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CALIBRATION AND APPLICATION OF QUAL-II TO THE LOWER WINOOSKI RIVER[1]

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ABSTRACT: A modified version of the U.S. Environmental Protection Agency's QUAL-II water quality simulation model is calibrated and applied to the Lower Winooski River, Vermont. The river flows through the metropolitan Burlington area and is impacted by several industrial and municipal point sources and by operation of hydropower facilities. Several structural modifications are made in the model to improve water quality simulations in rivers impacted by algal growth; these include the addition of organic nitrogen and organic phosphorus compartments and provision for algal uptake of ammonia and/or nitrate nitrogen. The model is interfaced with statistical programs which facilitate tabulation, display, and analysis of observed and predicted concentrations. The model is calibrated and tested against data from two intensive water quality surveys. Applications demonstrate the factors controlling water quality and sensitivities to point source waste management strategies and flow, as influenced by hydropower operations.
(KEY TERMS: water quality; mathematical model; simulation; river; oxygen; algae; nutrients; wasteload allocation; assimilative capacity.)

INTRODUCTION

In recent years, the application of water quality models by state regulatory agencies for wasteload allocation purposes has undergone increased scrutiny. The U.S. Environmental Protection Agency, for example, has established a review process which requires that model applications and the resulting wasteload allocations are technically justified. The issuance of federal funds to support facility design and construction are linked to this review process.

Wasteload allocation studies are subject to numerous technical pitfalls, particularly in riverine systems where simulation of complex algal/nutrient/dissolved oxygen relationships is required. Problems can result from inadequacies in the data used in calibration and testing, inadequacies in model structure, and user inexperience. The calibration procedure can be awkward and time consuming because model outputs are generally not structured so that they can be easily manipulated or compared with observed data. In cases where the model is not structured to simulate important phenomena, compensation is often made by unrealistic adjustments in model coefficients. When such problems arise, the resulting water quality management decisions can result in unnecessary advanced waste treatment or inadequate treatment and continued violations in water quality standards.

The objectives of this paper are to outline changes which have been made in the QUAL-II water quality model in addressing some of the above problems and to demonstrate the calibration and application of the model to the Lower Winooski River in Vermont. This river system includes a combination of physical, cultural, and ecological factors which are typically encountered in model applications. River reaches include hydroelectric dams and impoundments, rapids, and a "freshwater estuary" at the entrance to Lake Champlain. Eight point sources discharge wastes into this river, the flow of which is regulated daily for power generation. In addition to oxygen demanding organic waste discharges, the input of nutrients is also important because of the large influence exerted by algae on the river's dissolved oxygen balance.

The following sections describe modifications to the QUAL-II model, the monitoring programs undertaken to provide a data base for model calibration and testing, and examples of model applications. The revised QUAL-II model and its calibration and application to the Lower Winooski should be useful for other state regulatory agencies responsible for developing wasteload allocations.

SETTING

The Winooski River is located in Central Vermont and flows westerly through the Green Mountains to Lake Champlain. The river is approximately 144 kilometers in length and drains an area of 2560 square kilometers. Stream elevations vary from 732 meters above sea level at the headwaters to 29 meters at the confluence with Lake Champlain in Burlington. Streamflow is typified by intense runoff from snowmelt in April, followed by a summer low flow period in July and August. The average annual discharge into Lake Champlain is 48 m3/sec; the 7Q10 flow is 4.2 m3/sec.

In contrast to the upper basin, which is predominantly rural, the final 32 kilometers, the so-called "Lower Winooski" has a

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population of about 90,000, almost 20 percent of the entire state population. Waste discharges from seven municipalities and one industry enter the Lower Winooski. Figure 1 shows the locations of point source discharges, hydropower facilities, and stream sampling stations. Table 1 identifies point sources and dam sites according to river kilometer and mile indices measured upstream from Lake Champlain. The local watershed is narrow in the last 32 kilometers and nonpoint sources are considered relatively insignificant, particularly under low flow conditions.

Green Mountain Power Company operates two dams (No. 18 and No. 19) on the Lower Winooski for peak power generation. Operation of these power facilities results in summer streamflow fluctuations from 43 m3/sec during power generation to leakage flows of about 1.4 m3/sec below the dams when water is being stored between generation cycles. Impoundment volumes have been reduced to about 0.2 million cubic meters as a result of siltation. Between the two power dams is a 2.5-kilometer section of rapids which supports extensive periphyton communities as a result of nutrient enrichment from upstream and local sources. A third hydropower facilities is planned below the other two, near the site of the abandoned crib dam in the city of Winooski.

