USING CE-QUAL-W2 TO ASSESS THE AMMONIA ASSIMILATIVE CAPACITY OF THE TUALATIN RIVER, OREGON

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Abstract

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 lower reaches of the Tualatin River, a low-gradient stream that meanders through a mixture of urban and rural landscapes on the western side of the Portland, Oregon metropolitan area. Simulated water-quality constituents included nutrients (nitrogen and phosphorus), phytoplankton, and dissolved oxygen. Once calibrated, the model was used to quantify the river's ability to assimilate ammonia wasteloads from the basin's two largest wastewater treatment plants without causing violations of the State of Oregon minimum dissolved oxygen standard. This assimilative capacity increases with increasing river discharge and solar insolation, and decreases with increasing water temperature. Model simulations were used to determine that the 30-day mean dissolved oxygen concentration would decrease by only about 0.2 milligrams per liter under the most sensitive observed conditions when each of the wastewater treatment plants releases a constant load of 100 pounds per day of ammonia nitrogen. This determination of the ammonia assimilative capacity will aid in the ongoing reassessment of a Total Maximum Daily Load for ammonia in the Tualatin River.

INTRODUCTION

During the warm, sunny, and dry conditions characteristic of summer in northwestern Oregon, discharge in the reservoir reach of the Tualatin River (fig. 1, river miles [RM] 30 to 3.4) typically decreases to less than 150 ft^3/s (cubic feet per second), and concentrations of dissolved oxygen (DO) sometimes decrease to levels that violate the State of Oregon minimum DO standard (6.5 mg/L [milligrams per liter] as a 30-day mean). Oxygen demands that combine to cause these problems include sediment oxygen demand, carbonaceous biochemical oxygen demand, phytoplankton and zooplankton respiration, and instream nitrification of ammonia. The most significant point sources of ammonia to the river are the two large wastewater treatment plants (WWTPs) operated by the Unified Sewerage Agency (USA). Prior to upgrades at the WWTPs in the late 1980s and early 1990s, ammonia loads from these plants caused a very large instream oxygen demand when nitrifying bacteria converted the ammonia to nitrate; this demand was typically large enough to produce violations of the minimum DO standard. To prevent these violations and to protect the river's designated beneficial uses, the Oregon Department of Environmental Quality (ODEQ) in 1988 established a Total Maximum Daily Load (TMDL) for ammonia nitrogen in the Tualatin River, including ammonia wasteload allocations for the WWTPs. Since that time, ODEQ personnel have determined that the ammonia TMDL does not adequately protect the river against ammonia-related DO violations; the ammonia TMDL is currently being revised. This modeling work, performed in collaboration with both USA and ODEQ, was designed to aid in the revision of this TMDL.

MODEL CALIBRATION AND LOADING SCENARIOS

CE-QUAL-W2, a two-dimensional, laterally-averaged reservoir model (Cole and Buchak, 1995) was used to simulate flow, water temperature, and water quality in the lower Tualatin River from RM 38.4, a point just upstream of one of the WWTPs, to a low-head dam at RM 3.4, downstream of the second WWTP (fig. 1). Some modifications of the model code were required to simulate flow past the dam and to allow one-dimensional transport in several shallow reaches of the river (S.A. Rounds, U.S. Geological Survey, unpub. data). The model was calibrated to the summer low-flow conditions observed from May 1 through October 31 of 1991, 1992, and 1993, and then used to evaluate the effects of hypothetical WWTP ammonia loads on DO concentrations in the Tualatin River. These model simulations were run using the same hydrologic and meteorological conditions under which the model was calibrated, thus providing a wide range of imposed conditions, from the low-flow drought conditions of 1992 to the wet conditions of 1993. Ammonia loads from the two WWTPs were held constant in each simulation. Loads of 0, 50, 100, 250, 500, 750, 1000, 1250, and 1500 lb/d (pounds per day) of ammonia nitrogen from each plant were evaluated. (Typical WWTP ammonia loads are in this range, depending on the nitrification efficiency of the plant.) These simulations were designed to keep all other factors as constant as possible from simulation to simulation to minimize changes in other components of the oxygen budget. Therefore, to keep the availability of nutrient nitrogen identical to that of the calibration, the total inorganic nitrogen load (ammonia plus nitrate) from each plant was not changed. When the

