Climate in the Lake Winnipeg Watershed and the Level of Lake Winnipeg

Prepared for the Manitoba Clean Environment Commission

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This document has been prepared at the request of the Clean Environment Commission. The main objective are 1) to describe climatic patterns and inflow history to Lake Winnipeg over the 100 years since widespread, continuous meteorological and hydrometric records were initiated in the early 20th century, and to describe climate patterns predicted for the 21st century, and 2) to describe the effects of trends and variability in climate over the watershed on the water level record in the lake. Finally, there is a brief summary of how regulation since the late 1970s has interacted with these historical relationships.

Disclosure

In my current employment at the University of Manitoba, I conduct scientific research that is partially funded by Manitoba Hydro, including research related to the effects of climate change and hydro-electric regulation on Hudson Bay. However, none of the research described below was supported by funding from Manitoba Hydro.

Executive summary

Over the last century, the total annual inflow to Lake Winnipeg has ranged by almost 4X from 35,000 to 136,000 cfs. The variability of tributary discharge and underlying climate in the watershed happens at four scales: seasonal, year-to-year, multi-decadal, and long term trends. The level of the lake has varied at all of these scales in rough synchrony with the supply of water from its watershed.

Based on analyses reported in scientific literature, over the last century, precipitation has increased in the watersheds of the Winnipeg and Red Rivers. No significant trend has been identified in the precipitation record for the Saskatchewan watershed. Annual discharge of the Winnipeg and Red Rivers has also increased significantly. The discharge of the Saskatchewan River has decreased, partly due to increasing consumptive use of water in the South Saskatchewan watershed.

Based on the median output of multiple global climate models, precipitation over the southeastern half of the watershed is likely to increase by of the order of 10% over the next century, although based on the wide range of model results among many different models and future climate scenarios, it is apparent that there is a very great uncertainty the prediction of regional precipitation. Modeling studies in the Lake Winnipeg watershed, produce widely varying runoff responses, from increases of a few percent to over 100% depending on the watershed studied. However, modelling results published in the literature do agree that higher precipitation will produce higher runoff, in spite of the higher evapotranspiration that will accompany warming. The exception is the Saskatchewan watershed, where there is no consensus as to whether either precipitation or runoff will increase or decrease through the next century.

Because the Winnipeg and Red Rivers supply over half the total inflow to Lake Winnipeg, that inflow also increased through the last century. The peak decadal mean inflow is currently about 107,000 cfs, almost 50% higher than the peak of 73,000 cfs in another relatively wet period at the beginning of the 20th century. If predicted increases in runoff in the Winnipeg and Red River watersheds are borne out, then total inflow to Lake Winnipeg will increase considerably, perhaps as much again as through the 20th century, though that is far from certain. Regardless, it is unlikely that the 21st century will see a continuous progression of increasing runoff. It is reasonable to assume that the wet/dry cycle evident in historical records will continue, so that the current high flow period will likely be succeeded by a drier one. And even in a wetter climate, there will be dry years when the amount of water delivered to the lake is not far off the low flow years in the historical record.

Over the last century, the multi-decadal pattern water levels in Lake Winnipeg has tended to follow the pattern in inflow, with three extended periods of predominantly low stands separating periods of higher water, with each successive high water period tending to be higher than the last. The decadal mean lake level from 2002–2011 was 714.1 feet above mean sea level (ft MSL), 1.1 ft higher than the decadal mean level at the beginning of the period of record—713.0 ft MSL from 1913–1922. Without regulation, the lake would have averaged another foot higher over the recent decade.

Measured in the south basin, daily mean water level has ranged from 709.1 to 719.4 ft MSL. The 3-day mean level (averaged between stations in both the north and south basins to exclude short-term setup) has ranged from 709.2 to 717.7 ft MSL. Prior to regulation, the seasonal and annual lake level record also followed total inflow, with slightly lagging seasonal peaks, but largely synchronous individual high inflow/high lake level years (and vice versa). Setup events superimpose abrupt, brief surges in level measured at either end of the lake. Along the south shore, the water level change can exceed 4 ft in hours to days, but most setup events are smaller. In general, they appear to have become slightly less frequent, and smaller, over the last century.

