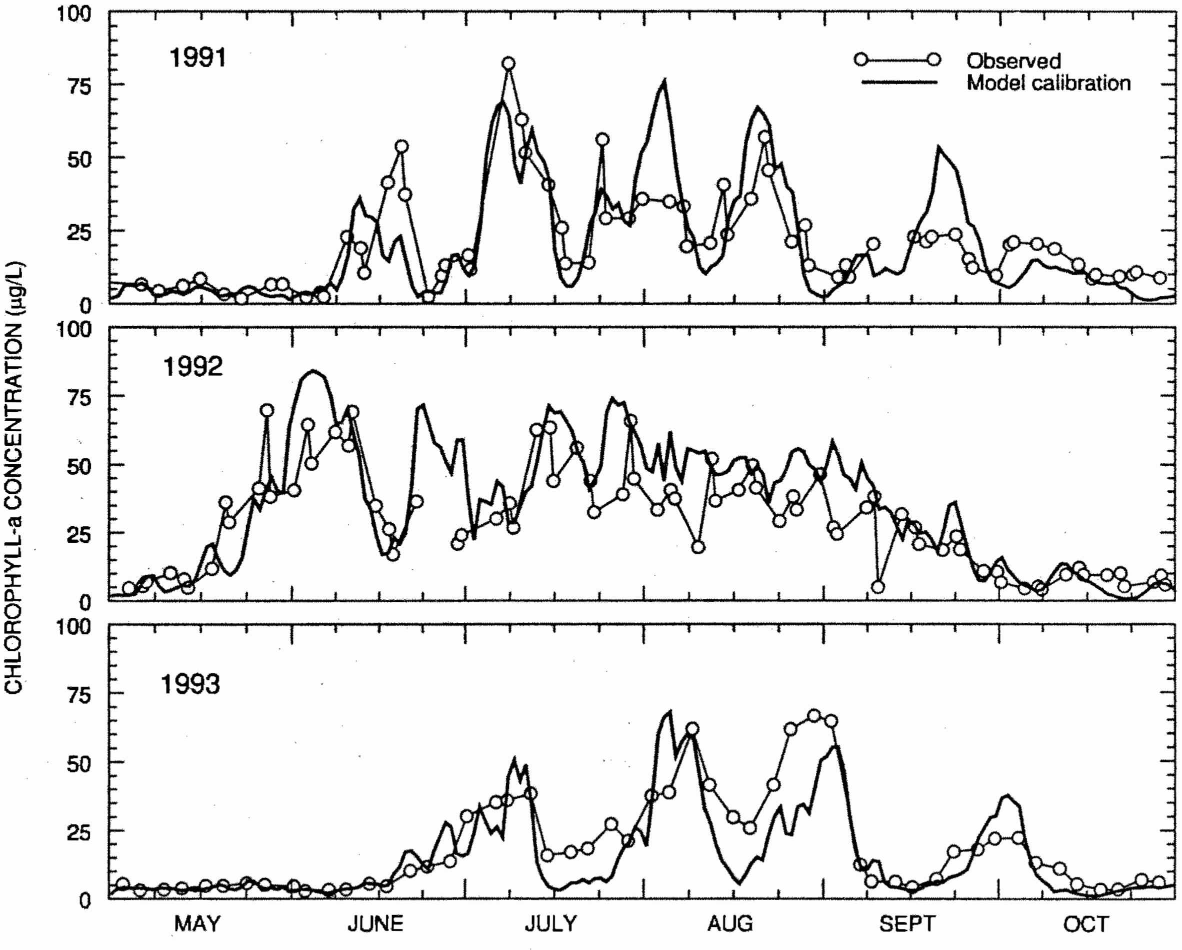

Figure 1. Measured and simulated chlorophyll-a concentration in the Tualatin River at RM 16.2.

Dissolved Oxygen

The largest oxygen demands in this system are: allochthonous carbonaceous biochemical oxygen demand (CBOD) entering at the upstream boundary and tributaries (including the WWTPs) in the form of detrital organic matter (OM); autochthonous CBOD produced within the model reach, primarily from the excretion of readily recycled organic material from viable cells; and sediment oxygen demand (SOD). Autochthonous

CBOD is significant only where algal growth occurs, but during algal blooms, this component of the CBOD dominates the other oxygen demands downstream of RM 16.2. Each type of demand dominates for short periods of time (days to weeks), but when demands are averaged from May to October, the largest oxygen demand comes from the SOD.

