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Spatial and temporal trends in reservoir physicochemistry and phosphorus speciation within Lake Diefenbaker, a Great Plains reservoir, as inferred from depositional sediments

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ABSTRACT

Previous research and observations by area residents suggested that the frequency of algal blooms in the Qu'Appelle arm of Lake Diefenbaker, Saskatchewan, Canada, has been increasing over time. However, limited historical data were available to assess long-term trends in the overall reservoir. Narrow river-valley reservoirs, such as Lake Diefenbaker, are known to display marked longitudinal physicochemical and biological gradients. To assess both spatial and temporal geochemical trends, sediment cores were collected from eight sites along the longitudinal axis of this reservoir and sectioned vertically for analysis of various parameters. Surficial sediments showed an increasing trend in organic carbon, total phosphorus concentrations, and $\delta^{15}N$ values, and decreasing trends in $\delta^{13}C$ values and in the carbon to nitrogen ratio, with distance down-reservoir. This was attributed to reduced deposition of allochthonous detritus and increased entrainment of nutrients as settled autochthonous materials, as the reservoir transitioned to less dynamic lacustrine conditions. A strong correlation was determined in the Qu'Appelle arm between chlorophyll *a* concentrations and the more biologically available forms of P (non-apatite inorganic P + organic P) in the sediment profile ($r = 0.955$, $p < 0.001$), suggesting an increase in autochthonous production in this region of the reservoir in the mid-1990s, which subsequently plateaued. The spatial and temporal trends illustrated in the sediment core profiles of this study demonstrate that paleolimnological investigations of narrow river-valley reservoirs need to consider geochemical and biological spatial gradients associated with reservoir zonation.

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Introduction

Lake Diefenbaker is a man-made reservoir created through the flooding of a portion of the South Saskatchewan River valley in 1967, after construction of the Gardiner and Qu'Appelle dams (Saskatchewan Environment and Public Safety and Environment Canada [SEPS and EC], 1988). It is a major body of water on the Canadian prairies and indirectly supplies approximately 45% of Saskatchewan's drinking water. This multi-purpose reservoir also supplies water for industrial and agricultural purposes, aquaculture (Wild West Steelhead fish farm), hydroelectric power generation (Gardiner Dam), and maintains an important sport fishery.

Personal observations by area residents near the Gardiner and Qu'Appelle arms of the reservoir suggest that the frequency of algal blooms has increased in the reservoir over time, possibly indicating decreasing water quality. Due to limited historical monitoring since formation of this reservoir, few empirical data are available to assess current and past water quality conditions and long-term trends throughout the broader reservoir. Such data are necessary for effective resource management. Nevertheless, a temporal increase in trophic status is supported by the findings of Hall et al. (1999), who conducted a paleolimnological investigation of the Qu'Appelle arm of Lake Diefenbaker. Using diatom subfossil analysis of one sediment core, their data indicated three major shifts in community composition within this arm since reservoir formation. It was inferred that after formation of the reservoir there was an initial period of high trophic status (~1968–1972), attributed to rapid release of nutrients from soluble soil nutrients and rapid soil organic matter degradation. There was then a period of decreased trophic status (~1975–1986), which was assumed to have resulted from nutrient depletion. This was subsequently followed by an increase in trophic status up to the date of coring (~1986–1995). The authors were unable to determine the cause of the later shift towards higher trophic status but speculated that it could have been due to increased nutrient loading resulting from nearby aquaculture, or due to greater contributions of *in situ* nutrient cycling from sediments. Although Hall et al. (1999) suggest that, as of the

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date of coring (1995), the Qu'Appelle arm of Lake Diefenbaker was experiencing an upward trend in trophic status, subsequent long-term monitoring data for this arm (1995–2013) suggest no changes to water clarity or algal abundance for approximately the last two decades (Vogt et al., in this issue). Narrow river-valley reservoirs, such as Lake Diefenbaker, are known to display marked longitudinal physicochemical and biological gradients (Thornton et al., 1990), resulting in uncertainty as to the spatial extent of the temporal trends observed in the Qu'Appelle arm. Lake Diefenbaker has been found to experience P limitation (Dubourg et al., in this issue). Therefore, an assessment of spatial and long-term trends in P geochemistry in Lake Diefenbaker would be useful in inferring long-term trends in nutrient transport and availability in Lake Diefenbaker.

Dammed river-valley reservoirs are longitudinally heterogeneous and can often be divided into zones based on hydrological and limnological characteristics (Thornton et al., 1990). In long, narrow reservoirs such as Lake Diefenbaker, up-reservoir locations tend to be more riverine. Compared to down-reservoir sites, this region is characterized as having a narrower basin, greater flow rates, higher turbidity and an advective nutrient supply (Kimmel and Groeger, 1984; Thornton et al., 1990). The organic matter supply is also primarily allochthonous (Kimmel and Groeger, 1984), coming into the reservoir from surrounding soils, rivers and streams in the catchment (Ishiwatari, 1985). Down-reservoir locations closer to the outflow are typically more lacustrine and characterized by a wider and deeper basin, slower flow rates, lower turbidity, and more *in situ* nutrient cycling (Kimmel and Groeger, 1984; Thornton et al., 1990). Organic matter supply is primarily autochthonous (Kimmel and Groeger, 1984), being produced by aquatic organisms in the reservoir itself. A transition zone occurs between the up-reservoir riverine zone and the down-reservoir lacustrine zone and has features intermediate to the two (Kimmel and Groeger, 1984; Thornton et al., 1990). According to Cole and Hannan (1990), peak sedimentation of suspended materials occurs in the transition zone. The location and extent of the transition zone can vary spatially and temporally due to changes in flow regimes.

