Sensitivity of Dissolved Oxygen Regime to Nonpoint Source Phosphorus Inputs

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INTRODUCTION

The oxygen dynamics of shallow, nutrient enriched river channels in southern Ontario are often dominated by profuse growths of algae (Cladophora) and aquatic plants (potamogeton, milfoil). Hence dissolved oxygen (DO) models of these systems must account for photosynthesis and respiration, as well as the conventional oxygen demands from carbonaceous and nitrogenous waste loads. The Grand River Simulation Model (GRSM) has been used to predict the sensitivity of dissolved oxygen levels in the Grand River to point and non-point inputs of phosphorus. GRSM is a continuous dissolved oxygen model which includes time varying inputs from point and non-point sources, and models the impact of plant growth on DO as affected by nutrients including phosphorus and nitrogen.

The model was first developed and applied in the Grand River Basin Water Management Study (GRIC, 1982). The model was seen as a primary tool for planning, because of its unique capabilities and since it has formed the basis for the original plan in the 1982 study. The Ontario Ministry of Environment and Energy (MOEE) has required the municipalities on the Grand River to meet (or at least not further degrade) water quality objectives, primarily dissolved oxygen, in the face of potential sewage treatment plant expansions to meet urban development needs. Planning for urban expansion has proceeded on the basis that no increases in phosphorous loading will be allowed, requiring higher levels of phosphorous removal a municipal sewage treatment plants as sewage flows increase. This has increased the interest of the municipalities in the concept of effluent permit trading to achieve cost savings.

The Grand River Conservation Authority started in 1995 on developing a water management strategy in a partnership with the MOEE, and local and regional municipalities, and universities. This has included development of improved interfaces for the models, field work to provide data for re-calibration, and sensitivity testing to determine important parameters (CH2M G&S, 1996).

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DESCRIPTION OF MODEL

The Grand River Simulation Model predicts water quality variations using continuous inputs of background water quality, streamflow, and point sources of waste loads from sewage treatment plants, along with variations in environmental conditions such as temperature and sunlight. Continuous dissolved oxygen predictions were compared statistically with water quality objectives to determine the frequency of violations.

The model consists of a series of reaches, with flow routed between them. Inputs occur at the head of each reach, while reach dependent rate coefficients affect the DO prediction for each two hour time step. Inputs from upstream (boundary), local inflows, urban runoff, and sewage treatment plants, as well as withdrawals for water supply are allowed. Inputs can be specified as time series from actual data, or from other model output (as is done for urban runoff using STORM or GAWSER) or estimated in the model by a Monte-Carlo technique, using cumulative probability distributions of quality parameters.

Model Formulation

The water quality parameters simulated by GRSM include dissolved oxygen (DO), carbonaceous biochemical oxygen demand (CARBOD), nitrogenous oxygen demand (NOD), nitrite-nitrate (NIT), suspended solids (SS), total phosphorus (TP). Un-ionized ammonia (FA), although not directly, can also be estimated from the simulation results based on temperature and pH. The equations involved for dissolved oxygen and nutrients are described in detail below.

Dissolved Oxygen

The differential equation used for the computation of dissolved oxygen was developed by O'Connor and DiToro (1970). The equation accounts for the effects of carbonaceous and nitrogenous oxygen demand, atmospheric aeration, benthic oxygen demand, and photosynthesis and respiration. Photosynthetic oxygen production and respiration of aquatic plants, as well as resulting uptake and release of nitrogen and phosphorus are predicted by the ecological subroutine of GRSM. The dissolved oxygen deficit at any downstream distance, at any specific time is related to factors affecting it by the differential equation:

$$\partial D/\partial t + V\partial D/\partial x = K_a D + K_d L(x) + K_n N(x) + S/d - P(t) + R \qquad (1)$$

where: D = oxygen deficit (mg/L);
V = velocity of streamflow (m/s);
t = time (day);
x = downstream distance (m);
K_a = reaeration coefficient (day^{-1});
K_d = deoxygenation coefficient (day^{-1});
$L(x)$ = carbonaceous oxygen demand as a function of x (mg/L);
Kn = nitrogenous oxidation coefficient (day^{-1});
$N(x)$ = nitrogenous oxygen demand as a function of x (mg/L);
S = benthic bacterial respiration (gm/m^2 -day);
$P(t)$ = photosynthetic oxygen source as a function of time (mg/L-day);
R = algal and plant respiration (mg/L-day); d, depth, (m).

