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Nutrient sequestration in the Lake Winnipeg watershed

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ABSTRACT

Lake Winnipeg, Manitoba, has been subjected to significant increases in nutrient loading over the last few decades, and consequently has experienced significant and widespread algal blooms. The objective of our study was to identify sources of nutrients in the Lake Winnipeg basin, and quantify their removal (sequestration) into 28 of the largest lakes and reservoirs located in the Saskatchewan, Dauphin, Red, and Winnipeg river sub-basins, thus preventing their transport downstream to Lake Winnipeg. Discharges were determined daily, and nutrient parameter concentrations determined once or twice each month upstream and downstream from each of the lakes and reservoirs for three years. Concentrations of P and N in source waters of the Lake Winnipeg basin varied substantially, with the lowest concentrations occurring in pristine headwaters of the Saskatchewan River (mean TP = 14 μg/L; mean TN = 217 μg/L) and some of the highest concentrations occurring in small streams that originated within agricultural landscapes in the headwaters of the Dauphin River sub-basin (mean TP = 133 μg/L; mean TN = 1313 μg/L). Twelve reservoirs in the Saskatchewan River sub-basin collectively sequestered 92% of the TP inputs and 68% of the TN inputs to the sub-basin. In P-rich lakes, relatively more N was sequestered than P compared with nutrient impoverished lakes. A total 13,215 t/yr TP was discharged into Lake Winnipeg while 8234 t TP/yr, was sequestered into the lakes and reservoirs. The Red River sub-basin was the principal source of nutrients to Lake Winnipeg and should be the focus of nutrient management in the Lake Winnipeg basin.

Introduction

Many challenges complicate adoption of management strategies to mitigate eutrophication, especially in lakes with large watersheds having diverse landscapes and land uses. A fundamental management requirement for these large watersheds is gaining a basic understanding of external loading sources and how watersheds process nutrients in upstream lakes and reservoirs thereby affecting downstream water quality. Lake Winnipeg in Manitoba, Canada is the tenth largest freshwater lake in the world by surface area, and is undergoing combined cultural (Bunting et al., 2011; Schindler et al., 2012) and climate-related (McCullough et al., 2012) eutrophication. Lake Winnipeg's gross watershed, at nearly 1,000,000 km^2 is vast (Fig. 1); however, substantial parts of the watershed consist of non-contributing closed basins. These "closed" basins do not discharge into tributaries of Lake Winnipeg in most years. However, under a future climate with more precipitation, some of these basins may connect to established tributaries and contribute nutrients to Lake Winnipeg (Todhunter and Knish, 2014). Regardless, conversion of substantial portions of the watershed into agriculture, particularly in the vast prairies of the western and southern portions of the watershed, urban development and increasing precipitation and runoff in the Red River (of the North) watershed over the past century (McCullough et al., 2012) have combined to increase nutrient levels in the lake.

It is well known that upstream lakes and reservoirs can be effective at sequestering nitrogen and phosphorus and thereby reduce downstream nutrient loading (Dixit et al., 2000; Koiv et al., 2011; Leavitt et al., 2006; Patoine et al., 2006; Vaux et al., 1995). Indeed Dixit et al. (2000) infer that even a single lake may exert significant control over downstream water quality. Nutrient retention rates can be highly variable among waterbodies (Kelly, 2001; Harrison et al., 2009) [0 to ≈100% for N]. In general, sequestration of nutrients is thought to be proportional to water retention or renewal time and directly related to waterbody size (Canfield and Bachmann, 1981; Koiv et al., 2011; Tiessen et al., 2011), although there are exceptions. In some jurisdictions, pre-dams have been widely applied above reservoirs to reduce high nutrient loads and downstream eutrophication (Benndorf and Pütx, 1987). Nutrient sequestration may also depend on the nutrient limitation status of phytoplankton, with P limited systems, for example, preferentially sequestering P.

The presence of lake and reservoir chains may lead to successive reduction in nutrients as water passes through each waterbody (Miranda et al., 2008). In some cases simple alteration of hydrology, via

