Dissolved Oxygen Downstream of an Effluent Outfall in an Ice-Covered River: Natural and Artificial Aeration

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Abstract: In ice-covered rivers, dissolved oxygen (DO) might fall below critical levels for aquatic biota in the absence of surface aeration, combined with low winter flow conditions and reduced photosynthesis rates. Open-water zones, however, can be created downstream of a diffuser by warm effluent discharges, resulting in an increase in surface aeration. In this study, we modeled the behavior of the effluent plume and the resulting open-water lead development in the Athabasca River, Alberta, Canada downstream of a pulp mill diffuser. The DO was found to increase by 0.26 mg/L due to surface aeration of an open-water lead of 6.07 km. We also evaluated oxygen injection into the effluent pipeline to increase the DO in the river. At an injection rate of 3,500 and 5,000 lb/day of liquid oxygen, the DO was increased by 0.16 and 0.21 mg/L, which corresponded to an absorption efficiency of about 50%. The artificial aeration technique evaluated here appears to be an effective alternative to increase DO levels in ice-covered rivers. The results of this study are important in developing accurate DO models for ice-covered rivers and in evaluating oxygen injection systems.

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CE Database subject headings: Dissolved oxygen; Effluents; Diffusion; Ice; Rivers; Reaeration.

Introduction

The presence of sufficient dissolved oxygen (DO) in rivers is important for aquatic life. Since the late 1980s, pulp mills along the Athabasca River, Alberta, Canada have been under various stages of development or expansion (see Fig. 1). High levels of biochemical oxygen demand (BOD) loading from the mill effluents, in addition to natural and municipal discharges, have been shown to cause a pronounced decline in DO concentrations progressively downstream in the river (Chambers et al. 2000). The situation is more critical in winter seasons as a result of low flow conditions, which reduce the ability of the river to dilute BOD, and ice-cover conditions, which stop surface re-aeration and substantially reduce photosynthesis rates.

There is a growing concern that increased development, combined with reduced river flows in recent years, will cause DO concentrations to fall below critical levels for aquatic biota during winter months. The current guidelines for the maintenance of DO in Alberta Rivers are 5.0 mg/L for acute exposure and 6.5 mg/L for 7-day chronic exposure (Alberta Environment 1999). Historical low flows occurred in the Athabasca River during the winters of 2002 and 2003. As a result, very low DO concentrations were observed that fell below chronic threshold values. In 2002, for instance, DO concentrations in the Athabasca River declined to an average of 5.7 mg/L for a 28-day period upstream of Grand Rapids (see Fig. 1).

In order to minimize the impact of low DO levels in the Athabasca River, Alberta Environment has recently requested that the pulp mills along the river develop contingency plans for their operations. All of the mills are currently operating with efficient wastewater treatment systems and can maintain good water quality in the Athabasca River under all but extreme climate and flow conditions. A low-cost alternative is required for the infrequent climatic conditions that can generate low DO conditions in the river. Oxygen injection into the effluent stream has been proposed as a possible remedy. Alberta-Pacific Forest Industries Inc. (Al-Pac) has recently conducted two oxygen injection tests during one winter season by injecting oxygen into the mill effluent before it is discharged through an existing diffuser outfall (Stantec 2004) (see Fig. 2). While preliminary results seem to indicate that it is possible to increase the DO level by 0.5 mg/L, several complications need to be carefully addressed before its effectiveness can be evaluated: The mixing of the effluent with the ambient river water and the development of the open-water lead downstream of the diffuser.

The temperature of the mill effluent is typically much warmer than the river water in winter months. It ranges from 10 to 22°C, even when the ambient air temperature is below −30°C. This warm effluent thus keeps an open-water lead downstream of the diffuser outfall throughout the winter (see Fig. 3). The length of

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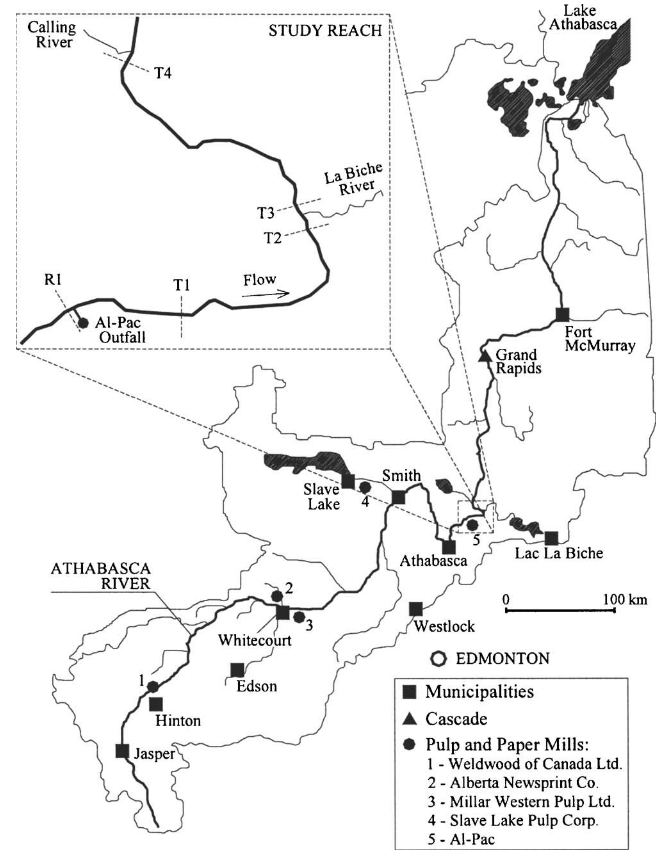

Fig. 1. Location map of the Athabasca River, with indication of the study reach

the open-water lead downstream of the Al-Pac diffuser ranges from a few hundred meters to several kilometers, and varies mainly as a function of air temperature and effluent rate and temperature. Given its significant length, it is important to properly estimate the size of the open-water lead as well as the amount of surface aeration it provides. In the Al-Pac's oxygen injection study, it is also important to quantify the amount of the DO level increase due to oxygen injection and that due to surface aeration at the open-water lead. In a recent study by Tian (2005) using USEPA's Water Quality Analysis Simulation Program (WASP), it is shown that the DO level is very sensitive to the ice-cover ratio, i.e., the ratio of the ice-covered surface area to the total river surface area. So far, there is no predictive model for estimating the size of the open-water lead downstream of an effluent outfall.

The objectives of this study are: (1) To develop a methodology for predicting the size of the open-water lead downstream of a diffuser; (2) to assess the ability of a modified Streeter-Phelps model to simulate the DO variation under partially and fully ice-covered conditions; and (3) to evaluate the effectiveness of the above-mentioned oxygen injection system. This study is important for the following reasons: (1) Effluent-induced open water zones have not been reported in the literature, and there are no reliable methods for quantifying their sizes. The amount of surface aeration through these open-water zones also needs to be quantified; and (2) injecting oxygen into an effluent diffuser has economical and operational advantages by making use of the existing in-stream diffuser systems. However, there is no documented literature on the application of this approach and its effectiveness.