Sources of dissolved oxygen (DO) include reaeration, point and nonpoint sources of water containing DO, and photosynthesis. Reaeration is not a particularly important source (or sink) of DO in the Tualatin River, and is small compared to photosynthesis and inputs of oxygenated water. Inputs of oxygenated water can be important sources in some subreaches of the river, but only when those inputs are also important components of the water budget; for example, discharges from the WWTPs increase the DO concentration downstream of the plants at low-flow times of the year.

Downstream of RM 16.2, photosynthesis is by far the most important source of DO. Thriving algal cells under favorable light and nutrient conditions produce more DO through photosynthesis than they consume through the combined processes of respiration and the decay of excreted OM. Prolonged production of DO by photosynthesis has another consequence, however; when it abates, respiration and the bacterial decay of cells continue to consume oxygen. Thus, a period of overcast weather that precipitates a "crash" of a large algal population can also precipitate a drop in DO. Photosynthetic production and the consumption of oxygen by respiration and autochthonous CBOD make the algae of primary importance in determining the DO concentration, particularly on the daily and weekly time scales that are typical of the algal growth cycle. It is not surprising, therefore, that the bloom cycle seen in the observations of chlorophyll-a (figure 1) is also apparent in the observations of DO (figure 2). In general, where the model overestimates the chlorophyll-a at the peaks of blooms, it overestimates the DO as well. The converse is also true.