The deficit D(x,t) at any time t and location x, is found by integrating Eqn. 1. The solution presented in O'Connor and DiToro (1970) is used, with the exception that the authors used a time series expansion to estimate the P term, while GRSM uses values from the ECOL subroutine.

The ecological subroutine ECOL calculates the photosynthetic (P) and respiration (r) rates of aquatic plants which are then utilized to calculate the dissolved oxygen concentration at each time step according to equation 1. This subroutine also provides estimates of biomass density for the plant species *(Cladophora, Potamogeton,* and milfoil) as well as the relative amounts of phosphorus and nitrogen uptake and release. Each time step, the model updates the biomass in each reach to account for the net production (growth minus decay and washout).

Photosynthesis and Respiration

The photosynthetic rate at any time, P(t) of aquatic plants, has been replaced by a term dependent on the growth of macrophytes or periphyton derived from the ECOL subroutine according to equation 4:

$$P(t) = \mu A d O_{rat} \tag{2}$$

where:

μ = plant growth rate (1/day);
A = density of plant biomass (gm/m^2);
O_{rat} = oxygen assimilation ratio (gmO_2/gm-biomass);
d = depth (m).

The growth term, μ, is of the general form:

$$\mu = \mu_{max} \; f(I) \; f(T) \; f(C_n, C_p) \qquad (3)$$

where:

μ_{max} = maximum plant growth rate (1/day);
I = sunlight intensity incident at the surface (Langleys/min);
C_p = concentration of phosphorus in water (mg/L);
C_n = concentration of nitrogen (mg/L); and,
T = Temperature (C).

The functional terms for sunlight intensity, temperature, and nutrient concentrations are described in the references (Walker *et al,* 1981; Willson *et al,* 1982). These terms are currently under review and will be modified in an upcoming release of the model. In field and model studies, only phosphorous has been shown to be limiting to photosynthetic growth.

WATER QUALITY INDEX

The frequency and duration of PWQO violations for DO is an important indicator of water quality. For the purposes of this study, it was necessary to develop a measurement of the impact or effect of point and non-point source TP reductions on DO regime along the entire length of the modelled portion of the river. To do this an index was developed similar to the one used in the 1982 GRBWM study. This index accounts for the magnitude, duration and extent (how many reaches, and length of reach) of DO violations simulated along the river. A violation is defined as an occurrence dissolved oxygen concentration below 4.0 mg/L - the Ontario provincial water quality objective (PWQO) for warm water fish.

The index is computed as follows. For each 2-hour time step in which a DO violation occurred, the violation magnitude (i.e. the amount the DO level was below the 4 mg/L level) was multiplied by the reach length. The individual time-step values were then summed to compute the index. The following summations were used:

$$\text{Index}_t = 1/\text{N} \sum_{j=1}^{N} (4.0 - DO_t) * Length_j \; .... \; if \; DO_l < 4.0 \qquad (4)$$

where: N = number of reaches in the selected stretch of the river, and
t = is a particular time step, and

$$TotalIndex = \sum_{t=1}^{T} Index_t \qquad (5)$$

where T = total number of time steps.

The index was calculated for the following sets of reaches (see Figure 1);