Regulation has affected water level differently in dry compared to wet periods. In the drier 1980s/early 1990s, the annual mean lake level tended to be increased by regulation and the seasonal peak was shifted from May or June to late summer or fall. In the wetter years since 1996, the annual mean level has tended to be reduced but the timing of the spring peak has not been shifted by regulation.

Both precipitation and tributary discharge are at, or nearing century-long peaks in the southeastern watershed of Lake Winnipeg, as is the total tributary inflow to the lake. Historically, each succeeding wet period has generated higher decadal mean total inflow into Lake Winnipeg. The watershed and lake may return to drier conditions, lower inflow and lower lake stands if the present wet period is succeeded by a dry spell. However, any near term dry spell is equally likely to be followed by another wet period. Both historical and predicted climate trends suggest that future wet periods will produce more runoff than previous ones. If so, then increasing inflow will make it increasingly difficult to maintain Lake Winnipeg below 715 ft MSL.

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Introduction

Increasing temperature will certainly change habitat and biological processes in Lake Winnipeg. However, except for the effect on evaporation, links between temperature and regulation are tenuous. Precipitation over the watershed and winds over the lake interact more directly with regulation of the outflow of Lake Winnipeg. Annual precipitation and changes in precipitation over the watershed, modified by evaporation, determine the discharge of Lake Winnipeg's tributary watersheds, and ultimately control seasonal rise and fall, and inter-annual and longer term variability and change in the level of Lake Winnipeg. Strong northerly and southerly winds drag water to superimpose short term, often dramatic fall and rise (setup) at opposite ends of the lake. The combination of high water and wind-generated waves is responsible for the most destructive events related to water level in the lake.

Methods

Historical Climate

Precipitation and temperature records used in this report were accessed from two online sources.

Adjusted and Homogenized Canadian Climate Data (AHCCD)
http://www.ec.gc.ca/dccha-ahccd/

United States Historical Climatology Network (USHCN)
http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html

Both data sets incorporate adjustments to correct for changes in instruments or procedures, or station locations through time, with gaps filled using best available methods.

Historical Discharge

River discharge records used in this report were downloaded from the Water Survey of Canada online data portal at

http://wateroffice.ec.gc.ca/index_e.html

Locations of hydrometric and water level stations used to calculate tributary discharge and lake levels are shown in Figure 1. Periods of record at each station are listed in Appendix 1.

Continuous discharge records were created for the period 1914–2013 from reported monthly data with differing periods of record and occasional gaps. For the period available for each river, I have used discharge from the discharge station nearest Lake Winnipeg. Gaps and earlier parts of the inflow record were filled using discharge estimated by empirical regression on the nearest continuous upstream discharge station, or combination of stations. For the Dauphin River, discharge from 1920 to 1955 was reconstructed with a stage-discharge relationship developed using data recorded prior to installation of the Lake Manitoba outlet control structure in 1961.

In the discussions below, "total tributary inflow" refers to the sum of discharges measured or estimated near the mouths of the Saskatchewan, Dauphin, Red and Winnipeg Rivers. "Total inflow" incorporates estimates for the remaining watershed. Although some smaller tributaries have been monitored since about mid-20th century, none have been monitored for the entire period of record. For consistency throughout the century long record, I have assumed that runoff per unit area in regions outside the major tributary watersheds is the same as in the nearest adjacent major tributary. Drainage areas outside the major tributary watersheds were determined by delineation and measurement on 1:250 000 scale National Topographical Survey maps. In practice, the annual mean inflow from 1914 to 2013 is estimated as

(1) Total inflow = SR + 1.233*DR + 1.050*RR + 1.459*WR

where SR, DR, RR and WR represent the annual mean discharges of the Saskatchewan, Dauphin, Red and Winnipeg Rivers, respectively.

Because it is more centrally located along the east side of the lake than the Winnipeg River, the Bloodvein River probably provides a better index of inflow from the east side. The Bloodvein River discharge record is continuous since 1976. Consequently, for the shorter post-regulation period, I have prepared a second record of total inflow by Equation 2, which I use to model post-1978 unregulated lake levels for comparison with the historic record of regulated levels.

