APPLICATION OF A WATER QUALITY MODEL TO DEVELOP NUTRIENT TARGETS FOR LAKE WINNIPEG TRIBUTARIES

Water Science and Management Branch

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Manitoba
Conservation and Water Stewardship

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EXECUTIVE SUMMARY

Over the past few decades, accelerated nutrient loading from the Lake Winnipeg watershed has led to the deterioration of the water quality within the watershed and has significantly impacted the health of Lake Winnipeg's ecosystem. Increasing nitrogen and phosphorus loading to Lake Winnipeg from a variety of sources including municipal sewage, industrial effluent and agriculture along with increased runoff from the current wet cycle have led to the eutrophication of Lake Winnipeg. Increasing frequency and severity of algal blooms as a result of increased nutrient loading has led to a variety of issues including reduced recreation appeal, clogging of fishing nets, and the proliferation of toxic algae. Long term, ecologically relevant nutrient targets are needed for Lake Winnipeg and its tributaries to provide targets for future nutrient reduction efforts and to measure progress over time.

The purpose of this report is to summarize the use of a WASP eutrophication model developed for Lake Winnipeg to simulate nutrient reduction scenarios and to develop nutrient targets for Lake Winnipeg's main tributaries that can support future nutrient management strategies and activities. This work is the final step in a series of steps recommended by the Lake Winnipeg Stewardship Board as a means to develop ecologically relevant nutrient targets for Lake Winnipeg. Previous steps included reconstructing the historical water quality conditions and algal community structure in Lake Winnipeg through paleolimnological records and developing a calibrated water quality model for Lake Winnipeg.

A set of principles and specific water quality targets were used to develop nutrient loading targets for Lake Winnipeg. In 2006, the Lake Winnipeg Stewardship Board developed a set of draft principles to guide the development of ecologically relevant nutrient targets for Lake Winnipeg. Among this list of principles was the need to either preserve or restore the important ratio between nitrogen and phosphorus; reflect but not necessarily restore the historical regime of nitrogen and phosphorus concentrations in Lake Winnipeg; ensure a healthy functioning of the Lake Winnipeg ecosystem; and minimize the duration, frequency, and intensity of blue green and other algal blooms and their impact on aquatic life, recreation, drinking water, and commercial and subsistence fishing nets. In association with these guiding

principles, the paleolimnological reconstruction of Lake Winnipeg's historical water quality and algal community structure allowed for specific in-lake water quality targets to be set to help determine the optimal nutrient reduction scenario for Lake Winnipeg. Total phosphorus concentration targets for the south and north basin were set at 0.05 mg/L to return Lake Winnipeg to conditions similar to those in the 1990s. Total nitrogen concentration targets for the south and north basin were set at 0.75 and 0.70 mg/L to ensure that the ratio of nitrogen to phosphorus in the lake will not promote the formation of nitrogen fixing cyanobacteria blooms.

With the guiding principles and nutrient concentration targets set for Lake Winnipeg, an extended version of the calibrated eutrophication model for Lake Winnipeg that was developed by Environment Canada using the Water Analysis Simulation Program (WASP) (version 7.3) was used to run nutrient reduction scenarios. The extended model was calibrated for the time period of 2002 to 2010. A wide suite of reduction scenarios were run to identify the optimal nutrient reduction scenario to meet the water quality targets set out for Lake Winnipeg, primarily the 0.05 mg/L total phosphorus concentration target for the south basin. Nutrient loading to Lake Winnipeg was reduced through reductions in flow, phosphorus concentrations, and nitrogen concentrations in the four main tributaries included in the model that input into Lake Winnipeg (Red, Winnipeg, Saskatchewan, and Dauphin Rivers). Reductions in these variables were applied to the various tributaries individually as well as in combination. Simulated changes in Lake Winnipeg's water quality and phytoplankton community as a result of nutrient loading reductions were assessed by examining changes in key water quality and phytoplankton variables through time and comparing results to the various targets set for Lake Winnipeg.

Modelled responses to reductions in flow, phosphorus, and nitrogen in each individual tributary provided some insight into the magnitude of nutrient reductions required to meet the water quality targets for Lake Winnipeg. As expected, larger flow and nutrient reductions to the south basin tributaries (Red and Winnipeg Rivers), particularly the Red River, were needed to achieve the water quality targets. However, even a 50 % reduction in total phosphorus concentration in the largest contributor to Lake Winnipeg, the Red River, did not achieve the

0.05 mg/L total phosphorus target in the south basin. As a result, reductions in nutrient loading from more than one tributary to Lake Winnipeg are necessary to achieve the targets set for Lake Winnipeg.

The results from the individual tributary nutrient reduction scenarios showed that all of the major tributaries to Lake Winnipeg play an important role in determining lake nutrient and phytoplankton dynamics. However, the amount of reduction in each tributary did not need to be the same to achieve the water quality targets. As a result, the modelled nutrient reduction scenarios were those where flow and nutrients in the tributaries were reduced relative to the proportion of nutrient loading contributed to Lake Winnipeg. Nutrient reduction scenarios that came closest to achieving the water quality targets while minimizing reductions required in the tributaries included a 5 % reduction in flow, 10 % reduction in phosphorus concentration, and 10 % reduction in nitrogen concentration in the Winnipeg, Saskatchewan, and Dauphin Rivers and larger nutrient and flow reductions in the Red River. The modelled optimal nutrient reduction scenario was a 10 % flow, 50 % phosphorus concentration, and a 30 % nitrogen concentration reduction in the Red River as well as a 5 % flow, 10 % phosphorus concentration and 10 % nitrogen concentration reduction in each of the Winnipeg, Saskatchewan, and Dauphin Rivers.

Under the optimal nutrient reduction scenario for Lake Winnipeg, the south basin total phosphorus concentration is not expected to meet the total phosphorus target of 0.05 mg/L in the south basin within the first nine years after nutrient reduction measures are fully implemented. However, a decreasing trend in total phosphorus near the end of the nine year period suggests that the total phosphorus concentration target would be achieved in the future. On the other hand, total phosphorus concentrations in the north basin are expected to meet the 0.05 mg/L target within nine years. Total nitrogen targets for both the south and north (0.75 mg/L and 0.70 mg/L) basin are met by the end of the modelled scenario. Furthermore, N:P ratios would be increased compared to current conditions (south basin = 17:1, north basin = 34:1) and generate a more phosphorus limiting environment aimed at limiting the frequency and severity of nitrogen fixing cyanobacteria blooms.

Under the modelled optimal nutrient reduction scenario, phytoplankton goals were mostly met as non-cyanobacteria phytoplankton taxa reductions were minimized while maximizing reductions in nitrogen-fixing and non-nitrogen fixing cyanobacteria taxa by the end of the nine year model timeframe. At the end of the optimal nutrient reduction scenario simulation, final year average concentrations of nitrogen-fixing cyanobacteria for both the south and north basin were zero while non-nitrogen fixing cyanobacteria concentrations were low at 0.40 mg/L for the south basin and 0.30 mg/L for the north basin. It is noted that phytoplankton relationships in the model, particularly the non-nitrogen fixing cyanobacteria, have a high relative sensitivity to certain parameters in the model including nitrogen concentrations. As a result, it is expected that non-nitrogen fixing cyanobacteria concentrations will remain low as per historical concentrations in the lake.

To achieve the optimal nutrient reduction scenario in Lake Winnipeg, each tributary's nutrient load must be reduced through a combination of reductions in flow and nutrient concentrations. Based on the modelled optimal nutrient reduction scenario, the annual total phosphorus load target for Lake Winnipeg is 4,850 tonnes of total phosphorus per year with 4,250 tonnes from the main four tributaries and an additional 600 tonnes from smaller tributaries to the lake. Of the 4,250 tonnes from the main tributaries, the target for the Red River is 2,800 tonnes, the target for the Winnipeg River is 1,050 tonnes, the target for the Saskatchewan River is 340 tonnes, and the target for the Dauphin River is 60 tonnes. Furthermore, based on the modelled optimal nutrient reduction scenario, the annual total nitrogen load target for Lake Winnipeg is set at 62,140 tonnes of total nitrogen per year with 52,010 tonnes from the main tributaries and an additional 10,130 tonnes from other smaller tributaries to the lake. Of the 52,010 tonnes from the main tributaries, the target for the Red River is 19,050 tonnes, the target for the Winnipeg River is 19,450 tonnes, the target for the Saskatchewan River is 8,960 tonnes, and the target for the Dauphin River is 4,550 tonnes.

The ability to achieve the phosphorus and nitrogen loading targets for the different tributaries will vary from year to year in part because changes in flow strongly influence total nutrient loads. In comparing historical measured loading from the main tributaries to the modelled nutrient loading targets, it is evident that in wet years significant nutrient concentration reductions will be required to meet the targets. To achieve the nutrient loading targets for the tributaries, a combination of reductions in flow and nutrients are needed. Reductions in flow will need to consider fish habitat and other instream flow needs but are expected to focus on reductions in high flow events. Nutrient and flow reduction efforts will require a variety of programs, policies, legislation, incentives, investments and education to be implemented across the inter-jurisdictional watershed.

As with any water quality modelling exercise, uncertainties exist. For example, the model used to develop nutrient targets does not take into account the role and impact of aquatic invasive species (such as zebra mussels) or the future role and impact of climate change. The model also uses water quality data from a number of sources and an interlab comparison has yet to be completed. Finally, there are no direct measures of internal nutrient loading, which could be significant source of future nutrients and could influence the timing for improvements in water quality.

Accurately modelling eutrophication in aquatic ecosystems such as Lake Winnipeg is a complex process that relies on the availability of a large amount of data in the development, calibration, and validation phases. While the model and the past research used to develop the nutrient targets for Lake Winnipeg use the best available information for the lake, ongoing monitoring, a better understanding of the uncertainties highlighted in this report, and future model development will be needed to further refine the targets and track the lake's response to nutrient reductions measures.

Through the use of the extended eutrophication WASP model developed for Lake Winnipeg, nutrient loading targets for Lake Winnipeg's main tributaries have been developed. Nutrient loading targets can be used to guide future action related to nutrient reduction within the Lake Winnipeg watershed.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

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Thanks to Weitoa (Tony) Zhang and Ram Yerubandi from Environment Canada for developing the Lake Winnipeg WASP model that was used in this report and for providing technical support and guidance throughout the development of these targets.

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This project was lead by Justin Shead, Water Quality Management Section with support and input from Elaine Page, David Hay, Sharon Gurney, Dylan Lyng and Nicole Armstrong from the Water Science and Management Branch, Conservation and Water Stewardship and technical comments from Brian Parker, Wildlife and Fisheries Branch.

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Lake Winnipeg's water quality has been deteriorating over time, with particular concern arising over the past few decades as to the effects of accelerated nutrient enrichment and the resulting increase in frequency and severity of algal blooms (Environment Canada and Conservation and Manitoba Water Stewardship 2011, McCullough 2007, Bourne *et al.* 2002, Jones and Armstrong 2001). Algal blooms can lead to a wide variety of issues including causing low dissolved oxygen conditions, contributing to taste and odour problems in drinking water, reducing recreational appeal, clogging of fishing nets, and the proliferating toxic algae. Long term, ecologically relevant nutrient targets are needed for Lake Winnipeg and its tributaries to provide targets for future nutrient reduction efforts and to measure progress over time.

The Lake Winnipeg Stewardship Board (2006), established in 2003 to provide recommendations to the Manitoba Government for improving water quality in Lake Winnipeg, set out three steps for developing ecologically relevant targets for Lake Winnipeg. The first step was to determine the nature of the historical water quality conditions and algal community in Lake Winnipeg through paleolimnological research and develop key targets for improving water quality in the lake (see Bunting *et al.* 2011, Bunting *et al.* 2012). The second step was to develop water quality models calibrated to existing conditions including the major nutrient and algal dynamics of Lake Winnipeg (see Zhang and Rao (2012) Water Analysis Simulation Program (WASP) model for Lake Winnipeg). The third step, the subject of this report, was to use the model to simulate nutrient reduction scenarios to support nutrient management strategies and assist in establishing ecologically relevant nutrient targets for Lake Winnipeg tributaries that meet the water quality targets set out in the paleolimnological work.

THE ROLE OF NUTRIENTS

Nutrient enrichment or eutrophication of freshwater ecosystems (streams, rivers, and lakes) is one of the most important surface water quality issues in Manitoba. While plant nutrients are naturally present and essential in all healthy aquatic systems, excessive nutrients can result in a proliferation of algae and aquatic plant growth. Algal blooms can lead to other problems such as oxygen depletion and fish kills, reductions in biodiversity, taste and odour, concerns with drinking water, increased water treatment costs, and production of toxins from cyanobacteria (also known as blue-green algae) (Smith *et al.*1995, Smith *et al.* 1999, Suplee *et al.* 2009, Sylvan *et al.* 2007, Anderson *et al.* 2008, Chorus and Bartram 1999).

The two main nutrients associated with eutrophication are phosphorus (P) and nitrogen (N). Phosphorus is an essential nutrient for all living organisms and is required for photosynthesis in plants as well as in energy transfer pathways in both plants and animals. Phosphorus is also incorporated into many biological important compounds such as DNA. Phosphorus is generally considered more limited than nitrogen in freshwater ecosystems (Elser *et al.* 1990, Conley 2000). Phosphorus is highly reactive and rather than existing in elemental form in nature, it is typically found in combination with other elements in a wide variety of dissolved and particulate organic and inorganic compounds. The total phosphorus (TP) concentration of surface water is the sum of the dissolved and particulate forms of phosphorus. Phosphorus, when available in aquatic systems, is readily taken up and assimilated by plants as inorganic ionic compounds such as orthophosphate. The total phosphorus in a given water body is not a measure of the specific amount of phosphorus that is immediately available to plants but rather is a measure of the potential amount of phosphorus available for plants.

Nitrogen is another essential nutrient for all living organisms and makes up amino acids, nucleotides, and chlorophyll molecules. There is increasing evidence suggesting that nitrogen may be as important as phosphorus in limiting algal growth in aquatic systems, particularly for algae that do not fix nitrogen (Fisher and Likens 1973, Downing *et al.* 1999, Conley 2000, Francoeur 2001, Tank and Dodds 2003, Patoine *et al.* 2006, Leavitt *et al.* 2006, Elser *et al.* 2007, Lewis and Wurtsbaugh 2008). Nitrogen is most often present in water as nitrogenous inorganic and organic compounds. Inorganic forms of nitrogen that are available to plants include ammonia, nitrate, and nitrite. However, since nitrite is rapidly converted to either ammonia or nitrate, the contribution of nitrite to the bioavailable content in aquatic systems is negligible (CCME 1987). When nitrogen concentrations are low in an aquatic environment, certain forms of algae, particularly nitrogen-fixing cyanobacteria, have the capacity to fix atmospheric nitrogen gas into more usable forms such as ammonia. The total nitrogen (TN) concentration of a surface water is the sum of the dissolved and particulate forms or can be calculated as the sum of the total kjeldahl nitrogen (ammonia, organic and reduced nitrogen) and nitrate-nitrite.

LAKE WINNIPEG, ITS WATERSHED, AND NUTRIENT LOADING

Lake Winnipeg

Lake Winnipeg (Figure 1) is the tenth largest lake in the world by surface area covering 23,750 km^2. The lake consists of two distinct basins separated by a narrows. The north basin is approximately 111 km wide, comprises approximately 74 % of the total lake area and holds 81 % of the lake's 284 km^3 volume. The south basin is about 40 km wide and comprises 11 % of the lake's area and holds about 10 % of Lake Winnipeg's volume. The narrows is a 2.6 km wide channel that separates the north and south basin and represents 15 % of the lake area and 9 % of the volume (Brunskill *et al.* 1980).

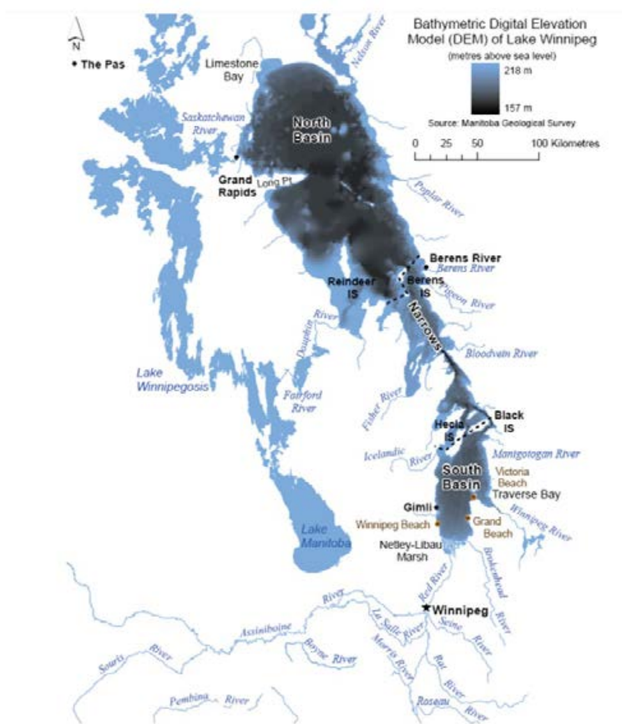

Figure 1. Dominant features and bathymetry of Lake Winnipeg. Dark grey denotes deeper portions of the lake basin; blue, shallower. Figure from Environment Canada and Manitoba Water Stewardship (2011).

The north and south basins of Lake Winnipeg are unique from one another in terms of physical, chemical, and biological characteristics. Differences between the basins are described in detail in the State of Lake Winnipeg report (Environment Canada and Manitoba Water Stewardship 2011). In general, the south basin typically has lower water clarity, higher total suspended solids, higher concentrations of total phosphorus and total nitrogen, and lower total chlorophyll *a* concentrations compared to the north basin. Variations are driven by the size and depth differences of the two basins as well as the quantity and quality of the water flowing into each basin. As a result, the basins can be considered as two relatively distinct water bodies. The narrows which joins the two basins is mostly defined by the rapid flow of water through this portion of the lake (Environment Canada and Manitoba Water Stewardship 2011).

Lake Winnipeg is shallow compared to the Laurentian Great Lakes that are shared between Canada and the United States. The average depths for Lake Winnipeg's north and south basin are 13.3 and 9 m respectively (Brunskill *et al.* 1980) whereas average depth for the Laurentian Great Lakes ranges from 19 m (Lake Erie) to 147 m (Lake Superior) (Environment Canada and Water Stewardship 2011). The relatively small lake volume and the significant tributary inflows to Lake Winnipeg result in a short water residence time for the lake of between three to five years. Lake Winnipeg's residence time is relatively short, particularly as compared to lakes of larger volume such as Lake Superior which has a residence time of 191 years (Environment Canada and Manitoba Water Stewardship 2011).

Lake Winnipeg Watershed

Lake Winnipeg's watershed is the second largest watershed in Canada spanning approximately one million square kilometres. Lake Winnipeg receives water from portions of Alberta, Saskatchewan, Manitoba and north-western Ontario as well as parts of Montana, North Dakota, South Dakota and Minnesota (Figure 2). Compared to the 5:1 watershed-to-lake area in the Laurentian Great Lakes, Lake Winnipeg's ratio of 40:1 is much higher (Lake Winnipeg Implementation Committee 2005) (Figure 3).

Figure 2. Lake Winnipeg watershed. Internal drainage consists of closed watersheds that do not drain to Lake Winnipeg via large rivers. Non-contributing drainage areas contribute flow only under the wettest of conditions. Figure from Environment Canada and Manitoba Water Stewardship (2011).

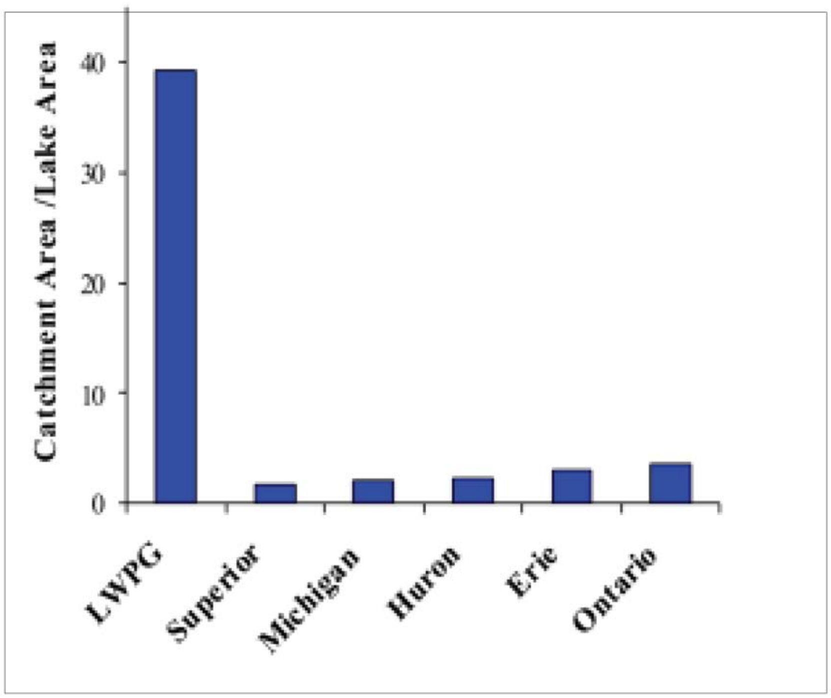

Figure 3. Catchment area ratios for Lake Winnipeg and the five North American Laurentian Great Lakes. (Data source: Environment Canada S. Watson. Figure from Environment Canada and Manitoba Water Stewardship 2011).

The Lake Winnipeg watershed is comprised of several large sub-watersheds (Figure 2). The majority of Lake Winnipeg's watershed lies within the Saskatchewan River sub-watershed (40 %), the Red-Assiniboine sub-watershed (31 %), and the Winnipeg River sub-watershed (17 %).

Lake Winnipeg's watershed is dominated by urban (Figure 4) and agricultural land uses (Figure 5) which are major sources of nutrients to Lake Winnipeg. The watershed is home to over 6 million people (Statistics Canada and U.S. Bureau of Census, as per Lake Winnipeg Stewardship Board 2006) with approximately 80 % of the human population located in urban centres (Lake Winnipeg Stewardship Board 2006). Cropland and pastureland are the dominant agricultural land uses within the watershed. The watershed is also home to over 20 million head of livestock that produce a significant amount of manure (Lake Winnipeg Stewardship Board 2006).

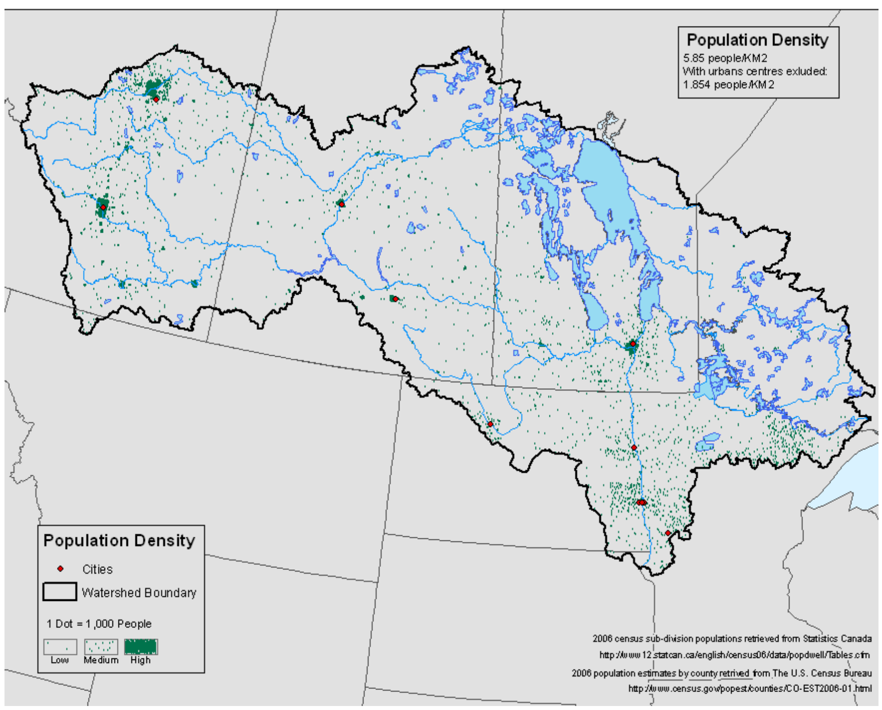

Figure 4. Sub-drainages and total population in 2006. (Data Source: Statistics Canada, Canadian Environmental Sustainability Indicators land use analyses).

