

THE EVOLUTION OF WATER QUALITY IN LARGE HYDRO-ELECTRIC RESERVOIRS: A MODEL OF ACTIVE AND STAGNANT ZONES

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ABSTRACT

The decomposition of vegetation and soils affects water quality in hydro-electric reservoirs, primarily through nutrient enrichment and oxygen consumption. A model of such decomposition was constructed and applied to the LG-2 reservoir in the James Bay region of Québec, Canada. The model incorporated information on vegetation and soils existing prior to flooding, river flow rates, and flow patterns within the reservoir, examining both active and stagnant zones. Coefficients for solubilization and mineralization were calibrated to laboratory data coming from other researchers. The results of the model indicated a peaking of effects on water quality three years after impoundment in the active areas of the reservoir, with a return to ambient levels three years after the peaking. In the more stagnant areas of the reservoir, peaking occurred one year later, and at the end of six years phosphorus especially continued to differ significantly from pre-impoundment levels. There was fair agreement between model results and observed trends, but model predictions did not show seasonal patterns observable in the data, since stratification and turnover were not included in the model. In its present form the model is capable of giving fairly good predictions of water quality in the LG-2 reservoir. The inclusion of stratification effects could further improve model accuracy, and make it a useful tool in impact assessment for reservoir creation.

1. INTRODUCTION

The creation of a reservoir causes flooding of relatively large quantities of vegetation and soil. The subsequent decomposition of these materials enriches the water with nutrients and creates a demand on dissolved oxygen. Up to the present there have not been any methods available to predict quantitatively the changes in water quality for a proposed reservoir.

Maystrenko and Denisova [1] examined the decomposition of pulverized samples of a variety of vegetation and soil types in aquaria, and monitored nutrient concentrations in the water for up to three years. Serodes [2] studied short-term effects on dissolved oxygen of the decomposition of soils and trees both in situ and in aquaria. These results were used by de Broissia et al [3] to construct a relatively simple model of decomposition. They recognized, however, that a more detailed model of the kinetics of decomposition was needed. Thérien and Spiller [4] developed a detailed model of the kinetics of decomposition, and applied it to the results of Maystrenko and Denisova [1]. Thérien et al [5] refined their model and applied it to a small reservoir in

northern Québec. The same model was then applied to the huge LG-2 reservoir in northern Québec to evaluate the impacts of 4 different operating scenarios [6]. Certain deficiencies were noted in the spatial representation of the reservoir. A study of water flows within the reservoir [7] demonstrated that two sections of the reservoir were almost stagnant, with very slow currents and reduced water exchange with other parts of the reservoir.

This paper documents further refinement of the same model, incorporating an improved spatial representation of the reservoir. The model is applied over a baseline period to the end of 1984.

## 2. STUDY SITE

The La Grande hydroelectric project is located to the east of James Bay in northern Québec, Canada (Fig. 1). Phase I, nearing completion, involves the flooding of a total of 11 500 km<sup>2</sup> [8]. The area is taiga, characterized by stunted trees and sphagnum bogs.

The LG-2 reservoir was the first of the complex to be completed, with impoundment starting in late 1978 and the reservoir coming on-line in November 1979. The reservoir has a surface area of 2 800 km<sup>2</sup> and a generating capacity of 5 300 MW. Extensive surveys of vegetation were made prior to impoundment, as of course were hydrological studies. Also, water quality has been monitored at several sampling stations in the reservoir since 1977 (Fig. 2).

## 3. SPATIAL REPRESENTATION

There are two aspects to the spatial representation of the reservoir: the division of the reservoir into distinct water masses or zones, and the distribution of vegetation and soil within the zones.

### 3.1. Distinct Zones

Flow patterns in the reservoir [7] suggested considering the reservoir to be made up of 5 more or less distinct zones falling into 2 categories: active and stagnant. The 3 active zones were characterized by high water exchange rates due to inflows and interchange with each other. The 2 stagnant zones had low flows and reduced exchange with adjacent active zones. This division of the reservoir is shown schematically in Figure 3.

### 3.2. Distribution of Vegetation and Soil

Within each zone, the vegetation and soils were grouped into vertical strata at 10 m intervals (Fig. 4). Each stratum participated in the initial process of fragmentation and solubilization only when flooded. In addition, the initial process of leaching occurred only the first time a stratum was flooded.