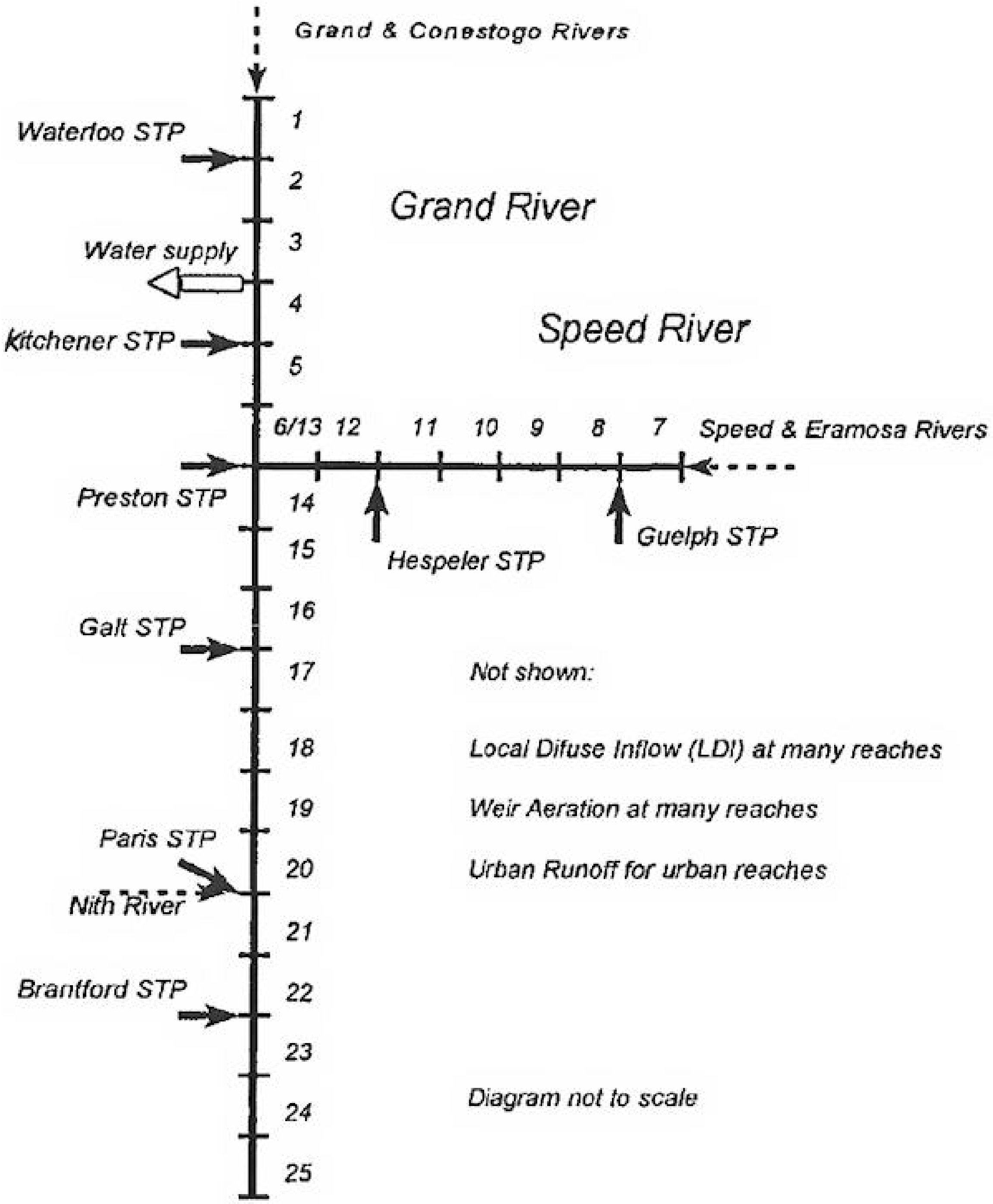

FIGURE 1. Schematic of Grand River Modelled by GRSM

- Upper Grand River (Conestogo River to Speed River): GRSM reaches 1 through 6
- Speed River from Eramosa River to the Grand: GRSM reaches 7 to 13
- Lower Grand River: Grand River from Nith River to Oshweken: GRSM reaches 20 to 25.

PHOSPHOROUS LOADS

The TP loads for all contributions to the modelled portion of Grand River were calculated from the input data set of the 1995 GRSM. The contributions were computed for each of the following sources: sewage treatment plants (STPs) at Kitchener, Waterloo, Guelph, Hespeler, Preston, Galt, Paris and Brantford; urban runoff inputs from Kitchener, Waterloo, Guelph, Cambridge, Paris and Brantford, which were developed from GAWSER (OMNR, 1989) simulations provided by the GRCA; the model's 3 boundary inflows; and, the local diffuse inflow (LDI) representing diffuse source tributary inflows that enter along the modelled portion of the system. The 1991 - 1995 summer load distribution is summarized in Table 1.

TABLE 1. Average TP Load Distribution.

Source	Average Seasonal Phosphorus Contribution, June 1 to Sept, 30 *based on GRSM data for 1991-1995*	
	tonnes	*% of total*
STPs	29.1	48.0
Rivers at model boundaries	11.4	19.0
Urban runoff	0.3	0.5
Local diffuse inflow (LDI)	19.6	32.5
TOTALS	60.5	100.0

From the 1982 study, rural NPS runoff accounted for 73% of the whole basin TP loading, compared to only 22% for STPs. Table 1 shows that for the peak growing season (June 1 - Sept. 30) for plants in the river, the STP load has more significance than on an annual basis.