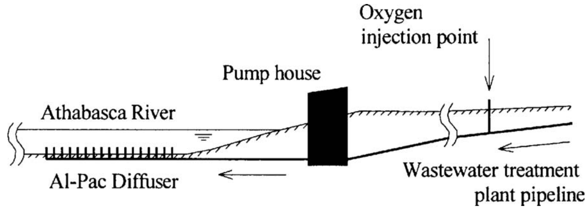

Fig. 2. Diagram of the effluent discharge near the right bank of the Athabasca River, with indication of the oxygen injection point

Fig. 3. Open-water lead in the Athabasca River downstream of Al-Pac diffuser, with indication of flow direction

Physical Characteristics and Field Work

The Athabasca River originates in the Rocky Mountains of Jasper National Park, Alberta and flows northeast across the province to Lake Athabasca, as indicated in Fig. 1. It is unregulated, and therefore, discharge is highly seasonal, with the lowest flows occurring typically in February (about 70 m^3/s), when the river is largely ice covered, and the highest flows occurring typically in June (about 1,000 m^3/s), when the river is under ice-free condition. As a result of a number of point and nonpoint discharges that contribute to the oxygen demand in the river, a DO sag occurs annually at the ice-covered section just above the Grand Rapids, a 10 m cascade located approximately 180 km downstream of the last significant point-source discharge, which is the Al-Pac effluent diffuser. The main characteristics of the river during ice-covered periods are given in Table 1. A typical river cross section at 50 m downstream of Al-Pac diffuser is shown in Fig. 4. The ice

Table 1. Characteristics of the Athabasca River during Ice-Covered Periods (Al-Pac Location) [Data Obtained from Beak Consultants Ltd. (1995) and Putz et al. (2000)]

Discharge (m^3s)	Water depth (m)	Width (m)	Average velocity (m/s)	Slope	Ice thickness (m)
84	1.1	250	0.30	0.000166	0.50

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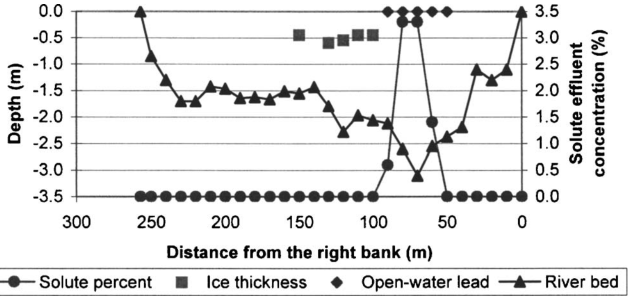

Fig. 4. Typical river cross section at 50 m downstream of Al-Pac diffuser (river discharge is 84 m^3/s), indicating solute (Rhodamine WT dye) effluent concentration, ice thickness, and width of the open-water lead [adapted from Beak Consultants Ltd. (1995)]

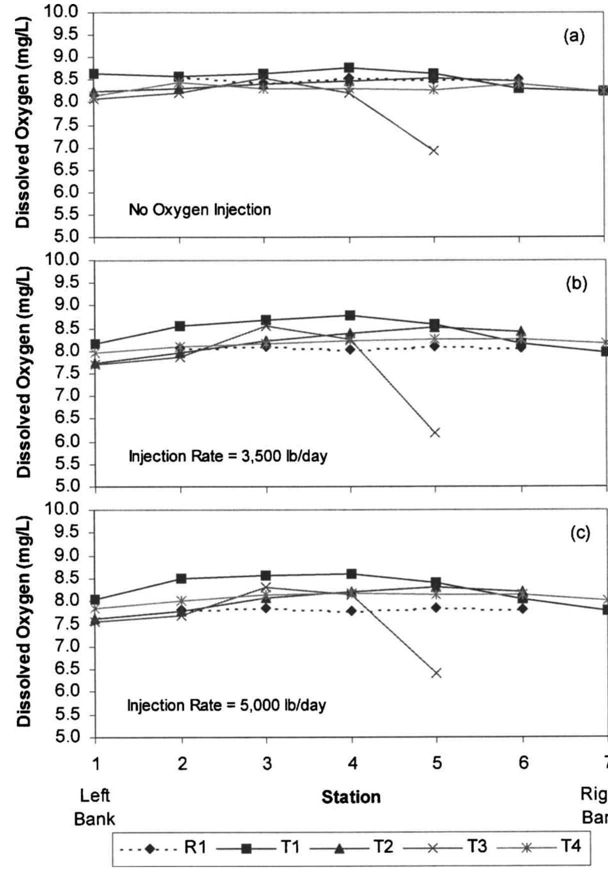

Fig. 5. Cross-sectional DO variation for each test [adapted from Stantec (2004)]: (a) baseline study with no oxygen injection (Feb. 7, 2004); (b) oxygen injection at 3,500 lb/day (Feb. 10–13, 2004); and (c) oxygen injection at 5,000 lb/day (Feb. 17–20, 2004)

thickness, width of the open-water lead caused by the warmer effluent, and solute effluent concentration obtained from a field study conducted by Beak Consultants Ltd. (1995) are also shown in this figure.

The Al-Pac diffuser is located about 2.7 m below the river bed and extends from approximately 30 to 82 m from the right bank (looking downstream) of the Athabasca River (see Fig. 2). Its structure consists of a coated steel pipe of 0.9 m diameter, containing 25 outlet ports with height of 3.0 m and inner diameter of 0.15 m. These outlet ports are oriented along the flow direction with a vertical angle of 45 deg and have a typical flow velocity of 2 m/s. Since the effluent comes out from the diffuser at a much higher velocity than the river water, it behaves as a series of turbulent jets that act as a propeller contracting the flow and inducing entrainment of the surrounding ambient water. As the effluent is warmer than the river water, buoyancy will also force the jet trajectory to bend upwards. In this region, usually called the near-field zone, significant dilution is achieved within a short distance from the discharge point. After a sufficiently large distance from the diffuser, the effluent is vertically fully mixed and the turbulence in the river becomes the dominant mixing mechanism. In this region, usually called the far-field zone, the effluent behaves as a passive plume that grows in width due to turbulent diffusion processes.

Field work was conducted to evaluate the efficiency of the oxygen injection in the winter of 2004 (Stantec 2004). The DO level was monitored at five transects across the river channel with one transect before the Al-Pac diffuser to provide background DO concentrations, and four transects below the diffuser from a distance of 6 km up to 32 km (Fig. 1). The details of these transects are given below:

(1) Rl—Background control site, 0.5 km upstream of the diffuser outfall;
(2) Tl—6 km below the diffuser outfall;
(3) T2—15 km below the diffuser outfall (0.5 km above La Biche River confluence);
(4) T3—15.5 km below the diffuser outfall (0.2 km below La Biche River confluence); and
(5) T4—32 km below the diffuser outfall (0.1 km above Calling River confluence).

A baseline study with no oxygen injection was conducted on Feb. 7, 2004. At the beginning of the tests, the open water lead was about 2 km downstream of Al-Pac diffuser (from Al-Pac, unpublished data). The average wind speed for the time of this survey was 2.8 m/s (Alberta Ambient Air Data Management System 2004) and air temperature was −8.9°C (Environment Canada 2004). In the subsequent days, two oxygen injection tests were conducted with oxygen being injected into the Al-Pac effluent pipeline at 500 m upstream of the pump house (see Fig. 2). The first oxygen injection test was conducted from Feb. 10–13, 2004, when the open-water lead was about 4 km downstream of Al-Pac diffuser. The average wind speed was 2.6 m/s and air temperature was −7.2°C. The second oxygen injection test was conducted from Feb. 17–20, 2004, when the open water lead was about 6 km downstream of Al-Pac diffuser. Due to the continuing increase in the open water length and the safety concerns with working in open areas, the transect T1 was moved to 7 km below the diffuser outfall during this oxygen injection test. The average wind speed was 1.9 m/s and air temperature was −5.1°C. The point of the oxygen injection was before the stabilization well in the pump house and the pressure at the effluent pipeline was estimated at about 3 atmosphere pressure. There is a potential that some oxygen might leak into the atmosphere through the stabilization well.

