# OXYGEN MODELLING UNDER RIVER ICE COVERS

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## ABSTRACT

Downstream declines in dissolved oxygen (DO) occur in ice-covered rivers as a result of limited reaeration, inputs of oxygen-depleted groundwater and oxidation of organic matter. Increased municipal and industrial development may further decrease under-ice DO concentrations since sewage and industrial effluent are often anaerobic and have high biochemical oxygen demands (BOD). In February-March 1989, Alberta Environment initiated annual winter water quality surveys along the length of the Athabasca River, Alberta, Canada to monitor the impact of effluent from one pulp mill and four sewage discharges on instream DO and evaluate the potential impact of four additional mills slated for start-up between 1988 and 1993. Results from these studies showed that dissolved oxygen concentrations were greatest at the headwater of the river, averaging 11.8 ± 0.3 mg/L (x±S.E, n=4; January/February 1989-1992) and lowest approximately 800 km downstream (8.5 ± 0.5 mg/L, n=4, February/March 1989-1992). Thereafter, concentrations returned to near-saturation values as a result of reaeration in an open-water zone of turbulent mixing. Water quality simulation models were tested for predicting under-ice dissolved oxygen concentrations from river discharge and effluent biochemical oxygen demand (BOD) loads. These models are used in setting industrial discharge standards and evaluating the impact of changes in effluent loading on water quality.

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*Proceedings of the Workshop on Environmental Aspects of River Ice, T.D. Prowse (Editor), National Hydrology Research Institute, Saskatoon, Saskatchewan, 1993, NHRI Symposium Series No. 12, p. 235-260.*

## INTRODUCTION

Depression of dissolved oxygen (DO) during winter is a common occurrence in rivers which experience ice cover. Severe DO depletions had been noted as early as the mid-1940's in streams and rivers in Russia (Hynes 1970 after Mosevich 1974, Mossewitsch 1961) while in North America, one of the earlier accounts dates from the 1960's for rivers in Alaska (Schallock and Lotspeich 1974). The cause of DO depletion under ice-cover is generally attributed to three factors: (1) lack of reaeration due to ice cover, (2) inputs of oxygen-depleted groundwater, and (3) oxidation of organic material. However, while the importance of these factors in controlling under-ice depletion has long been recognized, little information is available on the relative roles of these factors and the impact that anthropogenic loading of organic material and oxygen-consuming substances may have in further depleting winter DO concentrations. Given the large-scale developments on many northern rivers (e.g. mining, timber harvesting and pulp mills, gas and oil extraction and changes in landuse patterns), the factors controlling natural declines in DO under-ice need to be identified and quantified in order to improve predictions of the impact of development on winter DO concentrations.

This paper presents results from an on-going study to determine the factors controlling DO depletion in the Athabasca River, Alberta, Canada under ice cover and to develop a quantitative model for predicting the impacts of effluent (municipal and pulp mill) loading on DO. This work forms part of a larger study, the Northern River Basins Study (NRBS), which is a joint initiative between Alberta Environment and Environment Canada aimed at gathering comprehensive information on water quality, fish and fish habitat, riparian vegetation and wildlife, hydrology and use of aquatic resources for the Peace, Athabasca and Slave River basins. This information will form a database to be used to predict and assess the cumulative effects of development on the water and aquatic environment of the Peace, Athabasca and Slave Rivers within Alberta and the Northwest Territories. In this paper, results from monitoring programs undertaken by Alberta Environment are used to determine the status of DO in the Athabasca River and assess predictive models for evaluating the impact of human activity on under-ice DO levels.

## DISSOLVED OXYGEN - IT'S SIGNIFICANCE AND REGULATORY GUIDELINES

While it is obvious that little or no DO would be lethal to fish and other organisms, the effect of DO on aquatic organisms is not simply an "all or nothing" response (e.g. Davis 1975). For most aquatic organisms, including aquatic insects and fish, lethal DO concentrations range between 1-3 mg/L (Doudoroff and Shumway 1967, Nebeker 1972, Gaufin 1973), however reductions in fish growth rates occur in response to decreases in DO even when concentrations are well above lethal limits (Table 1). Moreover, reductions in DO concentration increase the toxicity of many contaminants (Sprague 1985, Birtwell 1989). For example, toxicity of kraft mill effluent to juvenile coho salmon is inversely related to DO concentration such that median survival time in 33% effluent decreased from 27 to 11 h as DO concentrations decreased from 6.6 to 3.4 mg/L (Hicks and DeWitt 1971; Figure 1). In recognition of the direct and indirect effects of DO concentration on the survival and development of fish and other aquatic organisms, the Canadian Council of Ministers of the Environment have recommended guidelines for the protection of fisheries and plant life, protection against the onset of septic conditions and to enable the waterbody to assimilate organic material adequately (Table 2).

## METHODS

### Site Description

The Athabasca River originates in the Rocky Mountains of west-central Alberta, Canada and flows northeast across Alberta to Lake Athabasca where it joins with the Peace River to form the Slave River (Figure 2). The latter flows into Great Slave Lake which drains via the Mackenzie River to the Beaufort Sea. The Athabasca River is not regulated. Mean daily flows at the Town of Athabasca average 440 $m^3/s$ (1952-1988) with peak flows occurring in June after mountain snow-pack melt (1046 $m^3/s$ June monthly mean, 1952-1988) and lowest flows in February (92 $m^3/s$ February monthly mean, 1952-1988) (Environment Canada 1989).