MODELLING NON-POINT PHOSPHORUS REDUCTION

GRSM was used to examine the potential water-quality benefits that can be achieved through non-point phosphorus load control as though it were applied or achieved over the entire tributary basin. The objective of this initial study was not to look at the impact of specific control measures in specific tributary areas, subwatersheds or municipalities.

In GRSM's input, non-point loads are represented by two inputs:

- <u>Model boundary inflows,</u> which represent the river or tributary flows at the model boundaries. For the current GRSM model setup, there are three boundary inflows (see below and Table 2).

- <u>Local diffuse inflows (LDI)</u> which represent smaller tributaries and non-urban runoff inputs that enter along the modelled portion of the river and which are not otherwise accounted for in model input. In the current GRSM setup, 13 of the 25 GRSM reaches receive an LDI (discussed below).

Urban runoff loads, while included, were not modified as their magnitude is insignificant. Method of Adjusting Boundary TP Loads Water quality for the boundary flows are given to GRSM in the form of cumulative frequency distributions. A separate distribution is provided for each of the six water-quality parameters. Data from the MOEE Provincial Water Quality Monitoring Network for the period 1985 to 1995 was used to determine the distributions for each of the three model boundaries (Table 2):

- Grand River below the confluence with the Conestogo River
- Speed River in Guelph at Highway 6 (i.e. at confluence of Speed and Eramosa Rivers)
- Nith River in Paris, just upstream of the confluence with the Grand River

TABLE 2. Boundary TP Frequency Distributions**.**

Percentile	*0*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
Grand	.01	.016	.016	.019	.021	.022	.024	.026	.029	.039	.067
Speed	.006	.013	.016	.019	.022	.024	.025	.028	.033	.036	.057
Nith	.013	.022	.026	.033	.037	.040	.044	.051	.070	.083	.290

The GRSM uses these frequency distributions to generate time series of TP concentrations in each of the boundary inflows. Over the course of a simulation period of sufficient length, the statistical characteristics of the TP time series will conform to the frequency distributions tabulated above. The TP input loads at the boundaries are adjusted by modifying the frequency distribution table, by shifting ....

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At year 2021, the RMOW plants have proposed TP effluent levels of 0.18 mg/L, the Guelph STP will have an effluent TP level of 0.3 mg/L and the Paris and Brantford plants were assumed to require a 0.18 mg/L TP effluent level also, although these plants are in the lower Grand River and the river is not as sensitive to TP changes. All other effluent parameters remained at 1995 levels.

GRSM was used to compare the 1995 versus 2021 situations. To fully examine the effects of changing STP effluent concentrations of TP and effluent flow volumes, a combination of scenarios was analyzed, including 1995 flows with 2021 TP effluent levels, 2021 flows with 1995 effluent TP levels. The former scenario represents a very large reduction in the STP TP loads while the latter represents an increase in both the hydraulic load and TP load. Table 5 lists the results.

TABLE 5. 1995 Versus 2021 STP Effluent Load.

STP Effluent Scenario	*Water Quality Index*		
	Upper Grand	Speed	Lower Grand
1995 flow and TP	278.9	80.6	16.7
1995 flow - 2021 TP	233.7	51.9	15.8
2021 Proposed	247.8	63.9	24.2
2021 Flow -1995 TP	347.2	88,4	24.6

These results show that the projected STP improvements at year 2021 have significant effect in the upper Grand River and Speed River sections. For the upper Grand section, the index improvement is roughly equivalent to a 10% reduction in non-point source loads (Table 3). For the Speed River section, the index improvement is due to a reduction of 1.7 tonnes of TP from the Guelph and Hespeler STPs. This is equivalent to over a 50% reduction in the non-point source loads which is about 0.45 tonnes. However, it should be noted that the index values for the upper Grand section likely do not adequately account for all the benefits of reductions at the Kitchener STP, since it discharges to reach 5 which is in the downstream portion of the section. The impact of reductions at the Kitchener plant will be felt further downstream, in reaches 14 to 25.

