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Hydrological forcing of a recent trophic surge in Lake Winnipeg

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ABSTRACT

Nutrient enrichment leading to eutrophication of lakes is frequently attributed to increasing anthropogenic loading to the watershed. We use a phosphorus mass balance model to demonstrate that a discharge increase in a major tributary contributed more than increased anthropogenic loading to a recent sudden doubling of total phosphorus (TP) and a shift to a cyanobacteria-dominated plankton population in Lake Winnipeg. Runoff from the Red River watershed rose abruptly during the mid-1990s. The decadal mean discharge has since been more than 50% higher than for any previous decade in the century-long record. Widespread spring flooding has become common. TP concentration roughly doubles during floods, magnifying the effect of higher runoff on downstream phosphorus loading. Concentrations of both dissolved and particulate phases are raised by flooding. Over 90% of dissolved phosphorus downstream of flooded farm land in one tributary was in the form of highly bio-available orthophosphate. From 1994 to 1999, TP in the lake rose from less than 30 to more than 50 mg m^{-3}. It has since remained over 50% higher than before the mid-1990s. We use the phosphorus model to demonstrate that the change in Red River discharge alone would have caused a sustained 32% increase compared to when phosphorus was first routinely monitored in the 1970s, while direct increases in the rate of anthropogenic loading alone would have caused only a 14% increase. It required both increased loading to the land and higher runoff to produce the observed increase in TP in the lake.

Introduction

The widely cited Vollenweider model links trophic status specifically to phosphorus loading from the watershed, mediated by water residence time of the lake (Vollenweider, 1975; Vollenweider and Kerekes, 1982). Such increases in phosphorus loading have frequently been attributed to land use changes, especially waste water discharge in regions of increasing urbanization (Hall et al., 1999) and to agricultural development. The latter is of growing concern, beginning with land clearing (Hecky, 1993) and continuing with intensification of farming practices and fertilization (Carpenter et al., 1998; Bunting et al., 2007) and more recently, with intense animal husbandry (Duda, 2007; Bunting et al., 2011). Conversely, decreasing nutrient concentrations in lakes are frequently explained by improved agricultural practices upstream (e.g. contour plowing, conservation tillage) leading to decreased losses from fields in the watershed (Richards and Baker, 2002; Richards et al., 2010). In a review article, Schindler (2006) discussed the significance of residence time and suggests that lengthening of residence times due to climate warming will aggravate eutrophication even in lakes receiving constant nutrient loading. Several recent papers have drawn connections between higher runoff and greater nutrient losses from agricultural land (Andersen et al., 2006; Sprague and Lorenz, 2009; Nõges et al., 2007). Climate change is expected to cause increased frequency and severity of storms in the northern mid-latitudes of North America (Meehl et al., 2007) leading to higher runoff and more frequent flooding in the Canadian Plains region (Clair et al., 1998). Treating Lake Winnipeg as a case study, we show that eutrophication can be a consequence of increased runoff from nutrient-rich terrain and can lead to dramatic trophic changes in even a very large lake. We show that phosphorus loss from flood-prone plains farmlands increases with increasing flood frequency. At a time when global demand for phosphorus is approaching economical rates of supply, such a loss from agriculturally productive land is of concern in itself (Steen, 1998).

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Until recently, Lake Winnipeg received little scientific scrutiny. After a limnological expedition in 1928–29 (Bajkow, 1930) no further systematic whole lake surveys were conducted until 1969 (Brunskill, 1973). Occasional mid-summer whole-lake surveys were done in the 1990s by both federal and provincial agencies, and multi-season whole lake surveys have been conducted in most years since 2002. Several indicators of eutrophication, including phosphorus concentration, algal biomass and frequency and extent of cyanobacteria blooms increased markedly in Lake Winnipeg since the 1969 survey. Unfortunately, no whole lake surveys were completed in the 1970s and 1980s, so that when and how rapidly these changes in trophic status occurred are not documented. In this paper, we demonstrate by use of a phosphorus loading model that although total phosphorus (TP) concentrations in two major tributaries increased *gradually* over the 30 years of record, TP in the lake increased *abruptly* in the mid-1990s. We show that this abrupt increase was due more to increased runoff and flood frequency in the lake's most phosphorus-rich tributary watershed – that of the Red River – than to the last 30 years of increases in anthropogenic loading.

Setting and background

At 440 km in length and with an area of 23,750 km^2 (Brunskill et al., 1980), Lake Winnipeg is the 10th largest freshwater lake in the world. It receives runoff from a 953,000 km^2 watershed (Brunskill et al., 1980) spanning on the west the foothills of the Rocky Mountains and the dry prairie of the northern Palaeozoic Interior Plain, and on the east a wetter, lake-rich region of the Precambrian Shield that reaches almost to Lake Superior (Fig. 1). Much of the watershed is agriculturally well-developed. However, with a population of only 6.6 million, and 80% of these in 8 cities, it is sparsely populated by global standards (LWSB., 2006). Four major tributary river basins account for 91% of the lake's terrestrial watershed (Brunskill et al., 1980). The Saskatchewan River drains intensely farmed land as well as sparsely populated regions of the northern boreal forest. The Winnipeg River, and numerous smaller tributaries on the east side of the lake, drain mostly thinly populated, forested land on the Precambrian Shield, with only a small proportion farmed. In both of these watersheds, and the smaller Dauphin River, major nutrient sources are mostly upstream of large lakes or reservoirs which function as nutrient traps.