(2) Total inflow = SR + 1.233*DR + 1.050*RR + 1.223*WR + 3.486*BR

where SR, DR, RR, WR are as for Equation 1, and BR represent the annual mean discharge of the Bloodvein River.

Historical lake level

Water level records used in this report were downloaded from the Water Survey of Canada online data portal identified above.

Where water level records are described as "setup free", I refer to a synthetic, smoothed record in which short term fluctuations at either end of the lake have been removed by calculating the running 3-day average of levels averaged between two stations, Berens River in the north basin, and Gimli (after July 1966) or Grand Beach (before July 1966) in the south basin.

Trends and variability

As will become clear below, through a century or more of recorded data, throughout the Lake Winnipeg watershed most climate variables exhibit multi-decade long alternating periods of relatively high and relatively low values—warmer versus cooler, wetter versus drier, and so on.

In consequence, one may easily find quite different average rates of change, or even opposite trends depending on the period of record. For example, although for the Winnipeg River the linear trend of discharge is positive over the 100 years of record since 1914, it is negative over the last 50 years, from 1964–2013. For consistency throughout this report, wherever possible I illustrate and cite analyses of century-long, or near century-long records.

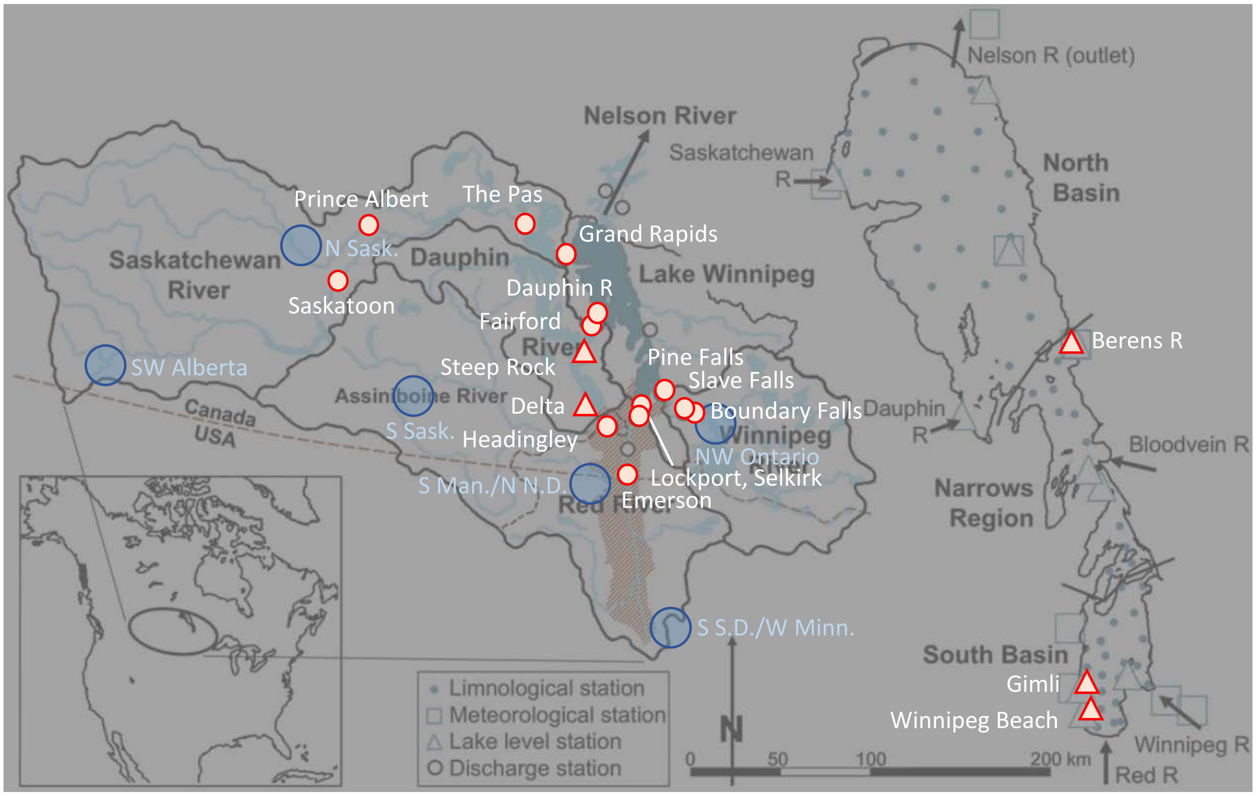

Figure 1. Location map. River discharge stations referred to in this report are indicated by red circles. Lake level stations are indicated by red triangles. Blue circles mark locations of meteorological station clusters used to create Figure 3. Base maps copied from McCullough et al. (2011).

Temperature

For the period 1895–1989, using data from 8 meteorological stations in the Canadian Prairies, Skinner and Gullett (1992) identified a significant increase in the daily minimum air temperature in spring and summer, but not in autumn (Table 1). Over the century, changes in daily maximum temperature were small (in spring and summer) and even negative (in autumn) and not statistically significant. From the data in Table 1, it appears that in summer and autumn, average air temperature may have increased by an average of 0.5°C, but the change was not likely statistically significant.