As of August 1993, three chemi-thermomechanical pulp mills and one kraft pulp mill operated in the Athabasca basin with another kraft mill under construction (Table 3). The mills discharge effluent for which the five-day biochemical oxygen demand ($BOD_5$) totalled 4931 kg/d (1991). With the exception of the kraft mill which commenced operation in Hinton in 1957, all have come on line since 1988. In addition to pulp mill activity, there are five municipalities and one oil sands project that discharge continuously to the Athabasca River (Table 4). Other activities in the basin include four active coal mines, at least 53 gas plants, another oil sands project and 12 gravel-washing enterprises; however, all have little or no discharge.

## Field Sampling and Analytical Methods

Water quality surveys of the Athabasca River were conducted by Alberta Environment during the 1990, 1991 and 1992 winters (14 February - 21 March 1990, 7 February - 14 March 1991 and 30 January - 10 March 1992) from upstream of Hinton (0.1 km upstream of the Weldwood of Canada Ltd. pumphouse, UTM coordinates 11 460950E 5917950N) to Lake Athabasca (Athabasca River at Big Point Channel, UTM coordinates 12 511200E 6496100N), a distance of 1243 river kilometers. Approximately 70 stations, including mainstem, tributary and effluent ("end-of-pipe") discharges, were sampled in a downstream order at time intervals corresponding to the water time-of-travel (see Noton & Shaw 1989 for details). All samples were analyzed for $BOD_5$; river and tributary samples were also analyzed for DO. River samples were generally collected from holes drilled through the ice in the centre of the channel. Tributaries were sampled near their confluence with the Athabasca River except for the Lesser Slave River which was sampled at the river mouth as well as three additional locations along its length. Effluent samples were collected upstream of the discharge point for every industry and municipality discharging to the river. Pulp mill samples were 24 h composites; all other industrial and municipal samples were grab samples. River and tributary samples for Winkler DO analysis were collected in duplicate with a displacement-type APHA sampler

(APHA 1985); instream samples for $BOD_5$ were collected as a grab below the ice surface. DO samples were fixed on site and titrated within 24 h following the azide-Winkler method (APHA 1985). $BOD_5$ samples were collected in glass bottles, stored at 4 °C and analyzed within 24 h at Chemex Labs Alberta Inc. following APHA (1985).

## DO Simulation Modelling

The dissolved oxygen simulation model DOSTOC (Dissolved Oxygen STOCastic model) has been widely used during the past six years by Alberta Environment to predict impacts of anthropogenic loadings on water quality in rivers. DOSTOC is a steady-state, one-dimensional model based on the system of ordinary differential equations developed by Streeter and Phelps in 1925 and described by, for example, Thibodeaux (1979). DOSTOC was developed in 1987 for the Planning Division of Alberta Environment by HydroQual Consultants Inc. and Gore & Storrie Ltd. (1987; Zielinski 1988). The original Streeter-Phelps equations were modified to include the major sources and sinks of oxygen in river processes, including atmospheric reaeration, consumption of DO as a result of the conversion of $NH_3$ to $NO_3$ (nitrogenous oxygen demand, NOD), consumption of DO by degradation of organic material (biochemical oxygen demand, BOD), production/consumption of DO as a result of plant photosynthesis and respiration, and consumption of DO at the streambed by benthic organisms and chemical processes (sediment oxygen demand, SOD) (Figure 3). In 1989, HydroQual Consultants Inc. calibrated DOSTOC to Athabasca river data collected during five water quality surveys from the 1988 and 1989 winters (Macdonald and Hamilton 1989). They assumed that there were two types of BOD in the river, namely background river BOD including that derived from headwaters and tributaries and effluent BOD including municipal and industrial effluents, and that each type had a different decay rate and ratio of ultimate biochemical oxygen demand ($BOD_u$) to $BOD_5$. In addition, the variable intended for respiration was treated as SOD.

Since the 1989 calibration, additional in situ and laboratory studies have been undertaken to refine and verify previously-measured model rates or to determine values for previously unmeasured rates. Using the recently available data, we calibrated DOSTOC with rate constants derived from field or lab measurements (Table 5). The approach whereby a model is calibrated with rate constants derived from field or laboratory experiments is useful in that discrepancies between model predictions and observed values identifies limitations in the models representation of the system or in the database (e.g. Gobas et al. 1989). The hydrologic structure (i.e., division of river into 9 hydraulic reaches and the calculation of Leopold-Maddock coefficients for estimating travel time and average depth for each reach) developed by Macdonald & Hamilton (1989) was maintained. The only rate constant in the model that was not calibrated by direct measurement was atmospheric reaeration at Grand Rapids, a 10 m cascade located 817 km downstream of Hinton, for which the reaeration rate was arbitrarily set to a value sufficient to increase DO to the concentration observed at the first downstream station. Diffuse loadings and BOD sedimentation rates were set to zero as there were no data for the Athabasca River. However, as the simulations were run with winter data when air temperatures are < 0°C, it is unlikely that diffuse loadings from overland run-off contributed a substantial BOD load. Diffuse loadings from groundwater were also likely minor as discharge at the headwater and from gauged tributaries summed to between 85 and 106% of the discharge measured in the river 960 km downstream of the headwaters.

Estimates of standard error:

$$RMS=\sqrt{\frac{1}{n}\sum(DO_{estimated}-DO_{observed})^2} \tag{1}$$

and coefficients of determination:

$$r^2=1-\frac{\sum(DO_{estimated}-DO_{observed})^2}{\sum(DO_{observed}-DO_{average})^2} \tag{2}$$

were calculated for the 808 km between Hinton and Grand Rapids, and were used to assess goodness of fit. Negative $r^2$ values are not possible in a maximum-likelihood least squares regression analysis. However, comparisons of observed values and predictions from a model that is not a least squares regression can result in negative $r^2$ values. Negative values signify that the model prediction is worse than simply using the mean observed value as an estimate.

