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Challenges of modelling water quality in a shallow prairie lake with seasonal ice cover

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ABSTRACT

The link between under ice processes and open water eutrophication dynamics has been proven in the field. Water quality models still lack the capability to capture the connection between both environments. The hydrodynamic-ecological model CE-QUAL-W2 is being applied to a eutrophic drinking water reservoir on the Canadian Prairies as part of larger collaborative research project. CE-QUAL-W2 is one of the few water quality models that includes an ice algorithm, yet is restricted by a fixed albedo coefficient. Field studies have shown albedo to change through the ice cover season – varying the solar radiation that reaches the ice-water interface as a result. In order to better represent the light and heat environment during the under ice periods we modify the ice algorithm to incorporate a variable albedo rate. While assessing the modified version of CE-QUAL-W2 on the reservoir we encounter a number of challenges during the calibration process. These challenges pertain to difficulties with modelling the under ice environment, and with modelling shallow lakes and reservoirs. We recommend a targeted monitoring program to supplement available data that will reduce the uncertainty associated with the results of the reservoir model.

1. Introduction

Buffalo Pound Lake (BPL) is a shallow, eutrophic, impounded natural lake. BPL has a history of water quality challenges and algal blooms (e.g. Kehoe et al., 2015; Slater and Blok, 1983), and treatment and processing costs are high for the on-site Buffalo Pound Water Treatment Plant (BPWTP). Of key importance are the winter processes under ice-cover (range of 4.5 months to more than 6 months over a 39 year period). Salonen et al. (2009) argue that winter should be considered a fundamental part of summer lake functioning, and lake annual succession, stating that an often misconception is that biological activities cease in this period due to low light and cold water. Heterotrophic growth instead provides competitive advantage for heterotrophic and mixotrophic species during ice-cover conditions (e.g. Wetzel, 2001). As winter comes to an end, the shorter the duration of ice-coverage before ice-off the earlier water temperatures in BPL will start to rise (as incoming heat starts warming waters below after melting the ice), and the earlier light becomes available for phototrophic productivity triggering spring blooms. Algae may grow in an under-ice layer (Vehmaa and Salonen, 2009; Kelley, 1997) and within certain forms of lake ice (Leppäranta, 2010) when snow cover is minimal and light can still penetrate. With ice-melt any impurities or algae confined in the different layers of ice will be released into BPL. Algal succession is therefore influenced by ice-cover duration, and winter snowfall quantity (Leppäranta, 2014).

Algal blooms require high water treatment costs for removal, particularly in waterbodies used for drinking water. Nonetheless, the relationship between ice cover and algal dynamics in BPL remains unexplored. Canada has seen a trend in earlier lake ice break-up dates attributed to warming spring air temperatures (Duguay et al., 2006). For the BPWTP to mitigate against bloom induced water restrictions, and processing costs, the influence of the under ice environment must be incorporated into management planning. The growing evidence that lake dynamics during the open water season are connected to winter processes (reviewed in Sommer et al., 2012, and Hampton et al., 2017) suggests it may even be possible to anticipate bloom occurrence on ice off by monitoring the preceding winter conditions. To do this, winter water temperature, nutrients, ice characteristics, and light penetration estimates would be vital information to collect due to their respective stimuli on phototrophic processes (Bertilsson et al., 2013).

BPL is the focus of a team of researchers investigating how temporal changes within the reservoir affect water chemistry and lead to algal

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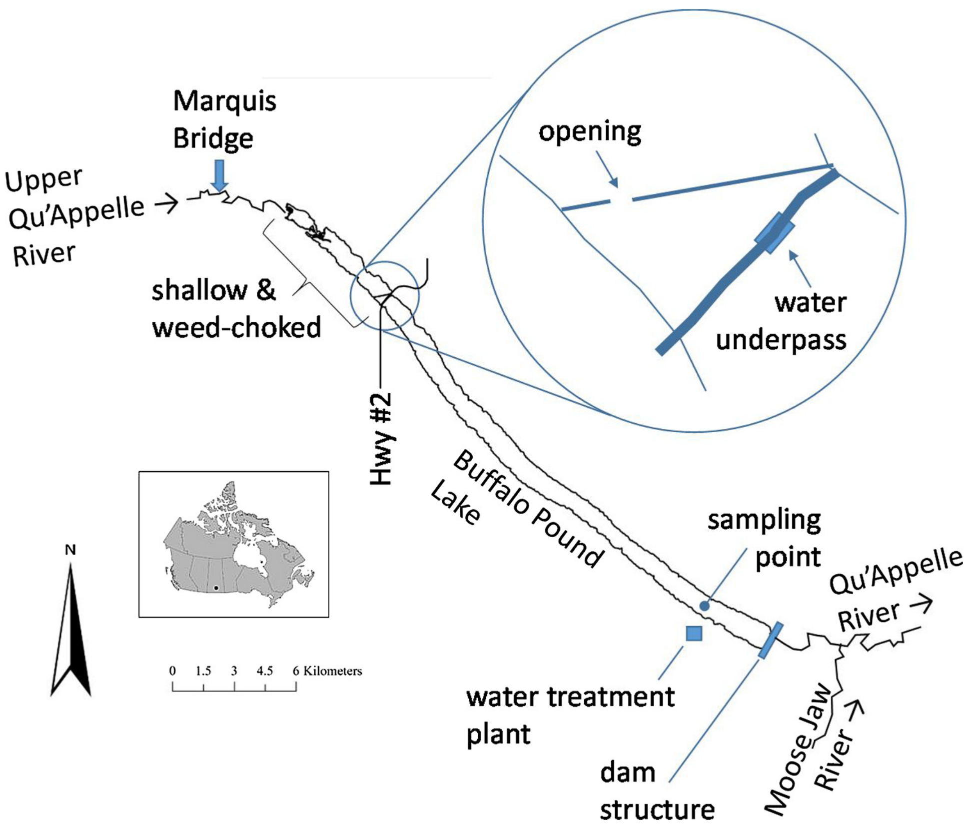