The DO concentrations for the baseline and oxygen injection tests were measured at midwater column of each station (spaced equally apart across the transects R1, T1, T2, T3, and T4) with dissolved oxygen meters with an accuracy of ±0.01 mg/L. Fig. 5 shows the cross-sectional DO variations for each test. Notice at transect T3, a significant DO deficit is observed at the station located near the right bank. This low DO is caused by the inflow plume from the La Biche River discharge, which does not have an opportunity to mix with the Athabasca river water. The La Biche

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River discharge is typically small (1.15 m^3/s) compared to the Athabasca River discharge, but it has a low DO concentration (3.55 mg/L) and a BOD of 1.02 mg/L (Chambers et al. 1996). Thus, transect T3 is ignored in the following discussion. At transect T4, the impact of La Biche River is accounted for by assuming complete mixing between the two rivers. Given the small discharge of the La Biche River (about 2% of the winter flow of the Athabasca River), its impact on the DO levels of the Athabasca River at transect T4 is not significant. The increase in the average DO concentration (at transect T1) above background levels (at transect R1) was much more pronounced for the oxygen injection tests than for the baseline test. However, part of this DO increase was due to the surface aeration at the open-water lead downstream of the outfall (see Fig. 3).

Modeling Open-Water Lead Development

In this section, we model the development of the open-water lead downstream of Al-Pac diffuser on a daily basis by studying the mixing of the warm effluent in the river. The hydrodynamics of the turbulent buoyant jet/plume in the river is modeled using an expert system, CORMIX2 (Akar and Jirka 1991). Once the temperature field of the effluent is obtained, the resulting open-water lead development is then predicted using a thermal breakup model (Hicks et al. 1997).

The CORMIX2 model is a subsystem of the software CORMIX-GI 4.3 (www.cormix.info) for simulating submerged multiport diffuser discharges into diverse ambient water conditions. It simplifies the receiving water body's actual geometry by a rectangular cross section (schematization) and uses the "equivalent slot diffuser" concept, which neglects the details of the individual jets issuing from each diffuser port to the distance of their merging, but rather assumes that the flow comes from a long slot discharge with equivalent dynamic characteristics. This model is based upon integral length scale, and passive diffusion approaches to simulate the hydrodynamics of both the near-field zone (where momentum flux, buoyancy flux, and diffuser geometry control the jet trajectory and mixing processes), and the far-field zone (where buoyant spreading motions and passive diffusion control the trajectory and dilution of the effluent discharge plume).

In this study, the development of the open-water lead during the period of field study (Feb. 7–20, 2004) is predicted and the results are compared with the field measurements. The following data were obtained from Stantec (2004) for these dates: The river discharge of 63 m^3/s, effluent flow rate of 0.87 m^3/s, and effluent temperature of 22°C. The river cross section was schematized into a rectangular cross section of a depth of 1.0 m and a width of 230 m according to the requirement of the CORMIX2 model. Manning's roughness for that section of the river was obtained from Beak Consultants Ltd. (1995) and Putz et al. (2000) with

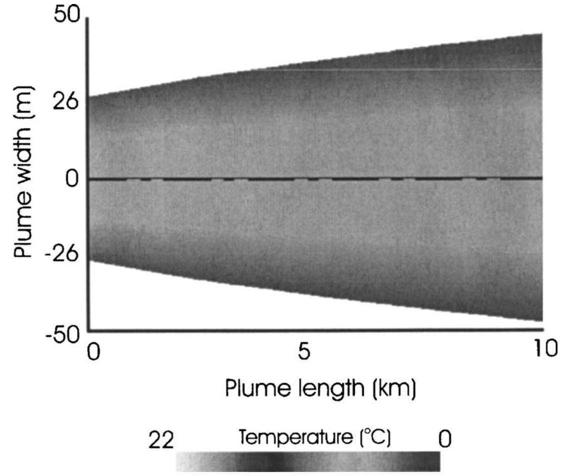

Fig. 6. CORMIX2 simulation of transverse mixing downstream of Al-Pac diffuser for Feb. 11, 2004, in which half-width of the effluent plume corresponds to the distance from the centerline where the temperature is equal to 46% of the centerline value

$n=0.027$, typical for mildly meandering channels. The depth at discharge of 1.2 m was also used as input data, whereas the multiport diffuser is located on the deeper part of the channel.

Using the above input data as well as information of the diffuser configuration, CORMIX2 classified the flow in the near field as a positively buoyant multiport diffuser discharge in uniform ambient layer flow (flow class: MU2) and the flow in the far field as a passive-diffusion plume. The results for the near-field zone simulation showed that vertical mixing is completed at approximately 26 m downstream of Al-Pac diffuser due to the shallowness of the river, where the effluent plume width is 46 m and the centerline temperature is 1.0°C. The results for the far-field zone simulation showed that at 10 km below the outfall, the effluent plume width is 98 m and the centerline temperature is 0.59°C. Fig. 6 shows schematically the simulation of the effluent plume downstream of Al-Pac outfall (for Feb. 11, 2004), where the boundary of the plume is the half-width of the plume, which is defined as the distance from the centerline where the temperature is equal to 46% of the centerline value. The above CORMIX2 model was validated using the field results of Beak Consultants Ltd. (1995). Adjusting the input data to the field conditions of the Athabasca River and Al-Pac effluent discharge during the tracer studies of Beak Consultants Ltd., CORMIX2 simulation provided plume widths of only 18% smaller and dilution rates of only 24% larger (see Table 2). Thus the results obtained in the present study with CORMIX2 are expected to be reliable.

According to Hicks et al. (1997), thermal breakup processes

Table 2. Comparison between the Plume Width and Dilution Rate Obtained by Beak Consultants Ltd. (1995) and CORMIX2 Simulation

	Plume width (m)[a]		Dilution (%)[b]	
Distance (km)	Beak Consultants Ltd. (1995)	CORMIX2 simulation	Beak Consultants Ltd. (1995)	CORMIX2 simulation
0.05	40	48	30	27
8	110	90	52	42
16	140	113	71	53

[a]Defined as the distance from the centerline where the concentration is equal to 46% of the centerline value.

[b]Defined as the initial concentration divided by the local centerline concentration.

