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Model development for prediction and mitigation of dissolved oxygen sags in the Athabasca River, Canada

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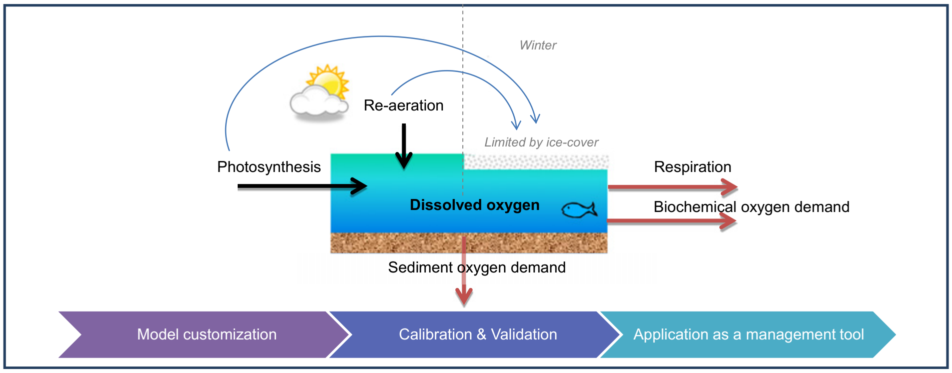
HIGHLIGHTS

- ► A water quality model was developed for the Athabasca River in Canada.
- ► The model was calibrated/validated for hydrodynamics, temperature and DO.
- ► The SOD was found as the main dissolved oxygen sink in winter.
- ► The model was applied to estimate the assimilative capacity and mitigation options.
- ► A variable flow threshold approach for BOD loading was recommended.

GRAPHICAL ABSTRACT



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ABSTRACT

Northern rivers exposed to high biochemical oxygen demand (BOD) loads are prone to dissolved oxygen (DO) sags in winter due to re-aeration occurring within limited open water leads. Additionally, photosynthesis is reduced by decreased daylight hours, inability of solar radiation to pass through ice, and slower algal growth in winter. The low volumetric flow decreases point-source dilution while their travel time increases. The Athabasca River in Alberta, Canada, has experienced these sags which may affect the aquatic ecosystem. A water quality model for an 800 km reach of this river was customized, calibrated, and validated specifically for DO and the factors that determine its concentration. After validation, the model was used to assess the assimilative capacity of the river and mitigation measures that could be deployed. The model reproduced the surface elevation and water temperature for the seven years simulated with mean absolute errors of <15 cm and <0.9 °C respectively. The ice cover was adequately predicted for all seven winters, and the simulation of nutrients and phytoplankton primary productivity were satisfactory. The DO concentration was very sensitive to the sediment oxygen demand (SOD), which represented about 50% of the DO sink in winter. The DO calibration was improved by implementing an annual SOD based on the BOD load. The model was used to estimate the capacity of the river to assimilate BOD loads in order to maintain a DO concentration of 7 mg/L, which represents the chronic provincial guideline plus a buffer of 0.5 mg/L. The results revealed the maximum assimilative BOD load of 8.9 ton/day at average flow conditions, which is lower than the maximum permitted load. In addition, the model predicted a minimum assimilative flow of about 52 m^3/s at average BOD load. Climate change scenarios could increase the frequency of this low flow. A three-level warning-system is proposed to manage the BOD load proactively at different river discharges. Other mitigation options were explored such as upgrading the wastewater treatment of the major BOD point source and

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oxygen injection in the effluents. The model can be used as a management tool with updated SOD values to forecast the DO in low flow years and evaluate mitigation measures. As well, the methodology presented here can be applied to manage other ice-covered rivers.

1. Introduction

The dissolved oxygen (DO) concentration in a river is an indicator of the overall health of the aquatic ecosystem. A low concentration may impact spawning success (Corsi et al., 2011). Incubation of burbot eggs at 6 mg/L delayed spawning up to 5 weeks (Giles et al., 1996). Mountain whitefish eggs incubated at 6.5 mg/L took much longer to hatch than eggs at higher DO concentration, while for bull trout eggs incubated at 5 mg/L post-hatch alevins were smaller (Giles and Van der Zweep, 1996). The low DO levels increase susceptibility to disease, and alter survival behavior such as predator avoidance, feeding, migration and reproduction. In extreme cases it can lead to cellular breakdown and death in fish (Giles, et al., 1996).

Dissolved oxygen (DO) sags in rivers have been traditionally related to the warm days of summer when eutrophic water bodies have high algal productivity and large diurnal DO changes. Different case studies have documented DO modeling in open water conditions (Drolc and Zagorc Koncan, 1999; Gautam and Sharma, 2011; Turner et al., 2009; Williams and Boorman, 2012), however, DO depressions have also been observed under winter ice-covered conditions (Whitfield and McNaughton, 1986; Schallock and Lotspeich, 1974; Schreier et al., 1980; Mossewitsch, 1961). The DO balance under these circumstances is affected by limited re-aeration and photosynthesis. Additionally, the low volumetric flow reduces dilution and the mass flow of oxygen relative to consumptive processes. Few model applications have investigated the DO balance under these conditions (Pietroniro et al., 1998). This study implemented a water quality model, CE-QUAL-W2, which focused on the dissolved oxygen processes under winter conditions for the Athabasca River in northern Alberta, Canada.