## Empirical Modelling

Regression equations were developed relating 1990, 1991 and 1992 DO concentrations to river distance for the reach from upstream of Hinton to upstream of Grand Rapids (a distance of 808 river km). The DO concentration at the most upstream site, hereafter referred to as the Headwater DO concentration, was subtracted from each of the downstream values and Headwater DO was substituted into the equation in place of the intercept. The data were statistically analyzed with SAS (1988). Estimates of standard error and coefficients of determinations were used to assess the models' predictive capabilities.

# RESULTS

## BOD and DO Profiles

$BOD_5$ loads from pulp mills discharging to the Athabasca River totalled 3955, 2892 and 2979 kg/d for the 1990, 1991 and 1992 winter water quality surveys, respectively (Figures 4, 5 and 6). Municipal $BOD_5$ loads were small except for Fort McMurray which discharged an average of 212 kg/d (n=3, 1990-92 winter surveys). Loads for tributaries without effluent discharges ranged from < 1 to 2135 kg/d $BOD_5$, with the Clearwater River representing the largest tributary load. $BOD_5$ loads were also high in 1991 and 1992 for the Lesser Slave River, however this value is attributable in part to the Slave Lake Pulp Corp. which began operations in December 1990 and discharged 311 and 58 kg/d $BOD_5$ during the 1991 and 1992 winter surveys, respectively, to the Lesser Slave River 50 km upstream of the Athabasca confluence.

DO concentrations in the Athabasca River decreased steadily from between 11.6 and 12.5 mg/L upstream of Hinton to between 8.7 and 9.5 mg/L upstream of Grand Rapids, a distance of 808 km (1990-92 winter surveys; Figures 4, 5 and 6).

Downstream of the rapids, DO concentrations were greater (12.2 to 12.7 mg/L) than upstream of Hinton but decreased to between 10.2 and 11.2 mg/L over a distance of 394 km.

## DO Modelling

DO concentrations in the Athabasca River decreased linearly from upstream of Hinton (river km 0) to upstream of Grand Rapids (river km 808). Regression equations relating DO concentration in the Athabasca River to river distance for each year are:

1990 $$\text{DO} = -0.00307\ \text{Distance} + (\text{Headwater DO}) \tag{3}$$

$(\underline{r}^2 = 0.74;\ \underline{P} < 0.0001;\ \underline{n} = 24)$

1991 $$\text{DO} = -0.00437\ \text{Distance} + (\text{Headwater DO}) \tag{4}$$

$(\underline{r}^2 = 0.92,\ \underline{P} < 0.0001;\ \underline{n} = 24)$

1992 $$\text{DO} = -0.00391\ \text{Distance} + (\text{Headwater DO}) \tag{5}$$

$(\underline{r}^2 = 0.96,\ \underline{P} < 0.0001;\ \underline{n} = 20)$

where DO is dissolved oxygen concentration (mg/L), Headwater DO is the dissolved oxygen concentration (mg/L) for the Athabasca River upstream of Hinton and Distance is the distance (km) downstream of the most upstream sampling site (Headwater equals river km 0). Despite considerable BOD loads from tributary and anthropogenic sources, the coefficients of determination for all three relationships were surprisingly good ($\underline{r}^2 \geq 0.74$) and highly significant ($\underline{P} < 0.0001$). Regression slope did not differ significantly (ANCOVA: $\underline{F} = 2.60$, $\underline{P} = 0.08$) among years, indicating that a major factor determining DO concentration in the river during these years was Headwater DO concentration. The data for the three years pooled to give the following relationship:

$$\text{DO} = -0.00374\ \text{Distance} + (\text{Headwater DO}) \tag{6}$$

$(\underline{r}^2 = 0.85;\ \underline{P} < 0.0001,\ \underline{n} = 68)$.

The water quality simulation model DOSTOC was less successful at predicting DO in the river (Figures 4, 5 and 6). Comparison of the DOSTOC model runs and linear regression showed that coefficients of determination were consistently greater for regression than simulation modelling (Table 5). Moreover, in the case of the 1990 and 1992 data sets, the DOSTOC model was less successful at predicting DO than simply using the mean value of all observed data as an estimate (i.e. a negative $\underline{r}^2$ value). The standard error of the models was, on average, two-fold less for regression than simulation modelling. While DOSTOC was less successful than linear regression modelling at predicting DO concentrations in the Athabasca River for 1990-92, sensitivity analyses of DOSTOC also identified headwater DO loading as the most sensitive input variable for prediction of river DO concentration (Macdonald and Radermacher, 1993; Pietroniro, Scrimgeour & Chambers, in prep.).

## DISCUSSION

DO concentrations in the Athabasca River decreased from 11.8±0.3 mg/L (x±S.E., $\underline{n}=3$; 1990-1992 winter surveys) to 8.5±0.5 mg/L over a distance of 808 river km. Thereafter, concentrations returned to near-saturation values as a result of reaeration in an open-water zone of turbulent mixing. Within this 808 km reach, $BOD_5$ loadings averaged 3275, 469 and 3519 kg/d (January-February 1990-1992) for pulp mills, municipal and other industrial sources, and tributaries, respectively. The 0.004 mg/L/km decrease in DO in the Athabasca River is less than values observed for other ice-covered rivers. For example, under-ice DO concentrations in the Yukon River, Alaska decreased by 0.005 mg/L/km (March 1971) while in the Chena River, Alaska DO concentrations decreased by 0.028 mg/L/km (January-February 1968) (Schallock and Lotspeich 1974). DO concentrations in the Tu Men River in northern China decreased by 0.179 mg/L/km along a 37 km reach receiving $2\times10^5$ tonnes of industrial and municipal wastewater per day (Ranjie and Huimin 1987).