The stream gradient for the last 16 kilometers of the river is reduced to about 0.2 meters/kilometer and results in low stream velocities. Mean stream depths range from 1 to 2 meters under summer flow regimes with maximum depths of about 8 meters at several locations. Water temperatures reach a summer maximum of about 30 degrees C.

The river is currently classified as a coldwater fishery and Vermont's Water Quality Standards specify a minimum dissolved oxygen (D.O.) level of 6 mg/l. Historical violations of the D.O. standard have occurred in the Lower Winooski owing to a combination of flow reductions, point source discharges of oxygen demanding wastes and respiration by algal populations stimulated by point source nutrient inputs. Minimum D.O. levels of 3 to 5 mg/l have been observed, usually during early morning hours. Diel fluctuations of 6 mg/l are not uncommon, especially near the river mouth. Sustained violations in the oxygen standard were observed in the last 16 kilometers over a four-day period in 1975, and were associated with river temperatures above 30 degrees C and an apparent die-off of algal populations (Meta Systems, 1979a).

A wasteload allocation for the Lower Winooski was originally adopted in 1976 and called for advanced waste treatment for all dischargers. It was soon recognized, however, that a system of this complexity required further study. Less stringent interim allocations were put into effect awaiting results of more detailed monitoring and modeling studies. Other water quality management actions affecting the Lower Winooski are the Vermont Phosphate Detergent Ban and a maximum total phosphorus concentration of 1 mg/l in point source discharges. The latter requirement was imposed because of concerns for the eutrophication of Lake Champlain, but has not yet been fully implemented.

MODEL DESCRIPTION

After a review of available water quality models, a version of the QUAL-II model was selected by the Vermont Agency of Environmental Conservation (VAEC) for use in its wasteload allocation study. The original QUAL-II, developed by Water Resources Engineers (1974), has been followed by numerous modified versions. The version implemented here was developed by Meta Systems (1979b), with later modifications by Walker (1980, 1981) and the VAEC (1982). QUAL-II permits simulation of oxygen dynamics in a one-dimensional system with steady state hydraulics. The following state variables have been used in this application:

(1) dissolved oxygen
(2) carbonaceous biochemical oxygen demand
(3) algae as chlorophyll-a
(4) organic nitrogen
(5) ammonia nitrogen
(6) nitrite nitrogen
(7) nitrate nitrogen
(8) organic phosphorus
(9) dissolved phosphorus

Control pathways relating these variables are depicted in Figure 2. General discussions of QUAL-II dynamics are provided by Roesner, *et al.* (1977), and NCASI (1982). Major features which distinguish this version of the model from others include:

(1) inclusion of algal self-shading,
(2) provision for algal uptake of ammonia and/or nitrate,
(3) inclusion of organic-N and organic-P compartments,
(4) specification of alternative (vs. multiplicative) algal growth limitation by phosphorus or nitrogen,
(5) inclusion of dam reaeration, and
(6) interface with SAS (SAS Institute, 1979).

Details of these modifications and other aspects of model structure are given elsewhere (Meta Systems, 1979b; VAEC, 1982). The revised code is available for use on the EPA's STORET computer system. An extended version has also been adapted for use on microcomputers and applied to other New England Rivers (Walker, 1983).

Based upon a comparison of the existing QUAL-II algorithm with state-of-the-art formulations (Zison, *et al.*, 1978), the first four modifications improve the representation of algal growth kinetics and nutrient cycling. One of the major inadequacies of previous QUAL-II versions is the lack of provision for algal uptake of ammonia nitrogen. This essentially forces the oxidation of ammonia to nitrite and nitrate prior to algal uptake, over-estimates the significance of nitrification on the stream oxygen balance, and generally makes it difficult to calibrate the model to observed ammonia concentrations. Relative to nitrate, ammonia is a high energy nitrogen source which has been shown to be preferred by phytoplankton in many situations (Dougdale and Goering, 1967; Bienfang, 1975). Accordingly, the model structure has been modified to permit algal uptake of ammonia and/or nitrate nitrogen using a "preference factor" formulation similar to that employed in