Table 1. Linear trends of mean seasonal temperatures in °C/100 y from 1989 –1989 (°C/40 y from 1950–1989) using average values at 8 meteorological stations across the Canadian Prairies (Skinner and Gullett, 1992)

	1895 -1989		1950 -1989	
	Mean maximum	Mean Minimum	Mean maximum	Mean Minimum
Winter	0.7	1.3	2.4	2.1
Spring	0.4	1.8*	3.8*	2.8*
Summer	0.2	1.3*	1.1	0.4
Autumn	-0.2	0.7	-0.3	-0.6

Based on more local records, the climate in southern Manitoba in mid-summer is warmer by almost 1.5°C than at the turn of the 20th century (Figure 2). However, the decadal average temperature was about a degree warmer through the 1930s than recently, and the decadal mean temperature has not changed by even a half a degree since the early 1940s, making it inappropriate to think of the overall increase as a linear trend through the period. Monthly mean water temperature in the lake varies very nearly a one-to-one with monthly air temperature (McCullough 2011), so that, although there is scant water temperature data for Lake Winnipeg from the first half of the 20th century we can be assured that the temperature of the lake in mid-summer would have closely followed the historical air temperature record.

Although temperature change is probably more significant to the biota of lakes than change in any other climate parameter, lake temperature is the climate parameter least likely to interact with regulation and will not be discussed further here. Annual evaporation removes of the order of 20% of the average inflow to the lake (Table 4 in McCullough, 2012). However, because annual large lake evaporation is difficult to calculate accurately, annual variability or long term trend of lake evaporation have not been estimated for this report. Warming over the century would have affected the hydrological cycle in the watershed, by increasing evaporation and evapotranspiration, and this will be discussed below.