## 4. MATHEMATICAL MODEL

For each of the five zones of the reservoir, changes in volume were represented as:

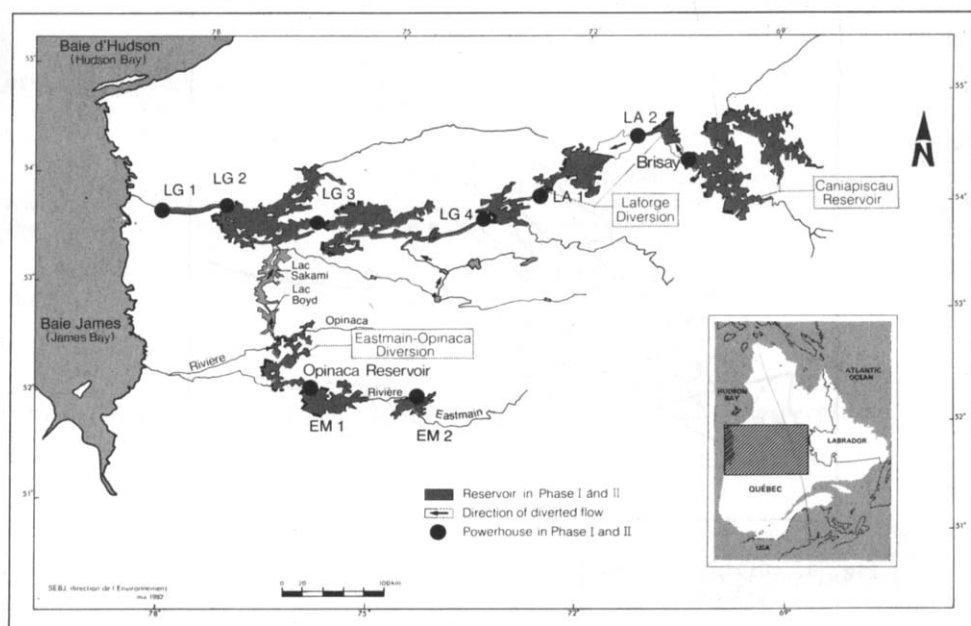


Fig. 1. The La Grande Hydroelectric Complex

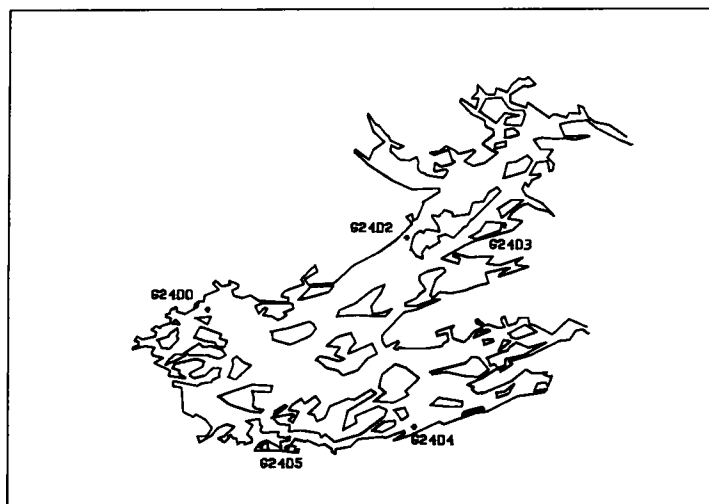


Fig. 2. Sampling Stations in the LG-2 Reservoir

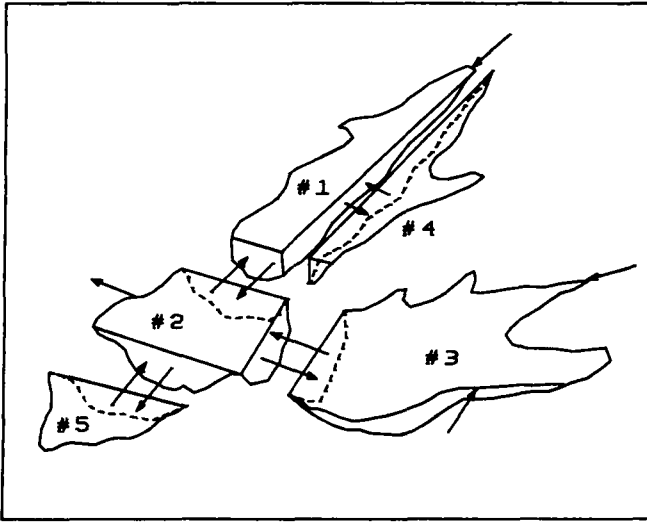


Fig. 3. Division of the LG-2 Reservoir into 5 Zones. Zones 1-3 are "Active", While Zones 4 and 5 are "Stagnant"