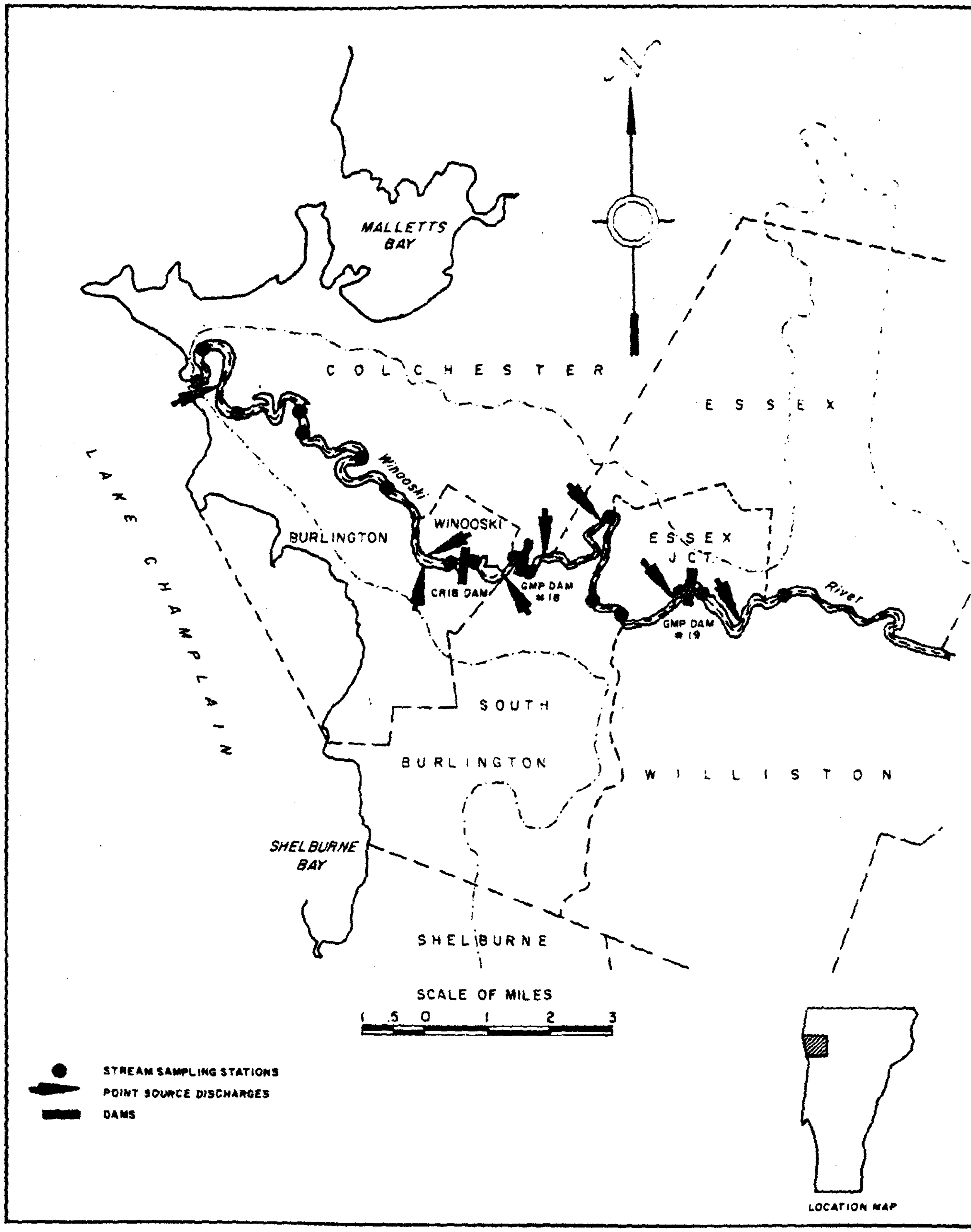

Figure 1. Map of Winooski River.

TABLE 1. Locations of Discharges and Dams on the Lower Winooski.

Index				Flow (m3/sec)*	
Km	Mi	Location	Comments	1978	1979
30.9	19.2	Inflow from Upper Winooski		5.583	10.202
30.4	18.9	IBM Discharge	Industrial/Sanitary	0.058	0.045
28.3	17.6	Green Mtn. Power Dam No. 19	Hydropower Facility		
27.7	17.2	Essex Village Discharge	Primary	0.028	0.036
25.6	15.9	USGS Streamflow Gauge		5.800	10.500
22.0	13.7	Essex Town Discharge	Primary	0.001	0.003
19.6	12.2	Colchester Discharge	Secondary	0.006	0.009
18.0	11.2	Green Mtn. Power Dam No. 18	Hydropower Facility		
17.3	10.8	South Burlington Discharge	Primary	0.033	0.039
16.1	10.0	Crib Dam	Abandoned		
15.6	9.7	Burlington Riverside Discharge	Secondary	0.032	0.032
15.1	9.4	Winooski Discharge	Secondary	0.027	0.029
3.2	2.0	North Burlington Discharge	Secondary	0.058	0.049
0.0	0.0	Lake Champlain		6.121	10.976**

*Flows are mean values during survey periods in 1978 and 1979.
**Local runoff accounts for difference between flow at Lake Champlain and sum of inflow from Upper Winooski and discharges.

estuarine models by DiToro, *et al.* (1977). The modified code also incorporates improvements in the calculation of algal growth rates as a function of light intensity and permits specification of dam reaeration at the downstream end of any river reach. Addition of organic nitrogen and organic phosphorus compartments completes the nutrient cycles and, in combination with inorganic and algal compartments, permits calibration and testing against observed organic and total nutrient concentrations.