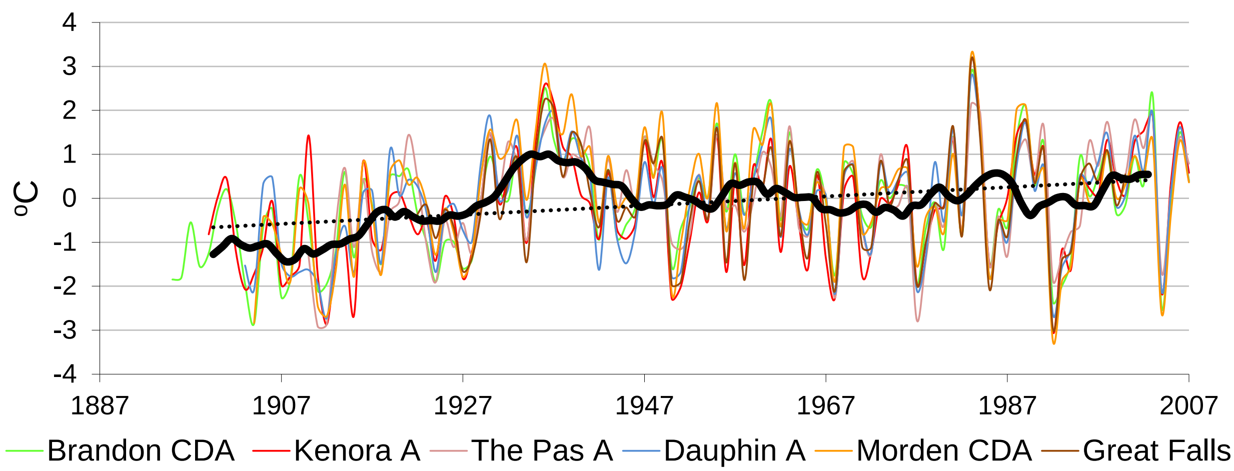

Figure 2. Long term record of July-August mean temperature at stations in southern Manitoba. Temperature for each station is expressed as the difference from the average for the period of record. The 10-year running mean is shown as a solid black line.

Precipitation and tributary river discharge

Three main drivers of possible changes in historical discharge of the Lake Winnipeg tributary rivers are changes in the precipitation/evaporation balance, changes in land use, including especially draining of wetlands, and consumptive use of water. Land use changes and consumptive use are not within the scope of this report, although increased consumptive use is mentioned in the discussion of decreasing discharge of the Saskatchewan River. However, it is important to bear in mind that, where river discharge can be shown to have increased over the past century, wetland drainage may share responsibility with increasing precipitation. Using a hydrological model for Smith's Creek, in the upper Assiniboine watershed in eastern Saskatchewan, Pomeroy (2014) showed that elimination of just over half of the wetland area that had existed in 1958 was responsible for 29% of downstream flow in the 2011 flood of record. Unfortunately, there appear to be too few consistent precipitation records reaching far enough back through the 20th century to draw unequivocal conclusions from historical data. Ehsanzadeh et al. (2011) do infer, from lack of trends in either precipitation or stream discharge, that land use and drainage have not increased the annual flow of Assiniboine River, but that inference is drawn from less than 40 years of precipitation records, and should be viewed with caution.

Over long periods, changes in storage become vanishingly small compared to the three other terms of the water balance equation—precipitation, evaporation and runoff—so that storage is not important to understanding past trends and future prediction of precipitation and runoff throughout the Lake Winnipeg watershed, may be ignored. A fifth term, net groundwater discharge, is probably only locally significant, and may also be ignored.

Historical evaporation

Throughout the Lake Winnipeg watershed, most of the precipitation that falls in any given year is returned directly to the atmosphere by evaporation from water surfaces, evapotranspiration from vegetation and sublimation from the snowpack. For simplicity, I will refer to the aggregate of water losses from the watershed to the atmosphere simply as evaporation. Evaporation is typically expected to increase with rising air temperature, especially in the main drying summer months.

For the period 1950–1989, Skinner and Gullett (1992) identified a significant increase in spring temperatures, but on average, almost no change in summer and autumn. Evaporation trends have been calculated for roughly the same period (1951–2000) over the same region (the Saskatchewan and Assiniboine River watersheds) in a study by Burn and Hesch (2006). They identified a significant increase in April evaporation which fits with the increase in spring temperature found by Skinner and Gullet for the overlapping 1950–1989 period, and a significant decrease in September. However, in the peak evaporation months, June through August, there was no significant change. Overall, annual evaporation either decreased (but not significantly) or did not change throughout the region from 1951–2000.

As will be described below, precipitation has increased since the early 20th century, at least in the southeastern Lake Winnipeg watershed, and the annual discharge of major tributary rivers has increased by a greater proportion in the same region. Hence, although evaporation may have increased due to spring and summer warming, evaporative water losses from watersheds has not measurably have prevented increasing runoff.

Historical precipitation

Figures 3 and 4 were constructed using precipitation records supplied by Canadian and United States meteorological agencies for the purpose of investigating historical trends. These records have been adjusted to correct for changes in instrumentation and, in some cases, changes in station locations.

