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Spatial and temporal patterns in physical properties and dissolved oxygen in Lake Diefenbaker, a large reservoir on the Canadian Prairies

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ABSTRACT

Lake Diefenbaker (LD) is a multi-purpose deep storage reservoir with complex longitudinal zonation. Despite the importance of LD to Saskatchewan, the last comprehensive evaluation of this large reservoir was completed 30 years ago. Therefore, an assessment of key features (patterns in stratification, turbidity, and dissolved oxygen (DO)) was undertaken during the ice-free period of 2011–2013 to characterize conditions that may affect water quality, including climate change. In addition, these features were compared with the expectations of the longitudinal zonation concept (LZC) of Kimmel and Groeger (1984). The reservoir was dimictic, and summer mixing depths (10–20 m) were similar between a drought year (1984) and the current study. Sections of the hypolimnia became hypoxic, or were sub-optimal for cold and cool water fish (≤5 mg/L). Volumetric hypolimnetic oxygen depletion rates were 0.034 to 0.12 mg L/day and overlapped with other lakes and reservoirs. Sections of LD would be prone to hypolimnetic anoxia had thermal stratification been prolonged for another 2 to 4 weeks. LD experienced three years of above average peak flows. The peak flow of 2013 brought high turbidity (e.g., 200 NTU) and organic matter that resulted in a metalimnetic DO minimum. Spatial patterns in thermal stratification and turbidity (but not DO) followed the expectations of the LZC. Drought conditions of 1984 resulted in reduced hypolimnetic volumes, anoxic conditions and algal blooms. Therefore, as the Northern Plains continue to warm, monitoring of Lake Diefenbaker during drought periods is warranted, especially when droughts follow high flow events.

Introduction

There are approximately 17 million reservoirs greater than 0.01 ha in area that store 8070 km^3 of water globally (Lehner et al., 2011). Of these, larger reservoirs (i.e., dam height >15 m) store approximately 15% of global runoff (Nilsson, 2009). The relevance and number of reservoirs worldwide are expected to increase as climate warms (Uhlmann et al., 2011). Rising global temperatures are expected to increase drought and water scarcity on the planet (Prudhomme et al., 2013; Schewe et al., 2013), and in turn, water scarcity will likely require more effective management of reservoirs for both water quantity and quality.

Compared to lakes, reservoir levels are under greater human control and leave more options for the control of water quality (Thornton et al., 1996). Reservoir water quality is not only the result of external loading of nutrients, but also a function of physical, chemical and biological factors (Uhlmann et al., 2011). Key physical and chemical factors include (but are not limited to) temperature, dissolved oxygen, and turbidity. An understanding of the temporal and spatial patterns of temperature in the water column is fundamental for managing reservoir water quality (Casamitjana et al., 2003; Wang et al., 2012). If sufficiently deep, reservoirs either become dimictic, or monomictic in temperate regions, and monomictic in tropical or polar regions (Thornton et al., 1996). Besides the typical parameters that affect thermal stratification (e.g., air temperature, fetch, morphology, and water transparency), reservoir stratification can be strongly impacted by changing inflows and the location, volume and timing of outflows (Casamitjana et al., 2003; Uhlmann et al., 2011). Reservoir stratification is particularly sensitive to changes in flow regimes because reservoirs typically have a greater proportion of catchment area to surface area than lakes (CA:LA), and therefore, shorter water residence times (Kalff, 2002; Welch et al., 2011).

Climate change is affecting many regions of the world; in Western Canada warming is well underway (Booth et al., 2012) and modifying the physical and chemical conditions of standing waters on the Canadian Prairies (Sereda et al., 2011). One predicted outcome of climate warming for deep reservoirs and lakes of the World is an increase in the thermal stability and duration of stratification of the water column (Jones et al., 2011; Sahoo et al., 2011; Wang et al., 2012). This has the potential to aggravate water quality problems, particularly those resulting from oxygen depletion (Butcher et al., 2015).