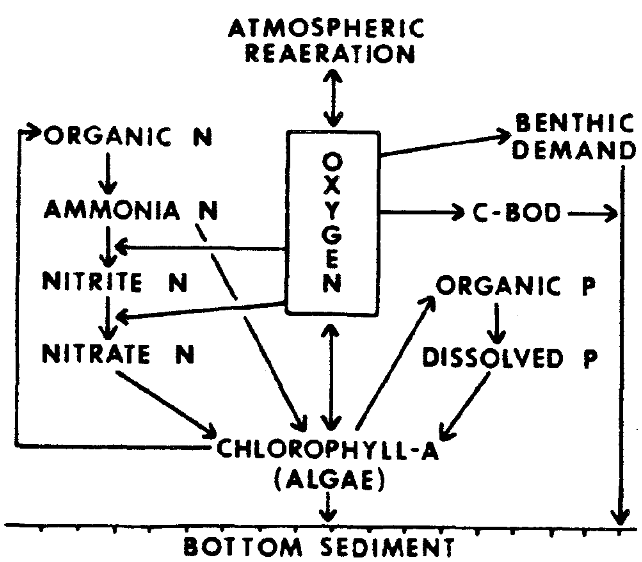

Figure 2. Control Pathways in the Modified QUAL-II Model.

The SAS interface (Walker, 1980) consists of (1) model code which generates an output data set containing the predicted values of 53 water quality, hydraulic, and process related variables (e.g., total photosynthetic rate) for each model segment (river mile increment); (2) an SAS program which reads the model output data set and merges it with another data set describing observed water quality conditions; and (3) an SAS program which generates a series of displays, tables, and statistical summaries comparing observed and predicted water quality conditions. The interface was developed to enhance the speed, flexibility, and accuracy or the calibration process.

Stream hydraulics, water temperatures, waste inputs, inflow concentrations, and other boundary conditions are fixed for a given model run. As discussed above, the steady state hydraulic representation is not typical of the Lower Winooski; a much more complex model would be required to simulate flow and water quality dynamics induced by hydropower operations. The objective of the study is to assess the impacts of point source discharges on water quality, however, not to examine hydropower operations. Based upon dilution and kinetic considerations, the impacts of point sources are expected to be most important during low flow, high temperature conditions. With the cooperation of the power utility, the steady state model has been calibrated and tested against data gathered under steady flow conditions (see below) and applied to assess water quality conditions likely to result from steady 7Q10 flows and a variety of wasteload scenarios. Vermont's water quality standards do not apply below 7Q10 flows and future regulations may require hydropower facilities to pass an instantaneous minimum flow of 7Q10 when it is available from upstream.

MONITORING

Data used for model calibration and testing were collected by the VAEC during two survey periods in the summers of

1978 and 1979 (VAEC, 1980). During each survey, ten stream stations and eight point source discharges were sampled at four-hour intervals for three consecutive days. Although summer stream flows in the Lower Winooski are usually subject to large daily fluctuations because of hydropower operations, steady flow regimes were maintained by the power company for each of the survey periods. Average daily discharge rates at the USGS gauge for the 1978 and 1979 surveys were 5.8 m3/sec (range 5.2-6.1 m3/sec) and 10.5 m3/sec (range 8.8-12.4 m3/sec), respectively, in relation to the estimated 7Q10 flow of 4.2 m3/sec.

Samples were analyzed for five-day biochemical oxygen demand, total Kjeldahl nitrogen, nitrate plus nitrite nitrogen, ammonia nitrogen, dissolved oxygen, and temperature. Chlorophyll-a, total phosphorus, and ortho-phosphorus determinations were also made in 1979. Methods of collection, analysis, and quality control are discussed elsewhere (VAEC, 1980).

Time-of-travel studies were conducted via dye injection and measurement. Generally, injections at two different flow regimes for each reach were made to determine discharge/velocity relationships. Stream widths and cross-sections were also measured at selected locations. Stream discharge was recorded at the USGS stream gage near Essex Junction.