Figure 3 shows precipitation time series for selected regions of the Lake Winnipeg watershed, where each bar represents the average of annual precipitation at three stations (or two, in the case of northwestern Ontario). All trends are positive over the period, ranging from 0.35 mm/y in southern Saskatchewan to 0.92 mm/y in southwestern Alberta, that is, from 35 to 92 mm over the century.

Figure 4 shows spatial distribution of changes in precipitation and stream flow in the Lake Winnipeg watershed, in this case comparing only recent data (1996–2005) with the latter half of the 20th century (1946–1995). A larger sample of complete records is available for this shorter period.

The values shown on each map are per cent difference, calculated as

$$\text{Change} = 100 * [\text{mean}\ (1995–2005) - \text{mean}\ (1946–1995)] / \text{mean}\ (1946–1995)$$

In general, the geographical pattern of precipitation change mapped in Figure 4 (60 year records) is similar to the distribution of trends shown in Figure 3, that is, ranging from little change in the central Prairies (and some decrease since mid-20th century in southern Saskatchewan) to considerable increases in the foothills of the Rockies and in the watersheds of the Red and Winnipeg Rivers. The greatest increases in the late 20th/early 21st century were due to higher spring rainfall, which has increased even in the central Prairies, at least since the 1940s. There was little change in summer and autumn rainfall, and for the most part, little change in winter snow—although there is a marked exception at Coté, Saskatchewan in the upper Assiniboine watershed (the largest December–March increase shown in Figure 4) and this before the anomalously high 2011 Assiniboine River flood.

Although it is possible to draw the above regional generalizations about precipitation, it should be clear from Figure 4 that there can be high station-to-station variability in the data (high local spatial heterogeneity). Moreover, autocorrelation in the data, in large part due to multi-decadal swings through succeeding wetter and drier periods, makes it difficult to prove significant change in precipitation records. The analyses cited below are all based on non-parametric statistical tests that attempt to overcome at least the latter obstacle. They represent the best estimates to date of the significance of apparent trends in the records.