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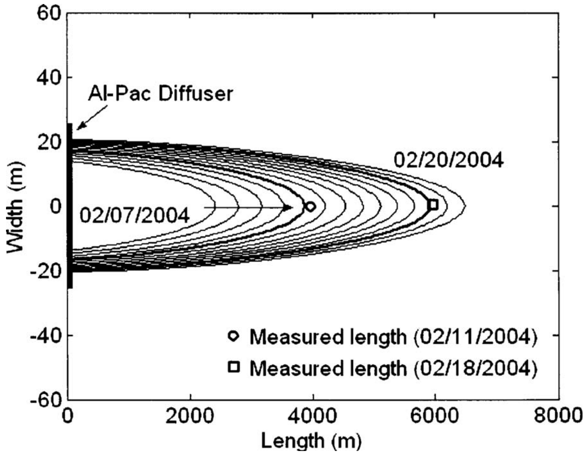

Fig. 7. Open-water lead development downstream of Al-Pac diffuser: Melting front follows temperature contour lines of 0.832, 0.811, 0.792, 0.775, 0.760, 0.746, 0.733, 0.722, 0.712, 0.703, 0.694, 0.686, 0.678, and 0.670°C

usually occur when warm water flows under the ice cover resulting in a downstream advance of a melting front. The thermal breakup model, validated by Hicks et al. (1997) for the Mackenzie River, Alberta, Canada, is used here to predict the open-water lead development in the Athabasca River. However, their model assumed that the temperature of the water was constant throughout the breakup period, as this warmer water came from a lake (Great Slave Lake). Hence, we modified this model in order to account for spatial variation of effluent temperature downstream of Al-Pac outfall. Thus, temperature contour lines were generated using the results from CORMIX2 and equations to relate effluent temperature and the area formed by these contour lines and the diffuser were obtained.

The open-water lead development was simulated assuming that the melting front follows the temperature contour lines. The ice cover is assumed to melt according to two main processes: Ice-thickness reduction, assumed to occur due to direct heat input at the ice surface for a given ice density and latent heat of fusion; and open-water lead development, assumed to occur uniformly over the depth of the ice-cover leading edge due to heat carried by the warm water for a given water density and specific heat. The effluent temperature at the ice-cover leading edge is then obtained with the equations generated from CORMIX2 simulation. This iterative process is repeated for each subsequent day until the simulation reaches the desired area (or length) of the open-water lead.

The following daily average values were used as input data for the thermal breakup model: Incoming solar radiation of 150 W/m^2 [obtained from Gray and Prowse (1993) for the Al-Pac's latitude], water surface albedo of 0.1, ice surface albedo of 0.8, and heat transfer coefficient between the air and the water surface of 20 W/m^2 °C (obtained from Hicks et al. 1997).

The development of the open-water lead was simulated from the first day of the field test. On the first day (Feb. 7, 2004), the length of the open-water lead was estimated at 2.0 km based on visual observation. The ice thickness was measured by drilling holes across the river with a power ice auger. While this thickness varied from location to location, an average value of 0.5 m measured upstream of the diffuser (transect R1 in Fig. 1) was used as initial ice thickness. A similar value (see Fig. 4) was also reported by Beak Consultants Ltd. (1995) for similar cumulative air temperature conditions. Ice surface temperature was taken to be equal to the mean daily air temperature, which varied from −12.8 to −0.6°C (Environment Canada). Fig. 7 shows the estimated open-water lead development obtained by the CORMIX2/thermal breakup model simulation. The open-water lead increased significantly from the first to the last day of the simulation. The results are in agreement with the field observations from Al-Pac, in which the open area length was about 4.0 km for Feb. 11 and about 6.0 km for Feb. 18. Except for the near-field zone, where the effluent jet contracts laterally, as mentioned above, the width of the open-water lead decreases from about 40 to 0 m in the far-field zone (see Fig. 3), according to the temperature contour lines sketched in Fig. 7. The variation of this width along the river bends is caused by variations in the channel cross-sectional characteristics and increases in the transverse mixing coefficient due to the river's secondary currents, which are caused by interactions between the main flow and the river bends, as reported in Dow et al. (2007).

Table 3. Sensitivity Analysis for the Parameters Used in the Thermal Breakup Model

Parameter	Standard value	Range	Variation of the final open-water length (%)
Initial ice thickness (m)	0.5	0.4–0.6	+10.13−−9.39
Initial open area length (km)	2.0	1.5–2.5	−4.05−+3.96
Incoming solar radiation (W/m^2)	150	100–200	−1.54−+1.51
Air-water heat transfer coefficient (W/m^2 °C)	20	15–25	+1.05−−1.08
Ice surface albedo	0.10	0.05–0.15	+0.29−−0.31
Water surface albedo	0.8	0.7–0.9	+0.22−−0.23

A sensitivity analysis was conducted to investigate the importance of some parameters that are not well known for the time and location of the survey for the following parameter ranges: Initial ice thickness (0.4–0.6 m), initial open area length (1.5–2.5 km), incoming solar radiation (100–200 W/m^2), heat transfer coefficient between the air and the water surface (15–25 W/m^2°C), water surface albedo (0.05–0.15) and ice surface albedo (0.7–0.9). Table 3 shows that the initial ice thickness and initial open area length have the largest influence on the results. However, since the maximum variation of the final open area length from the model calculation by using the standard values was about 10%, it can be inferred that the model is not highly sensitive to the range of parameters evaluated in this study.

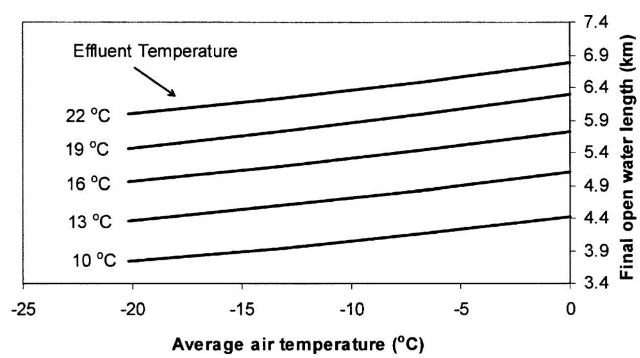

Fig. 8. Influence of air and effluent temperatures on the final open-water length

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The final open-water length as a function of the air and effluent temperatures is studied in Fig. 8, with the other input values the same as those in the above simulation. We can see that the lower the air and effluent temperatures, the shorter the final open-water length. For example, when the effluent temperature decreases from 22 to 10°C while the average air temperature remains constant, the length of the final open lead decreases by about 2.4 km. On the other hand, when the average air temperature decreases from 0 to −20°C while the effluent temperature remains constant, the final open lead length decreases by only 0.7 km. This means that the effluent temperature is the main parameter affecting the length of the open-water lead. Fig. 8 can be used as a quick predictive tool for estimating the final length of the open-water lead for similar conditions to our examined case. This graph also shows the sensitivity of the final open-water length to air and effluent temperatures, and it will be useful for plant operation.

Dissolved Oxygen Balance Model and Surface Aeration

Dobbins (1964) extended Streeter-Phelps's equation by obtaining a one-dimensional unsteady advection-dispersion equation incorporating reaction terms to simulate the coupling variation of BOD concentration and DO deficit in the river, assuming complete mixing across the channel

$$\frac{\partial L}{\partial t} + U\frac{\partial L}{\partial x} = \frac{\partial}{\partial x}\left(K_x \frac{\partial L}{\partial x}\right) - K_1 L \tag{1}$$

$$\frac{\partial D}{\partial t} + U\frac{\partial D}{\partial x} = \frac{\partial}{\partial x}\left(K_x \frac{\partial D}{\partial x}\right) + K_1 L - K_2 D + K_3 - K_4 + S \tag{2}$$

where L=BOD concentration; D=DO deficit ($C_s - C$), in which C=DO concentration and C_S=saturation value; U=mean river velocity; K_x=longitudinal dispersion coefficient; K_1=BOD decay rate, K_2=re-aeration coefficient, K_3=oxygen uptake rate by algae; K_4=oxygen supply rate by algal photosynthesis; and S=sediment oxygen demand (SOD). Assuming a constant width along the river, Eqs. (1) and (2) are simplified as the following for partially and fully ice-covered conditions.