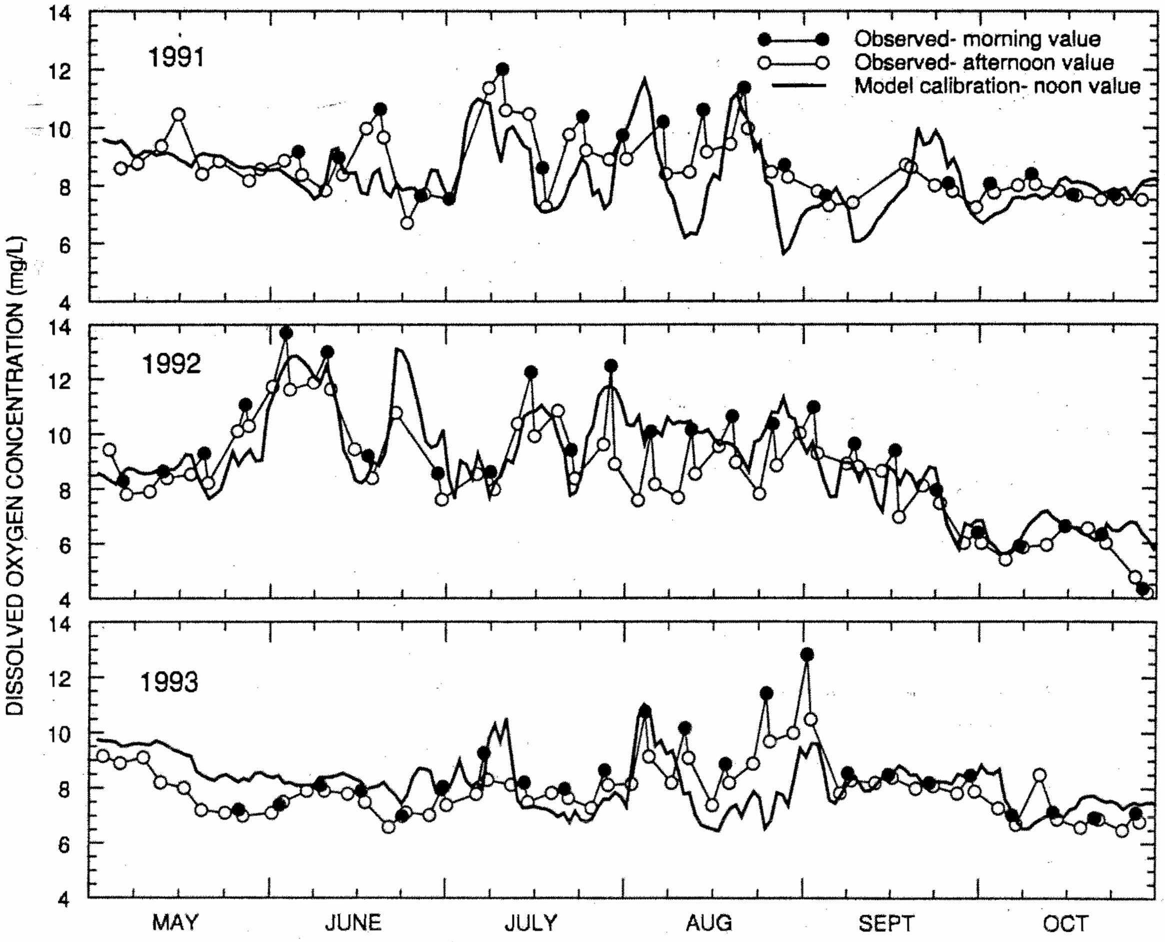

Figure 2. Measured and simulated DO concentration in the Tualatin River at RM 16.2.

It is important to distinguish between the daily to weekly effect of the algae on DO and their net *seasonal* effect. The algae clearly act to increase the DO concentration when they are growing and decrease it when they are in decline, but the magnitude of the increase or decrease is limited by residence time. The size of a bloom under continuously favorable light conditions is limited by the travel time through the reach between RM 16.2 and the low-head dam at RM 3.4, which usually does not exceed 9 days, even during low flows. Conversely, when light conditions become unfavorable for algal growth, the extent of oxygen depletion is also limited by travel time, because dead and respiring algal cells will eventually be advected out of the system. Dead algal cells that settle to the sediments continue to consume oxygen as they decay, but this does not significantly augment the high "background" SOD in the Tualatin River. The *duration* of a bloom, however, is not limited by travel time, but only by the duration of favorable light, temperature, and nutrient conditions. As a result, the effect of phytoplankton on the seasonal average of DO in the Tualatin River is largely a consequence of western Oregon's summer weather, which is characterized by favorable light conditions that often last for weeks at a time. The number of days that the algae are net producers of oxygen exceeds the number of days that they are net consumers; consequently the seasonally averaged concentration of DO downstream of RM 16.2 is increased over what it would be in the absence of primary production. A corollary is that if primary production were reduced, the SOD and allochthonous CBOD would remain largely unchanged over a single summer season, and the seasonally averaged concentration of DO downstream of RM 16.2 would likely decrease. It is important to remember this point when interpreting various management strategies for the river.

HYPOTHETICAL SCENARIOS

A primary goal of this application of CE-QUAL-W2 to the Tualatin River was to create a calibrated model that could be used to determine the probable efficacy of water-resources management decisions quickly and inexpensively by testing various hypothetical scenarios. The testing of hypothetical scenarios requires that the model be applied in a prognostic mode and, by definition, that it be applied under conditions to which it has not been explicitly calibrated. In order to ensure that the environmental conditions (including hydrology, meteorology, and water quality) of the hypothetical scenarios were small deviations from those under which the model was calibrated, and that the calibration parameters remain valid, the hypothetical scenarios were tested by using the same forcing functions and boundary data used in the calibration with the minor changes required for the scenario being tested. Each scenario was tested using all three (1991-1993) calibration seasons in order to simulate its effect for a wide range in hydrologic conditions. The strategy of testing the hypothetical scenarios by reusing the calibration datasets has the further advantage that the performance of the model has already been determined by a comparison with the observations. The accuracy of the hypothetical scenarios depends in large part on the accuracy of the calibration runs; for those time periods and river reaches that the calibration runs were more (or less) accurate, the hypothetical scenarios should also be more (or less) accurate.

Many of the hypothetical scenarios that have been tested with the model were designed to reduce the magnitude of algal blooms, either by reducing the length of time the algae are in the river (the travel time) or by making environmental conditions less favorable for growth. There are two reasons for the focus on reducing algal growth. The first is that the algae are a "nuisance" factor, and the second is the presumption that a reduction in algal growth will result in improved water quality, primarily as measured by DO and pH.