This result again reflects the load distribution for each section. For the upper Grand section, the Waterloo and Kitchener STPs together account for about 64% of total 1995 load. Therefore, any substantial improvements at these plants will have an impact in this section of the river. The year 2021 scenario represents a 62% reduction in the load from these plants, and a 40% reduction in total load to the upper Grand River section.

On the Speed River, the Guelph and Hespeler STP inputs represent over 80% of the total 1995 load. Therefore, there is significant effect from reducing those STP loads.

The index improvement values per tonne of STP TP load reduction are as follows:

- For the upper Grand section, the Waterloo and Kitchener STP reductions at year 2021 total 6.58 tonnes, resulting in index improvement of 4.7 index units per tonne.
- For the Speed river section, the index change of 16.7 has resulted from STP load reduction of 1.70 tonnes (Guelph and Hespeler STPs) or a drop of 9.8 index units per tonne of STP TP load reduction.

Note that these per-tonne index improvement values are significantly lower than those produced through boundary-inflow load reduction given in Table 6. This can be partly attributed to the fact that in both the upper Grand and Speed River sections, not all reaches benefit from STP load reductions, whereas all reaches do benefit from boundary load reductions, (For example, in the case of the upper Grand section, only reaches 5 and 6 benefit from the Kitchener STP reductions; in the Speed River section, only reaches 12 and 13 benefit for Hespeler STP reductions). This effect represents a limitation to the index-based evaluation approach that results from the fact that the various inputs are spread along the system.

The wide differences in sensitivities of the index to changes in point and non-point source loads is non-intuitive and difficult to explain as shown in Table 6.

TABLE 6. Index Unit Response To TP Load Reductions.

Point Source	Point Source Index Change/Tonne	Boundary Inflow Index Change/Tonne	LDI Index Change/Tonne
		Speed River Impact	
Guelph STP	15 to 22.2	22 to 27	15.7 to 18.7
Guelph/Hespeler	9.8	same as above	same as above
		Upper Grand River Impact	
Waterloo	11 to 14	52 to 74	52 to 125
Waterloo/Kitchener	4.7	same as above	same as above

DISCUSSION

Intuitively, one would expect the stream response, as represented by the index changes, would be the same for each source, and that different point sources would have the same impact. The possible explanations for the differences include:

- Location of the source. Upstream sources have more reaches which are affected by the source. This effect is illustrated by noting that the unit effect (index change per tonne of TP reduction) of singular point sources (Guelph and Waterloo) is greater than two point sources combined on the same reach (Guelph/Hespeler and Waterloo/Kitchener). In the case of the Speed River, the index ranges for the singular point source, versus the local drainage input and boundary condition inputs are similar.

- Concentration threshold effect. If concentrations instream drop below a threshold for each algae and aquatic plant species, the growth is inhibited. If concentrations stay above this threshold, then less effect is noted from a reduction. Also, as the water moves downstream, plants in each reach remove some phosphorus, leaving less available downstream, so this effect is not felt in each reach in a uniform way.

- Timing effect of discharges. Discharges from the STPs are varied according to time of day, to reflect the observed variation in water usage (less at night, more during the day). With the plug flow routing scheme in the model, and relatively stable river flows in the summer, this may result in some sections being chronically lower in the supply of TP from point sources, thus lessening the impact of the point source reductions.

Additional sensitivity analyses would have to be done to explain the effect more fully. It is not uncommon to get a non-intuitive result from a complex, non linear model.

The effect of TP load reductions on DO deficit occurrence is generally as expected. Reducing TP loads results in reductions in the extent, duration and magnitude of DO deficits. This indicates that at least qualitatively, the model is correctly representing the effect that reduced TP levels are expected to have on aquatic biomass growth and associated photosynthesis.

Further consideration should be given to optimizing water quality in the Grand River using the most cost-effective combination of point and nonpoint source controls. Minimization of costs to achieve water quality goals can only be obtained by considering the scope and costs for implementation of controls in both sectors.

The impact of annual loads (non summer) of phosphorus on summer growth of algae should be considered. If P loads associated with sediments in spring washoff are available in summer through recycling, contributing source processes such as agricultural land erosion will have to be considered in P control and trading plans. A strategy which recognizes all opportunities for effluent permit trading (or offsetting) could then be completed based on both annual and seasonal considerations.

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