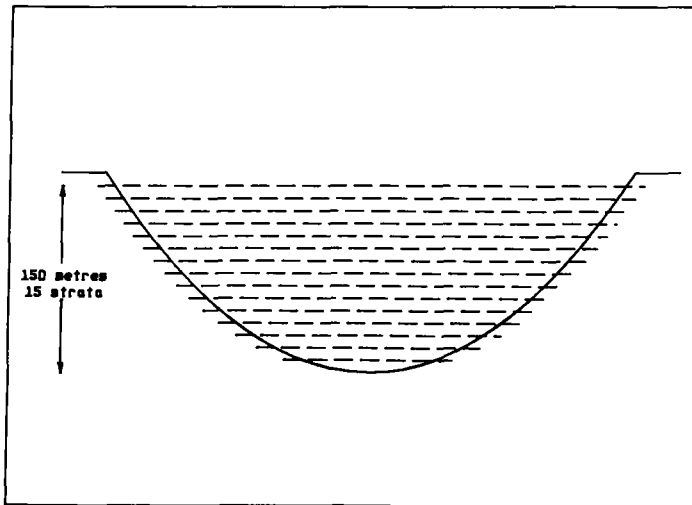


Fig. 4. Division of the Vegetation and Soils into 10-m Strata

$$\frac{dV_i}{dt} = \sum_{j=0}^5 (Q_{ji} - Q_{ij})$$

with  $V_i$ : volume of zone i

$Q_{ij}$ : volume of water transferred from zone i to zone j (note: zone 0 indicates a source or sink external to the reservoir).

For the two stagnant zones (4 and 5), we included additional flows to account for exchange with the adjacent active zones (1 and 2 respectively). The values for these flows were calibrated in the model.

For each water quality parameter a mass balance was carried out such that:

$$\frac{dV_i C_{ki}}{dt} = \sum_{j=0}^5 (Q_{ji} C_{kj} - Q_{ij} C_{ki}) + V_i B_{ki}$$

with  $C_{ki}, C_{kj}$ : concentration of parameter k in zones i and j respectively

$B_{ki}$ : biological and physical transformations affecting  $C_{ki}$  in zone i.

There were in fact 4 concentrations in influents to the reservoir. Two of these influents were from natural rivers and the other two were from reservoirs. To account for sedimentation of entrained particulates for the river flows upon entering the reservoir, the concentrations of carbon and phosphorus in both influents were reduced by 60% and 80% respectively. No such reduction was made to the influents from the reservoirs since sedimentation would already have occurred prior to entry into LG-2.

The compartment submodel for the biological and physical transformations is shown in Figure 5. The principal kinetics of decomposition were included. The total organic material flooded (TOMF) was fragmented and pulverized into particulate organic matter (POM). At first contact with water a certain amount of soluble material was leached directly into labile dissolved organic matter (DOM) and refractory humic material (HUM). DOM and HUM also received material from the solubilization of POM. Mineralization of DOM and HUM produced ammonium ( $NH_4$ ) and phosphate ( $PO_4$ ).  $NH_4$  was nitrified to produce nitrites-nitrates ( $NO_3$ ). Since most of these reactions were biological, oxygen ( $O_2$ ) was consumed and carbon dioxide produced. For these two gases there was also exchange with the atmosphere, but the  $CO_2$  compartment was treated only as a sink.

For each of the five zones in the reservoir three parallel submodels were considered: one for soils and one each for gymnosperm and angiosperm vegetation. The first two compartments (TOMF and POM) were considered by vertical strata, and were in terms of mass only. The others were considered as dissolved concentrations. More details on the submodel can be obtained from Thérien and Spiller [4] and Thérien [6], including rate formulations and coefficient values.

## 5. AGGREGATION OF STATE VARIABLES

The decomposition submodel is very detailed, and was originally calibrated to equally detailed data. However, the data available to us on water quality of the LG-2 reservoir was not as detailed. Data on phosphates were scarce, while total phosphorus was measured frequently. Concentrations of the nitrogen