Linear regression and simulation (DOSTOC) models were fit to the DO data for the 1990, 1991 and 1992 winters. Comparisons of predicted versus observed values for both models showed that despite running the DOSTOC model with measured process rates and input data, the linear regression models were a better fit to the data (Table 6). The linear decline in DO, particularly for 1991 and 1992, is surprising given the fact that anthropogenic $BOD_5$ loads to the river average 3744 kg/d. This observation suggests that the effect of the current loadings is overshadowed by natural loads to the river or to natural instream processes that consume or replenish oxygen. This conclusion is consistent with the finding that for both the regression and simulation models, headwater DO was an important variable predicting downstream DO concentrations.

In conclusion, our results indicate that for the 1990-1992 winters, DO decay over a 808 km distance in the Athabasca River is approximately linear and can be represented by simple linear regression. Predictions from a mechanistic model calibrated with measured rates were less reliable. This finding indicates that despite inclusion of the dominant processes known to control riverine DO concentrations in the simulation model (i.e. reaeration, sediment oxygen demand and BOD decay) and actual measurements of both rates and input data (i.e. headwater and tributary DO and $BOD_5$ concentrations; municipal and industrial $BOD_5$ concentrations; tributary, mainstem, industrial and municipal discharge rates; time of travel), our knowledge of the system and DO kinetics is insufficient to accurately simulate oxygen dynamics and thereby predict river DO concentrations. This may be due to limited understanding of the processes regulating DO in ice-covered rivers and/or limitations in the existing database (particularly measurements of SOD and reaeration). While our regression model cannot be used to forecast river DO concentrations under different loading scenarios (e.g introduction of new sources of BOD loading such as the start-up of another industry), it provides a useful tool for predicting year-to-year variation in river DO concentrations in response to headwater variability under a stable loading regime. Given the costliness of running a winter water quality monitoring program and measuring DO process rates, a thorough analysis of existing data is advisable before embarking on the use of parameter-rich simulation models to predict water quality when, under steady-state conditions, simple regression models may work just as well.

## ACKNOWLEDGEMENTS

We thank L. Noton and I. Mackenzie, Alberta Environmental Protection for their reviews and for providing the Alberta Environment water quality data. This study was funded in part by the Northern River Basins Study, Edmonton, Alberta, Canada.

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Table 1. Percent reduction in growth rate in relation to dissolved oxygen concentration (after Barton & Taylor (1994) from JRB Associates 1984).

| **DO (mg/L)** | **Chinook Salmon**[1] | **Coho Salmon**[2] | **Trout (Rainbow, Brown, Lake)**[3] |
|---|---|---|---|
| 9 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 |
| 7 | 1 | 1 | 3 |
| 6 | 7 | 4 | 7 |
| 5 | 16 | 11 | 15 |
| 4 | 29 | 21 | 26 |
| 3 | 47 | 37 | 40 |

[1] median temperature 15°C
[2] median temperature 18°C
[3] median temperature 12°C

Table 2. Canadian Council of Ministers of the Environment (CCME) objectives for Dissolved Oxygen (DO).

| **Life Stage** | **DO (mg/L)** | |
|---|---|---|
| | **Warm-water Biota** | **Cold-water Biota** |
| Early life stages | 6 mg/L | 9.5 mg/L |
| Other life stages | 5 mg/L | 6.5 mg/L |

Table 3. Pulp and paper mills in the Athabasca River drainage basin, their production and operating characteristics.

| Location | Company | Mill Type | Start Up | Effluent Treatment | 1991 Production (ADt/d[1]) | 1991 Discharge ($m^3$/d) | 1991 $BOD_5$ (mg/L) |
|---|---|---|---|---|---|---|---|
| Hinton | Weldwood of Canada Ltd. | Kraft Pulp | 1957<br>Expansion 1990 | ASB[2] | 1,033 | 111,965[3] | 23.8 |
| Whitecourt | Alberta Newsprint Co. Ltd. | CTMP[4] & Paper | Aug. 1990 | Extended Aeration AST[5] | 519 | 15,612 | 10.1 |
| Whitecourt | Millar Western Pulp Ltd. | CTMP | Aug. 1988 | Extended Aeration AST | 611 | 12,699 | 89.1 |
| Slave Lake | Slave Lake Pulp Corp. | CTMP | late 1990 | Extended Aeration AST | 232 | 3,904 | 250.3 |
| Athabasca | Alberta-Pacific Forest Industries Inc. | Kraft Pulp | Sept. 1993 | Extended Aeration AST | | | |

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[1] ADt/d = air dried tonnes per day

[2] Aerated Stabilization Basin

[3] Hinton municipal sewage (population 9046 in 1991) is combined and discharged with Weldwood effluent

[4] Chemi-thermomechanical pulp

[5] Activated Sludge Treatment

Table 4. Continuously discharging effluents from municipal and other sources to the Athabasca River. (Hinton municipal effluent discharged with Weldwood of Canada Ltd. effluent.) Discharge and $BOD_5$ values represent the mean of three instantaneous samples collected during the 1990-92 winter water quality surveys unless otherwise noted.)

**(a) Municipal sources**

| Source | Treatment | Receiving Water | Discharge ($m^3/d$) | $BOD_5$ (mg/L) |
|---|---|---|---|---|
| Jasper | Aerated lagoon | Athabasca River | 5,700[1] | |
| Whitecourt | Mechanical | McLeod River | 3,456 | 20.7 |
| Slave Lake | Aerated lagoon | Lesser Slave Lake | 2,534 | 21.4 |
| Athabasca | Aerated lagoon | Athabasca River | 893 | 13.2 |
| Fort McMurray | Aerated lagoon | Athabasca River | 12,874 | 15 |

**(b) Other Sources**

| Source | Receiving Water | Discharge ($m^3/d$) | $BOD_5$ (mg/L) |
|---|---|---|---|
| Suncor Inc. Athabasca Oil Sands Project | Athabasca River | 27,504 | 8.2 |

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[1] after Tones (in prep.)