The Athabasca River originates in Western Canada's Rocky Mountains and flows 1538 km northeast towards the Arctic as part of the Mackenzie basin (Noel and Wilson, 1995). Its minimum, mean and maximum flows (1913–2007) at the town of Athabasca are 37 m^3/s, 442 m^3/s and 5440 m^3/s respectively (Environment Canada, 2010). The Athabasca River watershed has a gross area of 160,000 km^2, which represents about one-fourth of Alberta's area. Because five mills have been established in its watershed, this river has been crucial for the development of the pulp mill industry. At the same time, it is the habitat of a great variety of organisms, and is fundamental to the sustainability of a complex ecosystem. It is estimated that up to one million whitefish migrate each year from Lake Athabasca to spawn in the river due to the specific conditions found there (Alberta Environment, 1996). However, this river has experienced periods in winter with a DO concentration below the provincial's chronic guideline of 6.5 mg/L (Alberta Environment, 1999), reaching values as low as 5.4 mg/L in February 2003.

The pollutant travel time between the point sources and upstream Grand Rapids, where the minimum DO concentration has been observed, is from 15 days to 30 days. Without a model that can predict whether the DO would decline below the guideline there is risk of a substantial lag time between management action and mitigation of low DO levels monitored at Grand Rapids. For this reason, there has been great interest since the early 90s, of generating a model that can be used to enforce the BOD reduction from the point sources if necessary (Chambers, 1996; Golder Associates, 1995; Stantec, 2001b; Tian, 2005). The sensitivity analyses of previous modeling efforts have shown a strong relation between SOD and the low DO in winter (Stantec, 2001a; Tian, 2005). Important advancements in SOD techniques during the last few years (Sharma et al., 2009; Sharma, 2012; Tian, 2005; Yu, 2006) have improved the available data for model calibration and thus have enhanced the representation of in-river processes and model reliability. Additionally, the complexity of the models available has also increased with more powerful processors.

CE-QUAL-W2, a hydrodynamic two-dimensional model (assuming complete mixing in the lateral direction) was used in this study. It simulates water surface elevations, velocities, temperature, ice cover, sediment processes, and multiple water quality constituents. The DO is calculated by taking into account algae respiration and photosynthesis, organic matter decay, BOD, SOD and nitrification (Cole and Wells, 2008). Yu (2006) used this software to examine a short reach of the Upper Athabasca River; however, this study only included the direct discharge of one of the five pulp mills. Furthermore, the DO was simulated only for winter.

The aim of this research is to improve the model's customization by including summer and winter data, and increasing the spatial scope to the representative river reach. The calibrated and validated model will be used as a management tool to predict low DO events and guide the mitigation measures. It will also help to understand what the main sources and sinks are, the extent of the DO sag, and to which parameters the model is more sensitive.

2. Methods

The theory behind the DO modeling using CE-QUAL-W2 is very well documented in its manual (Cole and Wells, 2008). The mass transport and hydrodynamic governing equations are obtained by performing a mass and a momentum balance of the fluid phase in a control volume. The resulting three laterally averaged equations are continuity, x-momentum and z-momentum. The instantaneous velocity and concentration are decomposed into a mean and an unsteady component, which uses dispersion coefficients. The sources and sinks for constituents either come from outside boundaries or internal processes resulting from kinetic interactions. The internal sources and sinks for DO are:

Algal and epiphyton net production
$$+\left(K_g - K_r\right)\delta_{OM}\Phi \tag{1}$$

Zooplankton respiration
$$-\left(K_r\delta_{OM}\gamma_{zoo}\Phi_{zoo}\right) \tag{2}$$

Aeration
$$+A_{surface}K_L\left(\Phi_{sat}-\Phi_{DO}\right) \tag{3}$$

Organic matter decay
$$-K_{OM}\delta_{OM}\gamma_{OM}\Phi_{OM} \tag{4}$$

Sediment Oxygen Demand
$$-\mathrm{SOD}\,\gamma\,\frac{A_{bottom}}{V} \tag{5}$$

CBOD decay
$$-K_{CBOD}R_{CBOD}\theta^{T-20}\Phi_{CBOD} \tag{6}$$

Nitrification
$$-K_{NH_4}\delta_{NH_4}\gamma_{NH_4}\Phi_{NH_4}. \tag{7}$$

Where:

δ	oxygen stoichiometric coefficient
γ, θ	temperature rate multiplier
K	decay, growth (g) or respiration (r) rate
A	area
V	volume
Φ	concentration
R	conversion from CBOD to CBOD ultimate