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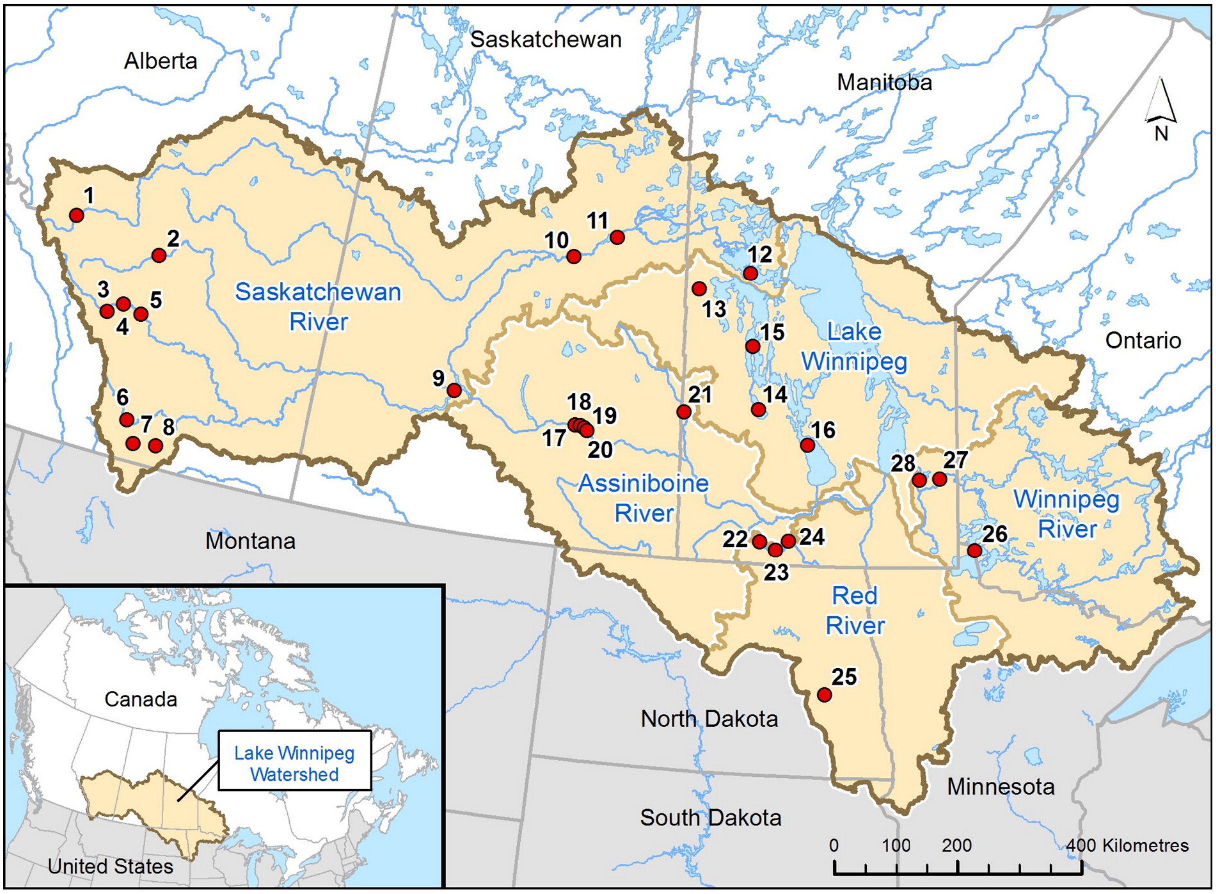

Fig. 1. Map of the Lake Winnipeg basin showing location of lakes and reservoirs included in the study (1 — Abraham, 2 — Gleniffer, 3 — Barrier, 4 — Ghost, 5 — Bearspaw, 6 — Oldman, 7 — Waterton, 8 — St. Mary, 9 — Diefenbaker, 10 — Codette, 11 — Tobin, 12 Cedar, 13 — Red Deer, 14 — Dauphin, 15 — Winnipegosis, 16 — Manitoba, 17 — Pasqua, 18 — Echo, 19 — Mission, 20 — Katepwa, 21 — Lake of the Prairies, 22 — Pelican, 23 — Rock, 24 — Swan, 25 — Ashtabula, 26 — Lake of the Woods, 27 — Point du Bois, 28 — Lac du Bonnet).

elimination of shortcuts in reservoir flows, has been shown to increase nutrient retention (Paul et al., 1998). Nutrient retention rates in systems with multiple sequestration sites and recycling of water through the system can be high, in some cases up to 99% for N and 98% for P (Yin et al., 1993).

Many of the world's great lakes are subject to anthropogenic nutrient enrichment and eutrophication (Hecky, 1993; Oguto-Ohwayo et al., 1997; Otu et al., 2011; Kravtsova et al., 2014; Kane et al., 2014). Reduction of nutrient loading has resulted in management success in some waterbodies (Jeppesen et al., 2005; Schindler, 2012) but not all (Carvalho et al., 1995). While the challenges of limiting or reversing eutrophication are substantial in great lakes, the need to understand hydrology and sources of nutrient inputs and losses remains a fundamental component to management initiatives (OECD, 1982). Thus, substantial efforts have been made to estimate nutrient loading at a watershed scale to identify point and non-point sources (e.g. Robertson and Saad, 2011; Brown et al., 2011; Han et al., 2012) and identify sites of nutrient sequestration (e.g. Brown et al., 2011; Powers et al., 2014). At the catchment scale of great lakes this can be especially challenging because of the immense geographic area of their watersheds, differences in geophysical areas, and differences in social and geopolitical priorities.

However, recent studies have improved understanding of the eutrophication process and the response of Lake Winnipeg to nutrient loading (Bunting et al., 2011; Schindler et al., 2012). Such studies are being used to support the development of nutrient objectives (phosphorus and nitrogen) for Lake Winnipeg.

In the present study, we undertake geographically extensive nutrient sampling to assess and quantify the effectiveness of large lakes and reservoirs upstream of Lake Winnipeg to sequester nutrients and thereby reduce nutrient loading to Lake Winnipeg. Results from this research may be used to allocate scarce resources toward nutrient management strategies that would have the greatest impact toward protection of Lake Winnipeg from anthropogenic eutrophication. An understanding of the role of lakes and reservoirs in the watershed nutrient budget, including the importance of size and water residence time could also inform decisions related to nutrient management in the Lake Winnipeg watershed. This approach to understanding watershed nutrient budgets could also be applied to the watersheds of other large lakes. The Lake Winnipeg catchment has numerous large lakes and reservoirs (>50 km^2) which could potentially sequester significant quantities of N and P. Our hypothesis was that these and smaller lakes and reservoirs play an important role in the nutrient mass balance of the Lake Winnipeg basin, and this watershed-wide assessment would provide further insight into identifying critical areas for nutrient management. Sequestration is defined herein to include the deposition and retention of nutrients associated with inorganic and organic particles into lake and reservoir sediments, transformations from total to dissolved nutrient fractions and denitrification. Lake and reservoirs within all the major tributaries of Lake Winnipeg were included in the study. These water bodies are located in different geographic zones (foothills of the Rocky Mountains, agriculture crop-lands in the prairies, and boreal forest of the Canadian Shield).

Study sites

Nutrient sequestration was assessed in 28 lakes and reservoirs of the Lake Winnipeg watershed, mainly between 1 September 2008 and 31