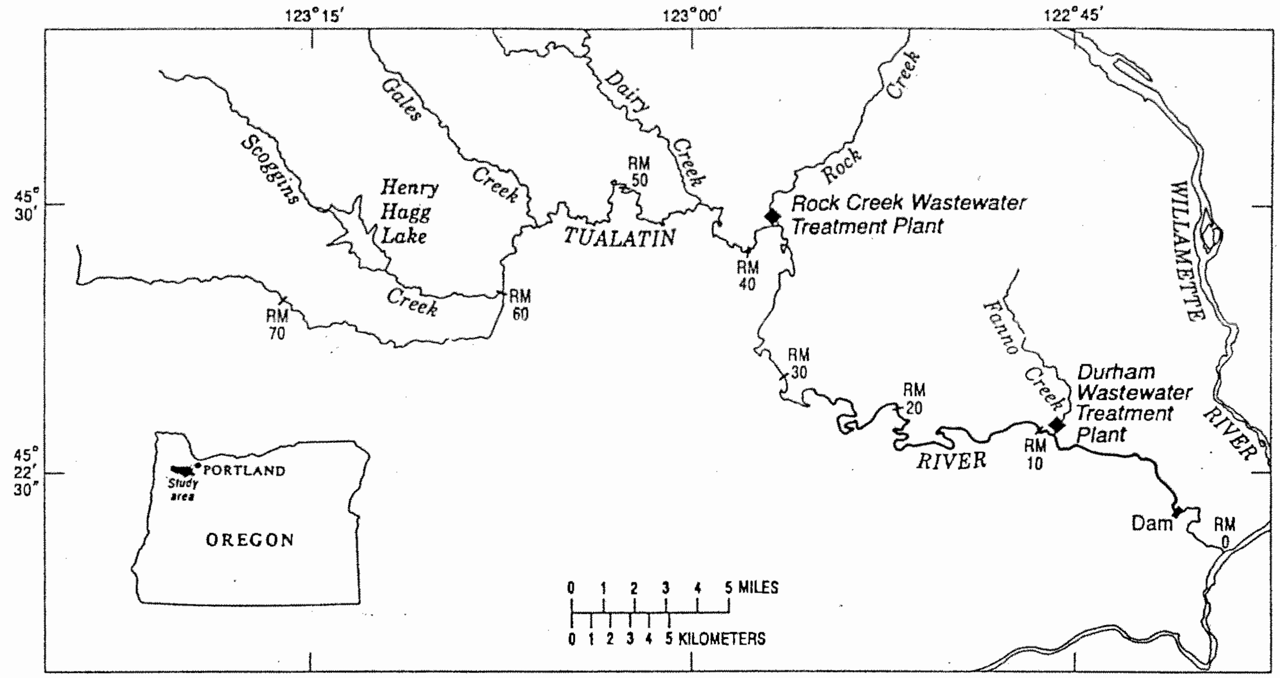

Figure 1. Map of the Tualatin River, Oregon, showing the location of the two largest wastewater treatment plants. The model extends from RM (river mile) 38.4 to the low-head dam at RM 3.4.

imposed ammonia load exceeded the observed load, the load of nitrate nitrogen was decreased to compensate; when the imposed ammonia load was less than the observed load, the nitrate load was increased accordingly. An instream nitrification rate of 0.11 day^{-1} was used for each simulation, based on instream ammonia data collected during a period of high ammonia concentrations in the summer of 1995.

FACTORS AFFECTING DISSOLVED OXYGEN

Several important factors control the effect of the imposed WWTP ammonia loads on the simulated DO concentrations, including the magnitude of the loads, river discharge, water temperature, and solar insolation. The effects of several of these factors are apparent when the simulated DO concentrations are analyzed for violations of the minimum DO standard. The DO standard for the Tualatin River has several parts, but the most frequently violated clause states that the 30-day mean DO concentration, with no credit for supersaturation, shall not be less than 6.5 mg/L (Oregon Department of Environmental Quality, 1997a). Violations of the DO standard usually occur within the reservoir reach of the river (RMs 30–3.4, fig. 1); representative monitoring sites within that reach are located at RMs 16.2 and 5.5. Table 1 shows the percentage of time that the simulated 30-day mean DO concentrations at RMs 16.2 and 5.5 violated the standard as a function of WWTP ammonia load and month during the low-flow summer period.

Ammonia Load

Increases in the simulated ammonia load from each of the WWTPs give rise to an increasing frequency of simulated DO violations (table 1). For example, the simulated frequency of violation at RM 5.5 in the months of September for 1991–1993 increases from 0 to 67 percent as the ammonia load from each WWTP increases from 0 to 1500 lb/d. As the imposed ammonia load is increased, the amount of DO consumed through instream ammonia nitrification increases, and the magnitude of the DO loss can be large. Even averaged over the entire May–October period, nitrification-caused decreases in the simulated DO concentration downstream of the WWTPs can be more than 1 mg/L for ammonia loads greater than 1000 lb/d (fig. 2). The slight increase in the mean DO concentration in figure 2 at RM 9 is due to the effect of dilution; both Fanno Creek and the Durham WWTP discharge into the Tualatin River at that point (fig. 1). Note that the incremental change in DO concentration for each additional 250 lb/d of ammonia load is similar, indicating that the relation between ammonia load and DO loss is approximately linear in this range of WWTP ammonia load. Although the reaeration rate must increase as the DO deficit increases, reaeration is slow enough in this reach that it does not offer much protection from DO violations under these ammonia loads.