On the other hand, the Red River has no large lakes or reservoirs in its lower reaches. TP concentration in the Red is an order of magnitude higher than in other monitored tributaries (Jones and Armstrong, 2001). In consequence, although it delivers only a small fraction of total water fluxes into Lake Winnipeg, it contributes almost two-thirds of TP loading, and the Red River basin itself, exclusive of the Assiniboine, its large, but relatively dry western tributary, supplies 87% of that (Bourne et al., 2002; LWSB., 2006). Winnipeg, with a population of 630,000, is only 60 km upstream of the mouth. Seventy-four per cent of the Red River basin (excluding the Assiniboine) is farmed (65% cropland, 9% pasture) and 12% is forested (combining U.S. data reported by Stoner et al., 1993 and Canadian data by Bourne et al., 2002). Crop fertilization and large scale animal husbandry have increased nutrient loading to the land dramatically since the middle of the last century (Schindler et al., 2011). Carlyle (1984) showed nearly 40,000 km^2 of drained lands in the watershed; he claimed that this was one of the largest artificially drained agricultural landscapes in the world.

Most of the population and the most intensely drained and cropped farmland in the Red River watershed are concentrated along a band of very low relief terrain (lateral slopes as low as 0.25 m per km—Wilson and Rashid, 2005) underlain by nearly impermeable glaciolacustrine fine sediments. Roughly 80 km wide, it stretches 450 km from near the river's headwaters to Lake Winnipeg (Fig. 1, after Stoner et al., 1993; Matile and Keller, 2007). This plain has been subject to frequent widespread flooding in recent decades, and it is the argument of this paper that a recent sustained increase in precipitation, runoff and flood frequency in the watershed of the Red River has been the primary contributor to the recent increase in TP and primary productivity in Lake Winnipeg.

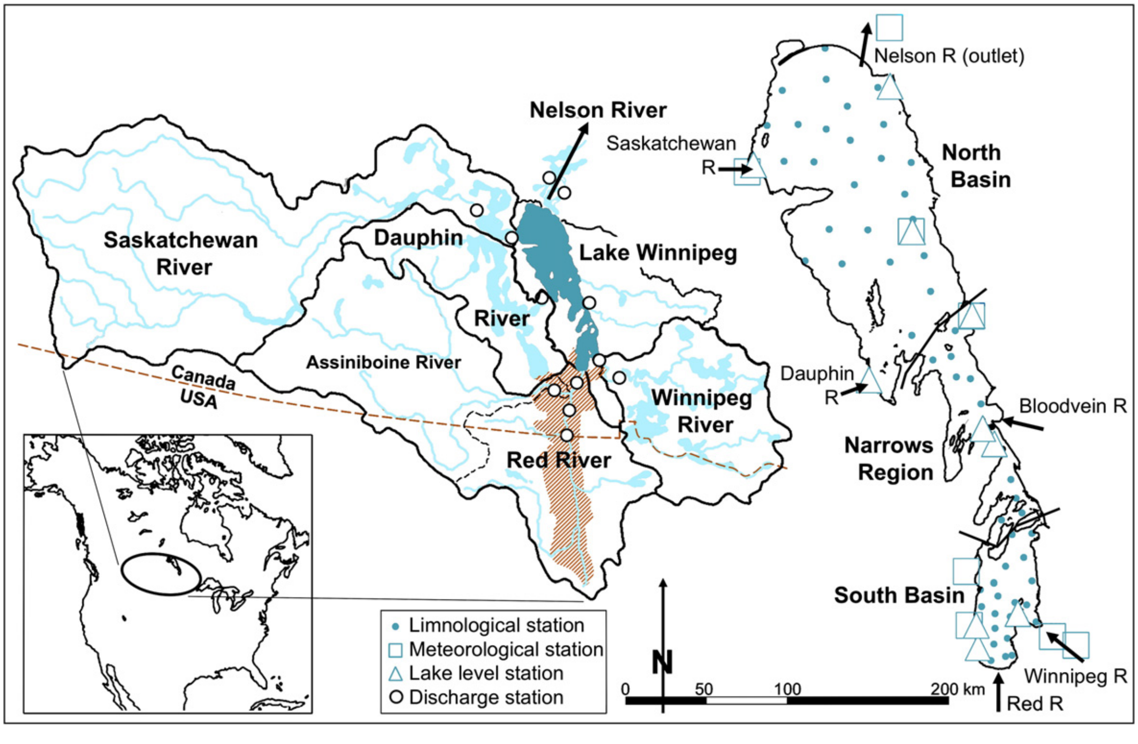

Fig. 1. Left: Lake Winnipeg and its tributary watersheds. Hatched area indicates the low-relief glaciolacustrine plain in the central Red River watershed. Right: Station map, with lines demarcating 3 major regions of the lake. (Limnological stations are for the 2003 mid-summer survey; for other years, see Appendix A.) North arrow and scale bar refer to the map on the right.