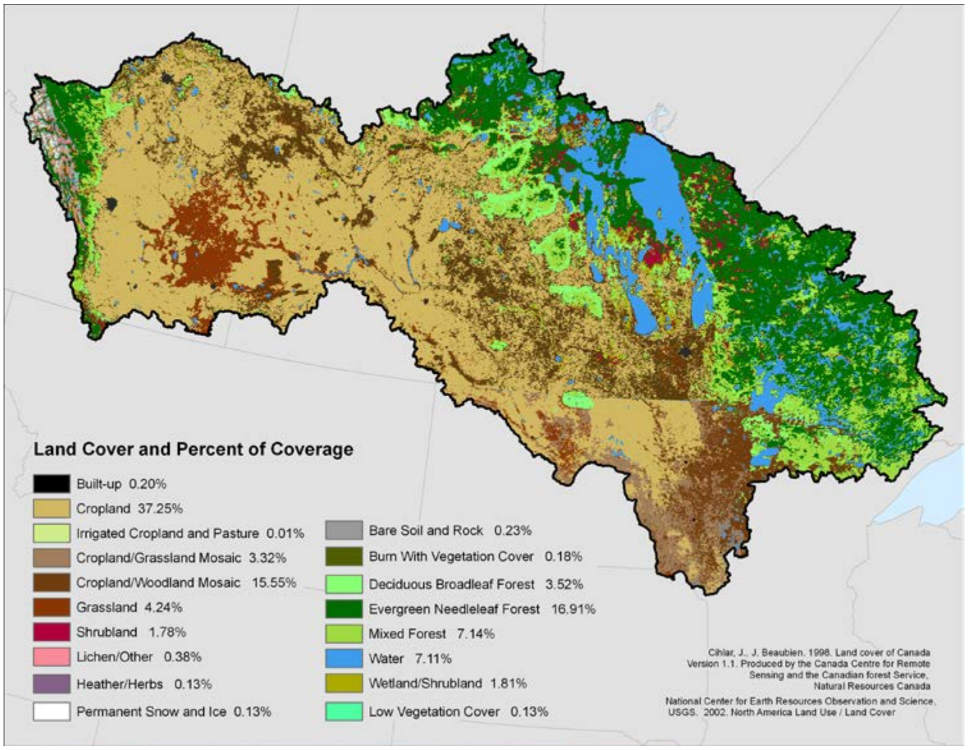

Figure 5. Land cover (light brown = cropland, dark brown = cropland/grassland mosaic, light/dark green = forest (Data Source: NRC 1998 and USGS 2002)). Land cover definitions vary slightly north and south of the Canada-United States border. Figure modified from Environment Canada and Manitoba Water Stewardship (2011).

Not limited to alteration of the watershed for urban and agricultural land use, the Lake Winnipeg watershed has also undergone extensive manipulation of waterways and hydrological characteristics. Dams, diversions, reservoirs and hydroelectric development all have the potential to impact not only the quantity but the quality of water that Lake Winnipeg receives (Donald et al. 2015). Furthermore, drainage and alteration of wetlands and riparian areas in the watershed have resulted in increased nutrient loading through erosion, runoff, and sedimentation (Environment Canada and Manitoba Water Stewardship 2011).

Nutrient Loading

Nutrient levels in Lake Winnipeg and the associated eutrophication status and dynamics of the lake are affected by nutrient loading from tributaries entering the lake (Environment Canada and Manitoba Water Stewardship 2011, Zhang and Rao 2012). Discharges through these tributaries are the most significant source of water, sediments, and nutrients to Lake Winnipeg (Environment Canada and Manitoba Water Stewardship 2011).

In terms of total flow to Lake Winnipeg, from 1999 to 2007, 49 % came from the Winnipeg River, 25 % from the Saskatchewan River, 16 % from the Red River, 6 % from unmetered flows, and 4 % from the Dauphin River (Environment Canada and Manitoba Water Stewardship 2011). Relative to the inflows calculated from 1964 to 2005, the Red Rivers contributed proportionally more to Lake Winnipeg from 1999 to 2007 than in previous years (Red River 11 %; Lake Winnipeg Stewardship Board 2006). The period from 1999 through 2007 was characterized by high flows in the Red River as compared to the previous 80 years of record (Armstrong and McCullough 2011) and thus the proportion of flow from the Red River increased.

Over the past several decades, nitrogen and phosphorus concentrations in most rivers and streams across Manitoba have been increasing (Jones and Armstrong 2001). In some Manitoba streams such as the La Salle River and the Seine River, increases in nutrient concentrations between 1970 and 2000 were as high as 194 % (Jones and Armstrong 2001). Further, annual total phosphorus (Figure 6) and nitrogen (Figure 7) loading to Lake Winnipeg is strongly tied to the total flow of Lake Winnipeg's tributaries with higher loads associated with higher inflows.

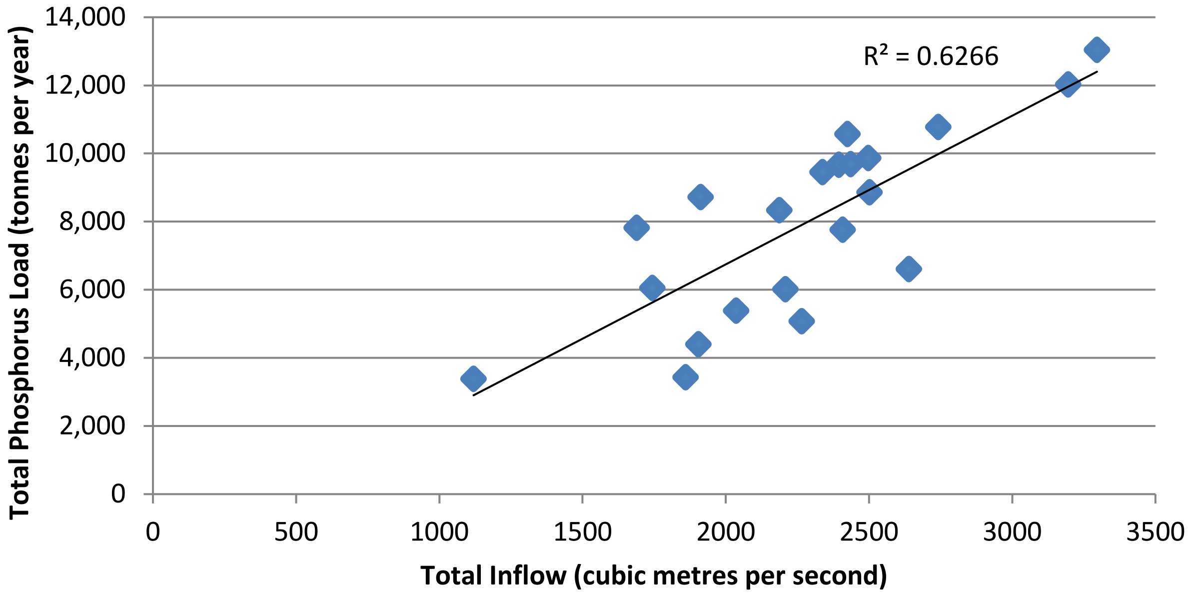

Figure 6. Relationship between annual total phosphorus load (tonnes/year) and total inflow to Lake Winnipeg from 1994 to 2014. Linear trend line and associated r^2 are presented.

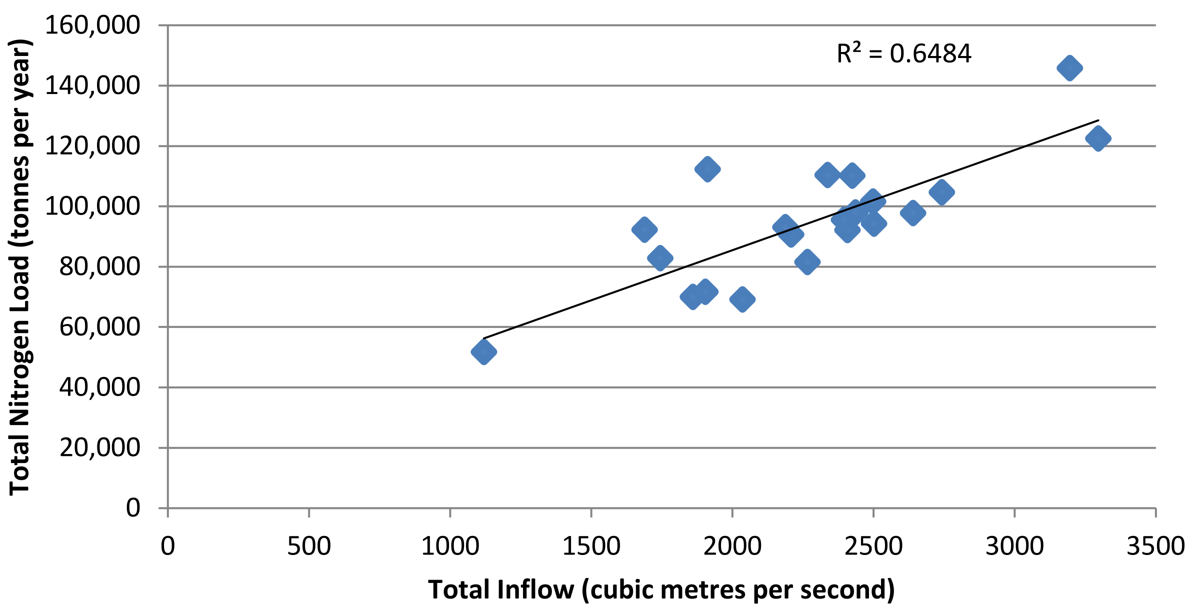

Figure 7. Relationship between annual total nitrogen load (tonnes/year) and total inflow to Lake Winnipeg from 1994 to 2014. Linear trend line and associated r^2 are presented.

Of the main tributaries to Lake Winnipeg (Figure 8) between 1994 to 2007, the Red River was the main source of phosphorus loading contributing an average 4,629 tonnes of phosphorus per year or 60 % of the average annual total load of 7,655 tonnes of phosphorus (Armstrong and McCullough 2011, Figure 9). The Winnipeg River was the second largest contributor of phosphorus to Lake Winnipeg with 14 % of the average annual load (1,049 tonnes per year) while the Assiniboine River contributed the third largest load with 10 % of the total annual load (751 tonnes). Other sources (Saskatchewan, Dauphin, small tributaries on the east and west sides of the lake) contributed a combined 10 % to the total phosphorus load to Lake Winnipeg. Atmospheric deposition contributed approximately 6 % of the total annual phosphorus load (500 tonnes per year).

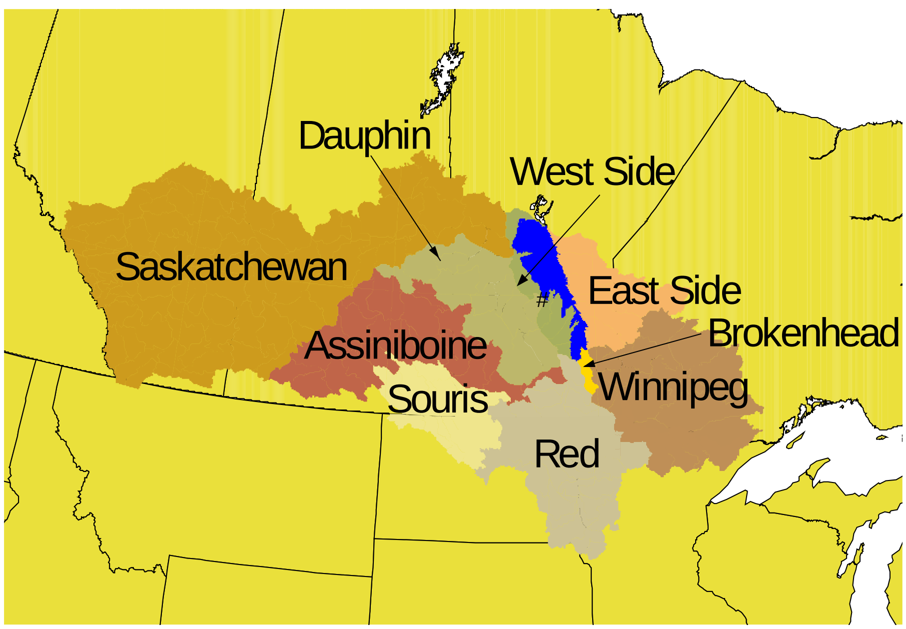

Figure 8. Major tributaries and their associated sub-watersheds within the Lake Winnipeg Watershed.

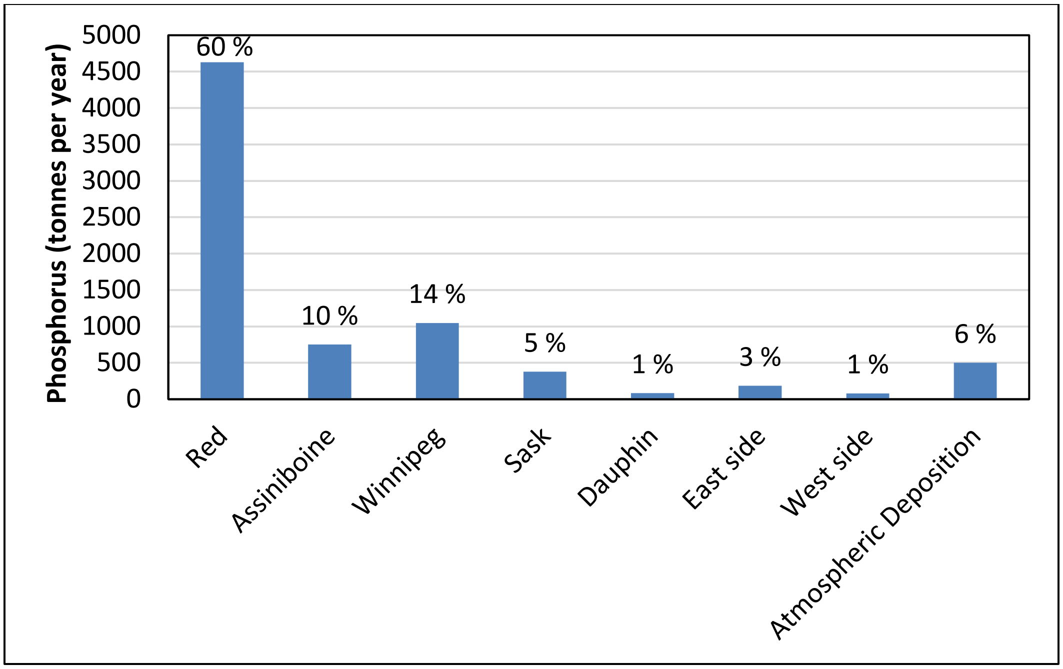

Figure 9. Average total phosphorus load (tonnes per year) from the major tributaries and atmospheric sources into Lake Winnipeg from 1994 to 2007. Average annual percent contribution of tributaries and atmospheric deposition to the total phosphorus load in Lake Winnipeg is also presented.

The Red River was also the main source of nitrogen loading to Lake Winnipeg between 1994 and 2007 contributing an average 27,683 tonnes of nitrogen per year, or 31 % of the average total annual nitrogen load of 90,701 tonnes of nitrogen (Armstrong and McCullough 2011, Figure 10). The second largest nitrogen contributor to Lake Winnipeg was the Winnipeg River with an average nutrient load of 22,544 tonnes per year, or 25 % of the annual total. Other large sources of nitrogen to Lake Winnipeg came from the Saskatchewan River (9,290 tonnes), atmospheric deposition (9,500 tonnes), and nitrogen fixation (9,500) which each contributed 10 % of the total annual nitrogen load. Smaller sources of nitrogen included the Dauphin River (5 %), Assiniboine River (4 %), and smaller tributaries on the east side (4 %) and west side (1 %) of the lake.

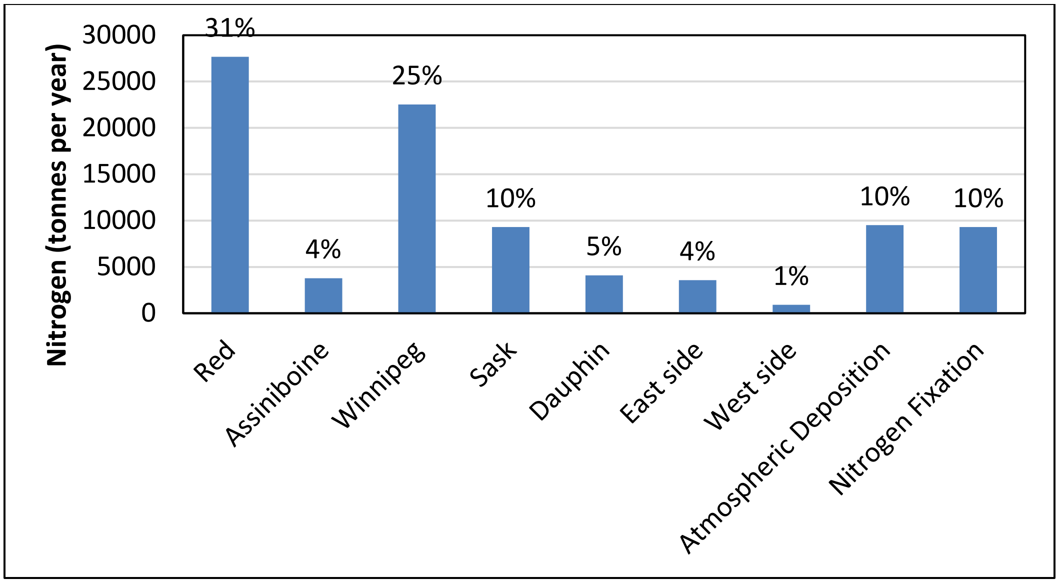

Figure 10. Average total nitrogen load (tonnes per year) from the major tributaries, atmospheric deposition, and nitrogen fixation into Lake Winnipeg from 1994 to 2007. Average annual percent contributions of rivers, atmospheric deposition, and nitrogen fixation to the total nitrogen load in Lake Winnipeg is also presented.

Of the total phosphorus load to Lake Winnipeg between 1994 and 2007, Manitoba was the largest contributor (48 %), while the United States contributed 33 %, 12 % came from Ontario, and 7 % was contributed from Saskatchewan/Alberta (Manitoba Conservation and Water Stewardship unpublished, Figure 11). Similarly for nitrogen, 50 % came from Manitoba sources, while 20 % came from Ontario, 19 % from the United States and 11 % from Saskatchewan/Alberta (Manitoba Conservation and Water Stewardship unpublished, Figure 11). For phosphorus contributions from Manitoba, agriculture and natural background contributed the most phosphorus to Lake Winnipeg with 17 % and 16 % of the total phosphorus load respectively. Point sources such as municipal and industrial wastewater treatment facilities (9 %) and atmospheric deposition (7 %) are also significant contributors of phosphorus to Lake Winnipeg (Manitoba Conservation and Water Stewardship unpublished, Figure 12). For the Manitoba contribution of nitrogen to Lake Winnipeg, 19 % came from natural background watershed processes, 10 % from atmospheric deposition, 10 % from nitrogen fixation, 6 % from point sources, and 5 % from agriculture (Manitoba Conservation and Water Stewardship unpublished, Figure 12).

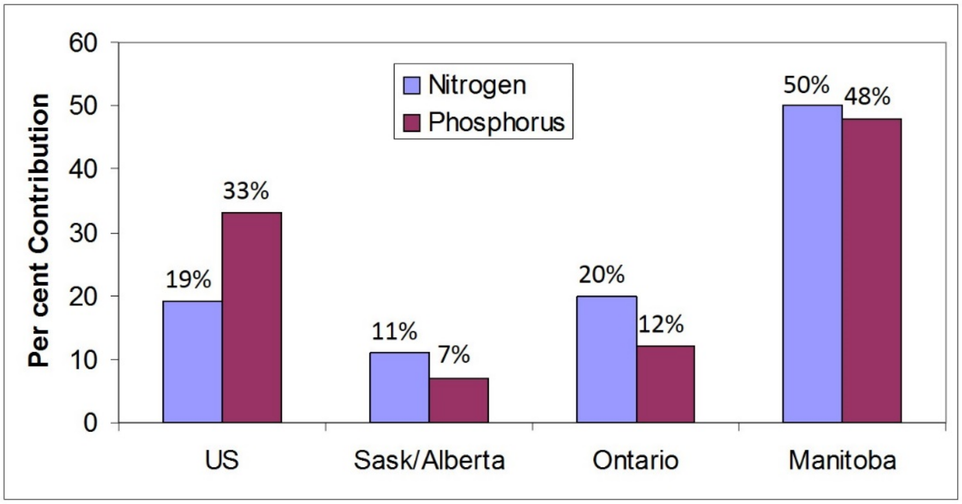

Figure 11. Average annual percent contribution from each jurisdiction within the Lake Winnipeg watershed to the total nutrient load in Lake Winnipeg from 1994 to 2007.

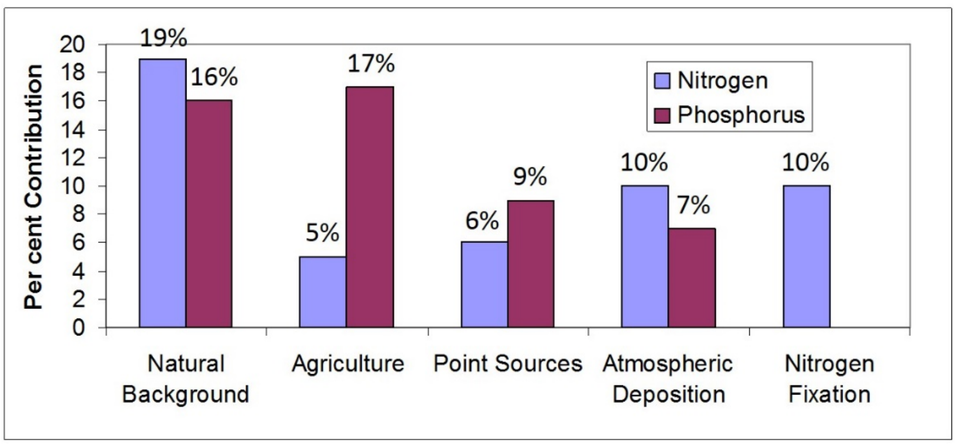

Figure 12. Average annual percent contribution from the various sources within Manitoba to the total Manitoba nutrient load in Lake Winnipeg from 1994 to 2007.

GUIDING PRINCIPLES FOR DEVELOPING ECOLOGICALLY RELEVANT NUTRIENT TARGETS

The Lake Winnipeg Stewardship Board Science Committee developed a set of draft principles to guide the development of ecologically relevant nutrient targets for Lake Winnipeg (Lake Winnipeg Stewardship Board 2006). These principles emphasized that to improve Lake Winnipeg ecosystem health, targets need to:

1) Preserve or restore the important ratio between nitrogen and phosphorus, and be reflective of both in-lake concentrations and watershed loadings;

2) Reflect but not necessarily restore the historical regime of nitrogen and phosphorus concentrations in Lake Winnipeg;
3) Ensure the healthy functioning of the Lake Winnipeg ecosystem;
4) Minimize the duration, frequency, and intensity of blue-green algal blooms including the need to minimize the production of algal toxins harmful to aquatic life, recreation, and drinking water;
5) Minimize the duration, frequency, and intensity of blooms of other forms of algae including those leading to fouling of commercial and subsistence fishing nets or that otherwise interfere with the successful harvest of fish;
6) Ensure that an optimum balance is achieved between nutrient enrichment, productivity of the commercial and subsistence fishery and subsequent economic return to communities, while protecting the lake's ecosystem health and recreational uses;
7) Be protective of the downstream environment in the Nelson River and Hudson Bay;
8) Recognize water quality objectives established for the contributing watersheds, and that water quality objectives for nutrients established in the contributing watersheds need to recognize Lake Winnipeg; and
9) Consider the social and economic implications of implementation and compliance.

Where possible, given information available on Lake Winnipeg, these principles were considered in the development of nutrient targets for Lake Winnipeg and its tributaries.