Table 1. Percentage of time that the running 30-day mean of the simulated dissolved oxygen concentration was in violation of the State of Oregon standard, based on simulated hourly concentrations averaged vertically over the top 10 feet of the water column. (lb/d, pounds per day; WWTP, wastewater treatment plant)

WWTP Ammonia Load (lb/d)	Percentage of time in violation of the 30-day mean dissolved oxygen standard											
	River Mile 16.2						River Mile 5.5					
	May	Jun	Jul	Aug	Sep	Oct	May	Jun	Jul	Aug	Sep	Oct
0	0	0	0	0	0	18	0	0	0	0	0	21
50	0	0	0	0	0	20	0	0	0	0	0	22
100	0	0	0	0	0	22	0	0	0	0	0	24
250	0	0	0	0	0	30	0	0	0	0	0	34
500	0	0	0	0	7	33	0	0	0	1	7	44
750	0	0	0	0	14	33	0	0	0	22	32	63
1000	0	0	0	9	47	76	0	0	3	42	45	77
1250	0	0	0	36	59	100	0	0	17	53	57	89
1500	0	0	1	53	78	100	0	0	32	60	67	100

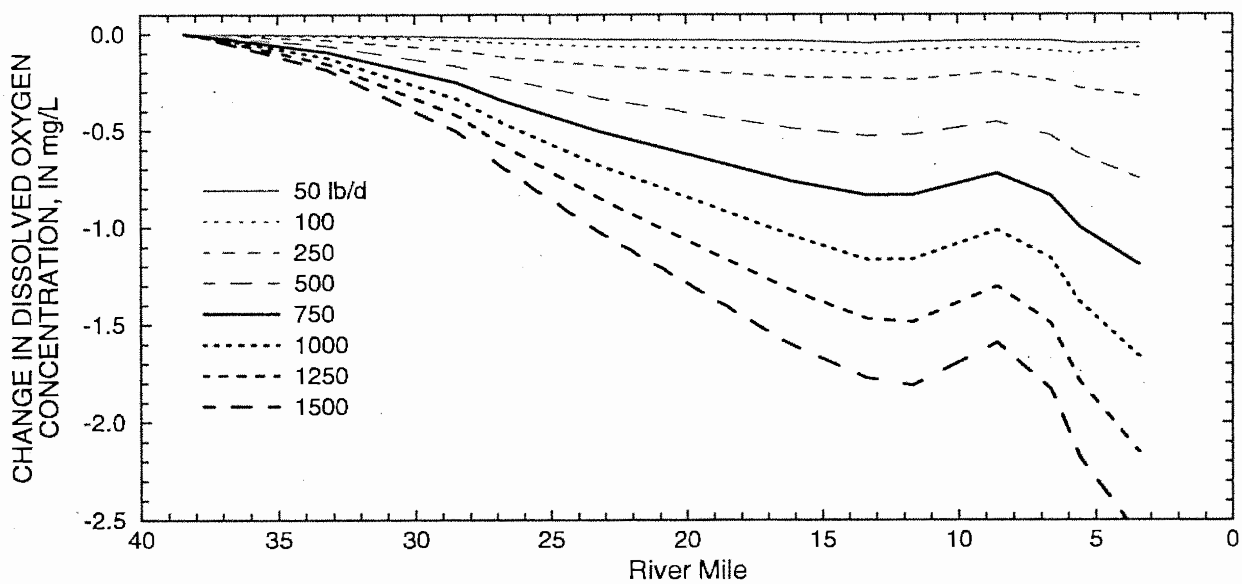

Figure 2. Simulated change in the mean dissolved oxygen concentration (May–October, 1991–1993) as a function of river mile for WWTP ammonia loads between 50 and 1500 pounds per day, relative to zero WWTP ammonia loads. (mg/L, milligrams per liter; lb/d, pounds per day; WWTP, wastewater treatment plant)

River Discharge and Water Temperature

River discharge and water temperature are important factors in determining the effect of WWTP ammonia loads on Tualatin River DO concentrations. Lower river flows result in longer travel times through the reservoir reach of the river, where slow moving water reduces the effectiveness of reaeration. As the travel time lengthens, more of the nitrogenous oxygen demand will be exerted in the reservoir reach, where most of the DO violations typically occur. Travel times through the reservoir reach can be as long as 14 days when river discharge decreases to 150 ft^3/s. Under those conditions, about 80 percent of the nitrogenous oxygen demand from the Rock Creek WWTP will be realized within the reservoir reach. In contrast, when river discharge is high, the travel time is short and the amount of oxygen demand exerted by instream ammonia nitrification within the reservoir reach will be a small fraction of the possible nitrogenous oxygen demand. Higher flows also carry larger loads of oxygen, resulting in smaller DO concentration decreases for the same mass of DO consumed. The effect of water temperature is important mainly because it influences the rate of ammonia nitrification; the reaction proceeds faster in warmer water.