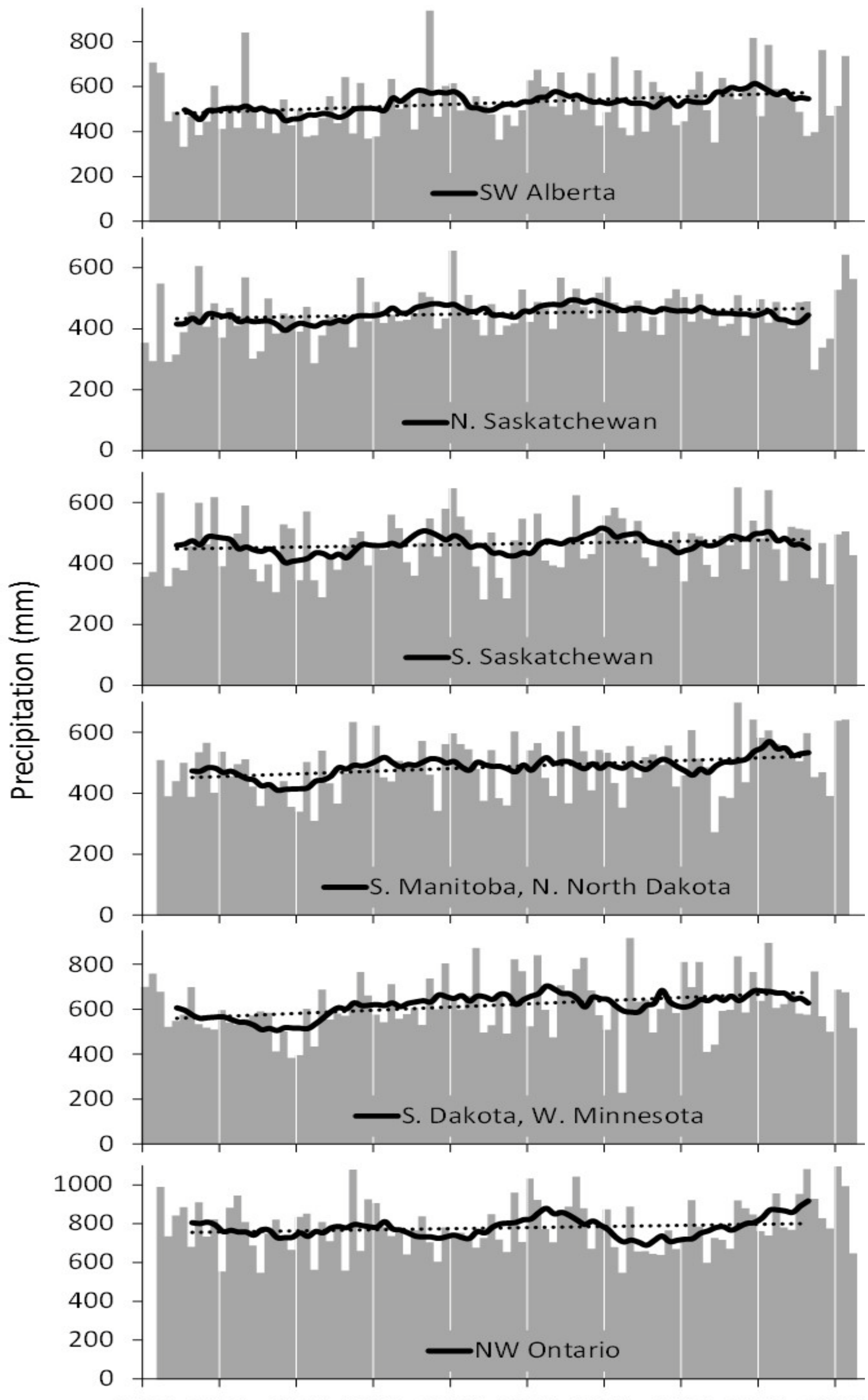

Figure 3. Annual precipitation records for selected regions within the Lake Winnipeg watershed. Each point represents the mean for three stations in the region (except NW Ontario, for which only two stations were averaged). Stations locations are reported in Appendix 1.