WATER QUALITY TARGETS FOR LAKE WINNIPEG

Work completed by Dr. Peter Leavitt (Canada Research Chair in Environmental Change and Society at the University of Regina) and his colleagues used paleolimnological techniques to 1) reconstruct the historical water quality conditions that most likely existed in the south and north basin of Lake Winnipeg prior to the early 1800s, 2) describe how the lake has changed up to the present time, and 3) identify the likely causes of those changes (Bunting *et al.* 2011, Bunting *et al.* 2012). In the south basin report, the authors describe four key phases in the history of eutrophication in Lake Winnipeg (Bunting *et al.* 2011). Phase 1 is referred to as the baseline condition and represents the time period of 1800-1900. During Phase 1, the authors concluded the south basin of Lake Winnipeg was mesotrophic with a phosphorus concentration of approximately 0.015 – 0.02 mg/L. The second phase (1900-1990) saw acceleration in eutrophication where nitrogen, phosphorus, and carbon contents increased by 10-50 % and concentrations of most algal pigments increased between 300-500 %. By the 1990s (end of Phase 2), phosphorus concentrations increased in the south basin to approximately 0.05 mg/L. Phase 3 (1990-Present) saw a further acceleration of eutrophication in the south basin of Lake Winnipeg to the point where phosphorus concentrations are currently around 0.10 mg/L. The authors further suggest that if phosphorus influx fails to be regulated, a fourth phase may be initiated in which pollution with nitrogen may promote potentially toxic cyanobacteria. The authors recommended that phosphorus influx must decline by approximately 50 % to suppress nitrogen fixing cyanobacteria (Bunting *et al.* 2011).

Significant increases in Lake Winnipeg phosphorus concentrations since the 1990s have been demonstrated by others. McCullough *et al.* (2012) used a phosphorus mass balance model to demonstrate that discharge increases in major tributaries played an important role to the recent doubling of total phosphorus and a shift to cyanobacteria dominated phytoplankton in Lake Winnipeg. McCullough *et al.* (2012) showed modelled mid-summer (July-August) whole-lake mean total phosphorus increased drastically from 1994 to 1999 from less than 0.03 mg/L to more than 0.05 mg/L. The authors also demonstrated that phosphorus levels in Lake Winnipeg have remained 50 % higher than before the mid-1990s.

The annual average water quality target recommended by Bunting *et al.* (2011) for the south basin of Lake Winnipeg is 0.05 mg/L, similar to the concentration observed in the early 1990s. Subsequent to the release of Bunting *et al.* (2011), the Government of Manitoba committed to reducing the concentration of phosphorus in the south basin of Lake Winnipeg to 0.05 mg/L (Province of Manitoba 2011).

Unlike the south basin study, paleolimnological records for the north basin did not provide evidence of a sudden increase in nitrogen-fixing cyanobacteria since the 1990s (Bunting *et al.* 2012). However, Bunting *et al.* 2012 observed that present conditions were the most eutrophic of the past 200 years. Although Bunting *et al.* (2011) suggested that a 50 % reduction in phosphorus influx could be sufficient to eliminate severe cyanobacteria blooms in the south basin, the north basin study (Bunting *et al.* 2012) concluded that the recovery of the north basin is more likely to be directly proportional to the magnitude of nutrient decline and that more stringent nutrient reductions may be needed to decrease cyanobacteria blooms in the north basin. Bunting *et al.* (2011) also concluded that despite the north basin's 50 % lower ambient total nitrogen and total phosphorus concentrations, the south basin's phosphorus reductions would also apply to the north basin of Lake Winnipeg as most nutrients enter the north basin from the south basin via the narrows. Given this information, the annual average phosphorus concentration target for the north basin of Lake Winnipeg is also 0.05 mg/L.

Determining water quality targets for nitrogen for the south and north basins were outside the scope of the two paleolimnological studies. However, Bunting *et al*. (2011) cautioned that failure to immediately reduce phosphorus loading to Lake Winnipeg may initiate and promote toxic cyanobacteria due to continued pollution with nitrogen. They cited similar situations that have occurred in the Canadian Prairies (Patoine *et al.* 2006; Leavitt *et al.* 2006), Europe (Scheffer *et al.* 1990, Bunting *et al.* 2007), and China (Paerl and Scott 2010; Xu *et al.* 2010). They highlight that these turbid polymictic lakes are usually situated in landscapes with phosphorus rich soils due to either natural geology or prolonged agriculture (Carpenter 2005). Bunting *et al.* (2011) also highlighted that several of these lake examples also have paleolimnological records that show nitrogen-fixing cyanobacteria being replaced by potentially more toxic non-nitrogen-fixing cyanobacteria within decades due to continued nitrogen pollution in phosphorus rich systems (Leavitt *et al.* 2006, Bunting *et al.* 2007). The authors cite that monitoring since 1992 shows that the south basin of Lake Winnipeg now exhibits some of these characteristics and suggest the lake is already subject to damage by nitrogen pollution. The authors conclude that there may be substantial benefits to reducing both nitrogen and phosphorus loading to Lake Winnipeg (Bunting *et al.* 2011). Others (such as Paerl and Scott 2010 and US EPA 2015) have also highlighted the benefits of reducing both nitrogen and phosphorus when managing eutrophication and harmful algae blooms. Jones and Armstrong (2001) demonstrated increases in nitrogen concentration across the Lake Winnipeg watershed providing further support for the need to reduce nitrogen.

Based on Bunting *et al.* (2011)'s recommendation to reduce phosphorus concentrations in the south basin of Lake Winnipeg by 50 % to 1990s levels (~ 0.05 mg/L), annual average nitrogen targets have been set for the north and south basin of Lake Winnipeg based on the range of historical nitrogen to phosphorus (N:P) ratios calculated for Lake Winnipeg from water quality surveys conducted in 1992 to 1994 (Green 1992, Green 1994, Manitoba Conservation and Water Stewardship 2015). From 1992 to 1994, annual mean N:P ratios for the south basin and north basin ranged from 22:1 to 35:1 and 34:1 to 55:1 respectively. The ratios during this time period indicate a phosphorus limited environment where cyanobacteria are less likely to occur (e.g. Smith 1983). Recent N:P ratios observed in Lake Winnipeg from 1999 to 2014 suggest that the south basin is generally co-limited by both nitrogen and phosphorus (ratio 17:1, range 10:1 to 22:1) while the north basin is mostly phosphorus limited (average ratio of 34:1, range 13:1 to 72:1) (unpublished Manitoba Conservation and Water Stewardship 2015). As such, nitrogen concentration targets have been set with the guiding principle of the Lake Winnipeg Stewardship Board Science Committee to "preserve or restore the important ratio between nitrogen and phosphorus" or to essentially increase the nitrogen phosphorus ratio in Lake Winnipeg (Lake Winnipeg Stewardship Board 2006). The annual average nitrogen concentration target for the south basin of Lake Winnipeg is 0.75 mg/L. Due to the overall lower nitrogen concentrations in the north basin compared to the south basin and Bunting *et al.* (2012)'s conclusion that more stringent nutrient reductions may be needed to decrease cyanobacteria blooms in the north basin, the annual average nitrogen concentration target is set at 0.70 mg/L. As such, this combination of nitrogen and phosphorus targets in the south and north basins, if achieved, would result in an N:P ratio of 33:1 across the lake that supports phosphorus limitation and mostly within the range of N:P ratios seen in the early 1990s.

METHODS

To develop ecologically relevant nutrient targets for tributaries to Lake Winnipeg, the Water Quality Management Section of Manitoba Conservation and Water Stewardship in association with Environment Canada developed an extended version (Zhang and Arhonditsis 2013) of the eutrophication Water Analysis Simulation Program (WASP) model that had previously been developed to assess water quality in Lake Winnipeg (Zhang and Rao 2012).

Overview of the Published WASP Model

The specifics of the published WASP model for Lake Winnipeg can be found in Zhang and Rao (2012). The model is a spatially segmented eutrophication model for 2002 to 2007 and was developed by applying the Water Analysis Simulation Program (WASP) version 7.3 (Ambrose *et al.* 1993). Lake Winnipeg was segmented into four boxes spatially within the model, one each for sediment and water in each of the south and north basins (Figure 13).

The model's water balance consists of river inflows, precipitation, evaporation, and outflow (Figure 13). In the south basin segment, there are two major river inflows – the Red River and Winnipeg River. The north basin segment has two major inflows – the Dauphin River and Saskatchewan River. Discharge from unmetered regions of the watershed were accounted for with a hydrological model produced by McCullough *et al.* (2012) where unmetered portions of the watershed were estimated by assuming the same runoff per unit area as for adjacent metered watersheds (for example, the unmetered south was assumed to be 5 % of the metered Red River discharge). Other unmetered parts of the watershed included the southeast (22.3 % of the metered Winnipeg River discharge), west (22.3 % of the metered Dauphin River discharge), and northeast (23.6 % of the metered Winnipeg River discharge). Flow between the south and north basin was also accounted for within the model. The Nelson River is the only outflow from Lake Winnipeg. Flow data used in the model are from provincial and federal monitoring stations (Water Survey of Canada and Manitoba Conservation and Water Stewardship 2015). Precipitation data were from records of the weather stations around Lake Winnipeg (Environment Canada 2015), while evaporation data were estimated from Dauphin Lake data (Zhang and Rao 2012).

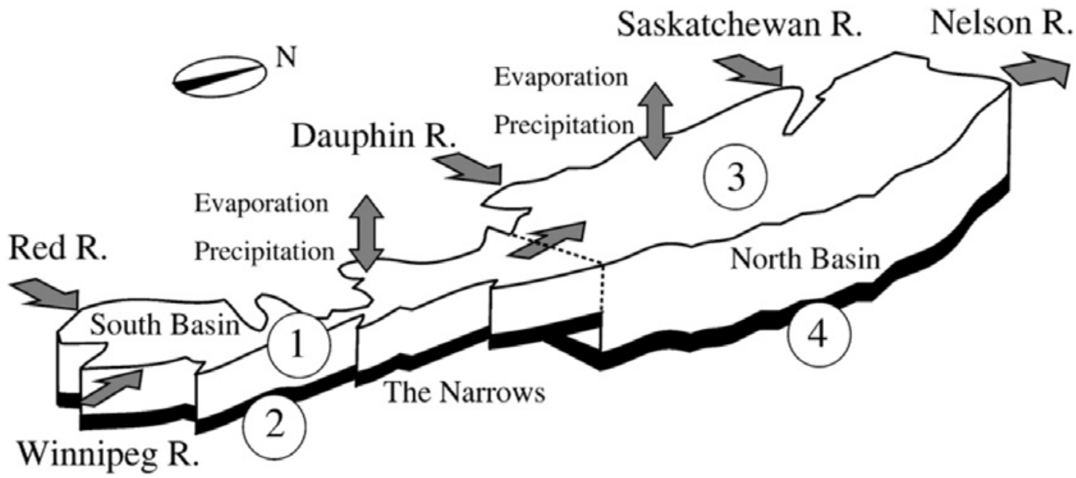

Figure 13. Schematic of segmentation of the Lake Winnipeg model. Segment 1: South Basin water column; Segment 2: South Basin sediment; Segment 3: North Basin water column; Segment 4: North Basin sediment. From Zhang and Rao (2012).

The eutrophication model for Lake Winnipeg includes two nutrient cycles (nitrogen and phosphorus) and three functional phytoplankton groups (non-cyanobacteria, nitrogen-fixing cyanobacteria, and non-nitrogen-fixing cyanobacteria) for the north and south basins (Figure 14). The ability to look at multiple functional phytoplankton groups enhances the model's capacity to examine seasonal variability of phytoplankton and more realistically reflect nutrient and phytoplankton dynamics. This makes WASP an ideal model for evaluating nutrient reduction scenarios to achieve nutrient and phytoplankton targets (Zhang and Rao 2012). Data used to calibrate and validate this eutrophication portion of the model were collected by various provincial and federal monitoring programs for the lake from 2002 to 2007.

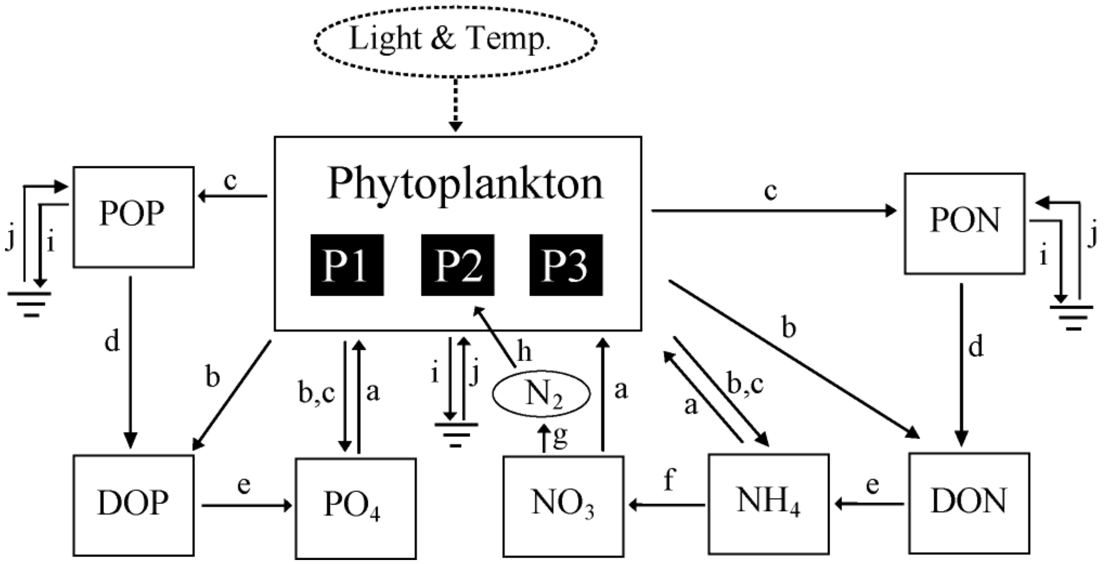

Figure 14. Schematic of the phosphorus and nitrogen cycles of the Lake Winnipeg WASP model. The solid line arrows indicate flows of matter through the system. P1: Phytoplankton group 1 (non-cyanobacteria); P2: Phytoplankton group 2 (nitrogen-fixing cyanobacteria); P3: Phytoplankton group 3 (non-nitrogen fixing cyanobacteria). (a) phytoplankton uptake; (b) phytoplankton respiration; (c) phytoplankton death; (d) detritus dissolution; (e) mineralization; (f) nitrification; (g) denitrification; (h) cyanobacteria nitrogen fixation; (i) settling; (j) resuspension. From Zhang and Rao (2012).

The non-cyanobacteria group (P1) represents phytoplankton species such as bcaillariophytes (diatoms) , cryptophytes, and chlorophytes (green algae) in Lake Winnipeg. Although non-cyanobacteria species are typically common in healthy lake ecosystems, under the eutrophic conditions of Lake Winnipeg, some non-cyanobacteria species (for example diatoms) bloom at certain points in the year resulting in the fouling of commercial fishing nets. The nitrogen-fixing cyanobacteria (P2) group consists of heterocystous blue-green species such as *Aphanizomenon* and *Anabaena* that are typically observed in Lake Winnipeg during mid to late summer. The non-nitrogen-fixing cyanobacteria (P3) group are non-heterocystous cyanobacterial species, such as *Microcystis*, which have the capacity to be more toxic than heterocystous taxa. Although this group has been shown to bloom in recent years (for example, 2007), phytoplankton samples collected from May to October in Lake Winnipeg from 1999 to 2007 showed this group was typically low in biomass (average 5.2 % of total phytoplankton biomass) and relative occurrence in samples (17.1 %) (Environment Canada and Manitoba Water Stewardship 2011). Due to their relatively low abundance and occurrence in samples, the relationship between nutrients and non-nitrogen-fixing cyanobacteria in the model is not strong which results in high relative sensitivity of non-nitrogen-fixing cyanobacteria when performing nutrient reduction scenarios (see Zhang and Rao (2012) sensitivity analysis).

The three functional phytoplankton groups are defined by their differing strategies for resource competition (nitrogen, phosphorus, light, and temperature), metabolism, and morphology (shading effects and settling velocity). The non-cyanobacteria (P1) group are modelled as r-selectors with relatively high maximum growth rates, higher respiration rates, strong phosphorus and weak nitrogen competitors, no nitrogen fixation capability, low temperature optima, and high sinking velocity. Conversely, nitrogen-fixing cyanobacteria (P2) and non-nitrogen-fixing cyanobacteria (P3) groups are modelled as K-strategists with lower maximum growth and metabolic rates, weak phosphorus and strong nitrogen competitors, higher temperature optima, and lower settling velocity. Nitrogen-fixing cyanobacteria (P2) differ from non-nitrogen-fixing cyanobacteria (P3) due to their ability to fix nitrogen, higher maximum growth rates, lower phosphorus uptake affinity, higher ability to assimilate nitrogen, and a slightly lower temperature preference (Zhang and Rao 2012).

The modelled nitrogen cycle consists of four variables: nitrate (NO_3), ammonium (NH_4), dissolved organic nitrogen (DON), and particulate organic nitrogen (PON) (Figure 14). As described previously, ammonium and nitrate are used primarily by phytoplankton during growth. As Figure 14 shows, there are many physical, chemical, and biological processes that regulate the nitrogen cycle such as phytoplankton uptake, respiration, death, nitrogen fixation, settling, and resuspension.

The modelled phosphorus cycle consists of three variables: phosphate (PO_4 or DIP dissolved inorganic phosphorus), dissolved organic phosphorus (DOP), and particulate organic phosphorus (POP) (Figure 14). Phytoplankton only takes up phosphate while redistributing the three forms through metabolism. Like the modelled nitrogen cycle, there are many physical, chemical and biological processes that govern this cycle within the model.

Extension of the Published WASP Model

To enhance the strength of the WASP model that was developed for Lake Winnipeg (Zhang and Rao 2012), the Water Quality Management Section of Manitoba Conservation and Water Stewardship in association with Environment Canada developed an extended version of the published Lake Winnipeg WASP model (Zhang and Arhonditsis 2013). The structure and framework of the WASP model as described above remained the same. The model was extended by adding another three years of data to the original published model timeframe. As a result, the extend WASP model was calibrated and validated for the time period of 2002-2010. Details regarding the extension of the model, the model's performance, and uncertainty analysis are described in Zhang and Arhonditsis (2013).

There are several benefits to extending the model to the end of 2010. First, the extended model captured more variability within the loading and hydrological cycles of Lake Winnipeg such as the flooding of the Red River in 2009. As the average water residence cycle of Lake Winnipeg is three to five years, adding three more years of data added another water residence cycle to the model. The extended model simulated two to three residence cycles for the lake. Finally, extending the model helped strengthen relationships within the model in terms of nutrient and phytoplankton dynamics.

Nutrient Reduction Scenarios

For the development of nutrient targets for Lake Winnipeg tributaries, a wide suite of scenarios were tested to find the optimal scenario to achieve the water quality targets for nitrogen and phosphorus established for the north and south basin (Table 1). A secondary goal was to "preserve or restore the important nitrogen to phosphorus" ratio in the lake (Lake Winnipeg Stewardship Board 2006). Corresponding phytoplankton goals for Lake Winnipeg include the significant reduction (if not elimination) of cyanobacteria taxa (P2 and P3) while minimizing the reductions in the non-cyanobacteria (P1) taxa. Given that Zhang and Rao (2012)'s sensitivity analysis of the original published WASP model for Lake Winnipeg determined that total chlorophyll *a* and biomasses (represented as chlorophyll *a*) of the three functional groups of phytoplankton (P1, P2, and P3) have high relative sensitivity (RS) values, phytoplankton results were not heavily relied upon to determine the optimal reduction scenario for Lake Winnipeg. The highest relative sensitivity was for non-nitrogen fixing cyanobacteria (P3) which were extremely sensitive to several parameters, followed by nitrogen-fixing cyanobacteria (P2) and non-cyanobacteria taxa (P1). Given the three functional groups compete against each other for resources using different strategies regarding nutrients, light and temperature, these phytoplankton groups are sensitive to model parameters that impact their competitive ability such as growth, respiration, death, light extinction, nitrogen to carbon ratios, and supply/removal of available nutrients (Zhang and Rao 2012). Consequently, the phytoplankton results from the shortlist of reduction scenarios were used to supplement those from the water quality aspect of the model which has stronger relationships built within the extended WASP model.

Table 1. Phosphorus and nitrogen concentration targets for the south and north basin of Lake Winnipeg.

Basin	Phosphorus Concentration	Nitrogen Concentration
South Basin	0.05 mg/L	0.75 mg/L
North Basin	0.05 mg/L	0.70 mg/L

Nutrient loading to Lake Winnipeg was reduced though simulating reductions in flow and phosphorus and nitrogen concentrations in the four main tributaries included in the model (Red, Winnipeg, Saskatchewan, and Dauphin Rivers). Phosphorus concentration reductions were applied equally for both dissolved phosphorus and particulate phosphorus. Similarly, nitrogen concentrations reductions were applied equally for all nitrogen fractions. Flow reductions reduced the volume of water in the tributary. Together, reductions in nutrient concentrations and flow result in reductions in nutrient loading to Lake Winnipeg from the four main tributaries.

A two-pronged approached was taken to examine the wide suite of reduction scenarios tested to develop nutrient loading targets for Lake Winnipeg. The first approach was to examine nutrient and flow reductions from individual tributaries in a modified version of the originally published WASP model for Lake Winnipeg. Within this suite of scenarios, each main tributary underwent a range of flow, phosphorus, and nitrogen reductions. The range of scenarios that each individual input was tested for under the first approach is summarized in Table 2. This approach not only allowed for a better understanding of how the modelled Lake Winnipeg system responded to changes in flow, phosphorus and nitrogen from each main tributary, but it was also aimed at determining if nutrient reduction targets for Lake Winnipeg could be achieved through flow or nutrient reductions to a single major tributary.

The second approach was to use information gained from the individual reduction scenarios to examine reductions in flow, phosphorus, and nitrogen in a combination of inputs to Lake Winnipeg with the extended model. Reductions in the second approach were applied in two ways. The first was to apply reductions equally across all tributaries. The second was to apply reductions unequally across the four modelled tributaries (Table 3).

Table 2. Nutrient reduction scenarios tested on each individual major tributary input into Lake Winnipeg using a modified version of the original published Lake Winnipeg WASP model. When a range of reduction is presented, reductions were conducted at 10 % increments.

Flow	Phosphorus Concentration	Nitrogen Concentration
10 – 50 %	-	-
	10 – 50 %	-
-	-	10 – 50 %
-	10 – 50 %	10 %
-	10 – 50 %	20 %
-	10 – 50 %	30 %
10 – 30 %	10 – 50 %	10 %
10 – 30 %	10 – 50 %	20 %
10 – 30 %	10 – 50 %	30 %
10 – 30 %	10 – 50 %	40 %
10 – 30 %	10 – 50 %	50 %

Table 3. The shortlist of proportional nutrient reduction scenarios that best achieved the goals for Lake Winnipeg. When a range of reduction is presented, reductions were conducted at 10 % increments. TP and TN represent total phosphorus and total nitrogen respectively.

Red River			Winnipeg, Saskatchewan, and Dauphin Rivers		
Flow	**TP**	**TN**	**Flow**	**TP**	**TN**
10 %	10-50 %	10 %	5 %	10 %	10 %
10 %	10-50 %	20 %	5 %	10 %	10 %
10 %	10-50 %	30 %	5 %	10 %	10 %
20 %	10-50 %	10 %	5 %	10 %	10 %
20 %	10-50 %	20 %	5 %	10 %	10 %
20 %	10-50 %	30 %	5 %	10 %	10 %

To determine the optimal nutrient reduction scenario for Lake Winnipeg from the wide suite of scenarios tested, the scenario results were assessed in several ways. First, nutrient reduction scenario results were compared to normal modelled conditions in Lake Winnipeg to examine changes through time over the course of the model time period. Secondly, nutrient reduction results were compared to normal conditions to determine average annual percent reduction in the key water quality and phytoplankton variables. Finally, the average of the last year of scenario results was compared to the water quality targets for Lake Winnipeg to determine if those targets were achieved.