Both river discharge and water temperature have predictable seasonal trends. Flow in the Tualatin River reflects the regional precipitation pattern; most of the rain falls between November and April, and the lowest flows are observed in July and August — the months that typically receive the least precipitation. Water temperature is normally greatest during midsummer as a result of long sunny days and low flow conditions. The effects of river discharge and water temperature are illustrated in figure 3 for a WWTP ammonia load of 1500 lb/d from each plant. The effect of this ammonia load is smallest during May because river discharge typically is highest in May. As the flow decreases from May through August, the amount of DO consumed in the reservoir reach through nitrification increases due to lengthening travel times and faster nitrification rates in the warmer water. During September and October, the flow typically remains low, but the water becomes slightly cooler, resulting in slightly less DO consumption in parts of the reservoir reach. The month of September and October are critical periods for DO due to typically low river flow.

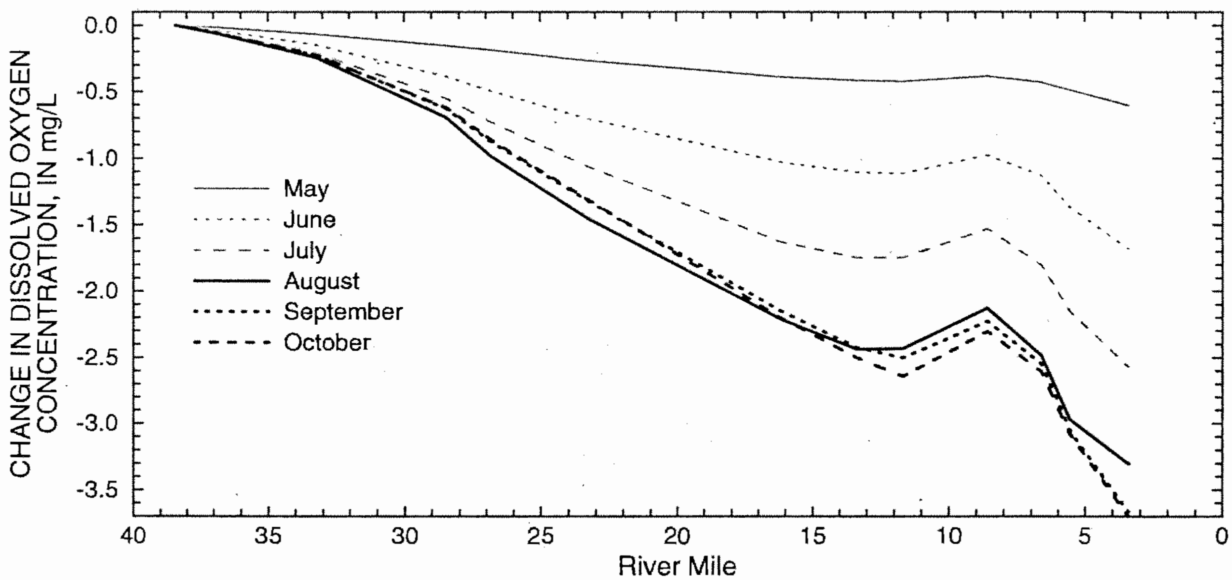

Figure 3. Simulated change in the monthly mean dissolved oxygen concentration (1991–1993) as a function of river mile using WWTP ammonia loads of 1500 pounds per day, relative to zero WWTP ammonia loads. (mg/L, milligrams per liter; WWTP, wastewater treatment plant)

Although more than 2.5 mg/L of DO can be consumed through the nitrification of a 1500 lb/d ammonia load during August, that consumption may or may not result in a DO violation. The results in table 1, for example, indicate that a 1500 lb/d ammonia load from both WWTPs produced August DO violations at RM 5.5 60 percent of the time, for the conditions observed in 1991–1993. Violations were not produced more frequently because the low flows of August also encourage the growth of large blooms of phytoplankton. The amount of DO produced through the photosynthetic activity of these algae often is large enough to offset a large nitrogenous oxygen demand and keep the DO concentration above the standard.

In an attempt to quantify how compliance with or violation of the 30-day mean DO standard varies with river discharge, the distribution of 30-day mean discharge was plotted against the imposed WWTP ammonia load for periods of both compliance and violation in the entire 18 month simulation period (fig. 4). Although river discharge and the ammonia load are not the only factors determining compliance or violation, figure 4 does suggest that violations are more likely to occur at the lowest flows and less likely to occur above certain levels of discharge for a given ammonia load. For example, most of the simulated violations for WWTP ammonia loads of 750 lb/d or less coincide with flows less than 150 ft^3/s, and no violations are simulated for flows above 220 ft^3/s.