For partially ice-covered conditions (with open-water lead), the effective surface re-aeration coefficient becomes αK_2, where α=open-water ratio (i.e., the ratio of the open-water width to the average river width of 230 m), and K_2=re-aeration coefficient for an ice-free surface. The value of α varies along the river according to the width of the open-water lead (see Fig. 7). Assuming steady-state conditions and neglecting the dispersion terms (Dobbins 1964) and the difference between the oxygen uptake and supply rates by algae (Hou and Li 1987), we obtain the following analytical solutions for Eqs. (1) and (2)

$$L = L_0 \exp\left(-K_1 \frac{x}{U}\right) \tag{3}$$

$$D = D_0 \exp\left(-\alpha K_2 \frac{x}{U}\right) + \frac{K_1 L_0}{\alpha K_2 - K_1}\left[\exp\left(-K_1 \frac{x}{U}\right) - \exp\left(\alpha K_2 \frac{x}{U}\right)\right] + \frac{S}{\alpha K_2}\left[1 - \exp\left(-\alpha K_2 \frac{x}{U}\right)\right] \tag{4}$$

in which L_0 and D_0=initial BOD concentration and DO deficit, respectively. In Eq. (4), the only source of oxygen is the re-aeration (controlled by K_2), and the sinks of oxygen are the BOD decay (controlled by K_1) and the sediment oxygen demand, S.

Table 4. Estimation of the Reaeration Coefficients by Using Predictive Equations

Reaeration equation	K_2 (day^{-1} at 20°C)	K_2 (day^{-1} at 0.90°C)
$K_2 = 3.90\ U^{0.5} H^{-1.5}$ [a]	2.06	1.31
$K_2 = 5.010\ U^{0.969} H^{-1.673}$ [b]	1.46	0.93
$K_2 = 173\ (IU)^{0.404} H^{-0.66}$ [c]	3.07	1.95
$K_2 = 543\ I^{0.6236} U^{0.5325} H^{-0.7258}$ [d]	1.22	0.77
$K_2 = 1{,}740\ I^{0.79} U^{0.46} H^{0.74}$ [e]	1.01	0.64
$K_2 = K_{2,\mathrm{channel}} + K_{2,\mathrm{wind}}$ [f]	1.63	1.04
$K_2 = K_{2,\mathrm{channel}} + K_{2,\mathrm{wind}}$ [g]	2.71	1.73

Note: H=average water depth (m); I=water surface slope; $K_{2,\mathrm{channel}}$=reaeration coefficient for pure open-channel flows (day^{-1}); $K_{2,\mathrm{wind}}$=reaeration coefficient for pure wind-driven flows (day^{-1}).

[a]O'Connor and Dobbins (1958).

[b]Churchill et al. (1962).

[c]Krenkel and Orlob (1962).

[d]Smoot (1988).

[e]Moog and Jirka (1998), valid for $I > 0.0000$.

[f]Combination of wind and open-channel flow induced reaeration equations given by Chu and Jirka (2003).

[g]Combination of wind and open-channel flow induced reaeration equations used in the USEPA's WASP model.

For fully ice-covered conditions, a field study conducted by MacDonald et al. (1989) showed the under-ice re-aeration coefficient K_2 approaching zero in the Athabasca River. This not only implies that re-aeration is negligible, but also that groundwater, which is often poorly oxygenated and can contain significant chemical oxygen demand (COD), did not influence K_2 in the studied reach (see Schreier et al. 1980). Thus, for ice-covered conditions, Eq. (4) can be simplified by setting K_2 to zero

$$D = D_0 + L_0\left[1 - \exp\left(-K_1 \frac{x}{U}\right)\right] + S\left(\frac{x}{U}\right) \tag{5}$$

where the variation of BOD concentration in the river is also calculated by Eq. (3). In Eq. (5), there is no source of oxygen due to the ice cover, and two sinks of oxygen: BOD decay and the SOD.

In order to apply the model to predict the change of DO in the Athabasca River downstream of Al-Pac outfall for the baseline study (Feb. 7, 2004), we used an average value of K_1 of 0.01 day^{-1} (Chambers et al. 1996), corrected to an average effluent plume temperature of 0.90°C (from CORMIX2 simulation), and an average value of S of 0.18 mg/L/day measured by Tian (2005) for the time and location of our study. However, the value for K_2 depends on several parameters, such as river flow conditions and wind-shear velocity. For the conditions of the field study: The river discharge (63 m^3/s), water depth (1.0 m), river width (230 m), water surface slope (0.000166), Manning's roughness (n=0.027), and average wind speed (2.81 m/s), as well as the average effluent plume temperature of 0.90°C, we calculated values for K_2 by using some of the most popular predictive equations for re-aeration induced by pure open-channel flows and combined wind/open-channel flows. Table 4 shows that these re-aeration coefficients varied from 0.64 to 1.95 day^{-1}. In this study, we adopt a value for K_2=1.63 day^{-1}, which was obtained by Chambers et al. (1996) from their field study for an open-water reach of the Athabasca River downstream of a pulp mill (Millar

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Western Pulp Ltd.). This value is within the range of K_2 shown in Table 4 and seems to be adequate under relatively calm wind conditions. Note that when the wind speed is beyond 6 m/s, K_2 value will increase significantly due to wind-generated waves and greater mixing at the air-water interface.

As the dissolved oxygen balance model is a 1D model, we need to obtain a cross-sectional averaged DO value in order to compare the field measurements with the model predictions. The measured DO varies across the channel due to the process of surface aeration and oxygen injection, with both of the processes giving a higher DO in the effluent plume. It is also interesting to point out that at the R1 section (see Fig. 1 insert), DO is more or less uniform (see Fig. 5). To obtain a cross-sectional averaged DO concentration, we cannot take a simple math average of the measured DO shown in Fig. 5, as in the deeper part of the channel, the unit-width flow rate is bigger, thus, the DO flux is larger. As the flow velocity typically increases with depth, the unit-width discharge can be taken from Manning's equation as proportional to the water depth to the power of 1.66. This power of 1.66 is also obtained by Chambers et al. (1996) for the same reach of the Athabasca River evaluated in the present study. Therefore, the cross-sectional averaged DO value is estimated by the following equation:

$$C_{\text{avg}} = \sum_{i=1}^{j} C_i (h_i)^{1.66} \Bigg/ \sum_{i=1}^{j} (h_i)^{1.66} \tag{6}$$

where C_i and h_i=local DO concentration and water depth for each station i, respectively.

The following water quality parameters were used as input data for the DO balance model: Background BOD of 0.9 mg/L (Alberta Environment 2004), saturation DO concentration of 13.7 mg/L (Stantec 2004), effluent DO concentration of 5.6 mg/L, and effluent BOD concentration of 3.8 mg/L (Tian 2005). Fig. 9(a) shows the prediction of the DO balance model with the measured (cross-sectional averaged) DO concentrations at transects R1, T1, T2, and T4. Here, an average length of the open-water lead (2.2 km) and open-water ratio α (varying from 0.112 to 0) were obtained from the CORMIX2/thermal breakup model simulation. The DO model presents good fit to the field data with correlation coefficient R^2=0.930.