Four hypothetical scenarios that involve bringing the main stem and tributaries into compliance with the phosphorus TMDLs at the boundaries will be discussed, along with the changes in chlorophyll-a and DO concentration produced by each scenario. In order to quantitatively summarize each of the hypothetical simulations concisely, a table of the bimonthly means of four relevent concentrations resulting from each scenario was constructed (table 1). The 2-month periods are intended to roughly capture a seasonal pattern in the summer cycle. The first 2 months, May and June, are generally characterized by higher streamflow and smaller algal blooms than the July-August period, when low summer flows have been established, the weather is generally favorable for algal growth, and the size of algal blooms is the largest of the year. The September-October period is often an important period in terms of water quality because streamflow remains low through this period, but light conditions become less favorable for the algae. Very low oxygen concentrations (figure 2) are often observed during this period because low flows and high temperatures result in continued strong oxygen demand from CBOD and SOD, but photosynthetic production of oxygen slows considerably. A very dry year presents an exception to this rough characterization of the bimonthly periods; in 1992, the May-June period behaves much like the July-August period because summer low flows were established earlier than normal. Bimonthly means for the model calibration run are also included in the table, and provide the base case against which the changes induced by the hypothetical scenarios are compared.

Tributary Phosphorus Reduction

In these scenarios, the total phosphorus entering the river at the upstream boundary and each tributary was reduced to the level of the regulated TMDL. The TMDL criteria are 0.07 mg/L total phosphorus for the three largest tributaries and 0.05 mg/L total phosphorus at the upstream boundary; the smaller tributaries do not have TMDLs, but were assigned concentrations of 0.07 mg/L for these scenarios. The reduction in total phosphorus was achieved in two ways. In the first case (scenario 1a), the phosphorus exceeding the TMDL was first removed from the detrital phosphorus compartment. If that compartment was depleted entirely, then the orthophosphate compartment was tapped for the remaining amount. This scenario amounts to a reduction primarily in allochthonous CBOD in order to achieve the phosphorus TMDL levels; a secondary decrease in orthophosphate occurs because less orthophosphate is released through CBOD decay. In the second case (scenario 1b), the process is reversed— the phosphorus is removed first from the orthophosphate compartment and then, if necessary, from the detrital phosphorus compartment. This scenario relies primarily on a reduction in orthophosphate and generally requires very little reduction in allochthonous CBOD to achieve TMDL levels at the boundaries. Both scenarios result in less orthophosphate in the water column, although scenario 1b reduces orthophosphate much more than does scenario 1a (rows 2 and 3 in table 1).

Although both scenarios reduce algal growth, preferentially removing orthophosphate (1b) to achieve TMDL levels reduces growth more than preferentially removing detrital phosphorus (1a) (compare row 12 with row 13 in table 1). Scenario 1a, however, results in a consistently higher bimonthly averaged DO concentration than scenario 1b, and for most of the 2-month time periods scenario 1a results in a higher bimonthly averaged DO concentration than the calibration run. In contrast, the bimonthly averaged DO concentrations from scenario 1b are almost always lower than in the calibration run because of reduced photosynthetic production (compare rows 16, 17, and 18 in table 1).

Tributary Phosphorus Reduction with Flow Augmentation

These scenarios combine scenarios 1a and 1b, in which phosphorus concentrations at the upstream boundary and in all tributaries were reduced to the TMDL criteria, with maintenance of a minimum streamflow of 150 ft^3/s at the upstream boundary of the model grid (RM 38.4). In scenario 2a, phosphorus was preferentially removed from the detrital phosphorus compartment, as in 1a; in scenario 2b, phosphorus was preferentially removed from the orthophosphate compartment, as in 1b. The combination of phosphorus reduction at the boundaries and flow augmentation results in a greater reduction in algal growth than phosphorus reduction produces alone (compare rows 14 and 15 to rows 12 and 13 in table 1). Scenario 2a results in consistently higher chlorophyll-a (by 0.9 to 8.5 μg/L) *and* consistently higher DO (by 0.31 to 1.22 mg/L) than 2b.

Chlorophyll-a Reduction and Improvements in DO Concentration

Some important conclusions are illustrated by the comparison of two particular scenarios (1a and 2b) with the base case. Scenario 1a achieves the maximum *overall* increase in DO concentration, and 2b achieves the maximum *overall* decrease in chlorophyll-a. (These assessments were made by taking average values over the entire 6-month season and comparing with the average value for the calibration.) A plot of chlorophyll-a at RM 16.2 (figure 3) shows that the combination of flow augmentation with a significant reduction in orthophosphate (scenario 2b) can very effectively limit the size of algal blooms, often by as much as 50%. A comparison of figure 3 with figure 4 shows that the reduction in algal growth in scenario 2b manifests itself primarily as a much lower oxygen concentration during algal blooms. There is little evidence that this scenario results in increased DO concentration during algal crashes, probably because of their short duration

Table 1. Summary statistics for the phosphorus reduction scenarios.