Table 5. Sources of data for DOSTOC runs.

| **Parameter** | **Source of Data** |
|---|---|
| Atmospheric reaeration | 0.001 for ice-covered reaches; 0.74 $day^{-1}$ for open-water leads (after Macdonald et al. 1989) |
| BOD decay rate | Mean annual (n = 2 to 16 for each mill for each year) decay rates for mill effluent obtained from each pulp mill. Decay rates set to 0.026 $day^{-1}$ for sewage and other effluent (mean of two samples from one sewage effluent) and 0.026 $day^{-1}$ for tributaries and headwater (mean of 12 samples from 4 sites in the Athabasca basin). |
| BOD sedimentation rate | No data; set to 0.001. |
| $BOD_5$ | Industrial, sewage, headwater and tributary data collected during the Alberta Environment synoptic surveys |
| $BOD_u$:$BOD_5$ | Mill effluent ratios (n = 2 to 16 for each mill for each year) obtained from the pulp mills. Ratio set to 7.80 for sewage and other industrial effluent (mean of two samples from one sewage efflutent) and to 8.03 for tributaries and headwater (mean of 12 samples from 4 sites in the Athabasca basin). |
| Diffuse loading | No data; set to 0. |
| DO | Collected during the Alberta Environment synoptic surveys. |
| Nitrogenous oxygen demand (NOD) | No data; set to 0. |
| Effluent discharge | Obtained from the industries and the sewage facilities. |
| River discharge | Obtained from Technical Services Division, Alberta Environment and Water Survey of Canada. |
| Sediment oxygen demand (SOD) | SOD ($mg/m^2/d$) was measured in situ during the 1989, 1990, 1992 and 1993 winters (Casey & Noton 1989; Casey 1990; Monenco Inc. 1992; HBT Agra Ltd. 1993a,b). There was no significant difference in SOD between years for any site ( $P > 0.1$; 3 or 4 years of data for 4 sites, January and February data for 48 h runs). Mean values were calculated for each site and, for sites where SOD was not measured, values were extrapolated from a plot of SOD versus river distance in which the nearest sites upstream and downstream of the site without SOD measurements were connected with a straight line. SOD was relatively constant for four sites between river km 447 and 615 ($0.169 \pm 0.063$ $mg/m^2/d$; mean±S.D., $n = 6$) and, for lack of further downstream data, this value was assigned to all sites further downstream. To meet the requirements of the model, areal SOD rates were then converted to volumetric values (mg/L/d) by multiplying by the average water depth of the reach. |
| Time of travel | From Macdonald & Hamilton (1989). The Athabasca River was divided into nine hydraulic reaches. Leopold-Maddock coefficients were derived for each reach from HEC-2 simulations using under-ice time-of-travel and river cross-sections measured by Andres et al. (1989) and Haufe & Croome (1980). The Leopold-Maddock were then used to estimate reach-average travel time and reach average depth. |

Table 6. Comparison of DOSTOC simulation models and linear regression models for dissolved oxygen in the Athabasca River from upstream of Hinton to upstream of Grand Rapids, Alberta. (RMS = residual mean square or standard error; $r^2$ = coefficient of determination.)

| Year | DOSTOC | | LINEAR REG. | |
|---|---|---|---|---|
| | RMS | $r^2$ | RMS | $r^2$ |
| 1990 | 1.25 | -0.76 | 0.26 | 0.74 |
| 1991 | 0.89 | 0.44 | 0.13 | 0.92 |
| 1992 | 1.67 | -1.49 | 0.05 | 0.96 |

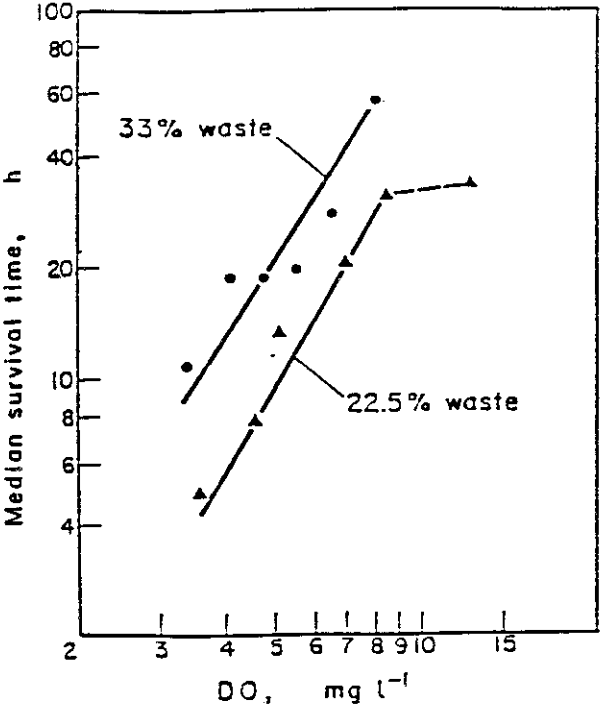

Figure 1. Survivorship of juvenile coho salmon in relation to the concentration of kraft pulp mill effluent (33 and 22.5 % dilution). (From Hicks & DeWitt 1971).