Solar Insolation

The solar insolation rate, averaged over a time scale at least as long as that of a typical algal bloom (5–20 days), is an important predictor of the level of algal photosynthetic activity in the Tualatin River. Light conditions affect the level

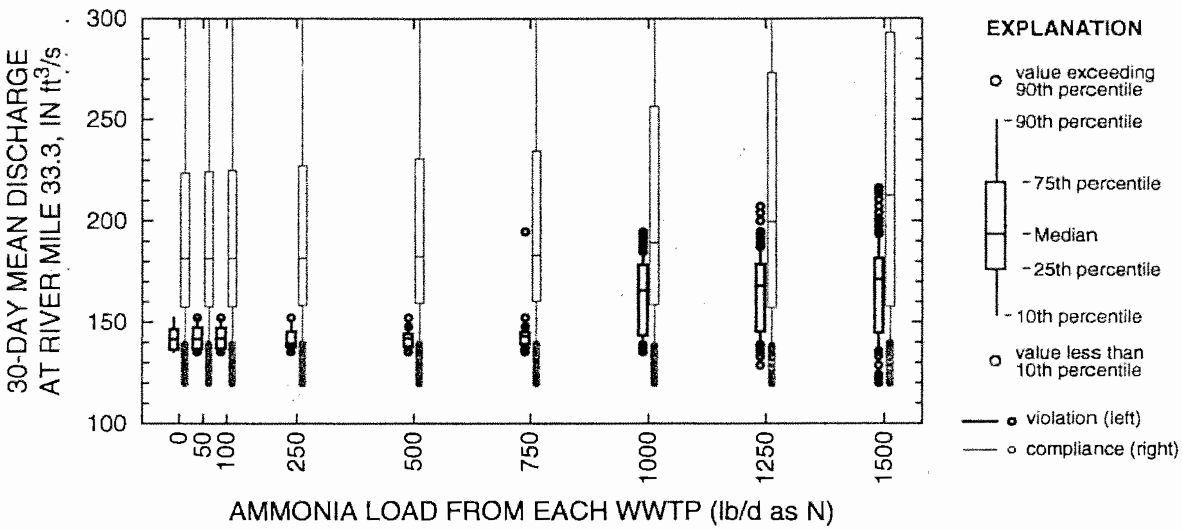

Figure 4. Box and whisker plot showing how compliance with or violation of the 30-day mean dissolved oxygen standard at river mile 16.2 varies as a function of both river discharge and the imposed WWTP ammonia load. (ft^3/s, cubic feet per second; lb/d, pounds per day; WWTP, wastewater treatment plant)

of photosynthetic activity, and photosynthetic DO production is important in determining whether a given WWTP ammonia load will produce a DO violation within the reservoir reach of the Tualatin River. This dependence is illustrated in figure 5, in which the distribution of the 30-day mean solar insolation rate, measured at the Durham WWTP, is plotted against the imposed WWTP ammonia load for subsets of the modeled period that produced either compliance with or violation of the 30-day mean DO standard. The dependence is strong. Under low light conditions and high WWTP ammonia loads, DO violations are more likely; when light conditions are more favorable for algal growth, DO violations are less likely. For example, all violations for WWTP ammonia loads of 750 lb/d or less coincide with solar insolation less than 150 W/m^2 (watts per square meter), and no violations are simulated for solar insolation above 220 W/m^2.

The dependence of compliance with or violation of the DO standard on the solar insolation rate is stronger than that produced by river discharge and illustrates the importance of photosynthetic production in the DO budget of the Tualatin River during the summer low-flow period. All of the simulated DO violations for WWTP ammonia loads less than 500 lb/d occurred in October (table 1), for a combination of reasons. First, the seasonal variation in solar insola-