[Bi-monthly mean concentrations for each constituent were derived from simulated, daily, 10-foot-average noon concentrations at RM 16.2. Concentrations given for the calibration simulation (c) are the model's best representation of observed conditions. The other runs superimpose combinations of phosphorus removal and flow augmentation on the calibrated conditions. In scenario 1a, total phosphorus concentrations were reduced to their target TMDL concentrations by removing detrital phosphorus first. In scenario 1b, the TMDL levels were achieved by removing orthophosphate first. The other two scenarios, 2a and 2b, removed phosphorus as in 1a and 1b while maintaining a minimum flow of 150 ft^3/s at RM 38.4. Shaded cells highlight concentrations that would be in violation of a TMDL criteria, the DO standard, or the chlorophyll-a action level. M/J=May/June; J/A=July/August; S/O=September/October.]

Parameter	Scenario	1991			1992			1993			row
		M/J	J/A	S/O	M/J	J/A	S/O	M/J	J/A	S/O	
Ortho-phosphate (mg/L as P)	c	0.051	0.048	0.056	0.042	0.018	0.055	0.055	0.048	0.053	1
	1a	0.042	0.035	0.046	0.031	0.013	0.042	0.047	0.039	0.044	2
	1b	0.015	0.022	0.030	0.014	0.010	0.025	0.017	0.022	0.027	3
	2a	0.042	0.038	0.045	0.033	0.015	0.038	0.047	0.040	0.044	4
	2b	0.015	0.023	0.031	0.016	0.011	0.024	0.017	0.022	0.027	5
Total Phosphorus (mg/L as P)	c	0.115	0.110	0.098	0.100	0.076	0.104	0.113	0.102	0.100	6
	1a	0.055	0.063	0.063	0.057	0.051	0.061	0.060	0.066	0.064	7
	1b	0.056	0.065	0.064	0.059	0.055	0.063	0.060	0.067	0.065	8
	2a	0.055	0.063	0.063	0.058	0.053	0.060	0.060	0.065	0.063	9
	2b	0.056	0.065	0.063	0.059	0.056	0.061	0.060	0.067	0.064	10
Chlorophyll-a (µg/L)	c	8.4	36.7	13.9	35.5	50.4	18.3	6.7	25.9	12.9	11
	1a	8.1	33.4	13.6	31.2	43.6	16.4	6.6	24.5	12.5	12
	1b	5.3	22.7	10.1	24.6	33.4	12.1	5.7	17.0	9.2	13
	2a	8.2	28.4	10.2	27.5	40.0	11.5	6.6	21.4	8.2	14
	2b	5.3	20.1	8.4	23.2	31.5	9.1	5.7	15.0	6.9	15
Dissolved Oxygen (mg/L)	c	8.56	8.62	7.74	9.79	9.85	7.21	8.61	7.99	7.92	16
	1a	9.03	9.14	8.22	9.88	9.69	7.81	8.95	8.46	8.41	17
	1b	8.50	7.63	7.51	8.84	8.07	6.74	8.64	7.22	7.70	18
	2a	9.03	8.84	8.14	9.54	9.63	7.82	8.95	8.33	8.22	19
	2b	8.50	7.62	7.68	8.86	8.41	7.27	8.64	7.27	7.79	20

and because the background oxygen demands are so high that they dominate oxygen consumption even during algal crashes. The only time period when scenario 2b significantly increases DO concentration is October of 1992, when the flow augmentation decreases the time-of-travel enough that oxygen consumption by CBOD and SOD is reduced substantially. Therefore, the management strategy that most effectively reduces algal growth is not the same strategy that generates the greatest overall increase in DO concentration.