After the optimal flow, phosphorus and nitrogen reductions to each tributary were determined, nutrient loads from each tributary under that optimal scenario were calculated. Nutrient loads from each tributary included a combination of flow and nutrient concentration reductions and represented the annual average nutrient loading targets for tributaries to Lake Winnipeg.

RESULTS AND DISCUSSION

Determining the Optimal Nutrient Reduction Scenario

Modelling the response of water quality and phytoplankton in Lake Winnipeg to changes in flow, phosphorus and nitrogen in each individual main tributary provided insight into the magnitude of nutrient reductions required to meet the water quality targets for Lake Winnipeg. For example, Figure 15 shows the percent reduction in south basin total phosphorus concentration when phosphorus concentrations in individual tributaries were reduced by 10 %, 30 % and 50 %. As expected, larger phosphorus reductions to the south basin inputs (Red and Winnipeg Rivers) resulted in higher percent reductions in south basin total phosphorus concentration. However, despite a 50 % phosphorus concentration reduction in the largest contributor of phosphorus to Lake Winnipeg (Figure 9), the Red River, there was less than an average annual decrease of 35 % in south basin total phosphorus concentration and the water quality target for phosphorus in the south basin could not be met (Figure 15). As a result, if individual tributary nutrient reductions are to be kept below 50 %, nutrient loads from more than one tributary to Lake Winnipeg will need to be reduced for the water quality targets to be met (Table 1). Given that the north and south basin exchange water in both directions through the narrows, nutrient reductions to northern basin tributaries such as the Saskatchewan River do have an impact on water quality in the south basin. However, the impact is minimal given that nutrient loads are lower from the north basin tributaries (Figures 9 and 10) and the flow through the narrows is typically from the south to north basin (Environment Canada and Manitoba Water Stewardship 2011).

When examining how the north basin responded to individual tributary phosphorus reductions, it was noted that reductions in nutrient loads from the north basin tributaries (Dauphin and Saskatchewan Rivers) resulted in larger per cent reductions in north basin total phosphorus concentration (Figure 16) as compared to that of the south basin (Figure 15). Given that water quickly flows from the south basin to the north basin through the narrows and that the majority of nutrient loading to Lake Winnipeg enters the south basin (Figure 9 and 10), applying nutrient reductions to the south basin tributaries results in large reductions in the nutrient concentration in the north basin (Figure 16).

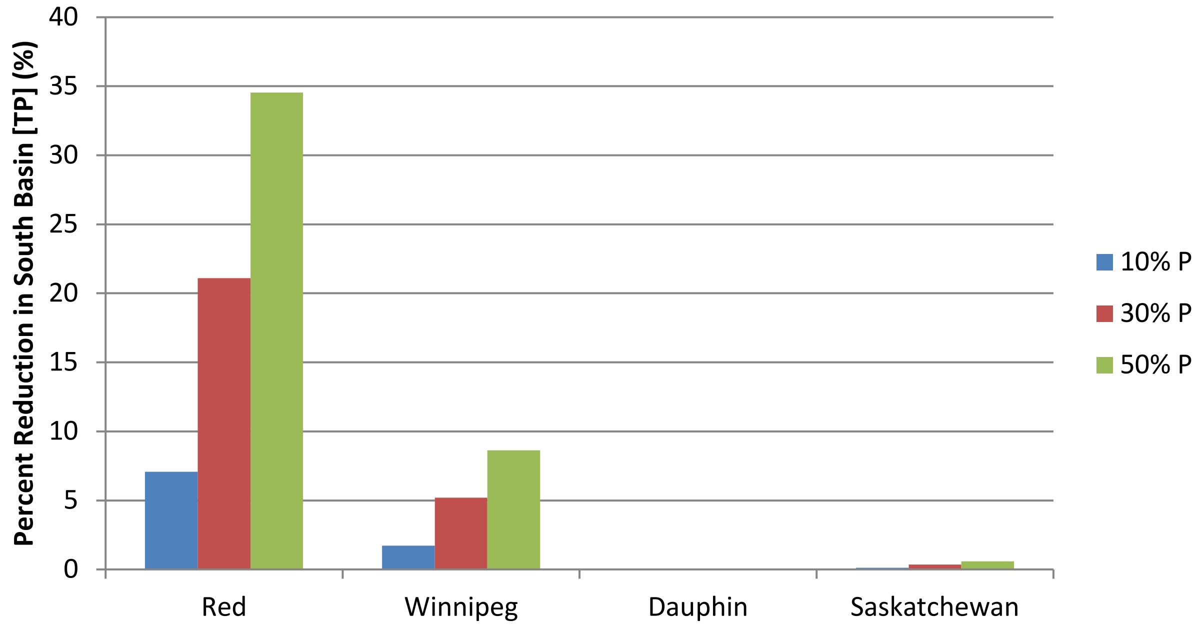

Figure 15. Average annual percent reduction in south basin total phosphorus concentration when phosphorus concentration in each major tributary to Lake Winnipeg is reduced individually by 10 %, 30 %, and 50 %.

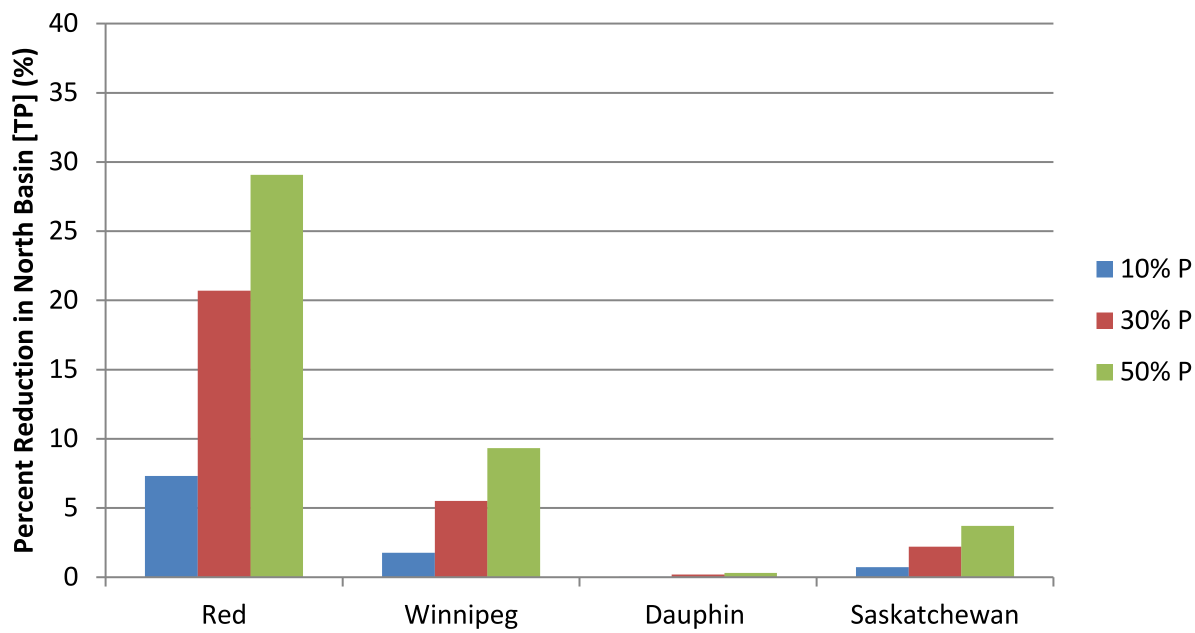

Figure 16. Average annual percent reduction in north basin total phosphorus concentration when phosphorus concentrations in each major tributary to Lake Winnipeg is reduced individually by 10 %, 30 %, and 50 %.

The results from this initial set of nutrient reduction scenarios show that the major tributaries that input into Lake Winnipeg play an important role in lake nutrient dynamics and that flow and nutrient reduction from each will be helpful as they each impact the water quality of both the south and north basins. However, the amount of reduction for each tributary does not necessarily need to be equal to ensure water quality targets are met. This conclusion was confirmed by the scenarios where a range of flow, phosphorus, and nitrogen reductions were applied equally to all tributaries and those results were compared to the individual tributary reduction scenario results. For example, Figure 17 shows that a 10 % reduction in phosphorus concentration to all the rivers only amounted to a small reduction in south basin total phosphorus concentration while a 50 % reduction to the Red River reduced total phosphorus concentrations to near the south basin water quality target. Comparatively, a 50 % reduction in phosphorus concentration in all of the tributary rivers led to little incremental benefit as compared to the Red River only scenario. Clearly, reducing nutrient concentrations (phosphorus and nitrogen) in the Red River by 50 % will result in phosphorus concentrations in the south basin that are closer to the water quality targets than when similar reductions are applied to the other three tributaries. As a result, this suggests that nutrient reductions to each tributary could be based on the relative contribution of phosphorus (Figure 9) and nitrogen (Figure 10) loading to achieve water quality targets while recognizing the significant effort that will be required to reduce nutrient loading across the watershed. Some reductions in nutrient concentrations in all tributary rivers led to phosphorus and nitrogen concentrations in Lake Winnipeg that were closer to the water quality targets and could support other nutrient reduction efforts within the watershed.

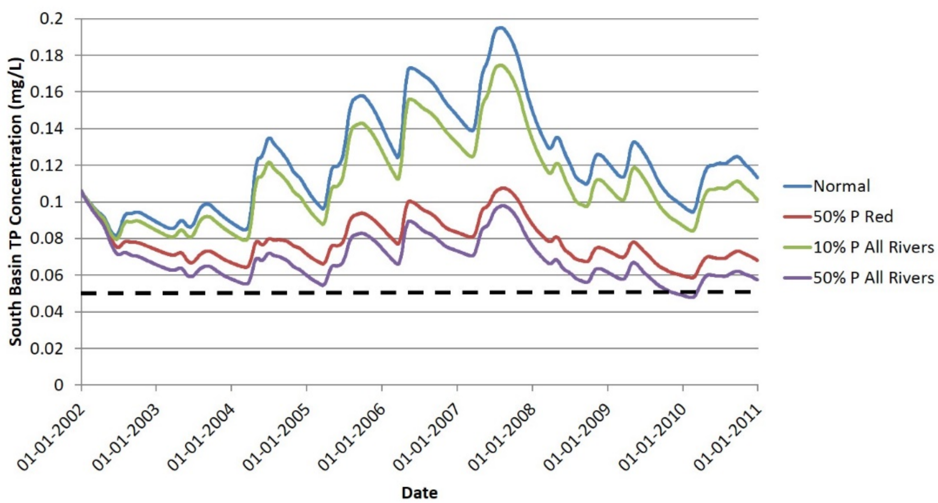

Figure 17. A comparison of south basin total phosphorus concentration (mg/L) under normal Lake Winnipeg conditions (blue line), a 50 % phosphorus reduction in the Red River (red line), a 10% phosphorus reduction in all rivers (green line), and a 50 % phosphorus reduction in all rivers (purple line). Dashed line represents the 0.05 mg/L total phosphorus water quality improvement benchmark set for the south basin.

Based on the information gained from the individual and combined but equal tributary reduction scenarios, a suite of proportionally based reduction scenarios were tested (Table 3). Under this shortlisted suite of scenarios, the Winnipeg, Saskatchewan, and Dauphin Rivers all received equal reductions of 5 % flow, 10 % phosphorus concentration, and 10 % nitrogen concentration. Given that the majority of nutrient loading to Lake Winnipeg comes from the Red River, larger reductions in nutrient concentrations and flow in the Red River will result in proportionately larger reductions in nutrient concentrations in Lake Winnipeg. Therefore, larger nutrient and flow reductions from the Red River were modelled with flow reductions between 10 % and 20 %, phosphorus concentration reductions between 10 % and 50 % at 10 % increments, and nitrogen concentration reductions between 10 % and 30 % at 10 % increments.

In evaluating this shortlist of proportionally based scenarios, reaching the south basin water quality target for phosphorus (0.05 mg/L) as set out by Bunting *et al.* (2011) was the primary goal in determining the optimal nutrient reduction scenario for Lake Winnipeg. As such, the south basin total phosphorus concentration under this shortlist of scenarios was examined and compared to the 0.05 mg/L target (Figure 18). As expected, the greater the combined flow and phosphorus concentration reduction in the Red River, the closer the scenarios were to meeting the 0.05 mg/L target. Higher flow and phosphorus reduction scenarios also resulted in higher average annual percent reductions in south basin total phosphorus concentration (Table 4). For example, a 10 % flow and 50 % phosphorus reduction in the Red River resulted in approximately a 36 % reduction in south basin total phosphorus concentration compared to approximately an 11 % reduction as a result of a 10 % flow and 10 % phosphorus reduction in the Red River. As a result, higher flow and phosphorus concentration reductions resulted in lower average final year concentrations for the south basin. For example, a 50 % reduction in phosphorus concentration and a 10 % reduction in flow in the Red River resulted in an average final year (2010) phosphorus concentration of 0.06 mg/L in the south basin of Lake Winnipeg which is just slightly above the 0.05 mg/L target (Table 5). In contrast, a 10 % reduction in flow and a 10 % reduction in phosphorus concentration in the Red River resulted in an average final year phosphorus concentration of 0.10 mg/L in the south basin which is just slightly below the normal modelled condition of Lake Winnipeg (0.11 mg/L). Only a 10 % and 20 % flow reduction combined with a 50 % reduction in phosphorus concentration in the Red River resulted in average final year concentrations (0.06 mg/L) near the water quality target of 0.05 mg/L (Table 5). As such, a 10 % flow reduction and a 50 % phosphorus reduction in the Red River (along with 5 % flow and 10 % phosphorus reductions in the Winnipeg, Saskatchewan and Dauphin Rivers) were selected as the optimal nutrient reduction scenario for Lake Winnipeg's south basin.

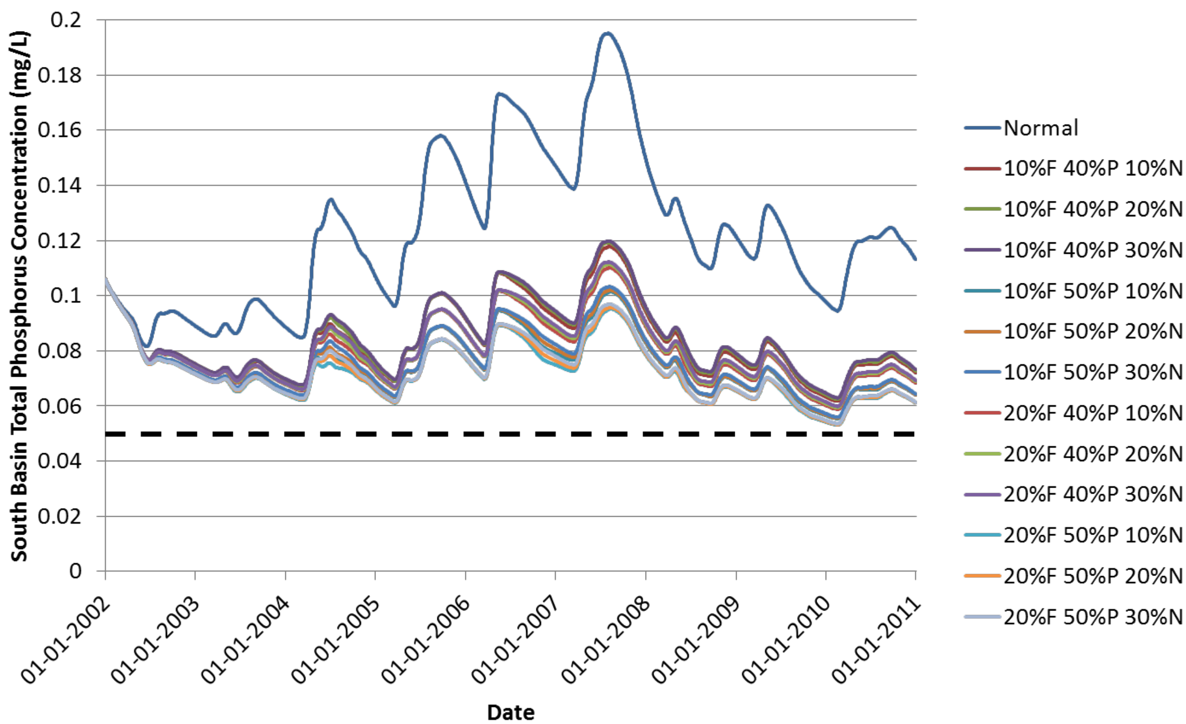

Figure 18. South basin total phosphorus concentration (mg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg. The dashed line represents the total phosphorus concentration target for the south basin of Lake Winnipeg (0.05 mg/L).

Table 4. Average annual percent reduction for south basin total phosphorus (TP), total nitrogen (TN), phytoplankton total chlorophyll a (Total Chl), phytoplankton group 1 (P1) chlorophyll, phytoplankton group (P2) chlorophyll a, phytoplankton group 3 (P3) chlorophyll a for the shortlist of nutrient reduction scenarios between 2002 and 2011. Negative average annual percent reductions indicate a percent increase in a particular variable. Nutrient reduction scenarios included alterations to flow (F), total phosphorus (P), and total nitrogen (N).

	AVERAGE ANNUAL PERCENT REDUCTION					
Scenario	**TP**	**TN**	**Total Chl**	**P1**	**P2**	**P3**
Normal	-	-	-	-	-	-
10 % F 10 % P 10 % N	10.8	8.3	13.8	23.6	-44.1	-19.6
10 % F 30 % P 10 % N	24.1	9.0	0.9	19.8	71.6	-536.8
10 % F 40 % P 10 % N	30.7	9.1	8.9	15.1	78.0	-191.4
10 % F 40 % P 20 % N	30.1	12.3	7.2	27.4	72.5	-470.0
10 % F 40 % P 30 % N	29.7	15.5	11.0	37.1	63.7	-600.8
10 % F 50 % P 10 % N	37.1	9.2	15.6	8.8	83.1	-22.9
10 % F 50 % P 20 % N	36.7	12.5	18.1	20.6	78.3	-95.6
10 % F 50 % P 30 % N	36.3	15.7	19.5	33.3	72.9	-231.5
20 % F 10 % P 10 % N	15.5	10.5	16.5	29.5	-35.3	-76.1
20 % F 30 % P 10 % N	27.5	11.1	4.7	26.1	72.0	-529.3
20 % F 40 % P 10 % N	33.5	11.2	13.5	21.2	77.3	-183.8
20 % F 40 % P 20 % N	33.1	14.1	12.8	32.2	72.4	-399.7
20 % F 40 % P 30 % N	32.7	17.0	14.2	41.7	66.6	-571.0
20 % F 50 % P 10 % N	39.3	11.2	20.4	15.1	82.1	-22.5
20 % F 50 % P 20 % N	39.0	14.2	22.5	26.0	77.7	-90.4
20 % F 50 % P 30 % N	38.6	17.1	23.6	37.7	72.8	-208.1

Table 5. South basin 2010 average total phosphorus (TP), total nitrogen (TN), phytoplankton total chlorophyll a (Total Chl), phytoplankton group 1 (P1) chlorophyll, phytoplankton group (P2) chlorophyll a, phytoplankton group 3 (P3) chlorophyll a concentrations, and N:P ratio. Nutrient reduction scenarios included alterations to flow (F), total phosphorus (P), and total nitrogen (N).

	2010 AVERAGE						
Scenario	**TP (mg/L)**	**TN (mg/L)**	**Total Chl (µg/L)**	**P1 (µg/L)**	**P2 (µg/L)**	**P3 (µg/L)**	**N:P Ratio**
Normal	0.11	0.85	4.28	3.49	0.68	0.11	16
10 % F 10 % P 10 % N	0.10	0.77	3.68	2.60	0.94	0.14	17
10 % F 30 % P 10 % N	0.08	0.76	4.66	2.64	0	2.01	21
10 % F 40 % P 10 % N	0.07	0.76	3.16	2.81	0	0.35	23
10 % F 40 % P 20 % N	0.07	0.73	3.78	2.39	0	1.39	22
10 % F 40 % P 30 % N	0.07	0.69	4.25	1.97	0	2.28	21
10 % F 50 % P 10 % N	0.06	0.76	2.90	2.88	0	0.03	26
10 % F 50 % P 20 % N	0.06	0.73	2.60	2.49	0	0.11	25
10 % F 50 % P 30 % N	0.06	0.69	2.48	2.08	0	0.40	24
20 % F 10 % P 10 % N	0.09	0.75	3.54	2.33	0.93	0.27	18
20 % F 30 % P 10 % N	0.08	0.74	4.22	2.44	0	1.77	21
20 % F 40 % P 10 % N	0.07	0.74	2.83	2.56	0	0.28	24
20 % F 40 % P 20 % N	0.07	0.71	3.16	2.18	0	0.98	23
20 % F 40 % P 30 % N	0.07	0.68	3.72	1.83	0	1.89	22
20 % F 50 % P 10 % N	0.06	0.74	2.64	2.61	0	0.03	27
20 % F 50 % P 20 % N	0.06	0.71	2.34	2.24	0	0.10	26
20 % F 50 % P 30 % N	0.06	0.68	2.18	1.88	0	0.30	24

As in the south basin, higher flow and phosphorus reductions in the Red River resulted in larger reductions in the north basin total phosphorus concentration (Table 6 and Figure 19). Percent reductions in north basin total phosphorus concentration ranged from 7 % to 31 % depending on the magnitude of flow and phosphorus reduction (Table 6). Unlike the south basin, several reduction scenarios resulted in average final year phosphorus concentration in the north basin that either met or surpassed the water quality target for the north basin (0.05 mg/L) (Table 7). Under the 10 % flow and 50 % phosphorus reduction scenario in the Red River, the north basin average final year total phosphorus concentration (0.04 mg/L) surpassed the water quality target of 0.05 mg/L (Table 7).

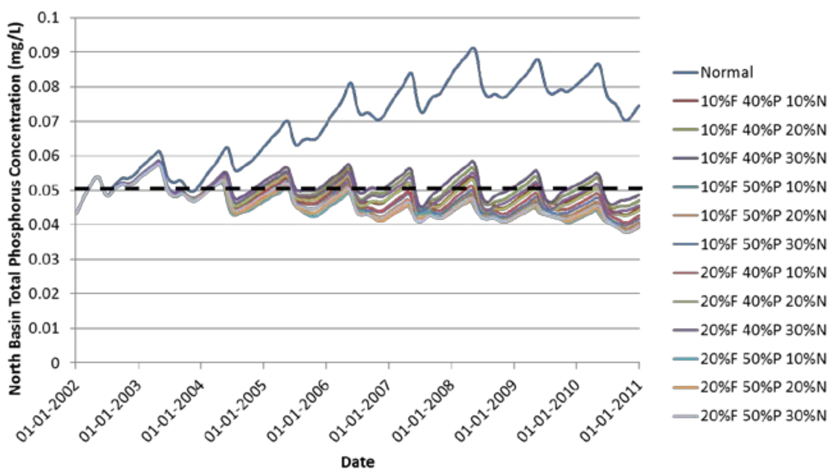

Figure 19. North basin total phosphorus concentration (mg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg. The dashed line represents the total phosphorus concentration target for the north basin of Lake Winnipeg (0.05 mg/L).

Table 6. Average annual percent reduction for north basin total phosphorus (TP), total nitrogen (TN), phytoplankton total chlorophyll a (Total Chl), phytoplankton group 1 (P1) chlorophyll, phytoplankton group (P2) chlorophyll a, phytoplankton group 3 (P3) chlorophyll a for the shortlist of nutrient reduction scenarios between 2002 and 2011. Negative average annual percent reductions indicate a percent increase in particular variable. Nutrient reduction scenarios included alterations to flow (F), total phosphorus (P), and total nitrogen (N).