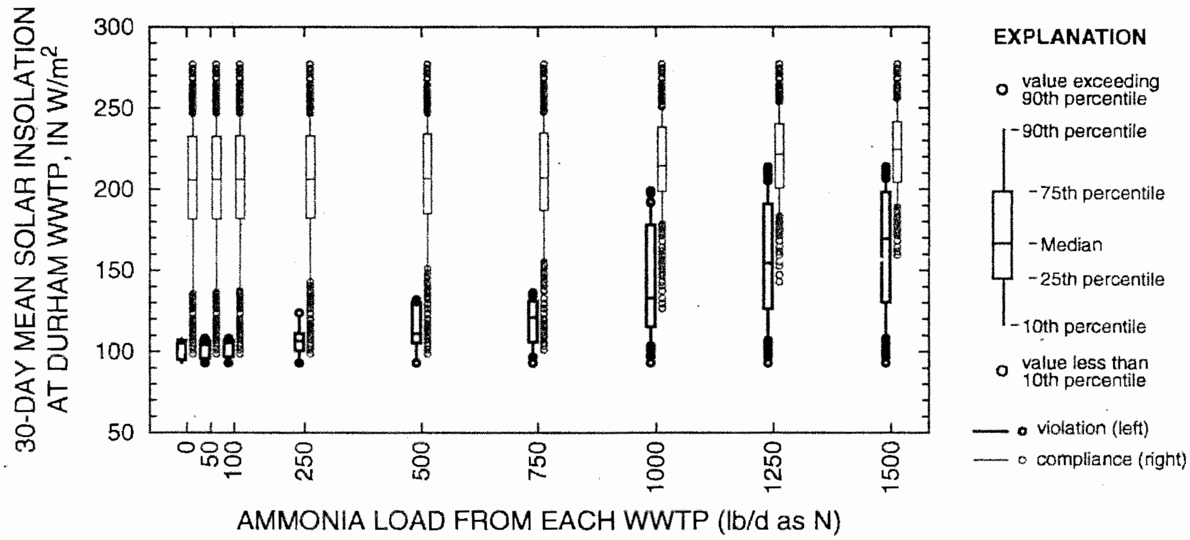

Figure 5. Box and whisker plot showing how compliance with or violation of the 30-day mean dissolved oxygen standard at river mile 16.2 varies as a function of both solar insolation and the imposed WWTP ammonia load. (W/m^2, watts per square meter; lb/d, pounds per day; WWTP, wastewater treatment plant)

tion, with shorter days and less intense light later in the summer, causes light conditions in October to be less favorable for algal growth and photosynthetic production. Second, the month of October is typically characterized by continuing low flow; sediment oxygen demand and carbonaceous biochemical oxygen demand continue to consume DO from the water traveling through the reservoir reach, depleting the DO to levels near the standard. The long travel time in the absence of significant photosynthetic production causes DO violations to be more likely in this period.

AMMONIA ASSIMILATIVE CAPACITY

Ammonia assimilative capacity is defined in this paper as the maximum load of ammonia that can be carried by a river without causing violations of a water-quality standard or criterion. For the Tualatin River, the relevant criterion is the State of Oregon minimum DO standard. Ammonia toxicity also may be a concern when large ammonia loads coincide with high pH and high water temperature. Under most conditions, however, prevention of DO violations also will prevent ammonia toxicity problems; therefore, the toxicity criterion is deemed secondary to the DO standard and is not addressed in this analysis.

The model results in table 1 and in figures 2–5 can be used to generate insight into the ammonia assimilative capacity of the Tualatin River. For example, table 1 shows, for the month of October in particular, that under certain conditions the Tualatin River has an ammonia assimilative capacity of zero; that is, it can carry no ammonia load from the WWTPs without decreasing a DO concentration that is already at or below the standard. Similarly, the model shows that under high-flow conditions (May and June, for example), the river can assimilate more than 1500 lb/d of ammonia from each WWTP without producing a DO violation. Indeed, the ammonia assimilative capacity may be as high as several thousand pounds per day under typical high-flow conditions. Furthermore, under low-flow and favorable light conditions in midsummer, photosynthetic production may exceed the nitrogenous oxygen demand produced by about 500 to 1500 lb/d of ammonia from each WWTP.

Under conditions where the ammonia assimilative capacity is zero, the Oregon Administrative Rules allow ODEQ, at its discretion, to allow the discharge of wasteloads that result in "no measurable reduction" of DO, where "no measurable reduction" is defined as approximately 0.2 mg/L (Oregon Department of Environmental Quality, 1997b). The 18 months of model output was analyzed to determine what level of WWTP ammonia load would result in a DO decrease of 0.2 mg/L under those conditions when the 30-day mean DO concentration was already at or below the standard in the absence of WWTP ammonia loads (fig. 6). Under these conditions, the effect of any additional ammonia load caused the greatest decrease in DO concentrations; when the 30-day mean DO concentration met or