The phosphorus reduction scenario in which detrital phosphorus is removed preferentially (scenario 1a) is most effective at increasing DO because of the reduced concentration of allochthonous CBOD. This scenario also reduces orthophosphate somewhat because phosphorus release from the decomposition of detrital OM is reduced, but the ability of this scenario to limit algal growth is minimal, except at the peak of very large blooms. Algal growth is affected by this scenario somewhat more in 1992 because simulated phosphorus concentrations during the mid-summer months were already growth-limiting, so the effect of the small additional reduction in orthophosphate is enhanced. The effect of scenario 1a on DO is primarily a relatively constant positive offset (figure 4), especially during non-bloom periods, because of the reduction in the background oxygen demand from the decay of allochthonous CBOD.

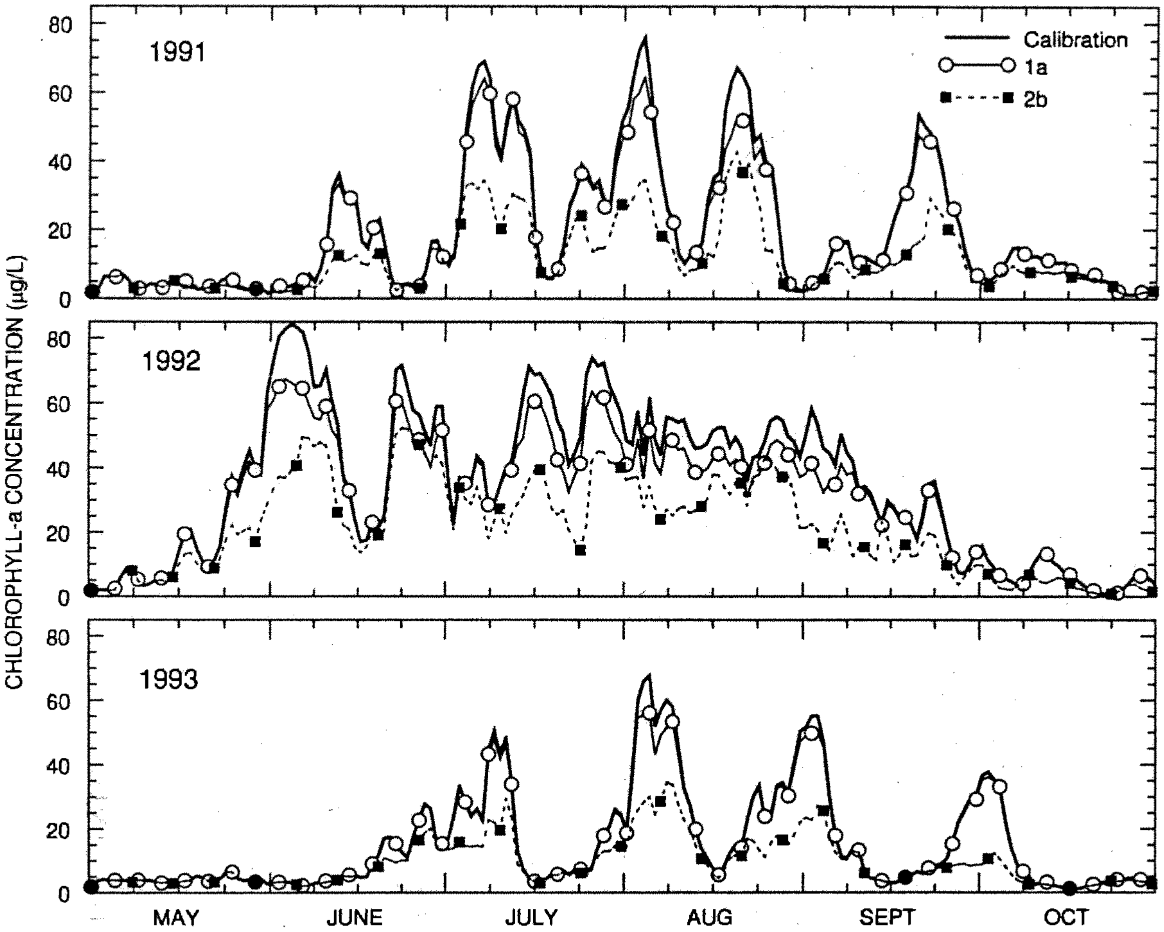

Figure 3. Calibrated chlorophyll-a at RM 16.2 compared with scenarios 1a and 2b.