MODEL CALIBRATION AND TESTING

Model inputs may be broadly classified as (1) "boundary conditions" or (2) "system parameters." Boundary conditions include such factors as river flows, waste inputs, morphometry, and climate; these can be directly measured or independently estimated. System parameters include the rate and stoichiometric coefficients which are used in simulations at the process level and are usually difficult to measure directly. In simulating a given river system, the boundary conditions vary from one time period to another, depending upon variations in flows, climate, etc. If the model is realistic, however, the system parameters should be relatively constant. One test of a model is whether observed water quality can be adequately simulated under at least two different sets of boundary conditions using one set of system parameters. Intensive survey data from the summers of 1978 and 1979 have been used for calibration and testing, respectively.

The development of input estimates within each category can be based upon combinations of the following:

(1) direct monitoring data
(2) calibration to observed water quality profiles
(3) literature values
(4) assumptions

The calibration process would be relatively straight-forward if all inputs could be directly measured. This is generally infeasible, however, because of the complexity of the model, implicit nature of some coefficients, and limitations in monitoring resources and technology. The other estimation methods rely partially upon user judgment because the feasible ranges of most coefficients are wide and more than one combination of coefficients could generally be selected to fit a given set of field data. Sensitivity analyses are useful for identifying the importance of parametric and structural assumptions.

Estimates of boundary conditions have been derived chiefly from direct monitoring (VAEC, 1980, 1982). The sources and estimates of the most important system parameters are outlined in Table 2. The calibration procedure used for some parameters has involved fitting observed and predicted profiles for the 1978 data set, subject to constraints imposed by literature ranges. Other parameters, selected based upon sensitivity analyses and feasible ranges, have been derived directly from previous modeling or experimental studies reported in the literature and without empirical adjustment. A few have been assumed or specified at zero levels (e.g., benthic ammonia and phosphorus release rates); these amount to structural assumptions.

Figure 3 presents observed and predicted profiles of average dissolved oxygen, nitrogen species and biochemical oxygen demand (BOD) for the 1978 (calibration) data set. Predicted profiles of phosphorus species and chlorophyll-a are also shown; these variables were not measured in the 1978 survey. To permit direct comparison with five-day BOD rates measured in the laboratory, "apparent BOD-5" values have been calculated from model output as the sum of five-day carbonaceous BOD and five-day algal respiration, both using rate coefficients adjusted to 20 degrees C. The significance of algae as sources of organic matter is indicated by the difference between the apparent BOD-5 and carbonaceous BOD-5 curves, particularly at the lower end of the river.

The 1978 calibration results generally show good agreement between observed and predicted variables, although a lack of phosphorus and chlorophyll-a data from this period limits a full evaluation of model performance. Preliminary calibration runs indicated a conversion of nitrate and ammonia to organic nitrogen in the rapids section below the first power dam (river miles 17.6 to 15.7) beyond that which could be accounted for by algal uptake. Nutrient uptake and sloughing by the dense periphyton beds in this section of the river could account for the observed variations. Since this process is not directly simulated by the QUAL-II model, it has been treated indirectly by specifying negative inflow concentrations for ammonia (−1 mg/l) and nitrate (−2 mg/l) and a positive inflow concentration for organic nitrogen (+3 mg/l) for the local runoff into this reach. These periphyton fluxes account for about 15 percent, 25 percent, and 20 percent of the total fluxes of nitrate, ammonia, and organic N in this reach, respectively, and have negligible impact on simulations at the lower end of the river.

Observed and predicted profiles for the 1979 data set used for model testing are presented in Figure 4. Field data from this survey suggest that samples taken at river mile 15.8 may not have been representative. Concentrations of ammonia nitrogen, BOD-5, and total phosphorus were considerably lower than those measured at stations immediately upstream and downstream. The increases moving downstream to the next station are particularly puzzling, since there are no intervening point sources. Accordingly, samples taken at river mile

TABLE 2. System Parameter Estimates.