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In reservoirs that are sufficiently deep to undergo thermal stratification, the suppression of the vertical movement of oxygen at the thermocline typically results in an oxygen gradient in the hypolimnion. This results from oxidative decomposition of organic matter located in the hypolimnion and in the bottom sediments (Boland and Griffiths, 1995). Depending on a variety of factors (e.g., reservoir trophic state, hypolimnetic volume and duration of stratification), decomposition may lead to hypoxic or anoxic conditions in the hypolimnion. Oxygen depletion has profound effects on the distribution of organisms, particularly cold and cool water species that rely on well-oxygenated habitat in cool deeper waters (Welch et al., 2011). More importantly, hypolimnetic oxygen depletion can lead to increased rates of internal loading of nutrients and the release of noxious substances (e.g., H_2S) from the bottom sediments to the overlying water. Internal loading of nutrients can stimulate algal and bacterial growth and cause significant declines in water quality of reservoirs and lakes (Cooke et al., 2005; Nurnberg, 2009). The dynamics between thermal stratification, oxygen depletion and internal nutrient loading in lakes has received considerable scientific attention. However, unlike lakes, oxygen dynamics can be much more complex in reservoirs because the distribution of oxygen is affected by horizontal and vertical gradients in flow velocity, suspended solids, thermal stratification, nutrient concentration and biotic productivity (Uhlmann et al., 2011). For example, anoxia may first occur in the hypolimnion of an upstream region, or at a mid-depth region in the thermocline (Thornton et al., 1996).

There is growing evidence that climate change may be responsible for increased frequency and intensity of rainfall and flood events, which has led to high sediment loads and turbidity in some rivers and lakes (Dankers et al., 2013; Gilbert et al., 2006; Sahoo et al., 2011; Wilhelm et al., 2013). Such extreme flows result in rapid flushing and high inputs of organic and inorganic particles (turbidity) in reservoirs (Gelda et al., 2013; Kim et al., 2000; Wang et al., 2012). Turbidity has deleterious effects on water quality and aquatic life in reservoirs (Bilotta and Brazier, 2008; Effler et al., 2006) and guidelines have been set for some jurisdictions (Bilotta and Brazier, 2008). The observation of a positive relationship between chlorophyll *a* and Secchi disk depth in turbid reservoirs, the opposite of that found in lakes and low turbidity reservoirs, demonstrates the impact turbidity has on water quality (Lind, 1986; Sobolev et al., 2009; Yip et al., 2014). The interplay between flow, thermal stratification, dissolved oxygen and episodic turbidity in deep storage reservoirs is complex, and poses serious issues for drinking water reservoirs (Gelda et al., 2013; Rinke et al., 2013). For example, during high river discharge the upper region of a deep storage reservoir is typically turbid. Depending on the degree of stratification and the density of the reservoir water, this inflowing turbid water may remain on the surface, or plunge to deeper regions once it reaches the mid-region of the reservoir (Gelda and Effler, 2002). In this region, reduced water velocities will result in particle sedimentation and, in time, organic particle decomposition may lead to metalimnetic, or hypolimnetic oxygen depletion (Huang et al., 2014).

The longitudinal zonation concept (LZC) by Kimmel and Groeger (1984) divides mainstream reservoirs into three zones: riverine, transition and lacustrine. Each zone is characterized by a series of unique physical, chemical and biological features. For example, the upstream riverine zone is described as narrow with high flow, suspended solids and dissolved oxygen in the water column. The transition zone is deeper with lower flow and reduced suspended solids and may, or may not be thermally stratified. Finally, the downstream lacustrine zone is deep and lake-like with little flow and most prone to thermal stratification. The LZC can serve as a useful model for comparison. With this approach the salient characteristics of a given reservoir may be readily identifiable (An and Jones, 2002; Lind, 2002; Scott et al., 2009).