Two important processes are clearly shown in Fig. 9(a): The increase of DO (about 0.05 mg/L) in the open-water lead downstream of the diffuser due to surface aeration, and the decrease of DO from the end of the open-water lead to T4 due to a lack of surface aeration and the effects of BOD and SOD. The slope of the DO depletion from T2 to T4 is well modeled, which indicates that the adopted K_1 and S values are reasonable. As K_1 is small compared to S, the DO decrease is dominated by SOD and its slope is almost linear under ice-covered conditions [see Eq. (5)]. This linear decrease in DO was also observed by Chambers et al. (1997), who evaluated the impact of effluent discharges in several ice-covered rivers. In the open water region, surface aeration dominates over the SOD and BOD, thus the DO increases. Clearly the values of K_1, K_2, and S can be adjusted to have a better fit of the measurement data in Fig. 9(a). However, by using the values obtained from the literature, we demonstrated the importance of the surface aeration in the open-water lead and the reliability of the DO balance model.

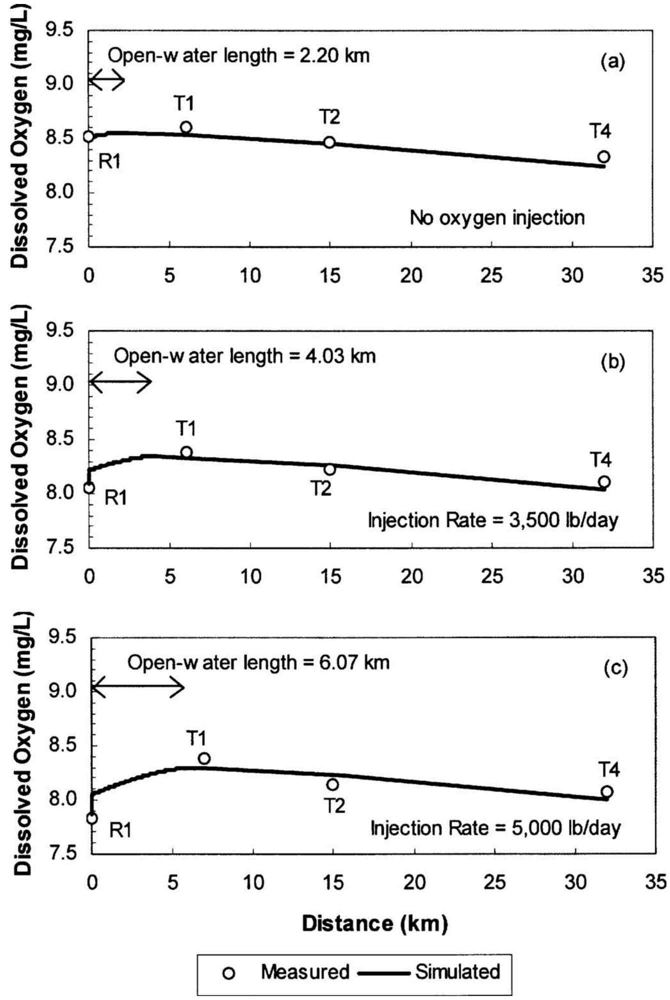

Fig. 9. Comparison of the DO balance model to field data: (a) total DO increase=0.05 mg/L (α varies from 0.112 to 0); (b) total DO increase=0.30 mg/L, being 52% of this total due to oxygen injection and 48% due to surface aeration (α varies from 0.148 to 0); and (c) total DO increase=0.46 mg/L, being 44% of this total due to oxygen injection and 56% due to surface aeration (α varies from 0.174 to 0)

Efficiency of Oxygen Injection

Artificial aeration has long been successfully applied to minimize the problem of low DO levels in rivers by injecting air or oxygen into the water through submerged multiport diffusers (Amberg et al. 1969; Whipple Jr. and Yu 1971; Marr et al. 1993). Here, we investigate the injection of oxygen into the existing effluent pipeline to make use of the existing in-stream diffuser for maximizing the mixing and oxygen transfer. The approach provides significantly economic benefits and operational advantages. There are, however, several fundamental issues that need to be addressed: Related to the dynamics of this air-bubbles-and-effluent-water mixture and whether or not the air bubbles separate from the effluent plume in the river (see Socolofsky and Adams 2002). In the present study, we estimate the bulk efficiency of the oxygen injection through a field pilot study.

The field study takes advantage of the existing Al-Pac diffuser by injecting oxygen into the Al-Pac effluent pipeline during periods of critical DO levels in the Athabasca River (see Fig. 2). Two tests were conducted with oxygen being injected at a rate of 3,500 lb/day (Feb. 10–13, 2004) and 5,000 lb/day (Feb. 17–20, 2004).

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Table 5. Absorption Efficiencies for Different Artificial Aeration Systems

Type of aerator	SOTE (%)
Coarse-bubble diffuser (Chicago River)[a]	2–10
Coarse-bubble diffuser (Tank)[a]	5–25
Fine-bubble diffuser (Tank)[a]	10–40
Oxygen diffuser (Androscoggin River)[b]	37
Oxygen sidestream/diffuser (Pearl River)[c]	55
U-tube/diffuser (Tombigbee River)[d]	80–90
Present study	50

[a]Mueller et al. (2002).

[b]Marr et al. (1993).

[c]Amberg et al. (1969).

[d]Speece (1996).

In this section, we apply the DO balance model to estimate the efficiency of this oxygen injection. We used the same values of K_1, K_2, S and water quality parameters assumed in the previous section of this paper. Fig. 9(b) shows the prediction of the DO balance model compared with the measured DO concentrations at transects R1, T1, T2, and T4 for the oxygen injection rate of 3,500 lb/day, considering an average length of the open-water lead (4.03 km) and open-water ratio α (varying from 0.148 to 0) obtained from the CORMIX2/thermal breakup model simulation. The DO model presents a good fit to the field data, with the correlation coefficient $R^2=0.935$. Three processes are shown in Fig. 9(b): DO increase due to oxygen injection, assumed to occur instantaneously right after the diffuser; DO increase from the diffuser to the end of the open-water lead due to the dominant effect of K_2 over K_1 and S; and DO decrease from the end of the open-water lead to T4 due to the effects of K_1 and S and lack of surface aeration. The predicted total DO increase from R1 to the end of the open water lead is 0.30 mg/L, which is composed of the surface aeration of the open-water lead and the oxygen injection. The DO increase over the open-water lead is 0.14 mg/L (i.e., 48% of the total DO increase). The remaining 52% of the total DO increase (or 0.16 mg/L) is due to oxygen injection. This gives the standard oxygen transfer efficiency (SOTE) of 53%. SOTE is defined here as the fraction of oxygen supplied that is actually transferred or dissolved into the water.

Fig. 9(c) presents the results for the oxygen injection rate of 5,000 lb/day, considering an average length of the open-water lead (6.07 km) and open-water ratio α (varying from 0.174 to 0) obtained from the CORMIX2/thermal breakup model simulation. The DO model also presents a good fit to the field data with the correlation coefficient $R^2=0.829$. The three processes shown in Fig. 9(c) are the same as those described for Fig. 9(b). The total DO increase from $R1$ to the end of the open-water lead is 0.46 mg/L, with 0.26 mg/L (or 56% of the total DO increase) due to the open-water lead. The remaining 44% of the total DO increase (or 0.21 mg/L) is due to oxygen injection. This gives the SOTE of 49%. In both tests, the amounts of oxygen transferred to the river due to oxygen injection were of the same order of those due to open-water lead re-aeration.