Coefficient	Code	Value and/or Comments
Oxygen Parameters		
Reaeration Rate	C	O'Connor and Dobbins (1958)
Benthic Respiration	C	0.5 g/m2-day
Benthic Photosynthesis	B/C	0 g/m2-day, except 2 g/m2-day in periphyton beds, river miles 15.8-17.6
BOD Parameters		
Oxidation Rate	C	Bottle rate (0.2 1/day) plus bed activity based upon slope (Zison, *et al.*, 1978)
Settling Rate	D	0 m/day
Nitrogen Cycle Parameters		
Organic N Decay Rate	B/C	0.1 1/day
Ammonia N Oxidation Rate	B/C	0.3-2.0 1/day, reach-specific
Ammonia N Oxygen Equiv.	C	3.43 mg O/mg N
Nitrite N Oxidation Rate	C	2 1/day
Nitrite N Oxygen Equiv.	C	1.17 mg O/mg N
Benthic Ammonia-N Rel.	D	0 mg/m2-day
Phosphorus Cycle Parameters		
Decay Rate (Phys./Chem)	D	0 1/day
Benthic Release	D	0 mg/m2-day
Organic P Decay Rate	B/C	0.1 1/day
Algal Parameters – Rates		
Maximum Growth	B/C	2.3 1/day
Respiration	C	0.11 1/day, or 5 percent of maximum growth
Settling	B/C	0.76 m/day
Algal Parameters – Stoichiometric Equivalents		
Nitrogen	B/C	0.08 mg N/mg A
Phosphorus	B/C	0.011 mg P/mg A
Chlorophyll-a	C	0.010 mg Chl-a/mg A
Oxygen (Photosynthesis)	C	1.6 mg O/mg A
Oxygen (Respiration)	C	2.0 mg O/mg A
Light Extinction	C	0.043 m2/mg Chl-a
Non-Algal Light Extinction	A	0.33 1/meter
Algal Half-Saturation Values		
Nitrogen	C	0.030 g/m3
Phosphorus	C	0.005 g/m3
Light	C	0.024 cal/cm2-min, visible
NH3-N vs. NO3-N Uptake Factor	B/C	0.90

Estimation Codes: A = direct monitoring data; B = adjusted empirically, within literature ranges; C = literature based; D = assumed.

15.8 have been given low weight in model testing and are shown in parentheses in Figure 4.

The data also indicate that the periphyton activity discussed above was less significant in 1979, though the nitrogen conversion process discussed above has been simulated identically in the model calibration and testing runs. Simulations indicate that phosphorus was the primary nutrient limiting algal growth during both survey periods, although nitrogen limited conditions were approached at the mouth of the river, particularly in 1979. The tendancy to over-predict dissolved phosphorus concentrations could be related to differences between the total dissolved phosphorus concentrations simulated by the model and the ortho-phosphorus concentrations measured in the survey.

APPLICATIONS

Through appropriate adjustments in boundary conditions, the model has been used to estimate water quality conditions and controlling factors under low flow, high temperature conditions. Waste inputs have been specified at secondary treatment limits with projected flows and phosphorus removal to 1 mg/l, in accordance with planned nutrient control strategies for protection of downstream Lake Champlain. This compares with average total phosphorus concentrations of 3.4 and 3.9 mg/l during the 1978 and 1979 surveys, respectively (flow weighted means of all discharges). Headwater flow has been specified at the estimated 7Q10 flow of 4 m3/sec and temperatures in the 26-28 degrees C range, based upon examination of the historical record of measured values for this portion of the river. The model has been applied under the above design

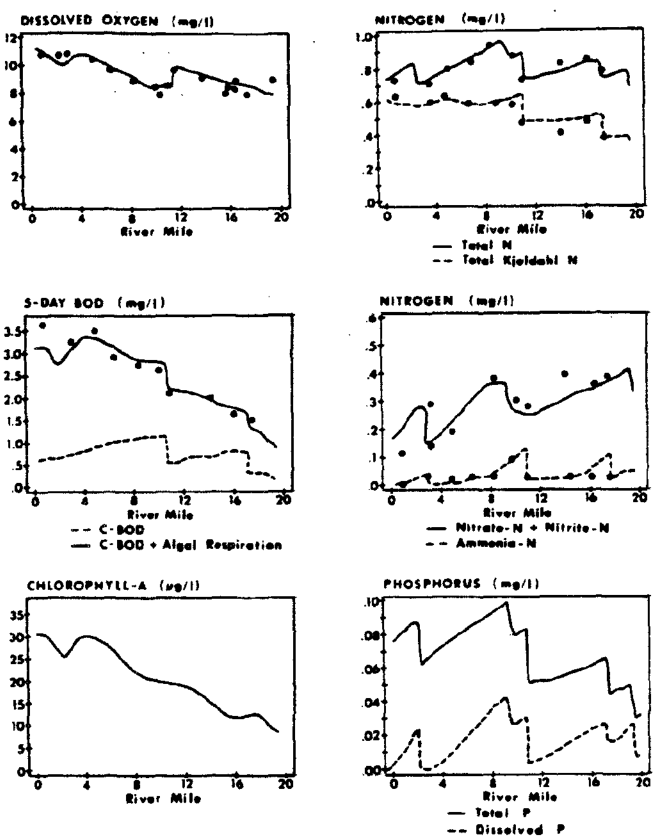

Figure 3. Observed and Predicted Concentrations – 1978 Monitoring Period. LEGEND: River flows from right to left. Lake Champlain is located at River Mile 0.0. Points are mean observed values; lines are simulated values.