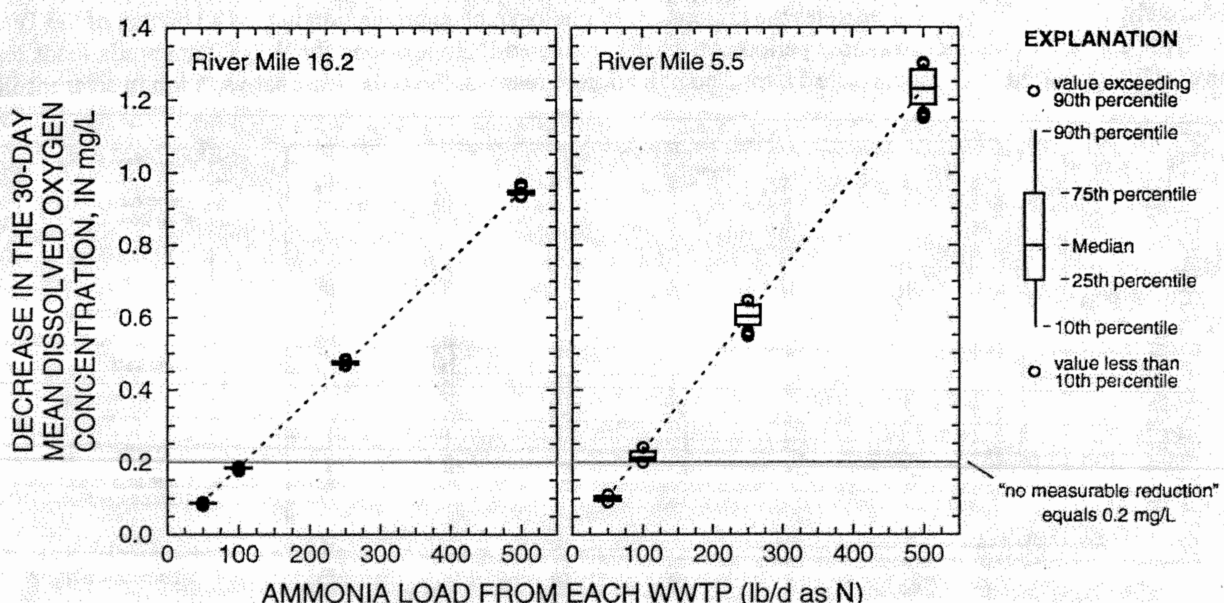

Figure 6. Box and whisker plots showing dissolved oxygen consumption due to ammonia nitrification as a function of the WWTP ammonia load. These plots include only conditions in the 18-month calibration period where the 30-day mean dissolved oxygen standard was violated in the absence of WWTP ammonia loads. (mg/L, milligrams per liter; lb/d, pounds per day; WWTP, wastewater treatment plant)

exceeded the standard, the same additional ammonia load caused less of a decrease in the DO concentration. Therefore, the data shown in figure 6 represent the most critical conditions for DO.

The dotted lines drawn through the medians of the distributions in figure 6 show that the predicted DO losses are linearly related to the imposed ammonia load. The slope of that line is slightly steeper for RM 5.5 than for RM 16.2 because RM 5.5 is downstream of both WWTPs, whereas RM 16.2 is downstream of only one WWTP (fig. 1). The slope of these lines depends mainly on river discharge and the instream nitrification rate, which is a function of water temperature. If the flow had been lower, the effect of instream ammonia nitrification would have been even greater and the slope of these lines would be steeper. Similarly, if the river flow could be augmented to maintain a higher minimum discharge, the slope of these lines would be more shallow. The results in figure 6 indicate that each WWTP could discharge about 100 lb/d of ammonia nitrogen under the most critical DO conditions and cause only a 0.2 mg/L decrease in the 30-day mean DO concentration. These results will aid in setting a new ammonia wasteload allocation for these two WWTPs under the revised ammonia TMDL.

These model results were used to generate a simple flow chart that illustrates the dependence of the Tualatin River's calculated ammonia assimilative capacity on measurable quantities such as river discharge (at a gage, RM 33.3) and solar insolation (fig. 7). The ammonia loads in the flow chart also depend on the instream nitrification rate, which is a