The SOTE decreased slightly from 53 to 49% when the amount of the oxygen injection increased from 3,500 lb/day to 5,000 lb/day. It should be noted that these numbers will change when the values of K_1, K_2, and S are adjusted. However, the above results appear to be quite consistent and are expected to be reliable. From Table 5, one can see the SOTE obtained in the present study is higher than those for conventional air injection systems and of the same order of those for oxygen injection systems. This efficiency is, however, lower than that for the U-tube/diffuser system, which has disadvantages such as higher construction/maintenance costs and inflexibility to be modified (Mueller et al. 2002). In this study, some amount of the oxygen injected into the effluent pipeline could have escaped through the stabilization well in the pump house prior to the diffuser outfall.

The amount of the oxygen injection in the present study is relatively small, with an increase of DO of about 0.2 mg/L in the river. The oxygen injection system used in the Pearl River (Amberg et al. 1969) was similar to the one used in this study. However, that system increased the DO level by 2 mg/L in the Pearl River by applying a much larger oxygen injection rate (30,000 lb/day). The discharge of the Pearl River (43.2 m^3/s) and the sidestream to be oxygenated (0.71 m^3/s) were of the same order of the Athabasca River discharge (63.0 m^3/s) and the Al-Pac effluent flow rate (0.87 m^3/s), respectively. This comparison illustrates how much the artificial aeration technique evaluated here could potentially improve the DO levels in the Athabasca River if a higher oxygen injection rate were effectively applied.

When a higher oxygen injection rate is applied, Amberg et al. (1969) and Mueller et al. (2002) reported that the SOTE becomes significantly lower as observed in other studies with different artificial aeration systems. Lower SOTE at a higher injection rate may be due to coalescence of more numerous bubbles, reducing the surface-to-volume ratio and the contact time with the river water due to increased bubble-slip velocities. A laboratory study is currently being conducted to better understand the dynamics of the gas bubble-water mixture and mass transfer under various flow and operation conditions in order to improve the efficiency of oxygen injection systems.

Summary and Conclusions

In this paper, dissolved oxygen level in an ice-covered river downstream of an effluent diffuser is studied with or without oxygen injection. A methodology for predicting the open-water lead development was presented, and natural aeration through this open-water lead is studied. The efficiency of oxygen injection into an effluent diffuser is also evaluated through a field test. This study is important in modeling and managing DO levels in ice-covered rivers.

A CORMIX2 model was used to predict the behavior of an effluent plume downstream of the diffuser, while a thermal breakup model was adapted to simulate the resulting open-water lead development. This combined CORMIX2/thermal breakup model was able to predict field observations of an open-water advance from about 2 to 6 km in the river over the period of the field study. Model simulations revealed that effluent temperature was the dominant parameter affecting the length of the open-water lead, while air temperature was of lesser importance. This predictive tool for estimating the final size of the open-water lead is essential to predict DO depletion resulting from BOD loading to the river and the amount of oxygen that should be injected to offset depletion.

With the results from the CORMIX2/thermal breakup model and the water quality parameters and rates obtained from the literature, it is shown that the spatial variation of DO along the river can be modeled with Streeter-Phelps equations proposed here for partially and fully ice-covered conditions. For the baseline study without oxygen injection, the model properly simulated two im-

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Table 6. Summary of All Input Parameters Used in the CORMIX2/Thermal Breakup and DO Balance Model Simulations

Parameter	Value
River discharge (m^3/s)[a]	63
Water depth (m)[b]	1.0
Average river width (m)[c]	230
Manning's roughness[d]	0.027
Background BOD (mg/L)[e]	0.9
Saturation DO concentration (mg/L)[a]	13.7
BOD decay rate, K_1 (day^{-1})[f]	0.01
Reaeration coefficient, K_2 (day^{-1})[f]	1.63
Sediment oxygen demand, S (mg/L/day)[g]	0.18
Effluent flow rate (m^3/s)[a]	0.87
Effluent temperature (°C)[a]	22
Depth at discharge (m)[h]	1.2
Diffuser length (m)[h]	52
Number of ports[h]	25
Port height (m)[h]	3.0
Port diameter (m)[h]	0.15
Port vertical angle (°)[h]	45
Distance to the right bank (m)[h]	30
Effluent DO concentration (mg/L)[a]	5.6
Effluent BOD concentration (mg/L)[g]	3.8
Daily average air temperatures (°C) (Feb. 7–20, 2004)[i]	−8.9, −3.3, −2.2, −6.2, −1.8, −2.4, −7.4, −11.6, −9.1, −9.9, −8.4, −7.4, −3.9, −0.6
Daily average wind speeds (m/s) (Feb. 7–20, 2004)[j]	2.8,3.1, 2.0, 4.2, 1.9, 2.2, 2.3, 2.8, 1.3, 1.9, 2.0, 1.4, 2.3, 2.0
Initial ice thickness (m)[k]	0.5
Initial open area length (km)[k]	2.0
Incoming solar radiation (W/m^2)[l]	150
Air-water heat transfer coefficient ($W/m^2\ °C$)[m]	20
Ice surface albedo[m]	0.1
Water surface albedo[m]	0.8

[a]Stantec (2004).
[b]Water Survey of Canada (2004).
[c]Estimated using the water depth of 1.0 and the river transects measured by Beak Consultants Ltd. (1995).
[d]Beak Consultants Ltd. (1995) and Putz et al. (2000).
[e]Alberta Environment (2004).
[f]Chambers et al. (1996).
[g]Tian (2005).
[h]Based on engineering plans of the diffuser outfall (Al-Pac).
[i]Environment Canada (2004).
[j]Alberta Ambient Air Data Management System (2004).
[k]Field measurements (Al-Pac).
[l]Obtained from Gray and Prowse (1993) for the Al-Pac's latitude.
[m]Obtained from Hicks et al. (1997) for the Mackenzie River, Alberta, Canada.

portant processes: DO increase from the diffuser to the end of the open-water lead (2.2 km long) due to the dominant effect of surface aeration over BOD and SOD; and DO decrease from the end of the open-water lead to the last transect due to a lack of surface aeration and the effects of BOD and SOD. The DO decrease was dominated by SOD with its slope close to linear.

The DO balance model was also applied to evaluate the efficiency of the artificial aeration system by injecting oxygen directly into the effluent pipeline at 3,500 and 5,000 lb/day. For the 3,500 lb/day test, a total DO increase of 0.30 mg/L in the river was estimated, from which 52% was added by oxygen injection and the remaining 48% was added by surface aeration through an open-water lead of 4.03 km long. For the 5,000 lb/day test, the total DO increase was 0.46 mg/L, from which 44% was added by oxygen injection and the remaining 56% was added due to surface aeration through an open-water lead of 6.07 km long. Therefore, the amounts of oxygen transferred to the river due to oxygen injection were of the same order of those due to open-water lead re-aeration.

The standard oxygen transfer efficiency was about 50% at both 3,500 lb/day and 5,000 lb/day. These efficiencies are higher than those for conventional air injection systems, and of the same order of those for oxygen injection systems described in the literature. From these results, it can be inferred that the artificial aeration technique evaluated here can be a low-cost and efficient alternative to minimize the impact of low DO levels in ice-covered rivers. The oxygen transfer efficiency at much higher injection rates is still not clear, as there are reports that this efficiency will decrease due to increased bubble-coalescence processes and increased bubble-slip velocities. Further lab and field studies are needed.