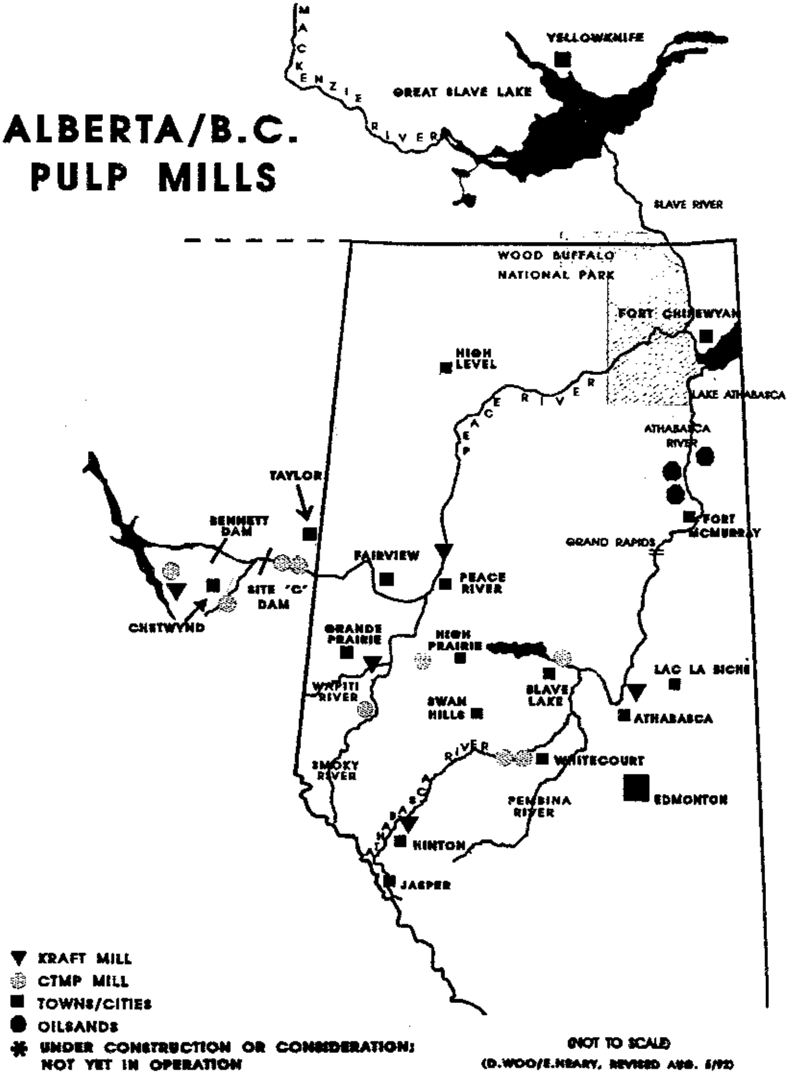

Figure 2. The Peace and Athabasca rivers showing location of municipal, pulp mill and other industrial discharges.

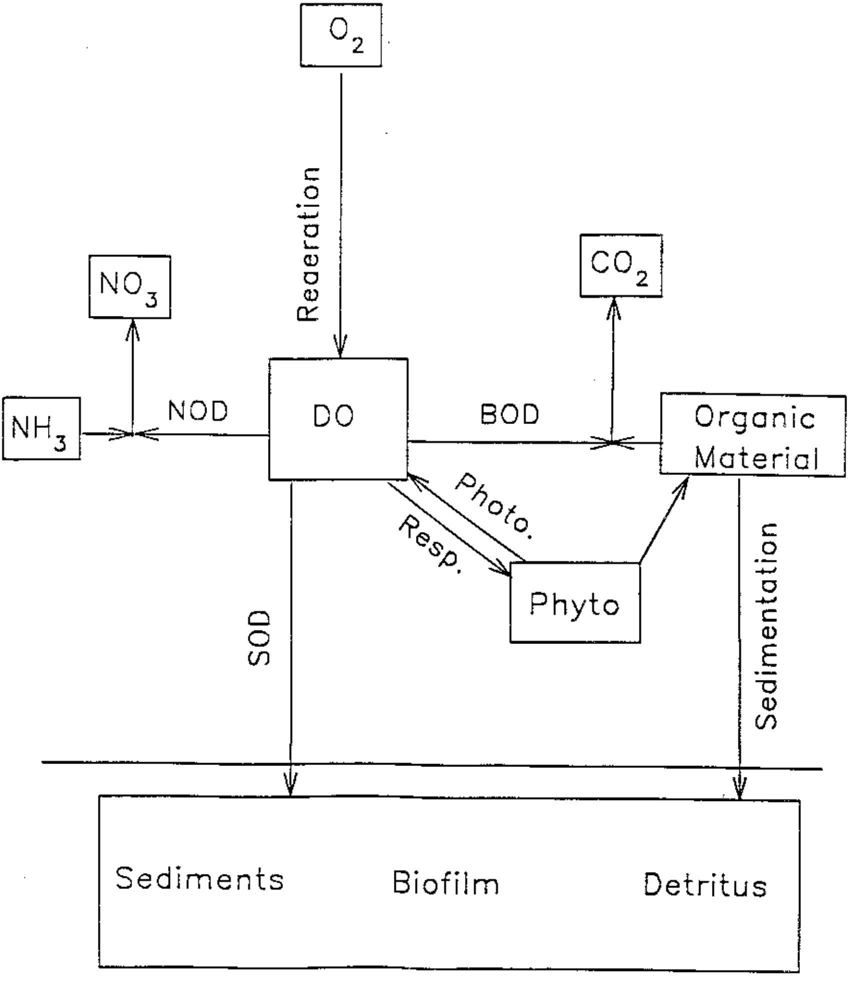

Figure 3. Dissolved oxygen cycle as modelled in the simulation model DOSTOC.