Lake Diefenbaker (LD) is a large reservoir located in Southern Saskatchewan. The reservoir plays a pivotal role in the economy of the province, but faces many emerging issues (Gober and Wheater, 2014). The demands on the reservoir are increasing with the province's rapidly growing economy and cities (Government of Saskatchewan, 2012). Plans are under consideration to significantly augment water extraction from LD for irrigation (Clifton Associates, 2012; Saskatchewan Ministry of Agriculture, 2014); the municipalities immediately surrounding LD are undergoing expansion, including growth in tourism-associated activities (WaterWolf, 2013). Meanwhile, complaints about deteriorating water quality in LD are being voiced by local residents (e.g., Soggie, 2011).

Approximately 98% of the flows entering LD originate in Alberta (Water Security Agency, 2012). Agricultural intensification combined with increasing urbanization in the LD watershed is occurring (Gober and Wheater, 2014). The northern prairie region and its source water are sensitive to climate change; evidence of warming trends has been observed over western North America (Booth et al., 2012) and in the immediate Saskatchewan River watershed (Sereda et al., 2011). The combination of these factors has considerable potential to impact water quality and quantity in Lake Diefenbaker. A comprehensive understanding of the limnological characteristics and the capability of the reservoir to accommodate these changes is lacking. For example, the last major study on the reservoir was conducted 30 years ago (Saskatchewan Environment and Public Safety and Environment Canada) (SEPS and EC, 1988).

The objectives of the current study were to provide a more comprehensive understanding of the limnology of LD and bring to light any concerns that should be considered in its management. Specifically, we characterized temporal and spatial patterns in temperature, dissolved oxygen, and turbidity from 2011 to 2013. We also compared our results with an earlier study in order to examine the dynamics of the reservoir in low flow (1984 drought) and high flow years (current study). Such a comparison would help isolate the effects of a changing climate (e.g., drought and extreme inflow years). Finally, we compare the physical and chemical attributes of Lake Diefenbaker to those presented in Kimmel and Groeger's (1984) LZC to determine if Lake Diefenbaker is similar to a typical mainstream reservoir.

Materials and methods

Site description and sampling

Lake Diefenbaker is a large multipurpose reservoir on the South Saskatchewan River in Saskatchewan, Canada (Fig. 1). It was formed by the construction of the Gardiner and Qu'Appelle Dams and began filling in 1967 (Saskatchewan Watershed Authority (SWA), 2012). The vast majority of water leaves the reservoir by the Gardiner Dam (99%, SWA, 2012), which is used to generate hydroelectric power. The primary water intake at the dam occurs at 34 m below the full supply level (FSL, 556.87 m above sea level). Surface water is only released over a spillway during brief periods of high flow. Average flow into the reservoir from the South Saskatchewan River (SSR) is between 200 and 300 m^3/s. Average annual volume of water input from the SSR (1969 to 2013) is 7.8 km^3 (range 6.9 to 8.5). The average water residence time (WRT) between 1969 and 2013 was 1.5 years (range 0.7 to 3.4 years, based on the bathymetry of 1985 (Saskatchewan Property Management Corporation, 1986) and the average volume of water in the reservoir each year). The trophic status of the reservoir is mesotrophic (Abirhire et al., in this issue). Additional morphometric and chemical characteristics of the reservoir are provided in Table 1, in other articles in the special issue, in SWA (2012) and in SWSA (2012).

Sampling was conducted at 10 sites along the main channel of Lake Diefenbaker in 2011 and 2012 and at 12 sites in 2013 (Fig. 1). Sites were sampled once per month from June to October each year. Some sites were also sampled at additional times when convenient, as part of other research on the lake. Sampling sites were chosen to span the length of the lake. Vertical profiles of each parameter were measured with a YSI 6600 V2 multi-parameter sonde; parameters included: temperature, dissolved oxygen concentration, specific conductance, and

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