	AVERAGE ANNUAL PERCENT REDUCTION					
Scenario	**TP**	**TN**	**Total Chl**	**P1**	**P2**	**P3**
Normal	-	-	-	-	-	-
10 % F 10 % P 10 % N	7.2	4.3	1.9	15.3	-12.2	13.0
10 % F 30 % P 10 % N	20.9	7.6	13.9	-2.1	79.5	-1869.3
10 % F 40 % P 10 % N	26.6	7.8	32.8	-4.1	84.0	-372.7
10 % F 40 % P 20 % N	25.0	9.0	21.3	1.4	81.8	-1360.1
10 % F 40 % P 30 % N	23.7	10.1	16.6	6.4	76.9	-1917.9
10 % F 50 % P 10 % N	30.3	7.0	44.7	3.3	87.0	-26.5
10 % F 50 % P 20 % N	30.0	8.7	41.6	3.2	85.1	-101.4
10 % F 50 % P 30 % N	29.2	10.3	36.3	4.8	83.1	-316.3
20 % F 10 % P 10 % N	11.4	5.7	6.0	16.1	-1.4	-33.8
20 % F 30 % P 10 % N	23.5	8.6	17.7	0.3	81.4	-1666.9
20 % F 40 % P 10 % N	28.4	8.6	36.4	-0.5	84.6	-228.3
20 % F 40 % P 20 % N	27.2	9.8	27.5	3.6	82.8	-914.1
20 % F 40 % P 30 % N	26.1	10.8	21.2	7.8	80.2	-1637.6
20 % F 50 % P 10 % N	31.5	7.7	46.9	7.7	87.3	-25.1
20 % F 50 % P 20 % N	31.2	9.4	44.0	7.4	85.6	-87.9
20 % F 50 % P 30 % N	30.7	10.9	39.6	7.8	83.8	-227.0

Table 7. North basin 2010 average total phosphorus (TP), total nitrogen (TN), phytoplankton total chlorophyll a (Total Chl), phytoplankton group 1 (P1) chlorophyll, phytoplankton group (P2) chlorophyll a, phytoplankton group 3 (P3) chlorophyll a concentrations, and N:P ratio. Nutrient reduction scenarios included alterations to flow (F), total phosphorus (P), and total nitrogen (N).

	2010 AVERAGE						
Scenario	**TP (mg/L)**	**TN (mg/L)**	**Total Chl (µg/L)**	**P1 (µg/L)**	**P2 (µg/L)**	**P3 (µg/L)**	**N:P Ratio**
Normal	0.08	0.71	9.36	2.61	6.71	0.04	20
10 % F 10 % P 10 % N	0.07	0.67	9.18	2.07	7.08	0.03	21
10 % F 30 % P 10 % N	0.05	0.63	6.94	2.93	0	4.01	26
10 % F 40 % P 10 % N	0.05	0.64	3.66	3.11	0	0.55	30
10 % F 40 % P 20 % N	0.05	0.62	5.59	2.78	0	2.81	29
10 % F 40 % P 30 % N	0.05	0.61	6.78	2.59	0	4.19	27
10 % F 50 % P 10 % N	0.04	0.64	2.74	2.73	0	0.01	34
10 % F 50 % P 20 % N	0.04	0.63	2.84	2.80	0	0.04	33
10 % F 50 % P 30 % N	0.04	0.61	3.05	2.76	0	0.30	31
20 % F 10 % P 10 % N	0.06	0.66	8.77	1.99	6.73	0.05	22
20 % F 30 % P 10 % N	0.05	0.63	6.38	2.83	0	3.55	28
20 % F 40 % P 10 % N	0.04	0.63	3.17	3.01	0	0.16	31
20 % F 40 % P 20 % N	0.05	0.62	4.41	2.70	0	1.71	30
20 % F 40 % P 30 % N	0.05	0.60	6.05	2.51	0	3.53	28
20 % F 50 % P 10 % N	0.04	0.64	2.50	2.49	0	0.01	34
20 % F 50 % P 20 % N	0.04	0.62	2.59	2.56	0	0.03	33
20 % F 50 % P 30 % N	0.04	0.61	2.75	2.64	0	0.12	32

The scenarios with the 10 % flow and 50 % phosphorus concentration reduction in the Red River are consistent with the paleolimnological study's conclusion that a 50 % reduction of phosphorus influx into Lake Winnipeg is needed to achieve the water quality target of 0.05 mg/L for the south basin (Bunting *et al.* 2011). The additional 5 % flow and 10 % phosphorus concentration reduction in the other tributaries helps further reduce phosphorus concentrations in the south basin towards the target of 0.05 mg/L. The additional reduction to the other tributaries is also consistent with the Bunting *et al.* (2012) conclusion that the north basin recovery is more likely to be directly proportional to the magnitude of nutrient decline in the south basin and the recommendation that more stringent reductions may be needed to decrease algal blooms in the north basin.

The shortlist of scenarios included nitrogen reductions in the Red River between 10 % and 30 % (Table 3). Similar to phosphorus, higher flow and nitrogen concentration reductions resulted in lower total nitrogen concentrations in both the south (Figure 20) and north basin (Figure 21) at the end of the modelled scenario. Most of the reduction scenarios resulted in total nitrogen concentrations lower than the water quality targets set out for the south basin (0.75 mg/L total nitrogen) while all reduction scenarios resulted in concentrations lower than the water quality target for the north (0.70 mg/L total nitrogen) basin. Average annual percent reductions for total nitrogen in both the south (Table 4) and north (Table 6) basins were highest when nitrogen reduction was 30 %. In terms of the model's final year of simulation, there was little to no difference in the average annual concentration of total nitrogen between 10 % flow and 20 % flow scenarios with a 30 % reduction in nitrogen for both the south (Table 5) and north (Table 7) basins. Given the increasing concentrations of nitrogen in many Manitoba streams (Jones and Armstrong 2001), the need to decrease the concentration and subsequent loading to Lake Winnipeg (Bunting *et al.* 2011) and that many nutrient reduction actions employed throughout the Lake Winnipeg watershed will reduce both nitrogen and phosphorus concentrations, it was determined that a 30 % reduction in nitrogen concentrations in the Red River would be the optimal scenario.

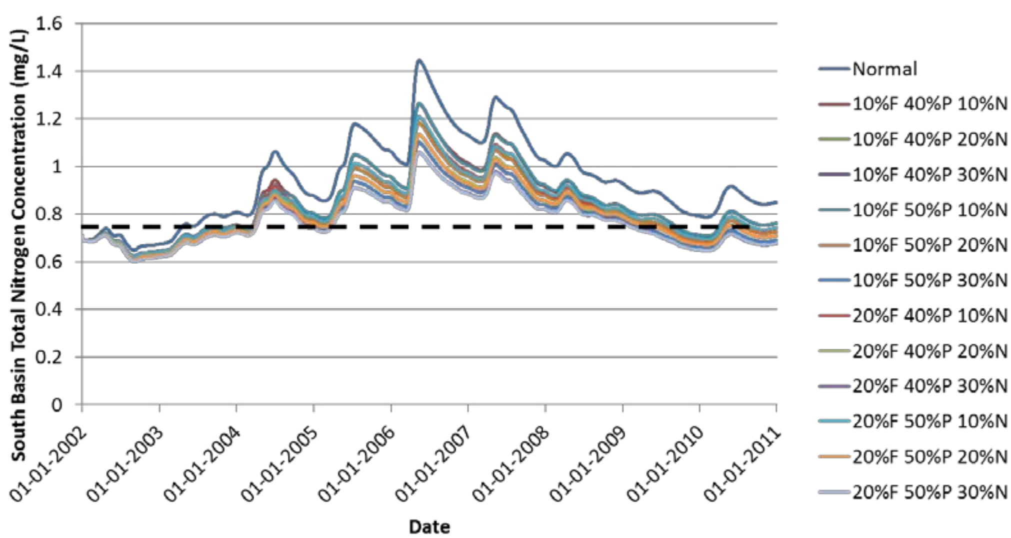

Figure 20. South basin total nitrogen concentration (mg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg. The dashed line represents the total nitrogen concentration target for the south basin of Lake Winnipeg (0.75 mg/L).

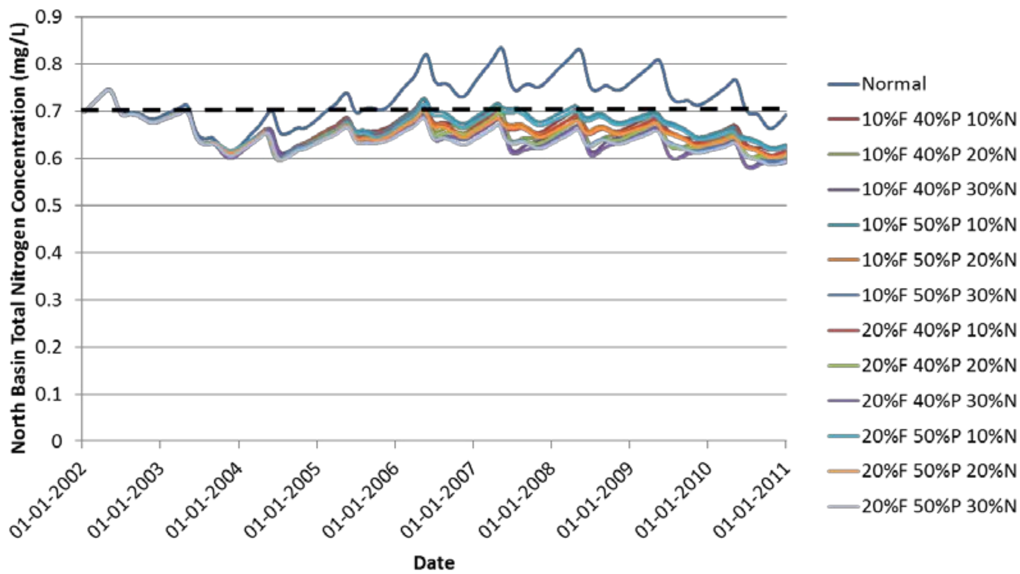

Figure 21. North basin total nitrogen concentration (mg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg. The dashed line represents the total nitrogen concentration target for the north basin of Lake Winnipeg (0.70 mg/L).

In addition to the phosphorus and nitrogen water quality targets, a secondary goal was to preserve or restore the important nitrogen to phosphorus ratio in the lake. Nutrients are typically considered sufficient for growth when molar nitrogen to phosphorus ratios (N:P ratio) are 16:1 (Redfield *et al.* 1963) and a deviation from the optimal Redfield ratio is generally indicative of nutrient deficiency. Ratios below 10:1 indicate phytoplankton are generally considered nitrogen limited while phosphorus limitation occurs at ratios above 20:1.

Under higher flow, phosphorus, and nitrogen reduction scenarios, nitrogen to phosphorus (N:P) ratios in the south (Table 5) and north (Table 7) basins change from a ratio that balances nitrogen and phosphorus limitation (south basin N:P ratio of 16, north basin N:P ratio of 20) to one that is more phosphorus limited (N:P ratio for south basin of 24-27, N:P ratio for the north basin of 31-34). Under these reduction scenarios, N:P ratios in Lake Winnipeg are similar to those found in the early 1990s where the south and north basin had N:P ratios ranging from 22:1 to 35:1 and 34:1 to 55:1 respectively. Lake Winnipeg's modelled phytoplankton community structure is affected by N:P ratios due to certain species being better nitrogen or phosphorus competitors. Typically, cyanobacteria are considered better nitrogen competitors and usually dominate aquatic systems with lower N:P ratios. This is evident in both the south (Table 4 and 5) and north basin (Table 6 and 7) where nitrogen fixing cyanobacteria (P2) taxa either show smaller percent reductions or higher concentrations in scenarios with lower final year N:P ratios. Similarly, non-nitrogen fixing cyanobacteria taxa (P3) concentrations increase with lower N:P ratios (Tables 4 to 7). Although increases in non-nitrogen fixing cyanobacteria concentrations appear large when plotted graphically or as a percentage of normal conditions, the associated concentration increases are minimal (Table 5 and 7). Also, the increases in non-nitrogen fixing cyanobacteria can likely be attributed to the high relative sensitivity of P3 taxa in the model.

To meet the phosphorus and nitrogen targets set for Lake Winnipeg as well as minimizing the severity and frequency of cyanobacteria blooms, the N:P ratio under the 10 % flow, 50 % phosphorus concentration and 30 % nitrogen concentration reductions in the Red River along with a 5 % flow and 10 % phosphorus and nitrogen concentration reduction in the Winnipeg, Dauphin, and Saskatchewan Rivers creates an optimal scenario for Lake Winnipeg where south and north basin N:P ratios would be approximately 24:1 and 31:1 respectively at the end of the nine year model run. Although Redfield *et al.* (1963) identify a N:P ratio of 20:1 as a phosphorus limiting environment, Smith (1983) demonstrated that cyanobacteria taxa tended to be rare when this ratio exceeded 29:1. As such, under the optimal nutrient reduction scenario, N:P ratios in Lake Winnipeg should contribute to the reduction in the frequency and severity of cyanobacterial blooms.

Larger declines in phytoplankton total chlorophyll *a* concentration for the south (Figure 22) and north (Figure 23) basins were observed with higher combined reductions in flow and phosphorus and nitrogen concentrations. Reductions in total chlorophyll *a* were higher in the north basin (Table 6) as compared to the south basin (Table 4) which is evident in the average annual concentration for the final year of the model simulation compared to normal conditions in Lake Winnipeg (south basin: Table 5, north basin: Table 7). Interestingly, the north basin showed lower average annual percent reductions when phosphorus and nitrogen reductions were closer in magnitude (50 % phosphorus and 30 % nitrogen) compared to others (50 % phosphorus and 10 % nitrogen) (Table 6). Both basins showed similar patterns of changes in the total phytoplankton with reductions in the initial spring/summer peaks and then a larger reduction in the late summer/early fall peaks (Figures 22 and 23). Changes in phytoplankton total chlorophyll *a* can be explained when results from the three functional phytoplankton groups are examined.

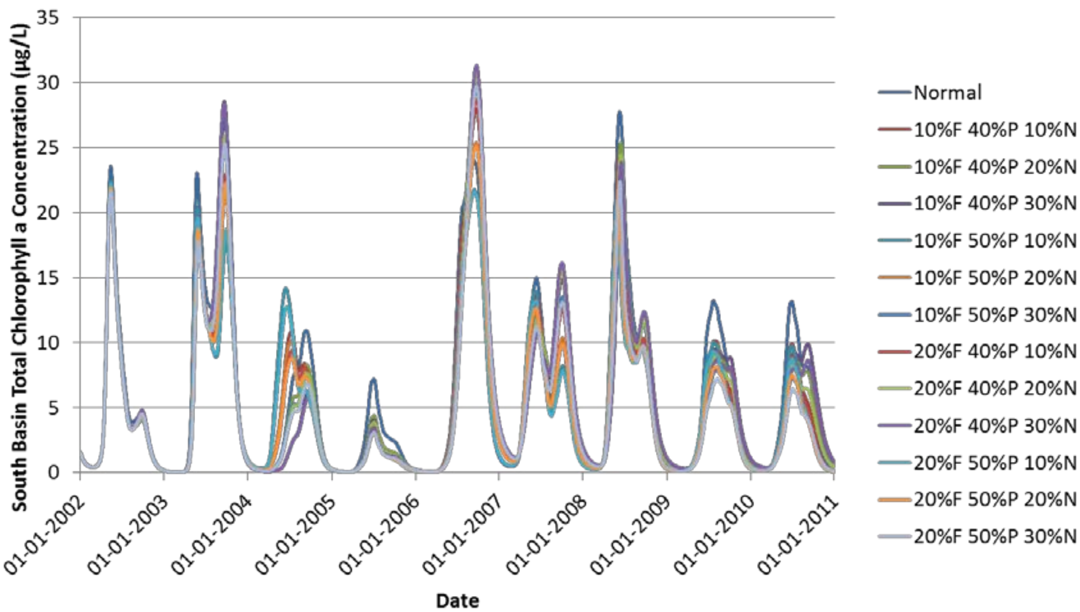

Figure 22. South basin total phytoplankton chlorophyll a concentration (µg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

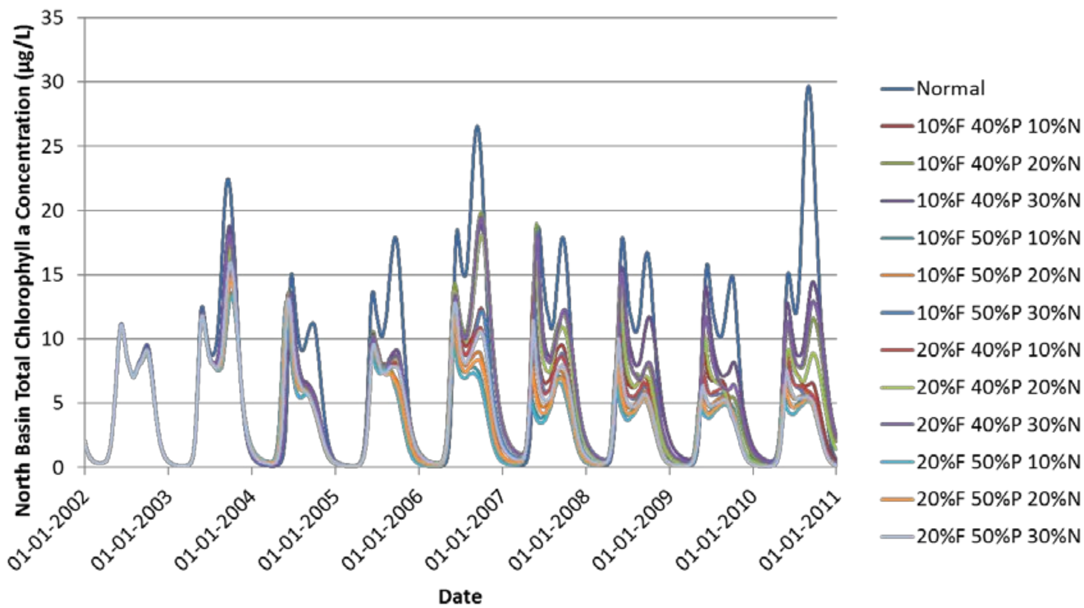

Figure 23. North basin total phytoplankton chlorophyll a concentration (µg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

For non-cyanobacteria algae (P1), peak chlorophyll *a* concentration decreased in both the south (Figure 24) and north (Figure 25) basin during the spring/early summer under the various shortlisted reduction scenarios. The reduction in non-cyanobacteria accounts for the total chlorophyll *a* reduction during that time period (Figures 22 and 23). In general, the average annual percent reduction in non-cyanobacteria chlorophyll *a* concentration was larger with combined higher flow, phosphorus and nitrogen reductions for both basins (Table 4 and 6). Compared to normal conditions in Lake Winnipeg, the average final year non-cyanobacteria chlorophyll *a* concentration decreased in the south basin (Table 5) under all scenarios while slightly increasing in the north basin in more than half of the tested scenarios (Table 7). For example, a 10 % flow, 50 % phosphorus, and 30 % nitrogen reduction in the Red River increased the north basin final year average annual non-cyanobacteria chlorophyll *a* concentration from the normal modelled condition of 2.61 µg/L to 2.76 µg/L (Table 7), despite an average annual percent reduction of 4.79 % in the north basin (Table 6). Although minimal reductions in non-cyanobacteria taxa are desired to ensure a healthy Lake Winnipeg, under current eutrophic conditions certain taxa such as diatoms do bloom at certain points in the year which can have an impact for example on the efficiency of commercial fisher’s nets.

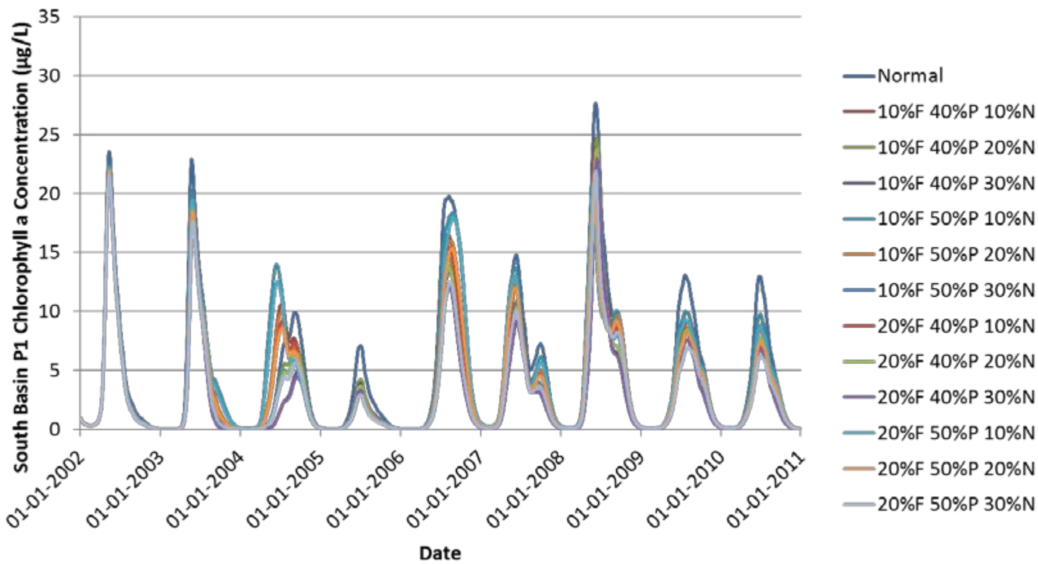

Figure 24. South basin non-cyanobacteria (P1) chlorophyll a concentration (µg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

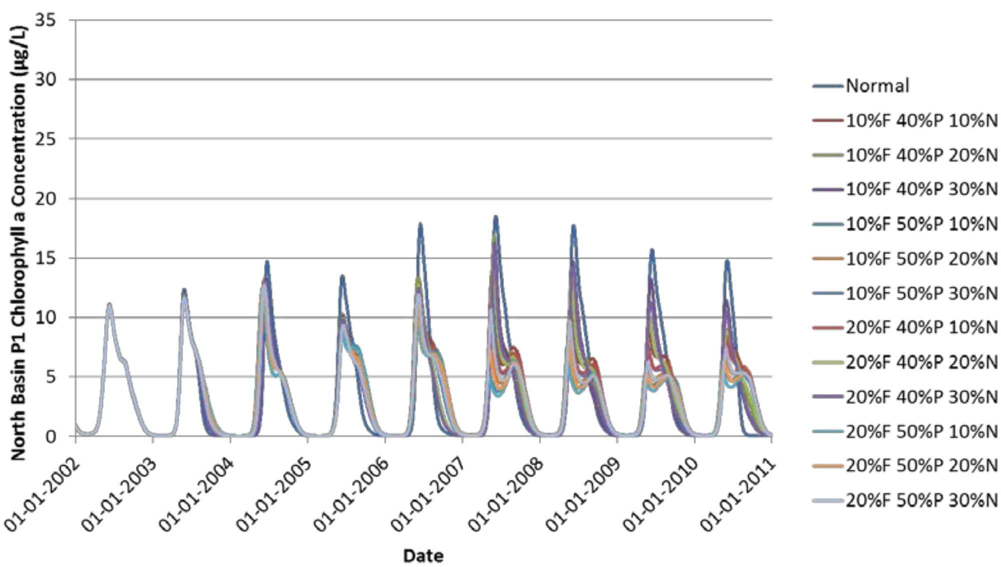

Figure 25. North basin non-cyanobacteria (P1) chlorophyll a concentration (µg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

For nitrogen-fixing cyanobacteria (P2), peak chlorophyll *a* concentrations in the last few years of the modelled simulation disappear in both the south (Figure 26) and north (Figure 27) basins under almost all the scenarios. Annual average percent reductions for the higher flow, phosphorus and nitrogen reductions scenarios were very high in both the south (Table 4) and north (Table 6) basins, ranging between 72 % and 87 %. As a result, the average annual nitrogen-fixing cyanobacteria chlorophyll *a* concentration in the final year of the WASP model scenario was found to be zero for both basins (Table 5 and 7) in those scenarios with larger reductions in flow, nitrogen and phosphorus in the Red River. The loss of nitrogen-fixing cyanobacteria chlorophyll *a* in the late summer/fall accounts for the reduction in total chlorophyll *a* during this time period in the open water growing season (Figure 22 and 23).