Fig. 1. Buffalo Pound Lake, Saskatchewan, Canada. The black reservoir outline is to the scale provided. The magnified section illustrates the Highway 2 water underpass and the wave break built to protect the highway. The reservoir has a mean depth of 3.8 m and a maximum depth of 5.98 m. Average surface width of the main reservoir body is 890 m.

blooms. Part of the objectives include the first application of a coupled hydrodynamic-ecological model to the system for long-term scenario development. This type of model has not been previously applied in Saskatchewan, in part due to a history of very limited monitoring. Traditionally, these more complex coupled water quality (WQ) models have treated open water and under ice periods in seasonally frozen waterbodies separately. WQ models have generally been applied to spring/summer eutrophication problems, and any complex winter modelling has tended to focus on hydrodynamics, ice characteristics and temperature. Research that explores the link between the under ice environment, and spring algae and nutrient dynamics has so far been based around field sampling studies and theoretical discussions. WQ models have yet to capture under ice chemical and biological feedback mechanisms, and are essentially simulating spring and summer processes without factoring for antecedent winter conditions. This limits the predictive capability of the model somewhat for a multi-year simulation.

In earlier work a dissolved oxygen and sediment oxygen demand model was applied to BPL (see Terry et al., 2017) for a seven-year continuous simulation using CE-QUAL-W2 (W2) (Portland, OR, USA). W2 is a public domain two-dimensional, laterally averaged, hydrodynamic and WQ model suitable for long, narrow waterbodies, and incorporating an ice model component. W2 is a complex model that has been applied to numerous lake systems worldwide (Gelda et al., 1998; Martin, 1988; Deliman and Gerald, 2002; Boegman et al., 2001), and is capable of investigating the WQ issues and algal bloom dynamics of BPL. Studies on the application of W2 to simulate ice cover, and under ice processes are much less available.

W2, like many WQ models, is set up for more temperate climates than the Canadian Prairies. In Terry et al. (2017) the authors discuss how W2 does not account for snow on top of the ice. Snow depth at BPL is generally between 0.1 to 0.3 m based on 99 snow depth measurements recorded by the Water Security Agency (WSA), for sites across the reservoir, between 1975 and 1996. Ice thickness growth is slowed down by early snow cover as conduction of heat fluxes is reduced due to the low conductivity of snow (Leppäranta, 2015). W2 may over-estimate the ice thickness in years with early snow events. This in turn may delay breakup of ice in the model. On the other hand, ice melting is strongly influenced by surface albedo and snow thickness (Kirillin et al., 2012) and W2 has the potential to simulate earlier breakup dates by absorbing extra solar radiation due to the perceived lack of snow cover.

To test the influence of a variable albedo on ice duration and WQ we develop a full WQ model for BPL. We modify the ice algorithm to include our variable albedo function. A number of challenges present themselves during model setup and calibration; these include difficulties in parameterising the reservoir in W2, and challenges pertaining to BPL reservoir itself. Many of the issues represent difficulties that can be faced when modelling any shallow Prairie lake in Canada. Other issues characterise complications in modelling the WQ of cold polymictic lakes. Here we present our findings. To our current knowledge we are the first to attempt to properly parameterise the ice algorithm of a popular off-the-shelf complex dynamic water quality model to better represent winter under-ice conditions (previous work by Sadeghian, 2015, and Terry, 2017, added two empirical coefficients to fix the ice cover prediction errors). The end objectives of this research are to better understand the factors limiting the ability to reproduce the under ice environment of BPL in a WQ model, and to make recommendations for future WQ monitoring of the reservoir.

2. Methods and model description

2.1. Site description

BPL is situated on the rural prairies of Saskatchewan, Canada along the Upper Qu'Appelle River System. BPL forms part of a landscape of lakes along a glacially formed (Hammer, 1971) river basin. Residence time is highly variable at approximately 6–36 months (Buffalo Pound Water Administration Board, 2015). The main inflows into BPL are through controlled releases from the upstream Lake Diefenbaker. The Upper Qu'Appelle River channel, between the two reservoirs, is a