Due to the physical, chemical and biological gradients anticipated in Lake Diefenbaker, several paleolimnological studies were conducted to assess local observations and the temporal trends reported in Hall et al. (1999), but over a spatial scale that takes reservoir zonation into consideration. The study herein focussed on nutrients, mainly P, with supporting physicochemical variables. A companion paper by the same authors (Lucas et al., in this issue) assessed trends in diatom and chironomid remains, in addition to a toxicological assessment of sediments. Tse et al. (in this issue) assessed phytopigment trends in the sediment profile to infer spatial and temporal trends in algae communities in Lake Diefenbaker. Spatial and temporal patterns of silicon deposition are presented in Maavara et al. (in this issue).

Beyond local interest in water and environmental quality trends, with a length of approximately 225 km and one major inflow, the long, narrow morphology of Lake Diefenbaker (Fig. 1) provides an excellent opportunity to assess the influence of hydrological, chemical and biological spatial gradients inherent to narrow river-valley reservoirs on P distribution and speciation in sediments. Using analyses of physicochemical variables in depositional sediments (described below), the main goal of this study was to answer the following questions: i) how do P concentrations and P speciation in sediments vary along the longitudinal axis of Lake Diefenbaker and ii) if changes to physicochemical variables are observed within sediment core stratigraphies, can they be used to infer temporal changes to water quality and trophic state?

The limited availability of historical data regarding limnological conditions in Lake Diefenbaker poses a problem for establishing environmental trends and determining the magnitude of any changes in environmental conditions (i.e., water quality) over time. Annual TP loading can vary substantially, ranging from 247 tonnes in 1984 (SEPS and EC, 1988) to greater than 4833 tonnes in 2013 (May to October only; North et al., in this issue) depending upon South Saskatchewan River flow. Nevertheless, Dubourg et al. (in this issue) and Hecker et al. (2012) determined that P was the limiting nutrient for primary production within Lake Diefenbaker (although light limitation also occurs, Dubourg et al., in this issue). To better understand spatial and temporal trends in sediment P geochemistry, as well as P dynamics within the reservoir, P concentrations and speciation were determined within the vertical profile of depositional sediments from various locations along Lake Diefenbaker. Total sedimentary P concentrations (TP) and three geochemical forms of P (apatite inorganic [AP], non-apatite inorganic [NAIP], and organic [OP]) were investigated (based on methods of Hiriart-Baer et al., 2011; Mayer et al., 2006; Williams et al., 1976b). Apatite inorganic P represents orthophosphates bound in a crystal lattice within apatite grains. Typically, this fraction is chemically stable and very insoluble in surface waters (Williams et al., 1976b). Non-apatite inorganic P represents all remaining orthophosphates bound to particulate matter. This fraction typically consists of orthophosphates bound to metal oxides (iron [Fe], manganese [Mn] and aluminum oxides) and hydroxides, and it tends to be redox sensitive. Organic P represents P associated with carbon. This fraction is typically made up of C–O–P or C–P bonds within the sediment (Williams et al., 1976b).

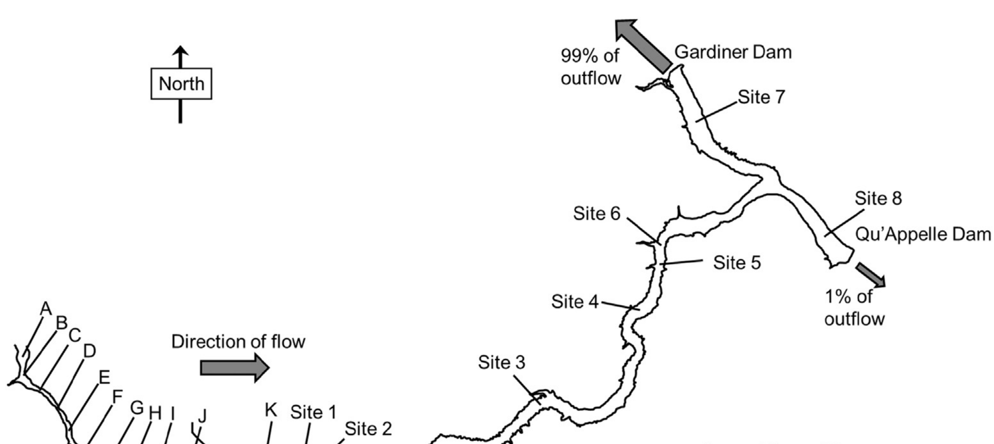

Fig. 1. Lake Diefenbaker (Saskatchewan, Canada) sediment core sampling locations in 2011 and 2012. Lettered sites A to K were characterized for only total phosphorus in the top 1-cm of the sediment profile. Sites 1 to 8 were characterized for the full suite of physicochemical variables investigated in this study. All cores were collected from mid-channel locations.

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