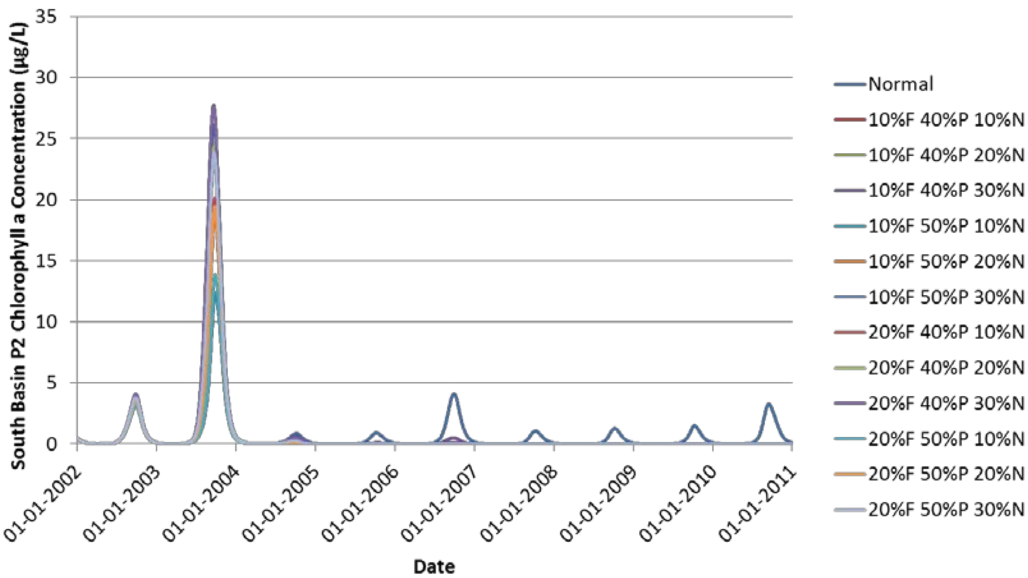

Figure 26. South basin nitrogen-fixing cyanobacteria (P2) chlorophyll a concentration (µg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

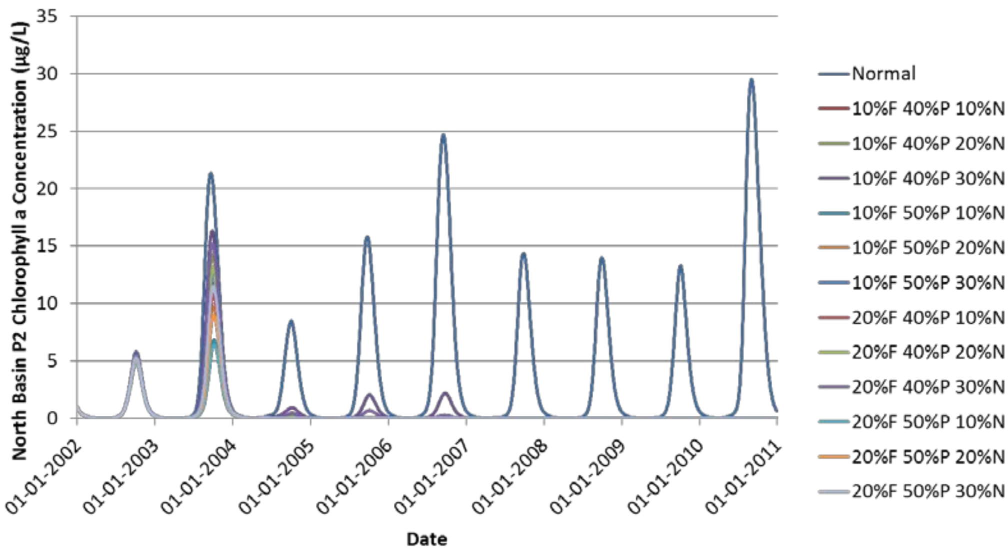

Figure 27. North basin nitrogen-fixing cyanobacteria (P2) chlorophyll a concentration (µg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

For the majority of the shortlisted reduction scenarios tested, non-nitrogen fixing cyanobacteria (P3) chlorophyll *a* concentrations increased in both the south (Figure 28) and north basin (Figure 29). Although the increases on an annual percent average basis seem high (south basin: Table 4, north basin: Table 6), the final year average concentration is relatively low in the higher flow, phosphorus, and nitrogen reduction scenarios (south basin: Table 5, north basin: Table 7). Under a 10 % flow, 50 % phosphorus concentration, and 30 % nitrogen concentration reduction in the Red River, the north (0.30 µg/L) and south (0.40) basin average final year non-nitrogen fixing cyanobacteria chlorophyll *a* concentration is higher than normal modelled conditions averages (north basin: 0.04 µg/L, south basin: 0.11 µg/L) but overall concentrations remain a very low proportion of total chlorophyll *a*. As previously mentioned, non-nitrogen fixing cyanobacteria have high relative sensitivity to changes in a number of model parameters (Zhang and Rao 2012). The modelled increase in non-nitrogen fixing cyanobacteria phytoplankton could be attributed to the significant decrease in nitrogen fixing cyanobacteria and subsequent reduction in competition for resources. Historically, non-nitrogen fixing cyanobacteria phytoplankton concentrations have been low in Lake Winnipeg (Environment

Canada and Manitoba Water Stewardship 2011) but blooms have been modelled in the lake with concentrations as high as 25 μg/L (Figures 28 and 29).

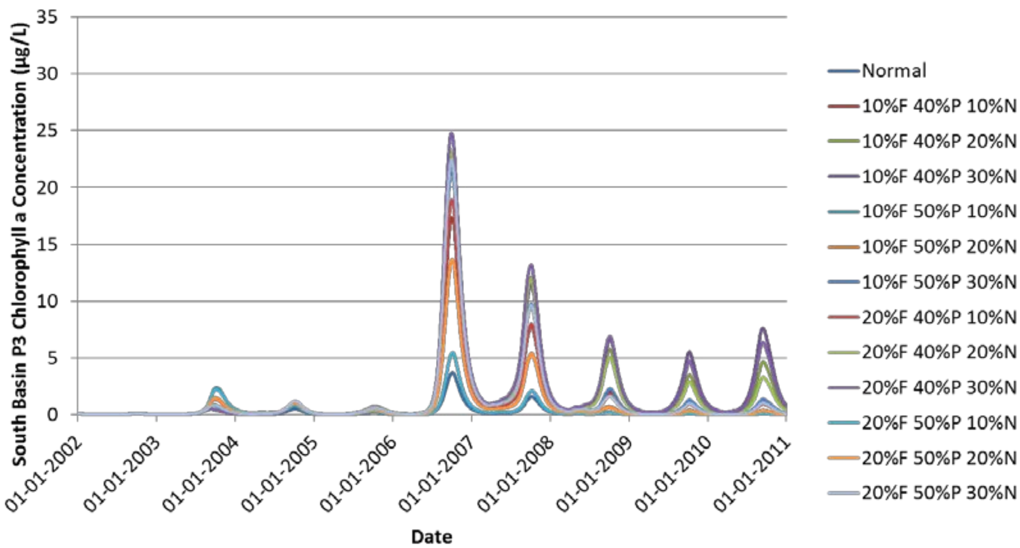

Figure 28. South basin non-nitrogen fixing cyanobacteria (P3) chlorophyll a concentration (μg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

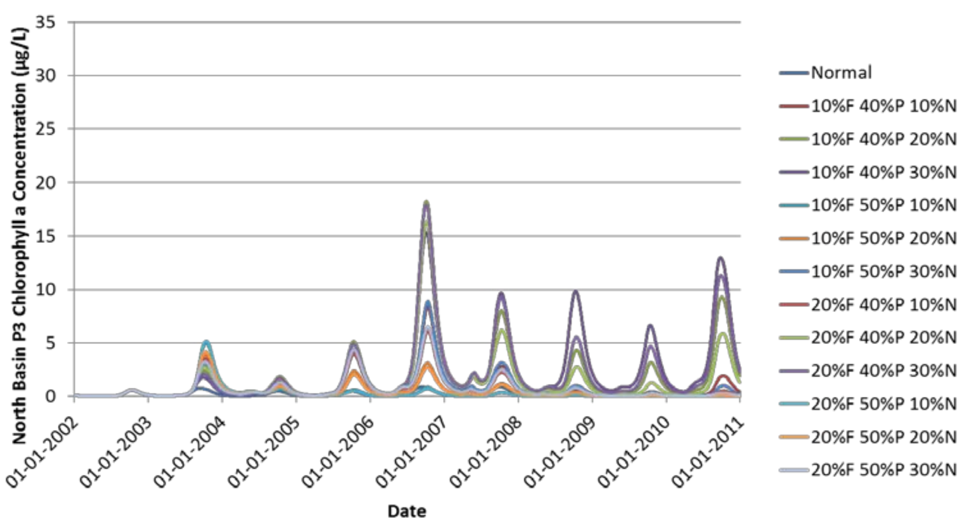

Figure 29. North basin non-nitrogen fixing cyanobacteria (P3) chlorophyll a concentration (μg/L) under normal conditions and those nutrient reduction scenarios that were short listed in developing nutrient targets for Lake Winnipeg.

Summary of Expected Changes in Lake Winnipeg

Based on the information presented above, the modelled optimal nutrient reduction scenario for Lake Winnipeg tributaries includes a 10 % flow, 50 % phosphorus concentration and 30 % nitrogen concentration reduction in the Red River along with a 5 % flow, 10 % phosphorus concentration, and 10 % nitrogen concentration reduction in the Winnipeg, Saskatchewan and Dauphin rivers. Expected changes in the south and north basins water quality and phytoplankton community are presented in Figures 30 and 31 respectively.

For the south basin, total phosphorus concentration is not expected to meet the target of 0.05 mg/L within the first nine modelled years after nutrient reduction measures are fully implemented (Figure 30 A). However, there is a decreasing trend in total phosphorus near the end of the model timeframe. As a result, the total phosphorus concentration target could be reached beyond the timeline of the model should the decreasing trend continue. Unlike total phosphorus, the total nitrogen concentrations in the south basin of Lake Winnipeg met the 0.75 mg/L target by the end of modelled period (Figure 30 B).

Phytoplankton total chlorophyll *a* concentration decreases near the end of the model simulation (Figure 30 C) which corresponds to the moderate reductions in non-cyanobacteria taxa (P1) phytoplankton (Figure 30 D) and large reductions in nitrogen fixing cyanobacteria (P2) phytoplankton (Figure 30 E). Despite a minor peak in non-nitrogen fixing cyanobacteria (P3) phytoplankton part way through the model simulation, non-nitrogen fixing cyanobacteria chlorophyll *a* concentrations are low at the end of the model simulation (Figure 30 F). Furthermore, the south basin N:P ratio is expected to be more phosphorus limiting (24:1) in the final year of model simulation compared to modelled normal conditions (16:1) (Table 5).

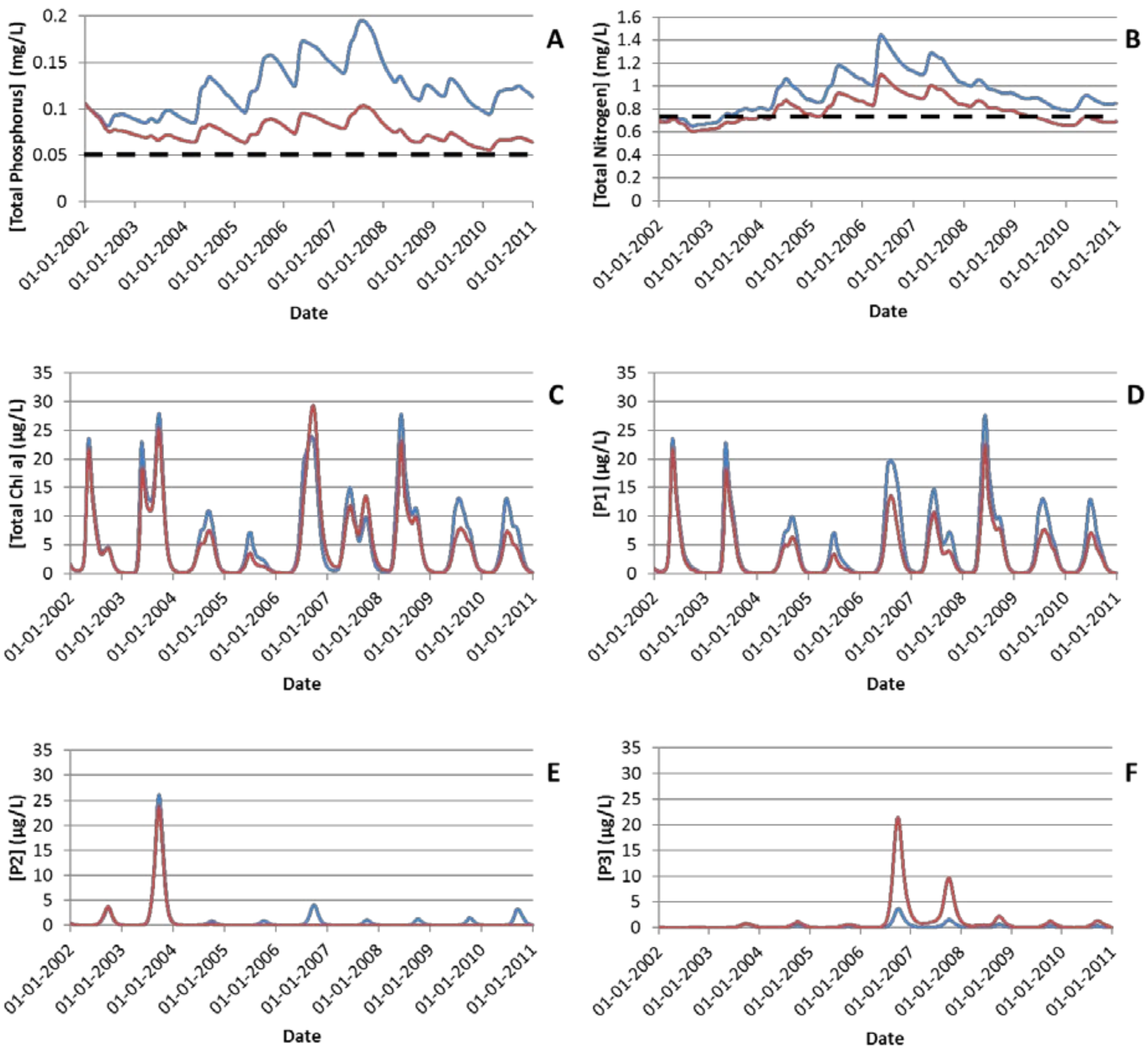

Figure 30. Expected changes in the south basin of Lake Winnipeg as a result of the nutrient reduction targets set for the major tributaries. (A) total phosphorus concentration (mg/L), (B) total nitrogen concentration (mg/L), (C) phytoplankton total chlorophyll a concentration (µg/L), (D) non-cyanobacteria (P1) chlorophyll a concentration µg/L), (E) nitrogen-fixing cyanobacteria (P2) chlorophyll a concentration µg/L), and (F) P3 non-nitrogen-fixing cyanobacteria (P3) chlorophyll a µg/L). Blue lines represent modelled normal condition for Lake Winnipeg. Red lines represent conditions for Lake Winnipeg under the nutrient targets. Dashed lines represent concentration targets for water quality variables.

Expected changes in the north basin of Lake Winnipeg are similar to those expected in the south basin (Figure 31). Unlike the south basin, north basin total phosphorus concentrations are expected to meet the 0.05 mg/L concentration target within the nine year model timeframe after nutrient reductions are fully implemented (Figure 31 A). Total nitrogen concentration reductions are also expected to meet the 0.70 mg/L concentration target (Figure 31 B).

Phytoplankton peak total chlorophyll *a* concentrations for spring/early summer and late summer/fall are reduced (Figure 31 C). The spring/early summer reductions in total chlorophyll *a* correspond to the moderate reductions in non-cyanobacteria (P1) phytoplankton (Figure 31 D), while the late summer/fall total chlorophyll *a* reductions correspond to the large reductions in nitrogen fixing cyanobacteria (P2) phytoplankton (Figure 31 E). Similar to the south basin, non-nitrogen fixing cyanobacteria (P3) chlorophyll *a* concentrations show minor peaks for a few years, but concentrations remain relatively low at the end of the model simulation (Figure 31 F). Although modelled normal conditions for Lake Winnipeg's north basin indicate a phosphorus limiting environment (20:1) in the final year, under the modelled optimal nutrient reduction scenario, the N:P ratio becomes more phosphorus limiting (31:1).

In summary, under the modelled optimal nutrient reduction scenario, phosphorus concentrations in the south basin of Lake Winnipeg were within 0.01 mg/L of the target, and phosphorus targets for the north basin, nitrogen targets for both basins, and the phytoplankton guiding principles were met. Furthermore, N:P ratios were restored to conditions similar to that of the early 1990s and generate a more phosphorus limiting environment aimed at limiting the frequency and severity of cyanobacteria blooms.

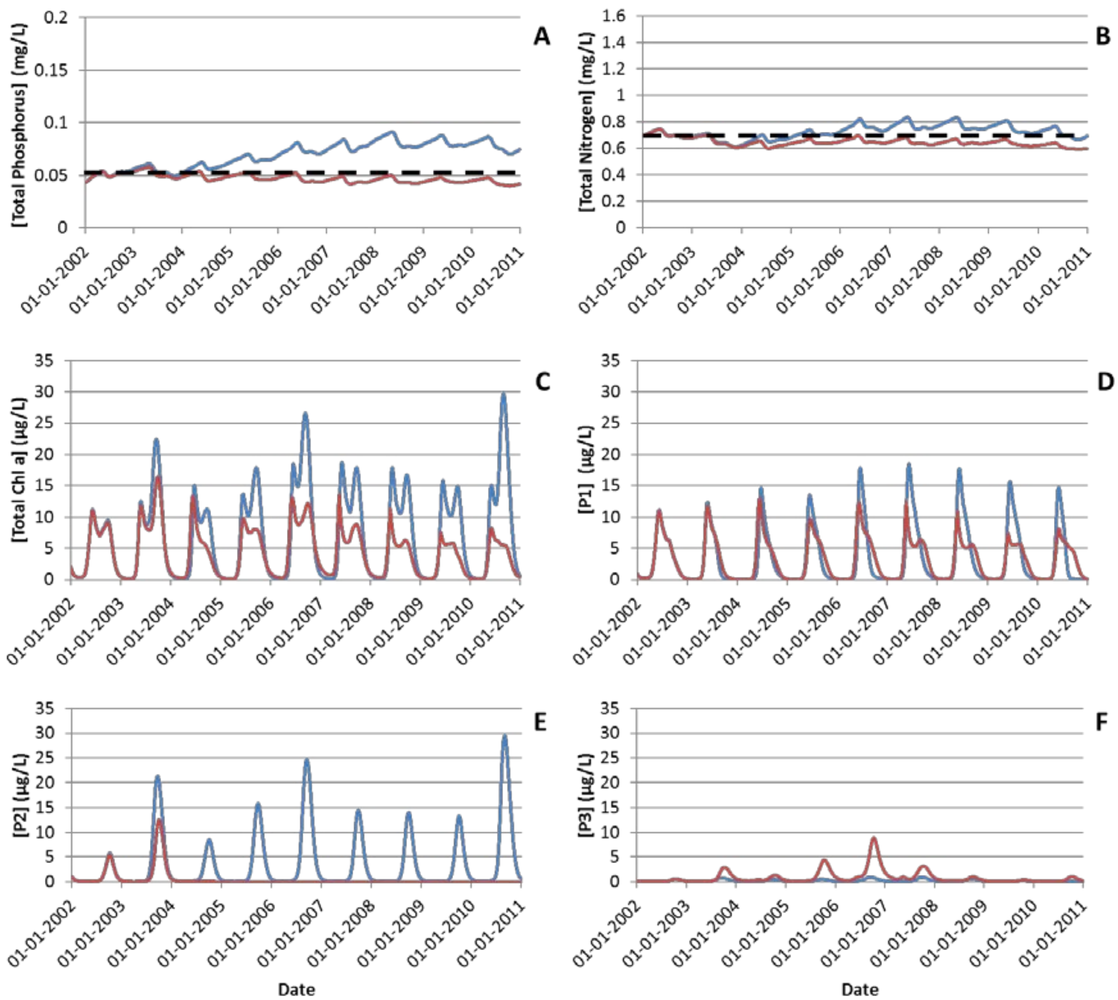

Figure 31. Expected changes in the north basin of Lake Winnipeg as a result of the nutrient reduction targets set for the major tributaries. (A) total phosphorus concentration (mg/L), (B) total nitrogen concentration (mg/L), (C) phytoplankton total chlorophyll a concentration (µg/L), (D) non-cyanobacteria (P1) chlorophyll a concentration (µg/L), (E) nitrogen-fixing cyanobacteria (P2) chlorophyll a concentration (µg/L), and (F) non-nitrogen-fixing cyanobacteria (P3) chlorophyll a (µg/L). Blue lines represent modelled normal condition for Lake Winnipeg. Red lines represent conditions for Lake Winnipeg under the nutrient targets. Dashed lines represent concentration targets for water quality variables.

Long-Term Phosphorus and Nitrogen Loading Targets for Lake Winnipeg's Tributaries

To achieve the optimal nutrient reduction scenario in Lake Winnipeg, each tributary's phosphorus and nitrogen load must be reduced through a combination of reductions in flow and nutrient concentrations. Factoring in both the loading targets for the main tributaries and the smaller tributaries simulated within the model, the annual total phosphorus and total nitrogen loading targets for Lake Winnipeg under the modelled optimal nutrient reduction scenario are 4,850 tonnes of total phosphorus per year (4,250 tonnes from the main tributaries and 600 tonnes from the smaller tributaries) and 62,140 tonnes of total nitrogen per year (52,010 tonnes from the main tributaries and 10,130 tonnes from the smaller tributaries).

Nutrient loading targets for each of Lake Winnipeg's main tributaries are presented in Table 8. Based on the model, the annual total phosphorus loading target for Lake Winnipeg from the main tributaries is 4,250 tonnes of total phosphorus per year (Figure 32). Of the 4,250 tonnes from the main tributaries, the target for the Red River is 2,800 tonnes, the target for the Winnipeg River is 1,050 tonnes, the target for the Saskatchewan River is 340 tonnes, and the target for the Dauphin River is 60 tonnes. Based on the model, the annual total nitrogen load target for Lake Winnipeg from the main tributaries is 52,010 tonnes of total nitrogen per year (Figure 33). Of the 52,010 tonnes from the main tributaries, the target for the Red River is 19,050 tonnes, the target for the Winnipeg River is 19,450 tonnes, the target for the Saskatchewan River is 8,960 tonnes, and the target for the Dauphin River is 4,550 tonnes.

Table 8. Total phosphorus and nitrogen loading targets for Lake Winnipeg's tributaries.

Tributary	Total Phosphorus Load Target (tonnes per year)	Total Nitrogen Load Target (tonnes per year)
Red River (at Selkirk)	2800	19050
Saskatchewan River (at Grand Rapids)	340	8960
Winnipeg River (at Pine Falls)	1050	19450
Dauphin River (near Dauphin River)	60	4550
Small tributaries	600	10,130

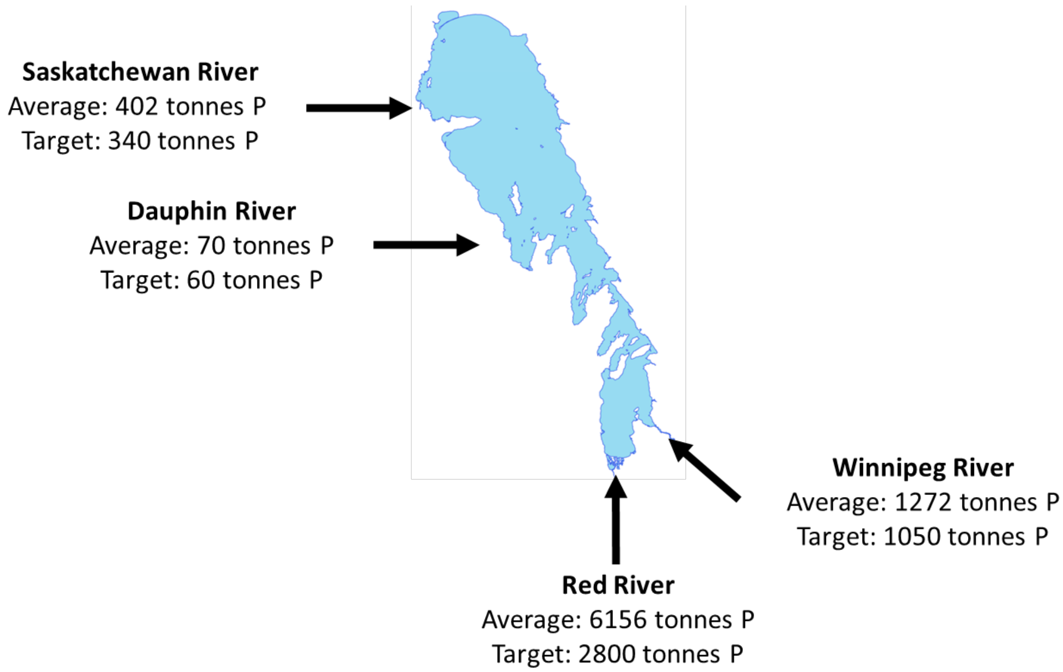

Figure 32. Total phosphorus nutrient loading targets for the main tributaries of Lake Winnipeg. Historical (2002-2010) average loading for each tributary based on Manitoba Conservation and Water Stewardship monitoring program is presented. The total phosphorus loading target for Lake Winnipeg from the four main tributaries is 4,250 tonnes.