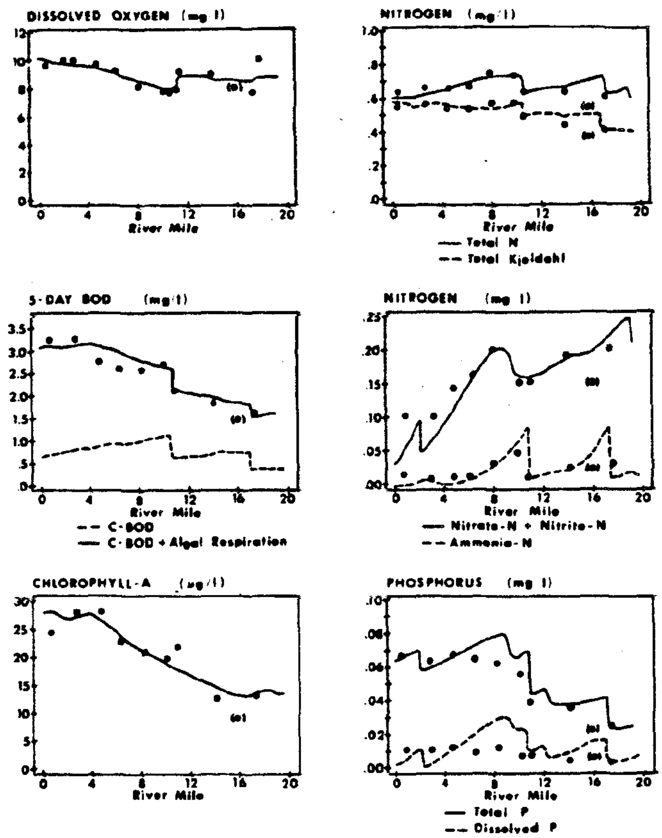

Figure 4. Observed and Predicted Concentrations – 1979 Monitoring Period. LEGEND: River flows from right to left. Lake Champlain is located at River Mile 0.0. Points are mean observed values; lines are simulated values.

conditions to assess sensitivity of oxygen profiles to processes, point source phosphorus controls, and steady-state flow regimes (Figure 5).

Vermont's Water Quality Standards specify an instantaneous dissolved oxygen concentration of 6 mg/liter for the Lower Winooski. Results of the model calibration and testing indicate that algal photosynthesis and respiration are extremely important factors controlling the levels of organic matter and dissolved oxygen in the river, particularly near the mouth. As shown in Figures 3 and 4, algal respiration accounted for most of the observed five-day BOD concentrations near the river mouth during the 1978 and 1979 surveys. When algae are controlling, use of a steady-state model to assess minimum oxygen levels is difficult because critical conditions result from unsteady-state processes: (1) diurnal variations in photosynthesis and (2) sudden die-off of algal blooms. The complexity and stochastic nature of the latter process preclude direct simulation using a time variable model. Critical conditions for algal impacts have been approximately simulated with the steady-state model by setting algal photosynthetic oxygen production equal to zero; this does not influence the simulated growth or respiration rates but approximately represents a bloom die-off condition. Simulations show reasonable agreement with the lowest oxygen levels measured during each of the survey periods.

Process sensitivity has been assessed by setting appropriate oxygen stoichiometric parameters to zero. Algal photosynthesis is an important oxygen resource, especially at the mouth of the river; under die-off conditions, however, algal respiration and decay are important oxygen sinks. Sensitivities to nitrogenous BOD and benthic demand are lower than those indicated for carbonaceous BOD. Process sensitivity is low immediately below dams because of the effects of dam reaeration.

Sensitivity of oxygen levels under bloom die-off conditions to phosphorus control strategies has been evaluated by setting point-source phosphorus discharge concentrations to 0, 1, and 3 mg/l, respectively, and setting algal photosynthetic oxygen production to zero. Sensitivity increases moving downstream to a maximum range of 3 to 6 mg/l at the mouth of the river. Results suggest that planned limitation of point source phosphorus discharges to 1 mg/l should markedly reduce the susceptibility of the river mouth to oxygen problems related to algal respiration and die-off.