The comparison of scenarios 1a and 2b demonstrates that the role of algae in determining the DO concentration is more often one of production than consumption; therefore, a reduction in algal growth more often reduces than increases DO concentrations. A reduction in the size of an algal bloom also will decrease the diel variations in DO and pH associated with that bloom that can cause stress to aquatic organisms. A reduced, but more stable, DO concentration during blooms may, therefore, be beneficial. The most effective way to increase DO concentrations during non-bloom periods, however, is to reduce the high background demand for oxygen.

SUMMARY

A modified version of the U.S. Army Corps of Engineers model CE-QUAL-W2 was used to simulate flow, temperature, and water quality in the Tualatin River, a low-gradient stream that meanders through a mixture of urban and rural landscapes on the west side of the Portland, Oregon, metropolitan area. Combined with warm temperatures and an ample nutrient supply, the travel time during the summer low-flow period is of sufficient duration to produce a thriving phytoplankton population that can cause large changes in the dissolved-oxygen (DO) concentration and the pH — large enough to violate Oregon State water-quality standards and degrade the designated beneficial uses. In 1988, the Oregon Department of Environmental Quality (ODEQ) established total maximum daily loads (TMDLs) for total phosphorus for the Tualatin River and its largest tributaries.

CE-QUAL-W2 was calibrated to the summer low-flow conditions observed from May through October of 1991, 1992, and 1993, and then used to evaluate the effects of various phosphorus loads and levels of flow augmentation on DO concentrations in the Tualatin River. These model simulations were run using the