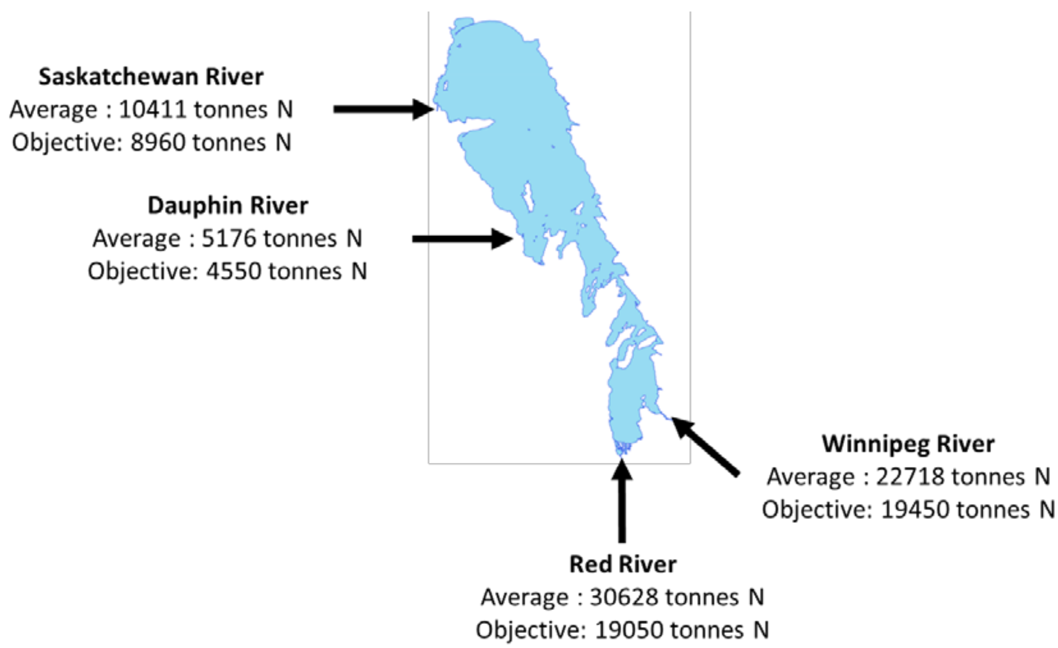

Figure 33. Total nitrogen nutrient loading targets for the main tributaries of Lake Winnipeg. Historical (2002-2010) average loading for each tributary based on Manitoba Conservation and Water Stewardship monitoring program is presented. The total nitrogen loading target for Lake Winnipeg from the four main tributaries is 52,010 tonnes.

Under the modelled optimal nutrient reduction scenario, the smaller tributaries would contribute an additional 600 tonnes of total phosphorus per year. Of this, 165 tonnes are from watersheds to the south, 255 tonnes from the southeast, and 180 tonnes from the west and northeast. The annual total nitrogen load target for Lake Winnipeg from the smaller tributaries is an additional 10,130 tonnes of total nitrogen per year. Of this, 1,070 tonnes are from watersheds to the south, 4,600 tonnes from the southeast, and 4,460 tonnes from the west and northeast.

Current Loads to Lake Winnipeg and Meeting the Loading Targets

The ability to achieve the phosphorus and nitrogen loading targets for the different tributaries will vary from year to year in part because changes in flow strongly influence nutrient loads. Measured annual average phosphorus (Figure 34) and nitrogen (Figure 35) loading to Lake Winnipeg from the Red River (from Armstrong and McCullough 2011) for the years that were modelled shows there is considerable inter-annual variability in load due to flow. In high flow years such as 2005, not only do nitrogen and phosphorus loads in the Red River exceed the historical average for that time period but loads also far exceed the nutrient targets set for the Red River. Clearly, meeting the targets will be more challenging in wet years. Conversely, in low flow years such as 2003, nitrogen and phosphorus loads in the Red River are less than the historical average for phosphorus and nitrogen, and below the nutrient targets (Figures 34 and 35). Similar patterns exist when phosphorus and nitrogen loading for the Dauphin River (Figures 36 and 37), the Saskatchewan River (Figures 38 and 39), and the Winnipeg River (Figures 40 and 41) are compared to their respective loading targets. Phosphorus (Figure 42) and nitrogen (Figure 43) loading from the main tributaries in more recent years (2011 to 2014) shows similar patterns where in years with higher flow (Figure 44) nutrient targets are exceeded. Interestingly, nutrient loads in the Saskatchewan River are well above the nutrient target (Figures 42 and 43). This can be attributed to higher flows in the Saskatchewan River in recent years (2011-2014) compared to earlier years used in the model (2002-2010) (Figure 44).

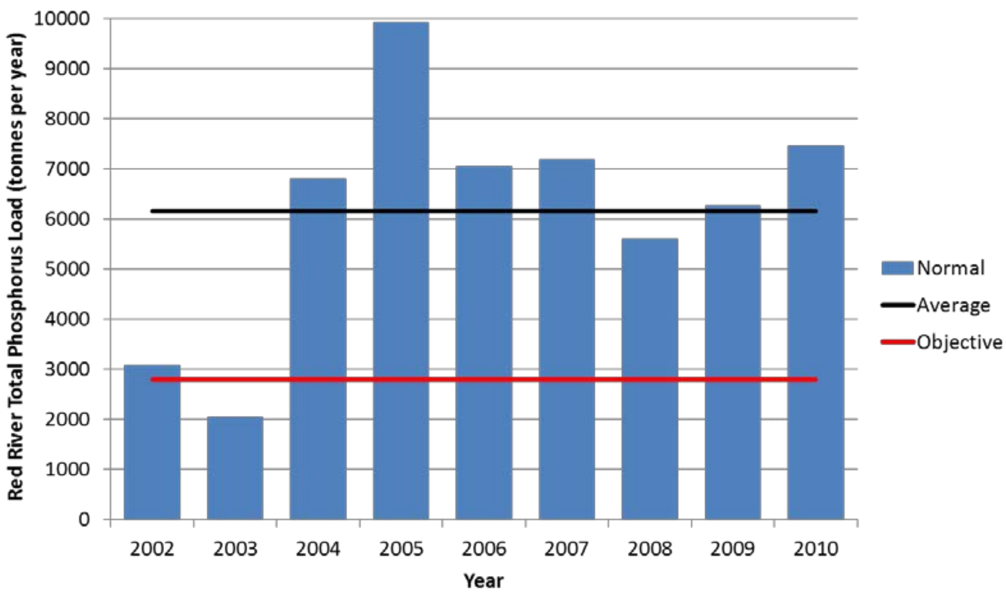

Figure 34. Red River total phosphorus loading (tonnes per year) to the south basin of Lake Winnipeg. Blue bars represent total phosphorus loads (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents the phosphorus target for the Red River.

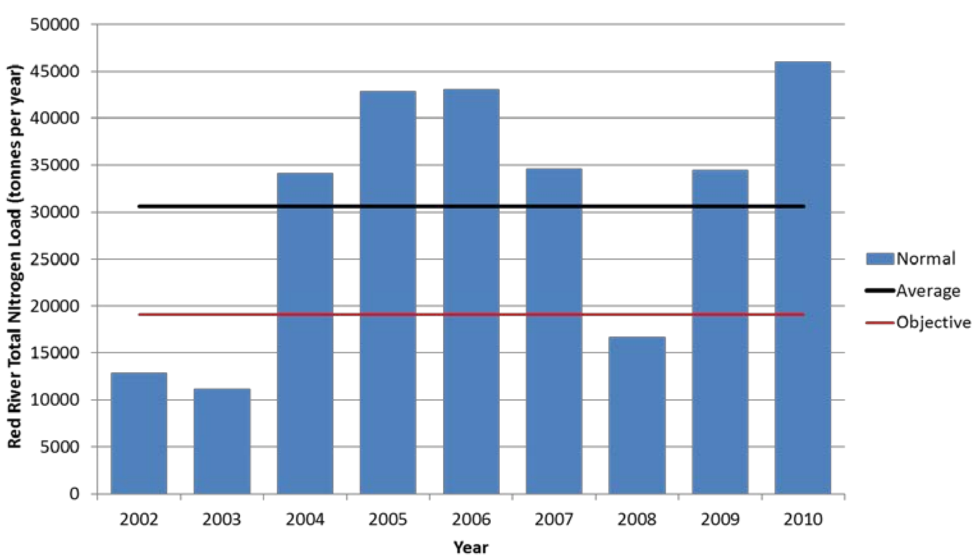

Figure 35. Red River total nitrogen loading (tonnes per year) to the south basin of Lake Winnipeg. Blue bars represent total phosphorus loads (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents the nitrogen target for the Red River.

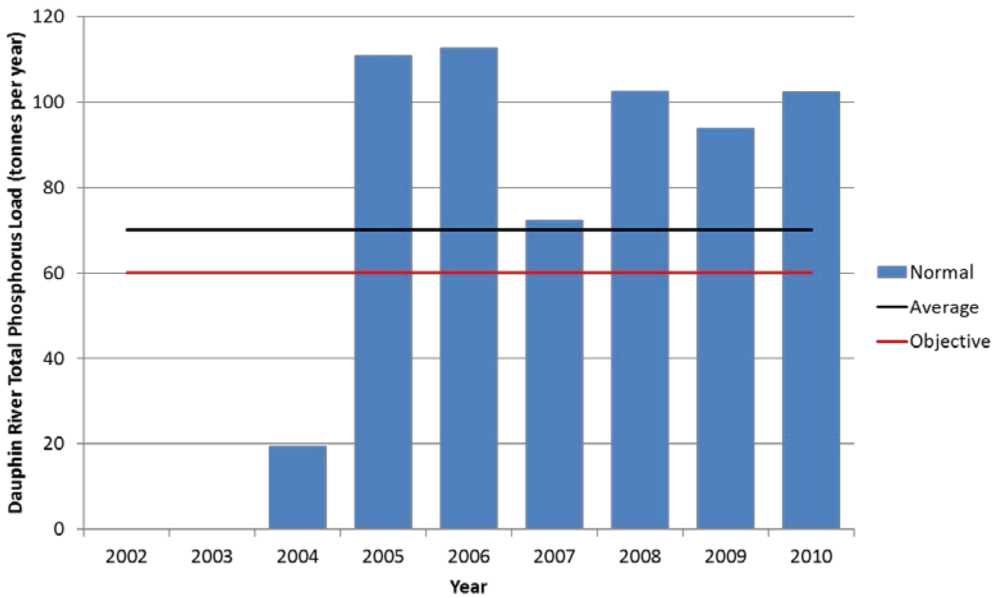

Figure 36. Dauphin River total phosphorus loading (tonnes per year) to the north basin of Lake Winnipeg. Blue bars represent total phosphorus loads (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents phosphorus target for the Dauphin River.

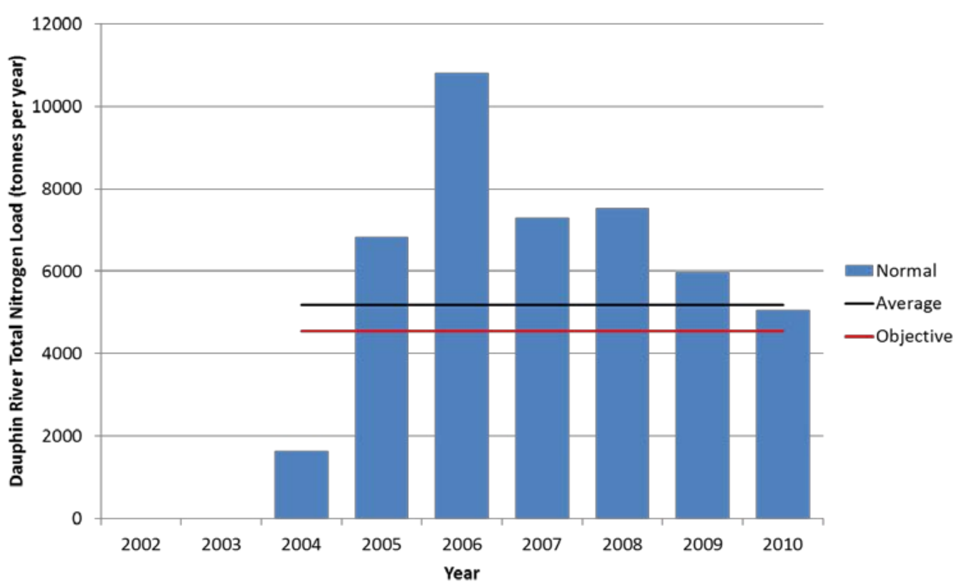

Figure 37. Dauphin River total nitrogen loading (tonnes per year) to the north basin of Lake Winnipeg. Blue bars represent total nitrogen loads (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents the nitrogen target for the Dauphin River.

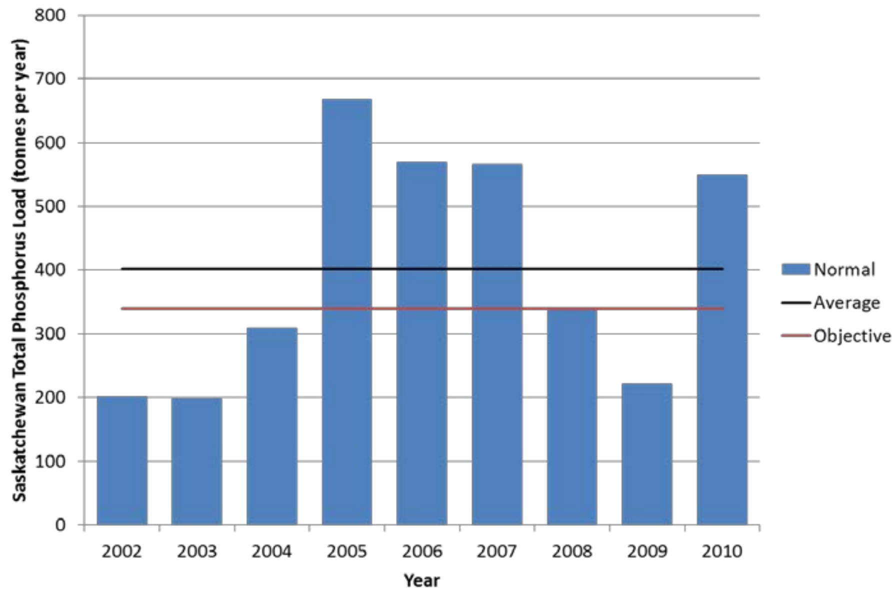

Figure 38. Saskatchewan River total phosphorus loading (tonnes per year) to the north basin of Lake Winnipeg. Blue bars represent total phosphorus load (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents the phosphorus target for the Saskatchewan River.

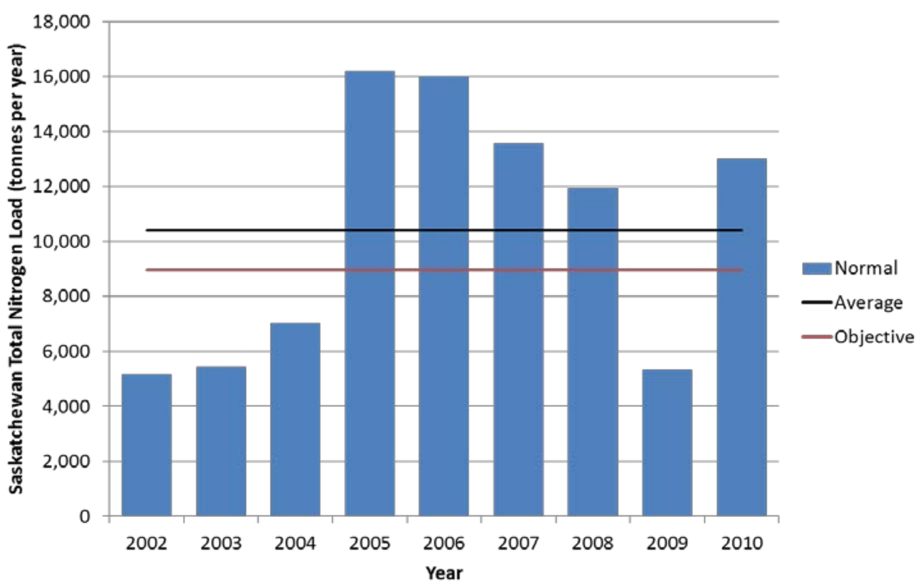

Figure 39. Saskatchewan River total nitrogen loading (tonnes per year) to the north basin of Lake Winnipeg. Blue bars represent total nitrogen load (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents the nitrogen target for the Saskatchewan River.

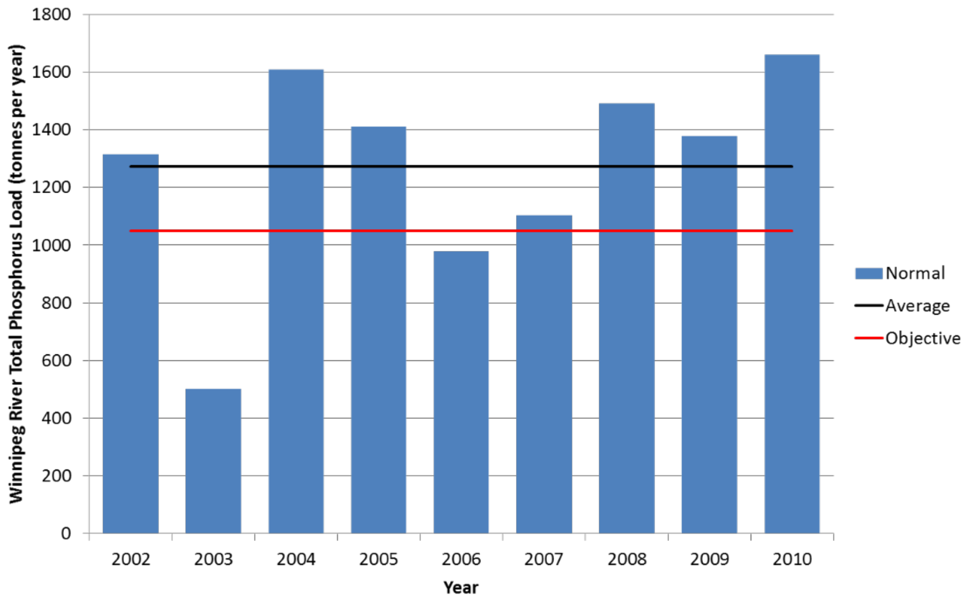

Figure 40. Winnipeg River total phosphorus loading (tonnes per year) to the south basin of Lake Winnipeg. Blue bars represent total phosphorus load (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents the phosphorus target for the Winnipeg River.

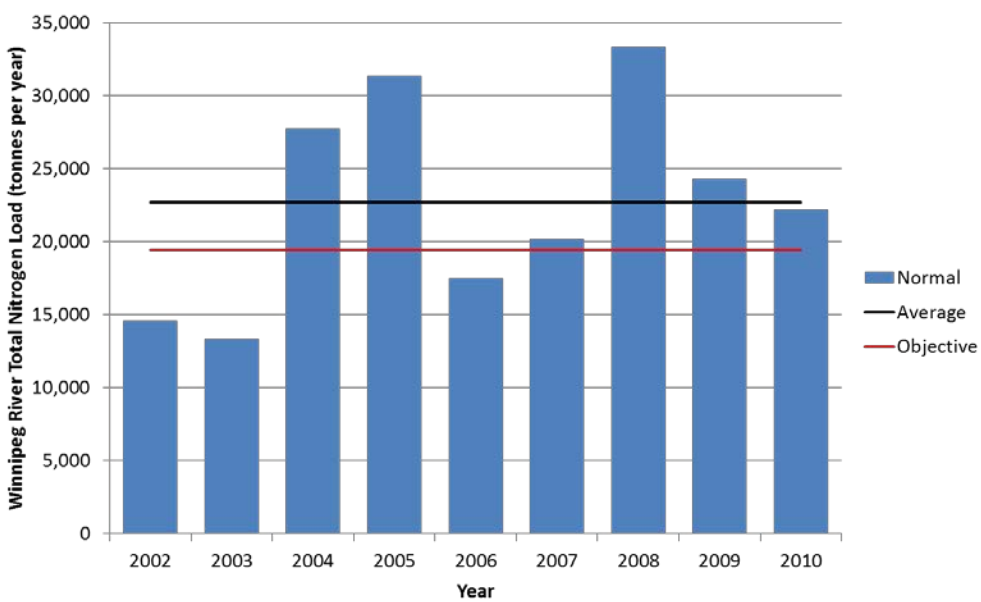

Figure 41. Winnipeg River total nitrogen loading (tonnes per year) to the south basin of Lake Winnipeg. Blue bars represent total nitrogen load (as per Armstrong and McCullough 2011). Black line represents the average annual loading for the timeline of the WASP model (2002-2011). The red line represents The red line represents the nitorgen target for the Winnipeg River.