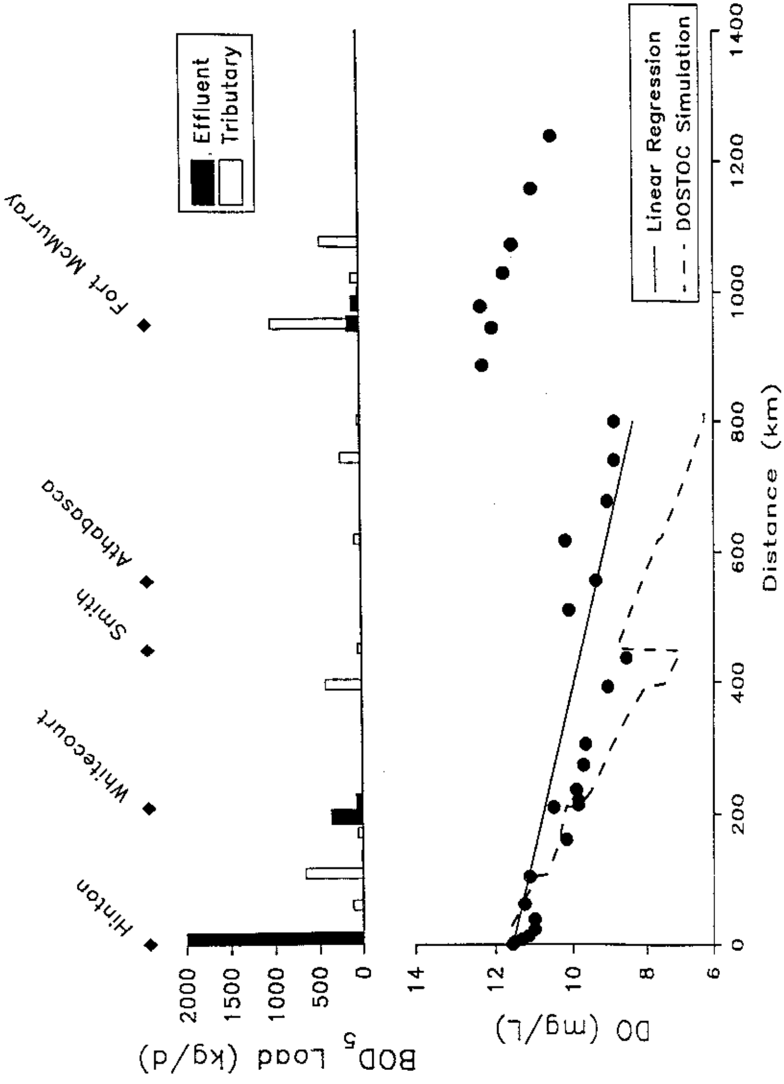

Figure 4. Five-day biochemical oxygen demand ($BOD_5$) loads to and dissolved oxygen (DO) concentrations in the Athabasca River measured during the 14 February - 21 March 1990 winter water quality survey. Linear regression and DOSTOC simulation models were fitted to the data from river kilometre 0 to 808.

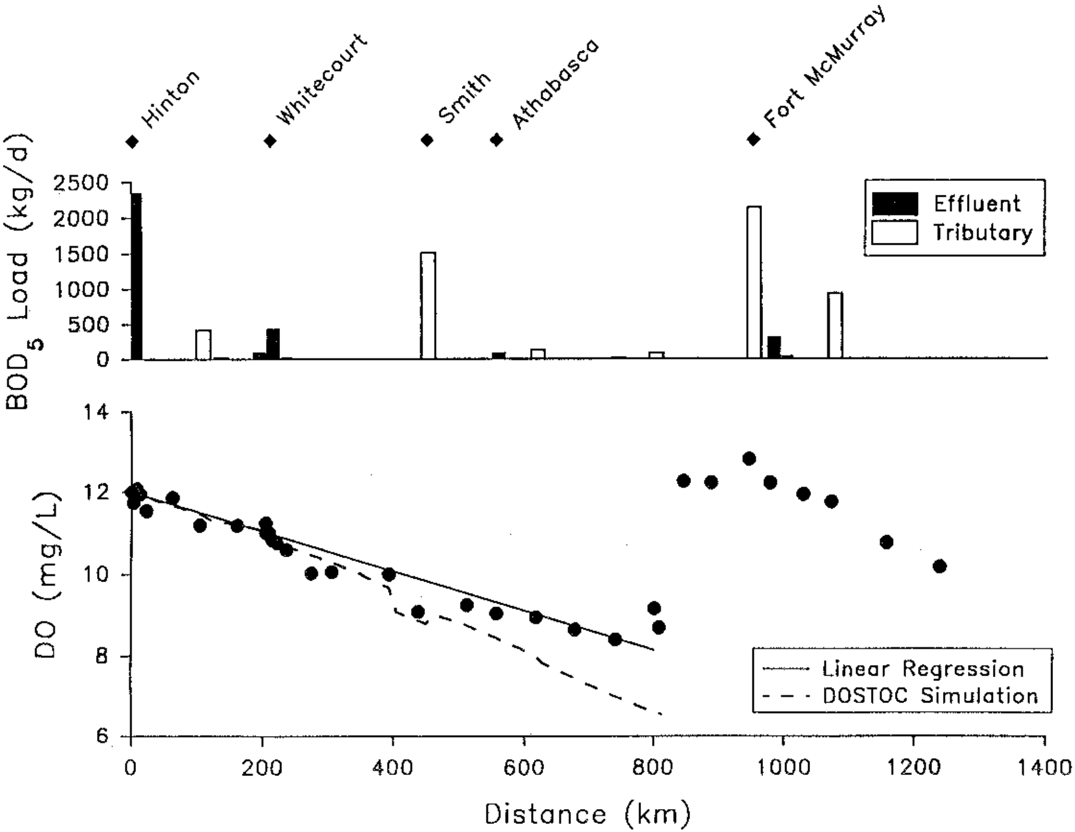

Figure 5. Five-day biochemical oxygen demand ($BOD_5$) loads to and dissolved oxygen (DO) concentrations in the Athabasca River measured during the 7 February - 14 March 1991 winter water quality survey. Linear regression and DOSTOC simulation models were fitted to the data from river kilometre 0 to 808.