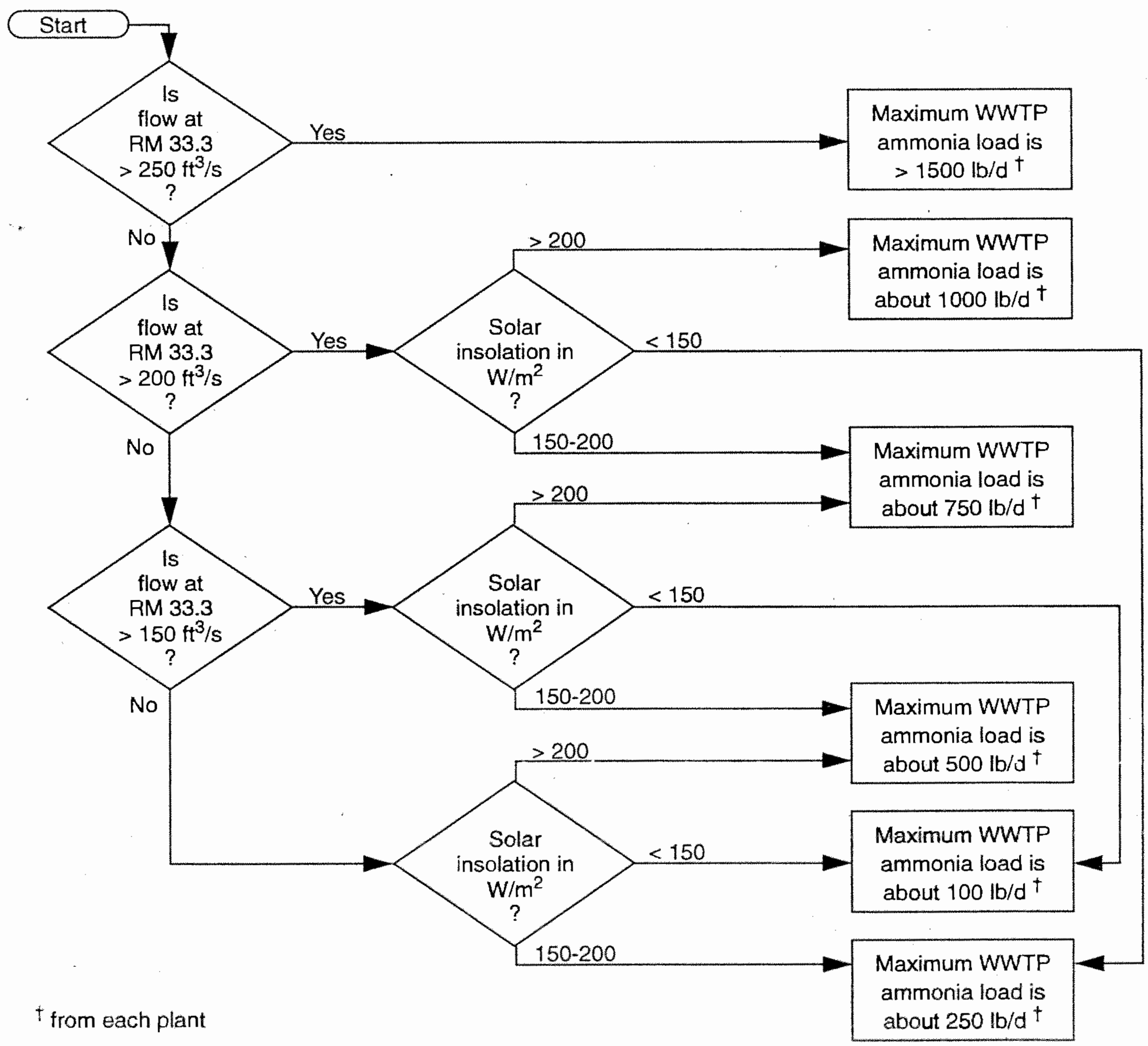

Figure 7. Flow chart illustrating the dependence of the ammonia assimilative capacity on flow and light conditions. (ft^3/s, cubic feet per second; W/m^2, watts per square meter; WWTP, wastewater treatment plant)

function of water temperature, and on the averaging interval used for flow and solar insolation. The results in figure 7 are based on 30-day means of flow and solar insolation, as in figures 4 and 5.

Under the high-flow conditions encountered in May, the flow chart leads to an assimilative capacity greater than 1500 lb/d. In midsummer, when river discharge is typically between 150 and 200 ft^3/s and the solar insolation rate is generally well above 150 W/m^2, several paths in the flow chart lead to assimilative capacities between 500 and 1000 lb/d of ammonia from each WWTP. In late summer, when river discharge typically is near 150 ft^3/s and solar insolation is less than 150 W/m^2, the flow chart leads to an assimilative capacity of 100 lb/d, as calculated from figure 6.

SUMMARY

A two-dimensional, laterally averaged flow and water-quality model, CE-QUAL-W2, was used to simulate flow, water temperature, and water quality in the reservoir reach of the Tualatin River. The model was calibrated for an 18-month period encompassing the May 1 to October 31 periods of 1991, 1992, and 1993. Model calibration included flow, water temperature, and water-quality constituents such as ammonia, nitrate, DO, orthophosphate, phytoplankton, zooplankton, sediments, and dissolved and particulate organic matter. Once calibrated, the model was used to simulate the effects of various ammonia loads from two large WWTPs on DO concentrations in the lower reaches of the Tualatin River. These hypothetical ammonia loads were superimposed on the observed calibration conditions, therefore providing a realistic and wide range of hydrologic and meteorological conditions for testing. Simulations were run with constant ammonia loads between 0 and 1500 lb/d of ammonia nitrogen from each of the two plants; the *total* inorganic nitrogen loads (ammonia plus nitrate) from the WWTPs, however, were not modified from those used for the calibration in order to maintain the same overall nutrient load.

The results from these hypothetical scenarios were used to determine how the ammonia assimilative capacity of the Tualatin River depends on river discharge, water temperature, and solar insolation. That capacity was quantified on the basis of compliance with, or violation of, the State of Oregon minimum DO standard. Most of the simulated DO violations occurred when both river discharge and solar insolation were low. When light conditions are poor, photosynthetic production of DO is low and cannot offset the nitrogenous oxygen demand of a large load of ammonia. The long travel times through the reservoir reach during low-flow conditions allow much of that nitrogenous oxygen demand to be exerted before the ammonia exits that reach. Ammonia assimilative capacity was found to increase with increasing river discharge and solar insolation, and to decrease with increasing water temperature.

On the basis of a definition of "no measurable reduction" of dissolved oxygen (0.2 mg/L) for conditions when the DO standard was being violated in the absence of WWTP ammonia loads, the model results were used to calculate the maximum permissible ammonia load from each WWTP under the most sensitive conditions. That ammonia load, about 100 lb/d, is sensitive to the instream nitrification rate (which depends on water temperature) as well as the level of river discharge. Flow augmentation may be a useful tool to reduce the frequency of these violations and to increase the allowable WWTP ammonia loads under the most sensitive conditions.

The results of these model simulations provide insight into how the Tualatin River might be managed to reduce the number of future violations of the DO standard under various ammonia loading conditions. These results are being used by ODEQ to develop new wasteload allocations and a revised ammonia TMDL for the Tualatin River.

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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>.