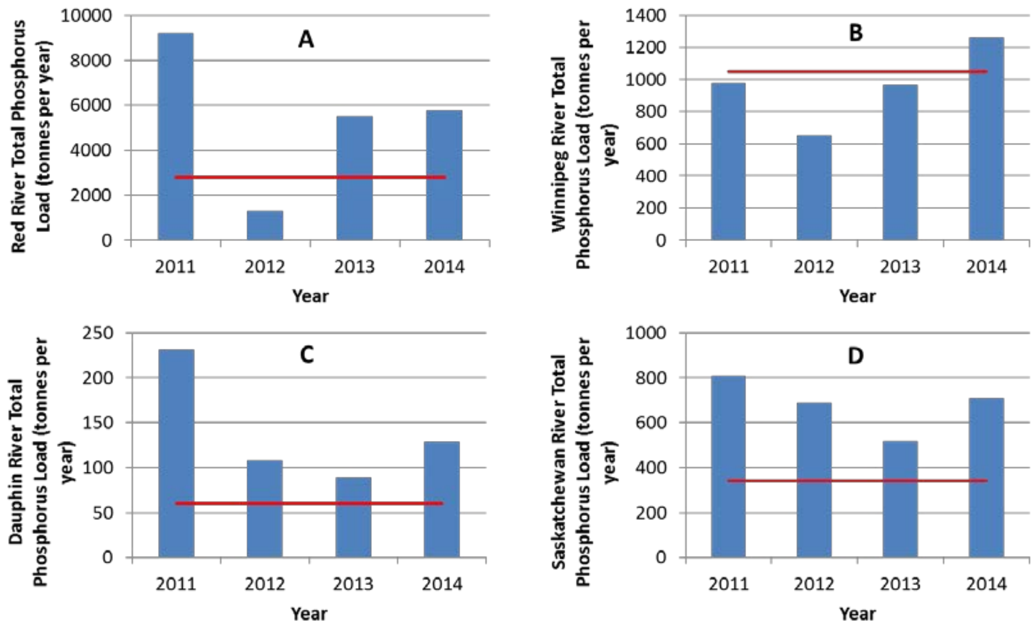

Figure 42. Total phosphorus loading (tonnes per year) to Lake Winnipeg from the Red River (A), Winnipeg River (B), Dauphin River (C), and Saskatchewan River (D). Blue bars represent total phosphorus load (Conservation and Water Stewardship, unpublished, methods are per Armstrong and McCullough 2011). The red line represents the nutrient targets for each tributary to Lake Winnipeg

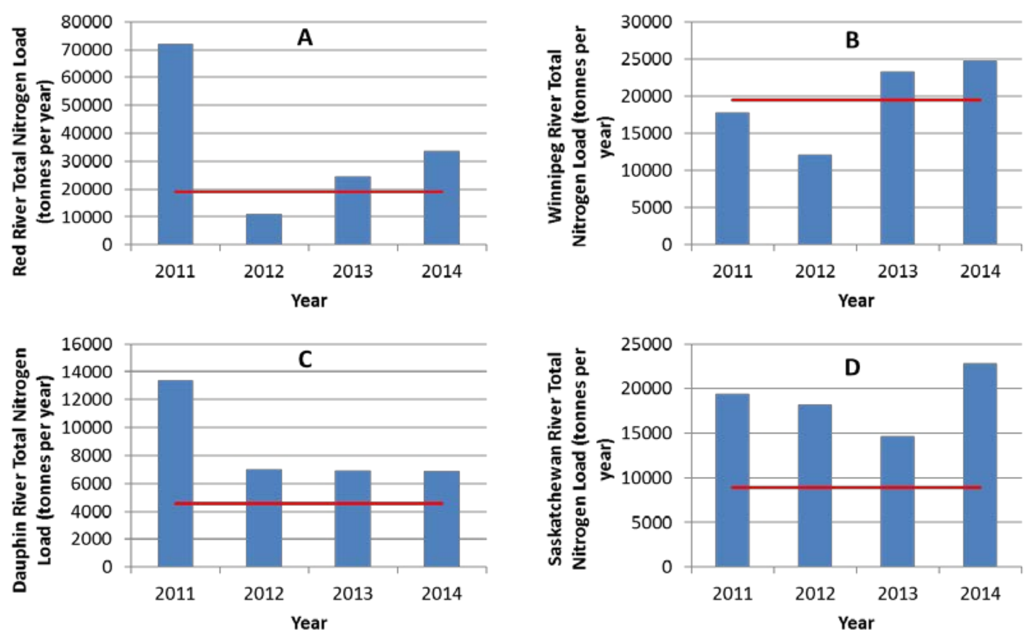

Figure 43. Total nitrogen loading (tonnes per year) to Lake Winnipeg from the Red River (A), Winnipeg River (B), Dauphin River (C), and Saskatchewan River (D). Blue bars represent total nitrogen load (Conservation and Water Stewardship, unpublished, methods are per Armstrong and McCullough 2011). The red line represents the nutrient targets for each tributary to Lake Winnipeg

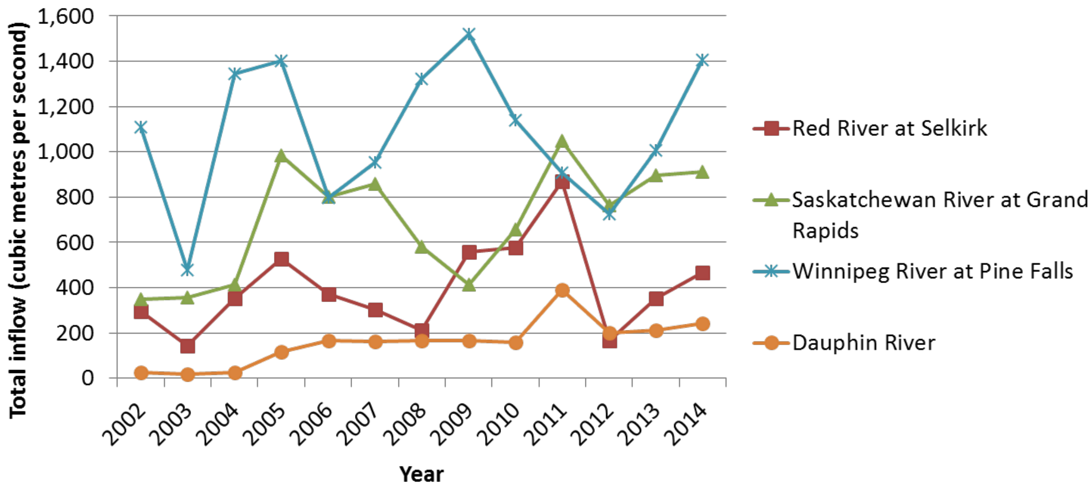

Figure 44. Total inflow (cubic metre per second) to Lake Winnipeg from the Red River (at Selkirk), Winnipeg River (at Pine Falls), Dauphin River (near Dauphin), and Saskatchewan River (Grand Rapids) from 2002 to 2014.

To achieve the phosphorus and nitrogen loading targets for Lake Winnipeg's tributaries, significant reductions in flow and nutrients are needed. Reducing flow across the Lake Winnipeg watershed will require a variety of programs, policies, legislation, incentives, investments and education to be implemented across the interjurisdictional watershed. Measures could include, but are not limited to, building water retention structures at key points in the watershed; protecting and restoring wetlands; implementing more sustainable drainage practices across the watershed; improved stormwater management and low impact development; and implementing other beneficial management practices (BMPs) that aim to keep water on the landscape. Moreover, changes in climate may reduce flow in the tributaries. Drought conditions (less precipitation, higher temperatures, and higher rates of evaporation) could result in lower flow across the entire Lake Winnipeg watershed.

Similar to reducing flow, reducing nutrient concentrations in the tributaries to Lake Winnipeg will require a variety of programs, policies, legislation, incentives, investments and education to be implemented across the interjurisdictional watershed to address all contributing point and non-point sources. Some possible measures that could be implemented to address non-point sources include implementation of beneficial management practices that reduce urban and rural non-point sources of nutrients such as surface runoff reduction through sustainable drainage practices, erosion control structures, developing conservation buffers along rivers and streams, improving nutrient management planning for developments (urban, rural, and cottage), implementing nutrient recovery projects, protection and restoration of wetlands, sustainable fertilizer application policies and practices (4Rs – Right Source, Right Rate, Right Time, and Right Place), and sustainable manure storage and application practices. Other beneficial management practices can be implemented to address point sources of nutrients such as water conservation, treatment of municipal and industrial effluent for both nitrogen and phosphorus removal, low impact development and improved stormwater management in urban areas, and implementing emerging and innovative technologies capable of reducing and recycling nutrients in wastewater. Training and outreach to support the delivery of the above programs will also be important.

UNCERTAINTY

As with any water quality modelling exercise, uncertainties exist. For example, the model uses water quality data from a number of sources and includes a change in laboratories that influences total phosphorus concentrations. The model used to develop the nutrient targets does not take into account the role and impact of aquatic invasive species (such as zebra mussels) or the future role and impact of climate change. Finally, the model estimates internal nutrient loading which could be significant source of future nutrients and could influence the timing for improvements in water quality.

Manitoba Conservation and Water Stewardship, Environment Canada and Fisheries and Oceans Canada use three different laboratories for the analysis of phosphorus including total, dissolved and particulate. In addition, Manitoba Conservation and Water Stewardship has used different contracted labs over the last fourteen years for the analysis of phosphorus and other variables. While all laboratories used by the three agencies are accredited through the Canadian Association for Laboratory Accreditation, differences in phosphorus analysis methodologies exist and results may not be directly comparable. Differences between analytical results provided by these laboratories are currently being assessed with a focus on phosphorus. The review is being guided by a multiagency steering committee. Future modelling efforts will benefit from a better understanding of the change in laboratories on the long term water quality data set.

The water quality model for Lake Winnipeg does not predict changes in higher trophic levels such as fish communities in Lake Winnipeg. Relating trends between trophic levels in food webs to describe the influence of one on another and to determine how lower trophic levels may affect fish production has long been a focus in aquatic ecology to answer questions about ecosystem productivity and sustainable fishery yields. Biological production of fish communities in freshwater lakes is positively correlated with phytoplankton production (primary productivity), total phosphorous concentration, and fish community standing biomass (Downing *et al.* 1990, Downing and Plante 1993). Spring total phosphorous concentration is often strongly linearly correlated with primary productivity in lakes, measured as average summer chlorophyll concentration (an estimator of phytoplankton concentration) (Dillon and Rigler 1974). Good habitat conditions during the spring and summer, including high prey abundance such as zooplankton, are important determinants of growth and survival of larval walleye (*Sander vitreus*), both of which are vital rates that influence year class strength (Roseman *et al.* 2005). In Lake Winnipeg, measured mid-summer total phosphorous concentration and phytoplankton biomass concentration increased sharply starting in the mid-1990s (McCullough *et al.* 2012). The commercial harvest of walleye has also increased since the mid-1990s, reaching its highest level in 2007, when the harvest was nearly double any previous peak (Lumb *et al.* 2011). The synchrony of these observed increases led to questions about the relationship between total phosphorous concentration and walleye yield in Lake Winnipeg.

To investigate the influence of total phosphorous on walleye yield, whole lake modelled total phosphorus concentration was correlated to walleye yield from Lake Winnipeg during a period when total phosphorus concentration in the lake increased nearly 100 percent (McCullough *et al.* 2012) and the commercial harvest was not meaningfully restricted (from 1983 to 2005; Geoff Klein, Wildlife and Fisheries Branch, Manitoba Conservation and Water Stewardship, unpublished data). Commercial harvest can provide an indication of walleye abundance during a time when commercial fishing quota is large enough that fishing is not restricted. Lake

Winnipeg commercial fishers were effectively harvesting as much walleye as they could during a time when total phosphorous concentration almost doubled in the lake. Historic midsummer phosphorous concentration was calculated using a mass balance model developed for Lake Winnipeg (McCullough *et al.* 2012). Modelled total phosphorous concentrations were monthly basin-volume weighted means from mid-January to mid-July each year, encompassing spring and early summer seasons when age-0 Walleye are dependent on zooplankton (Roseman *et al.* 2005). Walleye yield from the commercial fishery was lagged by four years, to match total phosphorous concentration to the hatch year of walleye, when percid populations are influenced by zooplankton density (Roseman *et al.* 2005), and the age when walleye fully recruit to the commercial fishing gear at age four (Lysack 1995).

Figure 45 shows modelled total phosphorous concentration and commercial Walleye yield (lagged 4 years) from 1979 to 2001, when the commercial harvest was not meaningfully restricted. Although modelled total phosphorous concentration values presented here are not comparable to estimates from the WASP model presented in this report (mid-summer vs. annual average), modelled total phosphorous from McCullough *et al.* (2012) shows a similar doubling between the early 1990s and the early 2000s. Similarly, walleye yield doubled over the same period. Therefore, it could be concluded that reducing total phosphorous concentrations by half would result in a mid-summer whole lake concentration of roughly 0.029 mg/L using estimates from McCullough *et al.* (2012) and a walleye yield of roughly 0.88 kg/ha, less than half what was observed in 2007 but comparable to what was observed between 1980 and the mid-1990s. A walleye yield of 0.88 kg/ha is thought to be the base for unrestricted harvest and could be higher with effective fisheries management. With the arrival of rainbow smelt (*Osmerus mordax*) and the heavy reliance of walleye on rainbow smelt for prey in the north basin of Lake Winnipeg (Sheppard 2013), walleye yield may be somewhat higher than during comparable total phosphorous concentrations in the lake pre-rainbow smelt establishment. It is possible walleye yield could be as high as 1.0 kg/ha with the 50 per cent reduction in phosphorus concentrations, as long as rainbow smelt remain abundant. Ongoing monitoring will be critical to understanding how Lake Winnipeg's fish productivity will respond to the implementation of nutrient targets.

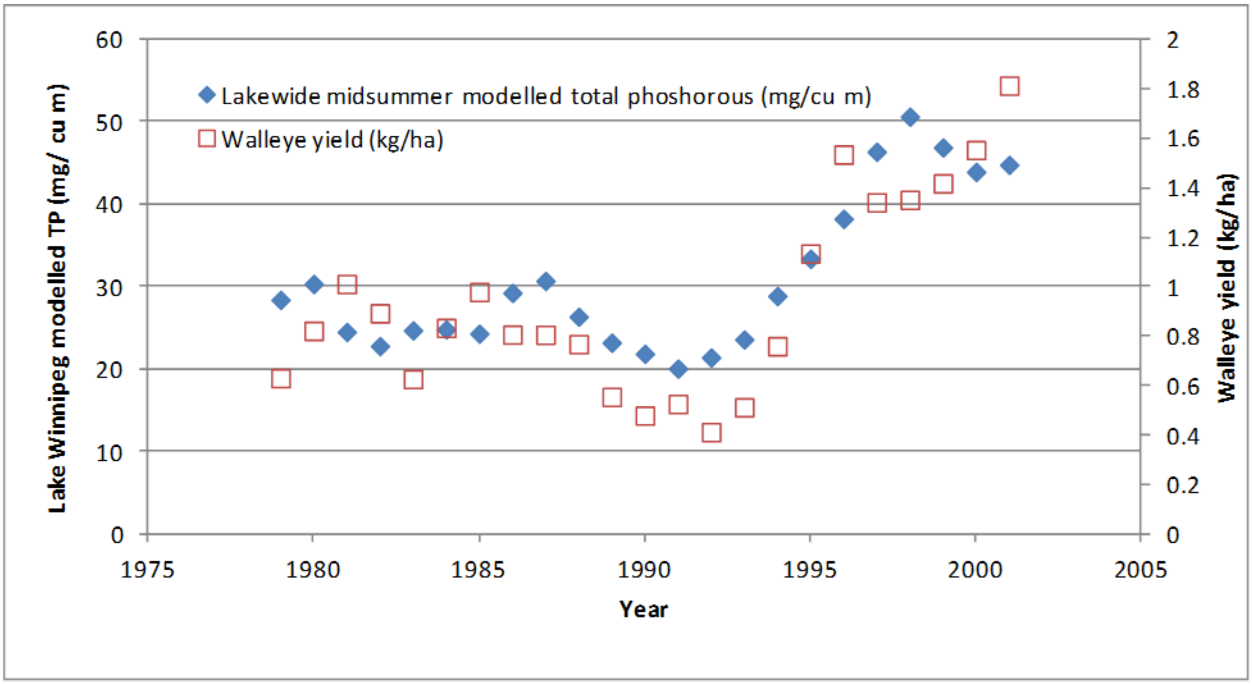

Figure 45. Whole lake modelled, midsummer total phosphorous concentration (mg/cubic meter) calculated using a mass balance model by McCullough *et al.* (2012) for Lake Winnipeg from 1979 to 2001. Also shown is commercial yield of Walleye (kg/ha) lagged four years to match total phosphorous concentration during the hatch year of Walleye, and to account for the age when Walleye are fully vulnerable to commercial fishing gear in Lake Winnipeg (age 4).

Third, the model does not include the affects of recent aquatic invaders such zebra mussels (*Dreissena polymorpha*) and spiny water flea (*Bythotrephes longimanus*) that could complicate the response of the lake to nutrient reductions including the response of the fishery. The potential effect of aquatic invasive species on the water quality and phytoplankton dynamics in Lake Winnipeg has not been well described. Since the extended WASP model used to develop the nutrient targets in this report was calibrated for Lake Winnipeg (2002 through 2010) prior to the arrival of zebra mussels (believed to be in 2013), their potential effects are not implicitly or explicitly included in the model simulations. However, there is a growing body of literature documenting the various impacts that aquatic invasive species, such as zebra mussels, can have on the physical, chemical, and biological components of aquatic ecosystems.

Higgins and Vander Zanden (2010) performed a meta-analysis of dreissenid (zebra and quagga) mussel impacts on freshwater ecosystems. Their analysis found that dreissenid invasions were associated with significant decreases in suspended particulate matter (suspended solids, turbidity, and phytoplankton) and significant increases in water clarity (secchi depth). Dreissenids were also found to have impact on major nutrients in freshwater lakes. Particulate forms of phosphorus were most affected, since these forms were directly filtered by dreissenid mussels. Increases in soluble phosphorus concentrations were common in rivers and some lakes, but not statistically significant across all lakes. Declines in particulate phosphorus were larger than small increases in soluble phosphorus, and total phosphorus concentrations in both the littoral and pelagic zones of the lakes declined significantly by 18 to 20 % following dreissenid invasion (Higgins and Vander Zanden 2010). Effects on particulate and soluble nitrogen compounds were generally minor and not statistically significant. In the pelagic zone there was no significant effect on the various fractions of nitrogen (NO_3, NH_3, dissolved organic nitrogen (DIN), or total dissolved nitrogen (TDN)). However, in the littoral zones, nitrate (NO_3) concentrations increased significantly while there was no detectable change in TDN. Although data on dreissenid effects on sediment organic carbon were only available for littoral zones of lakes, Higgins and Vander Zanden (2010) demonstrated a doubling of littoral sediment organic content.

The water quality trends observed by Higgins and Vander Zanden (2010) demonstrate a dreissenid-induced shift in nutrient cycling and energy flow in freshwater lakes from the pelagic-profundal pathway to the benthic-littoral pathway. Hecky *et al.* (2004) describe this phenomena as a “nearshore shunt” where over the long-term dreissenids, even in very large lakes like Lake Winnipeg, remove nutrients from the pelagic zone (offshore) and retain them within the littoral zone (nearshore) and deeper depositional zones. In support of the nearshore shunt hypothesis, Higgins and Vander Zanden (2010) demonstrated significant changes in biota within the pelagic-profundal (offshore) and benthic-littoral (nearshore) energy pathways (Figure 46). Within the pelagic-profundal pathway, large mean reductions in phytoplankton (-35 % to -78%) and zooplankton (-40 % to -77 %) were observed with higher reductions in littoral lake habitats compared to pelagic lake habitats. Conversely, for benthic energy pathways in lake littoral habitats there were significant increases in mean benthic algal and macrophyte biomass (+170 % to 180 %), sediment-associated bacteria (approximately +2000 %), non-dreissenid zoobenthic biomass (+160 % to +210 %), and total zoobenthic biomass (including dreissenid tissue, +2000 %).

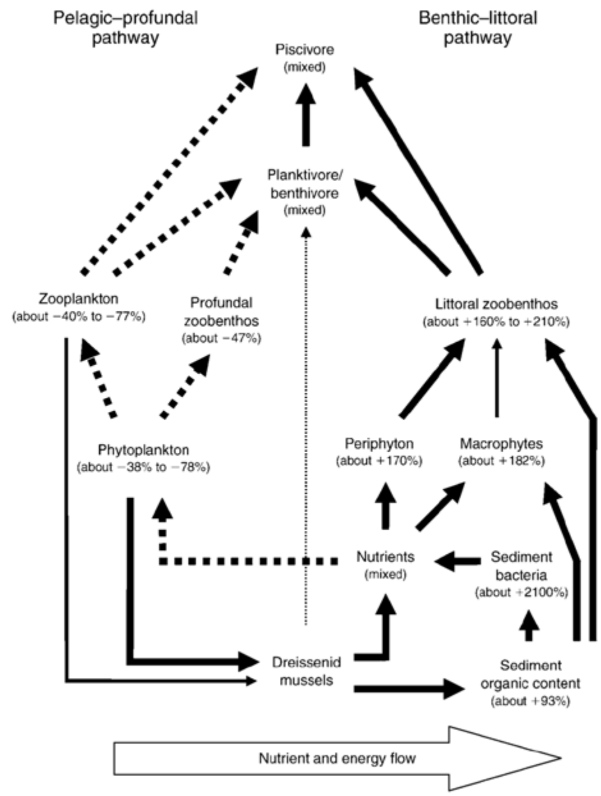

Figure 46. Dreissenid-induced shifts in the dominant energy pathways of freshwater ecosystems. Arrows represent the direction of energy flow. Solid lines represent increased abundance following dreissenid invasion, while dashed lines represent decreased abundance. The values given represent the mean percentage change in parameter values for different broad groups or organisms between pre- and post-dreissenid invasion periods. From Higgins and Vander Zanden (2010).

In some cases, nearshore algal blooms became severe and widespread following dreissenid establishment. Despite demonstrated reductions in overall phytoplankton biomass, in some cases specific taxa with a propensity to form harmful algal blooms such as *Aphanizomenon* spp., *Anabaena* spp., and *Microcystis aeruginosa* increased in biomass following dreissenid establishment, including some of the Laurentian Great Lakes (Vanderploeg *et al.* 2001, Raikow *et al.* 2004, Knoll *et al.* 2008). Higgins and Vander Zanden (2010) concluded that the response of fish communities to dreissenid invasion would be dependent upon the magnitude of ecological changes and the ability of fish species to respond to such changes as fish obtain food and energy from both pelagic-profundal and littoral-benthic pathways (Figure 43). Due to the wide range of impacts from zebra mussels and the unique physical, chemical, and biological composition of Lake Winnipeg, ongoing monitoring will be critical to understanding how the lake and its biota will respond to the invasion of these species and the concurrent implementation of nutrient targets.

Finally, given that flow is a major driver in the nutrient loading of Lake Winnipeg, the possible alteration of the thermal and hydrologic regime of Lake Winnipeg by climate change could have a significant impact on the eutrophication of Lake Winnipeg. Climate change, particularly warming, could result in warmer atmospheric temperatures in the region causing a possible increase in lake temperatures. An increase in temperatures could result in several environmental changes that could benefit harmful algal blooms including longer seasons of ice free conditions and elevated temperatures, changes to the lake's thermal regime, increases in evaporation rates, and intensification of storm magnitudes and drought frequency and duration. More extreme storms and flooding events can lead to enhanced runoff and nutrient delivery to the tributaries to Lake Winnipeg. Conversely, severe droughts could reduce the amount of nutrients supplied to the tributaries. Should extreme storms be followed by severe droughts, nutrient loadings to waterways will be retained longer due to increases in water residence times (Paerl and Scott 2010). As a result, to determine the impact of climate change on Lake Winnipeg's recovery from eutrophication, continued monitoring of Lake Winnipeg and its tributaries will be needed.

Finally, internal nutrient loading to Lake Winnipeg is a source of uncertainty. Jones and Armstrong (2001) noted that while nutrient concentrations in tributaries to Lake Winnipeg generally increased between the 1970s and 2000, nutrient concentrations in the outflow from Lake Winnipeg through the Nelson River actually declined. Armstrong and McCullough (2011) also noted that between 1994 and 2007, about 54 % of the nitrogen and 60 % of the phosphorus entering Lake Winnipeg was retained in the lake. This suggests that a significant amount of phosphorus entering the lake has either settled out (in the sediments) or is becoming assimilated by algae or other aquatic biota (in the water column). As such, there is potentially a large reservoir of phosphorus stored in Lake Winnipeg sediments. To gain some insight into the potential internal phosphorus release during low oxygen events, an initial estimate of internal phosphorus load was calculated for the north basin of Lake Winnipeg (Environment Canada and Manitoba Water Stewardship 2011). Estimates showed that the amount of phosphorus that may be mobilized during low oxygen events has the potential to contribute more phosphorus than the average load from the Saskatchewan River and more than three quarters of the average phosphorus load from the Winnipeg River. Internal nutrient loading will most certainly vary from year to year given variability in oxygen concentrations within the lake. This loading estimate was considered conservative as it does not consider the reintroduction of phosphorus through resuspension of sediments and remobilization that may occur during the ice cover period (Environment Canada and Manitoba Water Stewardship 2011). Internal loading through resuspension of bottom sediments can be an important pathway for phosphorus release into the water column, particularly in shallow lakes (e.g. Reddy *et al.* 1996), but has not been well studied in Lake Winnipeg to date. In the model, uniform resuspension rates have been used, though measured values of sediment resuspension, including inter- and intra- annual variation would be more appropriate for future model use and validation (Zhang and Rao 2012). Therefore, given limitations regarding modelling internal loading, the current model may underestimate the time for phosphorus concentrations in the lake to decline with reduced nutrient loading.

CONCLUSION

Modelling eutrophication in aquatic ecosystems such as Lake Winnipeg is a complex process that relies on the availability of large data sets. While the model and past research used to develop the nutrient targets for Lake Winnipeg describe the best available information for the lake, ongoing monitoring, a better understanding of the uncertainties highlighted in this report, and future model development will be needed to further refine the targets and track the lake's response to nutrient reduction measures.

Through the use of the extended eutrophication WASP model developed for Lake Winnipeg, nutrient loading targets for Lake Winnipeg's main tributaries have been developed. Nutrient loading targets can be used to guide future work related to nutrient reduction within the Lake Winnipeg watershed.

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