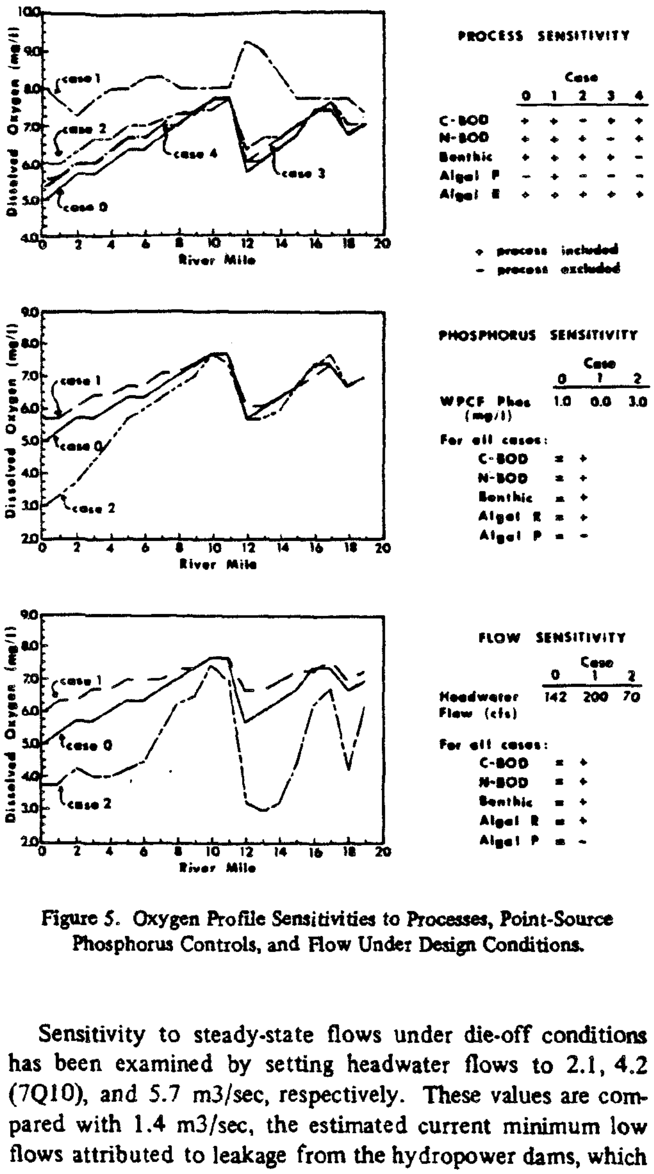

Figure 5. Oxygen Profile Sensitivities to Processes, Point-Source Phosphorus Controls, and Flow Under Design Conditions.

Sensitivity to steady-state flows under die-off conditions has been examined by setting headwater flows to 2.1, 4.2 (7Q10), and 5.7 m3/sec, respectively. These values are compared with 1.4 m3/sec, the estimated current minimum low flows attributed to leakage from the hydropower dams, which is experienced during daily and weekend storage periods. Sensitivity to flow increases moving downstream from each dam. A more complex model with unsteady-state hydraulics would be needed to assess the effects of hydropower operations on the success of waste management strategies in the Lower Winooski.

CONCLUSIONS

In applying the revised QUAL-II model to the Lower Winooski River, good agreement is evident between observed and predicted water quality constituents. Revisions to the model structure have resulted in better simulations of nutrient cycling, algal populations, and oxygen levels than was possible using the original model, based upon comparisons with observed conditions during the 1978 (model calibration) and 1979 (model testing) surveys. These revisions include improvements in the representation of algal growth rates as a function of light and nutrient concentrations, addition of compartments for organic nitrogen and organic phosphorus, and provision for algal uptake of ammonia and/or nitrate nitrogen. Model weaknesses identified in this application include the lack of provision for direct simulation of periphyton dynamics and a need for improvement in the direct simulation of diel oxygen variations.

Interfacing the model with SAS has provided a simple means for merging model output with observed concentration data and generating displays and summary tables which are useful in calibration, testing, and report production. Using SAS, revisions in display formats and other changes can be easily made without modifying the water quality simulation program.

From a water quality management standpoint, use of the model has helped in defining the importance of algae and point-source phosphorus inputs as factors influencing the Lower Winooski's dissolved oxygen regime. This is in contrast to earlier modeling studies which had indicated a need for control of point-source inputs of carbonaceous and nitrogenous oxygen demand. While the model provides approximate insights into the sensitivity of algae oxygen profiles to steady-state flow regimes and point sources, a more complex model with time variable hydraulics would be required to assess the relationships between hydropower operations and waste management strategies in the Lower Winooski.

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