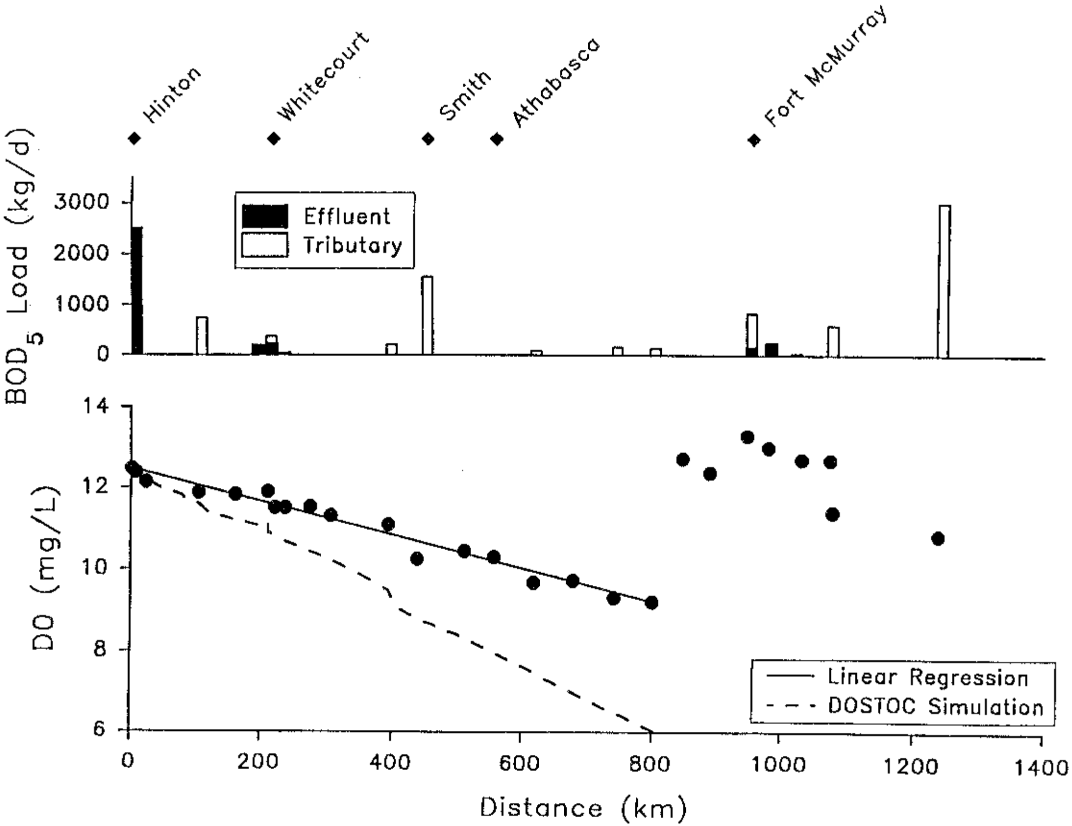

Figure 6. **Five-day biochemical oxygen demand (BOD$_5$) loads to and dissolved oxygen (DO)** concentrations in the Athabasca River measured during the 30 January - 10 March 1992 winter water quality survey. Linear regression and DOSTOC simulation models were fitted to the data **from river kilometre 0 to 808.**

## DISCUSSION

**Bill Mackay:**

What was considered as the head water in the model and what was the impact of this effluent from Jasper town on headwater DO.

Can DOSTOC predict the impacts of individual inputs and doesn't that ability make it more useful than linear regression.

**Reply:**

Headwater was the Athabasca River at Entrance, which is downstream of Jasper. Effects of Jasper townsite on headwater DO unknown.

Yes - DOSTOC allows one to vary the loads from any and all inputs, thereby facilitating evaluation of scenarios such as changes in an industries operation. The accuracy and precision of these predictions depends on the accuracy and precision of the model.

**Norman Gridley:**

Does the DOSTOC model assume completely mixed conditions across the river channel?

Is the BOD loading from the pulpmills assumed to be steady state?

**Reply:**

DOSTOC assumes complete mixing.

The BOD loads from the pulpmills can vary considerably from day to day. DOSTOC can be run deterministically (previously, the effluent $BOD_5$ concentration collected on a single date as part of each winter survey was used in the model) or stochastically (using a mean ± S.E.).

**S. Beltaoes:**

Are the DO concentrations mentioned in the paper cross-sectionally averaged values, or single-point values?

**Reply:**

DO samples were generally collected from mid-channel.

**Mike Ferrick:**

Has there been any discussion of mechanical reaeration by oxygen injection in order to counteract the effects of mill effluents and avoid low DO at critical locations and times?

**Reply:**

Yes - if oxygen levels at the new AlPac Mill (start-up Sept. 1993), which is located approximately 50 km downstream of the town of Athabasca, approach 6mg/L, then the industries under the authority of Alberta Environmental Protection are planning to inject liquid oxygen into the river water.

**Hanson Cheng:**

How did you derive the SOD rate for input to the model?

How did you or the model derive the reaeration coefficient?

**Reply:**

SOD was measured *in situ* at 11 sites along the river. For seven of these sites, data were collected during 2-4 winters. Mean values were calculated for each site and, for sites where SOD was not measured, values were extrapolated from a plot of SOD versus river distance in which the nearest sites upstream and downstream of the site without SOD measurements were connected with a straight line.

In March 1989, reaeration measurements were made at 2 sites on the Athabasca River (Macdonald et al, 1989; Report prepared for Alberta Environment). The observed open-water rate was equal to 16% of the reaeration rate calculated using the O'Conner and Dobbins (1958) reaeration coefficient for 20° and $50m^3/s$. The open water reaeration rate in the model was set to equal 16% of the calculated rate.