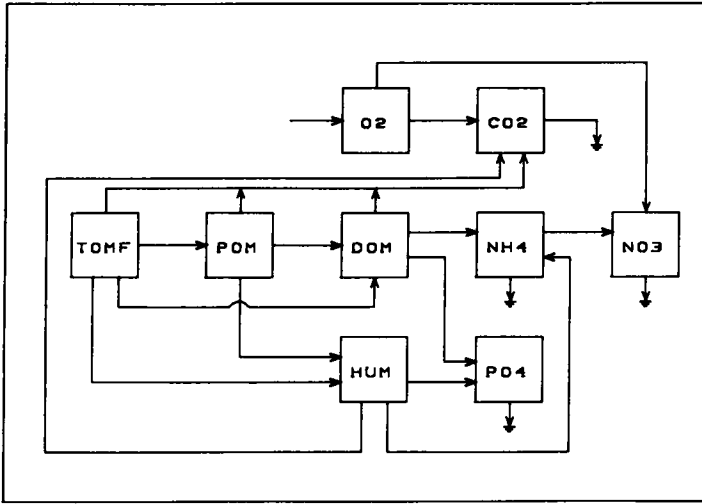


Fig. 5. Compartment Submodel for Decomposition of Soil and Vegetation

species hovered near the limits of detection, and so could not be compared reliably with model results. DOM and HUM were not measured as such, but measurements of organic carbon were available. Oxygen was the only state variable measured directly. This created difficulties also for consideration of inflows to the reservoir from rivers because there was no way to allocate the inflowing concentrations to the compartments of the different submodels.

To overcome these difficulties, two assumptions were made. The first was that inflowing carbon and phosphorus (and in fact nitrogen) were not taking part in the decomposition processes, and for them it was a simple mass balance situation. The second assumption was that fixed percentages of DOM and HUM compartments were composed of carbon and phosphorus. Therefore the model outputs were oxygen, organic carbon and total phosphorus. For phosphorus, for example, this means:

$$PTOT_i = \sum_{j=1}^3 (P_h HUM_{ji} + P_d DOM_{ji} + PO4_{ji}) + PND_i$$

with  $PTOT_i$ : total phosphorus concentration in zone  $i$   
 $P_h, P_d$ : proportion of phosphorus in HUM and DOM respectively  
 $HUM_{ji}, DOM_{ji}$ : concentrations of HUM and DOM respectively for submodel  $j$  (1 soil type and 2 vegetation types) in zone  $i$   
 $PO4_{ji}$ : phosphate concentration for submodel  $j$  in zone  $i$   
 $PND_i$ : concentration of non-decomposing phosphorus in zone  $i$

## 6. MODEL SIMULATION

The model has been run for the period of 1/11/78 to 31/12/84. For the inflows and inflowing concentrations data were interpolated between observation

points. For the final 1.5 years data were not available, and past observed cycles were repeated for this period.

The program is written in FORTRAN IV, requires less than 108 K of memory, and takes the equivalent of 100 seconds on an IBM 370/158 to execute.

## 7. RESULTS

Simulation results for organic carbon, total phosphorus and dissolved oxygen are shown in Figures 6, 7 and 8 respectively. All concentrations are in mg/l.

For organic carbon there is an initial pulse, especially in zone 1. Aside from this, the concentrations peak in 1981 in zones 1-3, and in 1982 in zones 4 and 5. Total phosphorus peaks at the same times in the same zones. For dissolved oxygen there is a noticeable seasonal effect (low in summer, high in winter). Aside from this, the general trend in zone 1 is for a minimum in 1981 followed by an increase. Zones 4 and 5 show the same trend. Zones 2 and 3 show a continuing decline over the simulation period.

## 8. DISCUSSION

### 8.1 Baseline Simulation

For organic carbon a point should be made prior to discussing the results. Zones 1-4 exhibit a peak in carbon in 1979, something not predicted by the model. Such a peak was noted throughout the territory, including unperturbed lakes. This peak would therefore seem to be due to external factors, possibly atmospheric.