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Appendix

Table 6 summarizes all the input parameters used in this paper to simulate the CORMIX2/thermal breakup and DO balance models.

Notation

The following symbols are used in this paper:

D = dissolved oxygen deficit (mg/L);
D_0 = initial dissolved oxygen deficit (mg/L);
K_1 = oxygen uptake rate by biochemical oxygen demand (day^{-1});
K_2 = re-aeration coefficient (day^{-1});
K_3 = oxygen uptake rate by algae (mg/L/day);
K_4 = oxygen supply rate by algal photosynthesis (mg/L/day);
K_x = longitudinal dispersion coefficient (m^2/s);
L = biochemical oxygen demand concentration (mg/L);
L_0 = initial biochemical oxygen demand concentration (mg/L);
S = sediment oxygen demand (mg/L/day);
SOTE = standard oxygen transfer efficiency, defined as the fraction of oxygen supplied, which is actually transferred or dissolved into the water (%);
t = time (s);
U = mean river velocity (m/s);
x = longitudinal distance (m); and
α = open-water width divided by the total river width (open-water ratio).

References

Akar, P. J., and Jirka, G. H. (1991). "CORMIX2: An expert system for hydrodynamic mixing zone analysis of conventional and toxic submerged multiport diffuser discharges." *Technical Rep. No. EPA/600/3-91/073*, U.S. Environmental Research Laboratory, Athens, Georgia.
Alberta Ambient Air Data Management System. (2004). "CASA data warehouse—Data reports." ⟨http://www.casadata.org⟩.
Alberta Environment. (1999). "Surface water quality guidelines for use in Alberta." Environmental Assurance Division, Science and Standards Branch, Edmonton, Alberta, 25.
Alberta Environment. (2004). "Alberta river basins—Water quality data." ⟨http://www3.gov.ab.ca/env/water⟩.
Amberg, H. R., Wise, D. W., and Aspitarte, T. R. (1969). "Aeration of streams with air and molecular oxygen." *Tappi J.*, 52(10), 1866–1871.
Beak Consultants Ltd. (1995). "Effluent plume delineation study for Alberta Pacific Forest Industries Inc." *Rep. No. 7.10610.1*, Brampton, Ontario.
Chambers, P. A., Brown, S., Culp, J. M., and Lowell, R. B. (2000). "Dissolved oxygen decline in ice-covered rivers of Northern Alberta and its effects on aquatic biota." *J. Aquatic Ecosystem Stress and Recovery*, 8, 27–38.
Chambers, P. A., Pietroniro, A., Scrimgeour, G. J., and Ferguson, M. (1996). "Assessment and validation of modelling under-ice dissolved oxygen using DOSTOC, Athabasca River, 1988 to 1994." *Project No. 2231-C1*, Northern River Basin Study, Alberta, Canada.
Chambers, P. A., Scrimgeour, G. J., and Pietroniro, A. (1997). "Winter oxygen conditions in ice-covered rivers: The impact of pulp mill and municipal effluents." *Can. J. Fish. Aquat. Sci.*, 54, 2796–2806.
Chu, C. R., and Jirka, G. H. (2003). "Wind and stream flow induced reaeration." *J. Environ. Eng.*, 129(12), 1129–1136.
Churchill, M. A., Elmore, H. L., and Buckingham, R. A. (1962). "The prediction of stream reaeration rates." *J. Sanit. Engrg. Div.*, 88(4), 1–46.
Dobbins, W. E. (1964). "BOD and oxygen relationships in streams." *J. Sanit. Engrg. Div.*, 90(3), 53–78.
Dow, K., Steffler, P. M., and Zhu, D. Z. (2007). "Intermediate field mixing of wastewater effluent in the North Saskatchewan River." *J. Hydrol. Eng.*, submitted.
Environment Canada. (2004). "National climate archive—Climate data online." ⟨http://www.climate.weatheroffice.ec.gc.ca⟩.
Gray, D. M., and Prowse, T. D. (1993). "Snow and floating ice." *Handbook of hydrology*, D. R. Maidment, ed., McGraw-Hill, New York, 7.1–7.58.
Hicks, F. E., Cui, W., and Andres, D. (1997). "Modelling thermal breakup on the Mackenzie River at the outlet of Great Slave Lake, N.W.T." *Can. J. Civ. Eng.*, 24(4), 570–585.
Hou, R., and Li, H. (1987). "Modeling of BOD-DO dynamics in an ice-covered river in Northern China." *Water Res.*, 21(3), 247–251.
Krenkel, P. A., and Orlob, G. T. (1962). "Turbulent diffusion and the reaeration rate coefficient." *J. Sanit. Engrg. Div.*, 88(2), 53–116.
MacDonald, G., Holley, E. R., and Goudey, S. (1989). "Athabasca River winter reaeration investigation." *Final Rep.*, Environmental Assessment Division, Alberta Environment.
Marr, D. H., Peterson, J. I., Critchfield, D. H., Danforth, R. H., and Wiley, Jr., F. A. (1993). "The Gulf Island Pond oxygenation project: A unique cooperative solution to an environmental problem." *Tappi J.*, 76(7), 159–168.
Moog, D. B., and Jirka, G. H. (1998). "Analysis of reaeration equations using mean multiplicative error." *J. Environ. Eng.*, 124(2), 104–110.
Mueller, J. A., Boyle, W. C., and Pöpel, H. J. (2002). *Aeration: Principles and practice*, CRC Press, Boca Raton, Fla.
O'Connor, D. J., and Dobbins, W. E. (1958). "Mechanism of reaeration in natural streams." *Trans. Am. Soc. Civ. Eng.*, 123, 641–684.
Putz, G., Odigboh, I., and Smith, D. W. (2000). "Two-dimensional modelling of effluent mixing in the Athabasca River downstream of Alberta Pacific Forest Industries, Inc." *Proj. Rep. No. 2000-2*. Univ. of Alberta.
Schreier, H., Erlebach, W., and Albright, L. (1980). "Variations in water quality during winter in two Yukon rivers with emphasis on dissolved oxygen concentration." *Water Res.*, 14, 1345–1351.
Smoot, J. L. (1988). "An examination of stream reaeration coefficients and hydraulic conditions in a pool and riffle stream." Ph.D. thesis, Virginia Polytechnic Institute and State Univ., Blacksburg, Va.
Socolofsky, S. A., and Adams, E. E. (2002). "Multiphase plumes in uniform and stratified cross flow." *J. Hydraul. Res.*, 40(6), 661–672.
Speece, R. E. (1996). "Oxygen supplementation by U-tube to the Tombigbee River." *Water Sci. Technol.*, 34(12), 83–90.
Stantec. (2004). "Alberta-Pacific Forest Industries Inc. dissolved oxygen trials—February 2004." Prepared for Alberta-Pacific Forest Industries Inc. by Stantec Consulting Ltd., Calgary, Alberta.
Tian, Y. (2005). "Dissolved oxygen modeling and sediment oxygen demand study in the Athabasca River." MS thesis, Dept. of Civil and Environmental Engineering, Univ. of Alberta.
Water Survey of Canada. (2004). "Water level and streamflow statistics." ⟨http://www.wsc.ec.gc.ca/staflo⟩.
Whipple, W. Jr., and Yu, S. L. (1971). "Aeration systems for large navigable rivers." *J. Sanit. Engrg. Div.*, 97(6), 883–902.