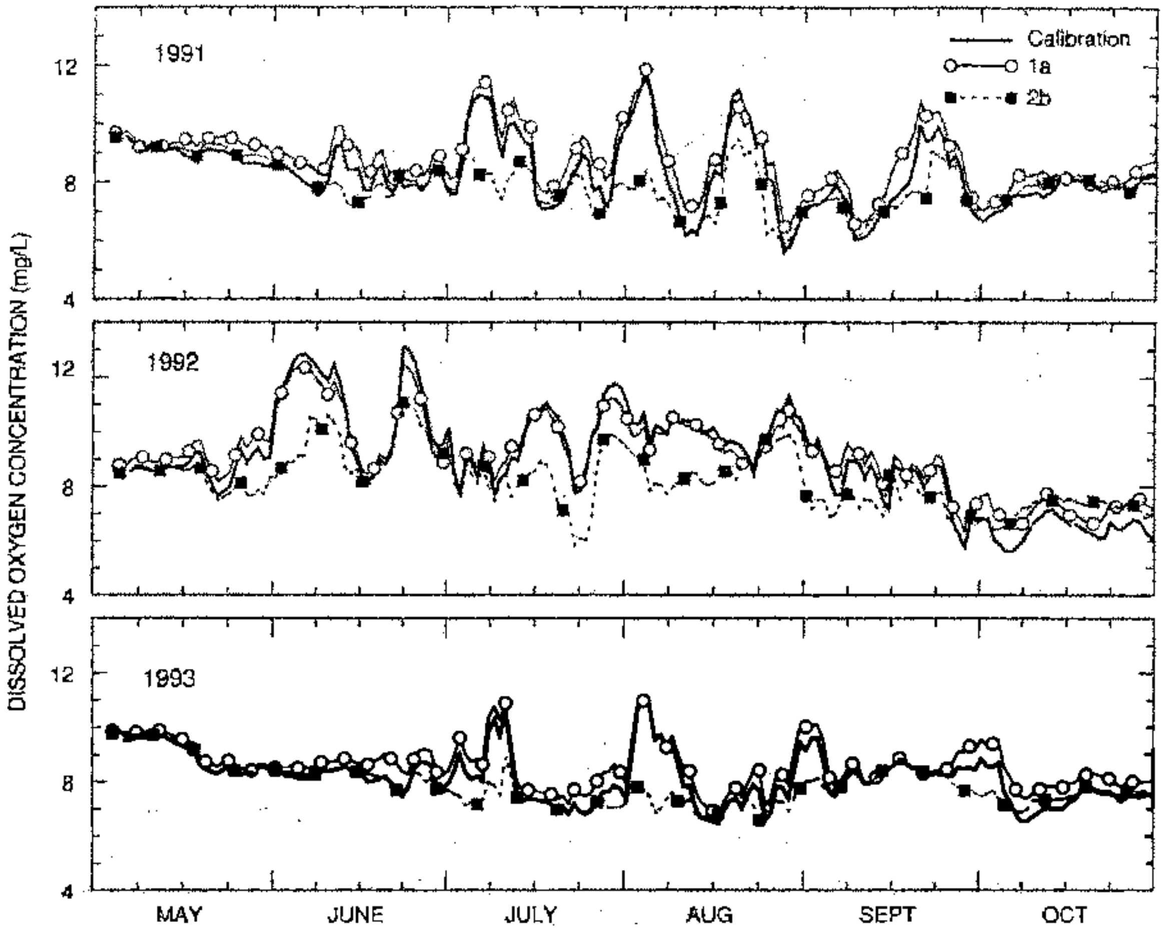

Figure 4. Calibrated DO at RM 16.2 compared with scenarios 1a and 2b.

same hydrologic and meteorological conditions under which the model was calibrated, thus providing a wide range of imposed conditions, from the very low-flow "drought" conditions of 1992 to the "wet" conditions of 1993. Several important results were obtained from these scenarios:

- For the period May through August, phosphorus-reduction scenarios showed some ability to limit algal growth during large blooms. When these scenarios failed to simultaneously reduce the background oxygen demands (carbonaceous biochemical oxygen demand [CBOD] and sediment oxygen demand), however, DO concentrations between algal blooms still decreased to near-problematic levels.
- Phosphorus reduction scenarios showed that if the total phosphorus TMDL was achieved in the tributaries and in the main stem at RM 38.4, the predicted effect on DO was unclear. If detrital phosphorus were removed preferentially, then DO conditions would improve, especially in October, because CBOD would be removed. If soluble orthophosphate were removed instead, then DO conditions actually would deteriorate due to reduced photosynthetic production of oxygen without a simultaneous loss of CBOD.
- During September and October, the most significant improvements in DO were obtained only through a large amount of flow augmentation, or through a lesser amount of flow augmentation combined with a reduction in the loads of CBOD from the boundaries.
- The model results indicate that the goals of limiting algal growth and reducing DO violations can be, at times, incompatible. (However, excursions to high pH values are also of concern, and reducing the number of pH violations *is* dependent on limiting algal growth.)

These results are being used by ODEQ to revise the total phosphorus TMDL for the Tualatin River.

Proceedings of the First Federal Interagency Hydrologic Modeling Conference

Theme: Bridging the Gap Between Technology and Implementation of Surface Water Quantity and Quality Models in the Next Century

Tropicana Hotel
April 19-23, 1998
Las Vegas, Nevada

Prepared by the Subcommittee on Hydrology of the
Interagency Advisory Committee on Water Data

Volume 1 of 2

FOREWORD

The Federal Subcommittee on Hydrology published these proceedings and sponsored the associated First Federal Interagency Hydrologic Modeling Conference. The general purpose of the Subcommittee is to foster effective communication and collaboration for technical surface-water quantity activities. Representatives of more than a dozen Federal agencies participate on the Subcommittee. The Subcommittee currently sponsors or co-sponsors four subordinate groups: (1) the Flood Flow Frequency Analysis Work Group, (2) the Satellite Telemetry Interagency Work Group (STWIG) that is co-sponsored by the Interagency Coordination Committee on Meteorology and Supporting Research, (3) the Federal Hydrologic Radio Frequency Coordination Work Group, and (4) the Modeling Conference Work Group that planned this conference.

The Subcommittee is an interagency group that has operated within the Federal Government under a variety of authorities for about 50 years. In the early 1980's when the Reagan Administration disbanded the Water Resources Council, the Water Information Coordination Program (WICP) became the sponsor of the Subcommittee. Office of Management and Budget Memorandum No. 92-01 requires all Federal agencies to coordinate their water-information activities through the WICP and designates the U.S. Geological Survey to be the lead agency. The general purposes of the WICP are to ensure effective decision making for natural-resources management and environmental protection at all levels of government and in the private sector. Federal and non-Federal organizations that fund, collect, or use water-resources information work together to carry out the objectives of the WICP.

For additional information about the WICP and its committees and products, please write or telephone the Water Information Coordination Program, U. S. Geological Survey, 417 National Center, Reston, VA 20192. Telephone:(703)648-6832. Fax: (703) 648-5644. Information on the WICP is available on the World Wide Web at <http://water.usgs.gov/public/wicp>.