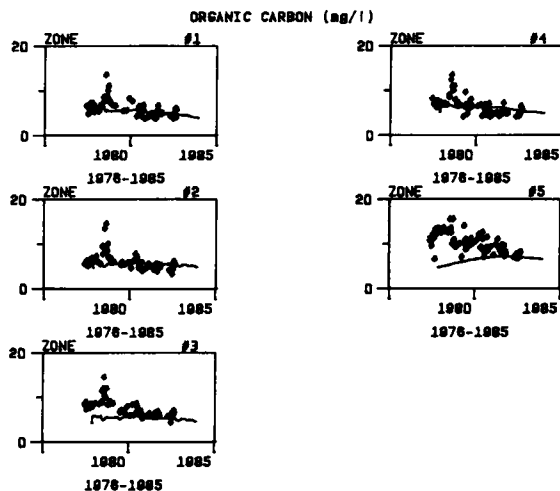


Fig. 6. Observations and Model Predictions for Organic Carbon

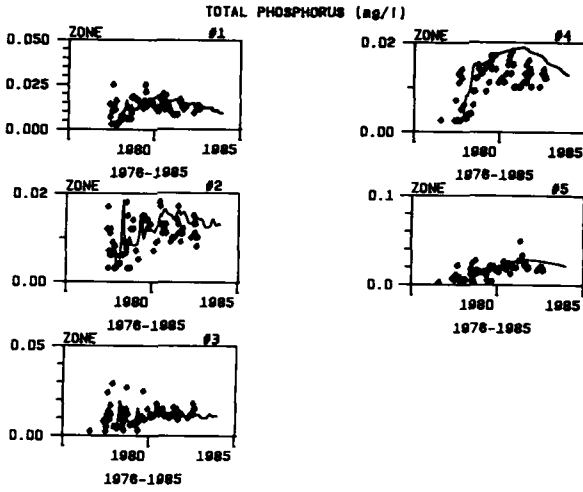


Fig. 7. Observations and Model Predictions for Total Phosphorus

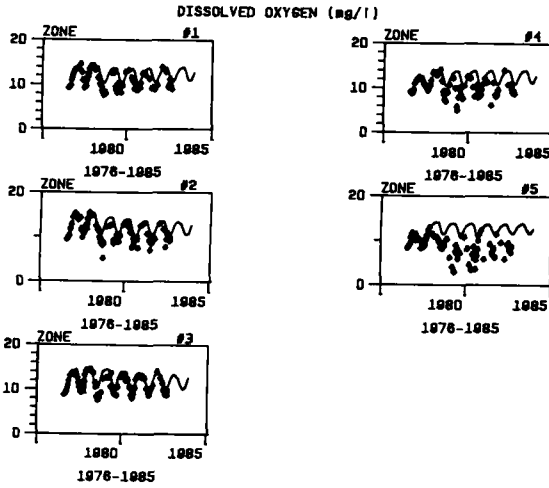


Fig. 8. Observations and Model Predictions for Dissolved Oxygen

Other than this, the trends predicted by the model are in some agreement with observed trends at all zones except zone 5. Here there is an extreme underestimation. For the other zones there is a seasonal pattern in the data not well reflected by the model. This is most likely due to a lack of summer stratification in the model. During stratification most decomposition will occur in the hypolimnion, and thus the lower strata will contain most of the nutrients. Over the summer the nutrients in the epilimnion will be consumed with only minor replenishment. At turnover, the entire water column is mixed and nutrients in the epilimnion are replenished for the next period of stratification. Periods of turnover will correspond to maxima in nutrients in the surface waters. The model does follow the observed maxima in zones 1-4.

An exception to this is the first two years in zone 3. There the model underestimates carbon levels by about 30%. For zone 5 the model underestimates carbon greatly until the last year of the simulation. We will return to a discussion of zone 5 further on.

For total phosphorus the model shows very good agreement with the trends in the data for all zones. As with carbon, the predictions follow the maxima of the observations, and the same comment on turnover applies here.

For dissolved oxygen the model predictions follow the observed winter maxima fairly well for zones 1-3, but do not drop to the observed minima. This is an especially strong indication of the importance of turnover, since the minima will correspond to the mixture of surface water with the oxygen-starved water of the hypolimnion. For zone 4 there is some overestimation of even the maxima, while overestimation is severe for zone 5.

Whether the two stations in the stagnant zones are representative or not is questionable. They are both somewhat isolated from the zones in which they are included, especially G2405 for zone 5. This station is located in a relatively small lake connected to the reservoir by a .5 km-wide channel. Even before the surrounding land was flooded due to a raised water level, this lake had a high input of allochthonous carbon (as can be seen from the organic carbon concentrations before flooding). The model does not have the spatial refinement to account for such a localized situation. Since the model does not account for this very localized input, it cannot predict the increased oxygen consumption either, thus explaining the overestimation of oxygen. Unfortunately, G2405 is the only station in zone 5. Station G2403 in zone 4 is also somewhat isolated from the rest of the associated zone, although this isolation is less pronounced. The station is located in the mouth of a bay on the east side of that zone. Even G2404 may not be a good representative of zone 3. It is at the southern edge of this zone. However, currents in zone 3 are fast and a great deal of mixing occurs here. For zones 1 and 2, the stations are centrally located and should represent conditions adequately.

## 9. CONCLUSIONS

The model is capable of predicting with fairly good accuracy the evolution of organic carbon, total phosphorus and dissolved oxygen in a large reservoir following flooding. Predictions depart from observations in one zone in particular, but the sampling station in this zone appears to be atypical. In its present form the model can be adapted easily to any projected reservoir if appropriate pre-inundation data are available.

The inclusion of stratification would improve the fidelity of the model even further for reservoirs where stratification will occur. This would effec-

tively double the number of differential equations to be solved, but that should not present great difficulties as the memory and execution time requirements of the model are modest.

The model represents a very powerful tool for assessing the impact of reservoir creation. Different operating scenarios can be compared easily by changing flow rates and/or surface areas and volumes to be flooded.

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