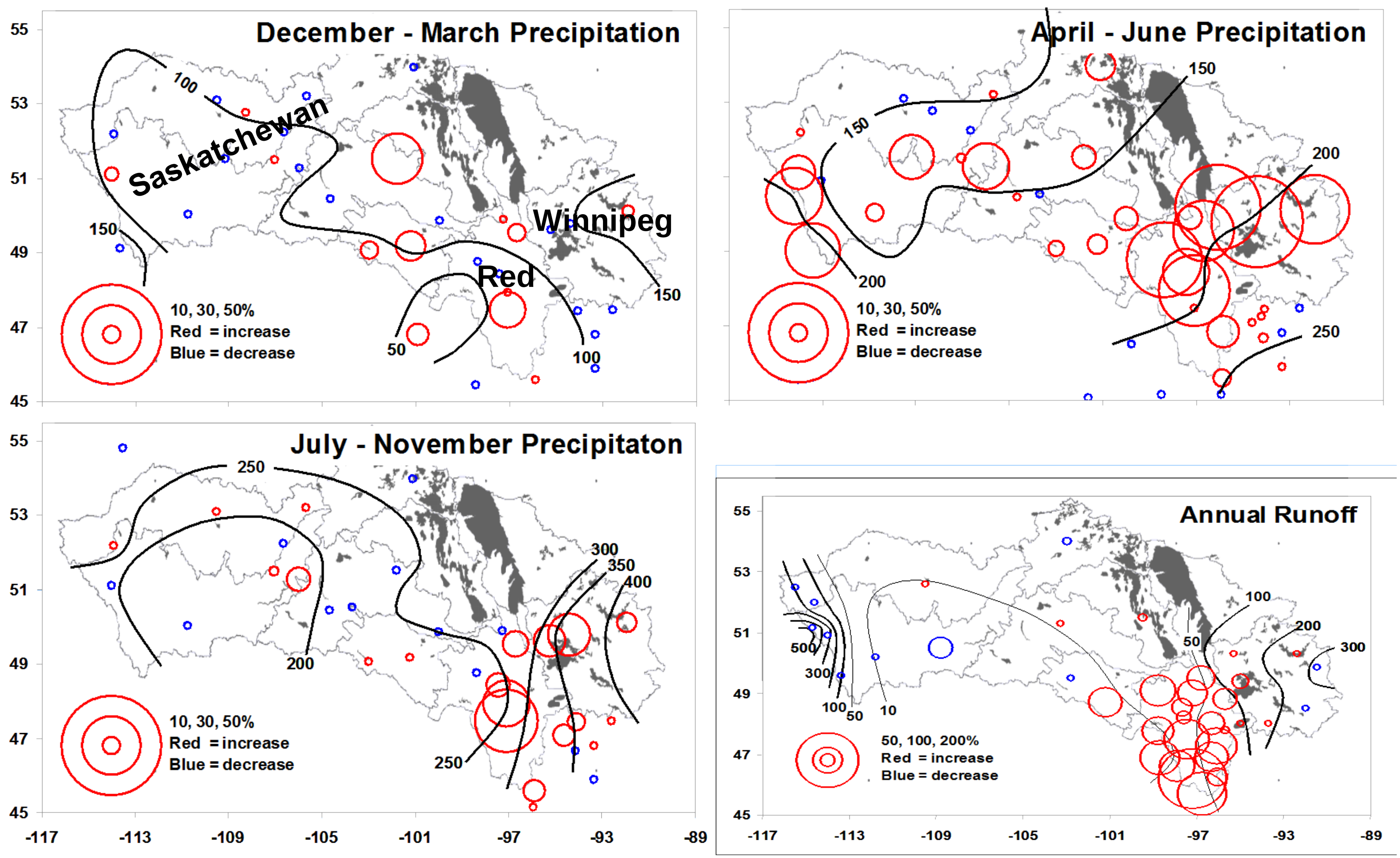

Figure 4. Seasonal precipitation and annual stream flow changes in the Lake Winnipeg watershed. Circle diameters compare 1996–2005 with 1946–1995. (See explanation in accompanying text.) Red indicates increases; blue indicates decreases. Note that the scale is larger for stream flow than for precipitation. The smallest circles indicate <5% and <30% change for precipitation and stream flow respectively. Contour lines indicate the spatial distribution of mean seasonal precipitation and annual stream flow in mm depth.

St. George (2006) used a 1902–1998 gridded data set (described by New et al. 2010) to map precipitation change over the entire Lake Winnipeg watershed, and found significant increases in summer rainfall in the headwater tributaries of the Saskatchewan River and in some northern parts of the Saskatchewan River watershed; in summer and autumn rain in much of the English River and parts of the Winnipeg River basins; and in autumn precipitation in the Minnesota portion of the Red River watershed. For the Assiniboine River watershed, and the Saskatchewan River watershed, with the exceptions noted above, St. George (2006) found that there had been no significant change in precipitation over the century. Using North American Regional Reanalysis (NARR) gridded data for the period 1902–2005, Ehsanzadeh (2006) identified a significant increasing trend in mean precipitation over the entire Red River basin upstream of Emerson.

Historical river flow

Four major tributaries—the Saskatchewan, Dauphin, Red and Winnipeg Rivers—drain 94% of Lake Winnipeg's terrestrial watershed. Although discharge is measured continuously near the mouth of each, not all of these bottom-of-watershed stations were monitored through the early 20th century. However, all four tributaries have been monitored nearly continuously at one or more upstream stations since at least 1914. For the purposes of this report, gap-free monthly and annual 1914–2013 records representing discharge at the mouth of each tributary have been developed using the technique of correlation with overlapping values from longer records at upstream stations. (See station information, including periods of record, in Appendix 1). The record of annual mean discharges for these tributaries is shown in Figure 5. To aid discussion of century-long trends and shorter term variability in the discharge of these rivers, smoothed hydrographs (10-y running means) and linear trends are shown in Figure 6.

There is a mix of seasonal, inter-annual and multi-decadal variability, and century long trends in discharge in these hydrological records (Figures 5 and 6). Seasonal variability is not discussed explicitly, except to the extent that regulation may shift the timing seasonal water level in relation to seasonal peaks in total inflow. Variability and change at each temporal scale are discussed below.

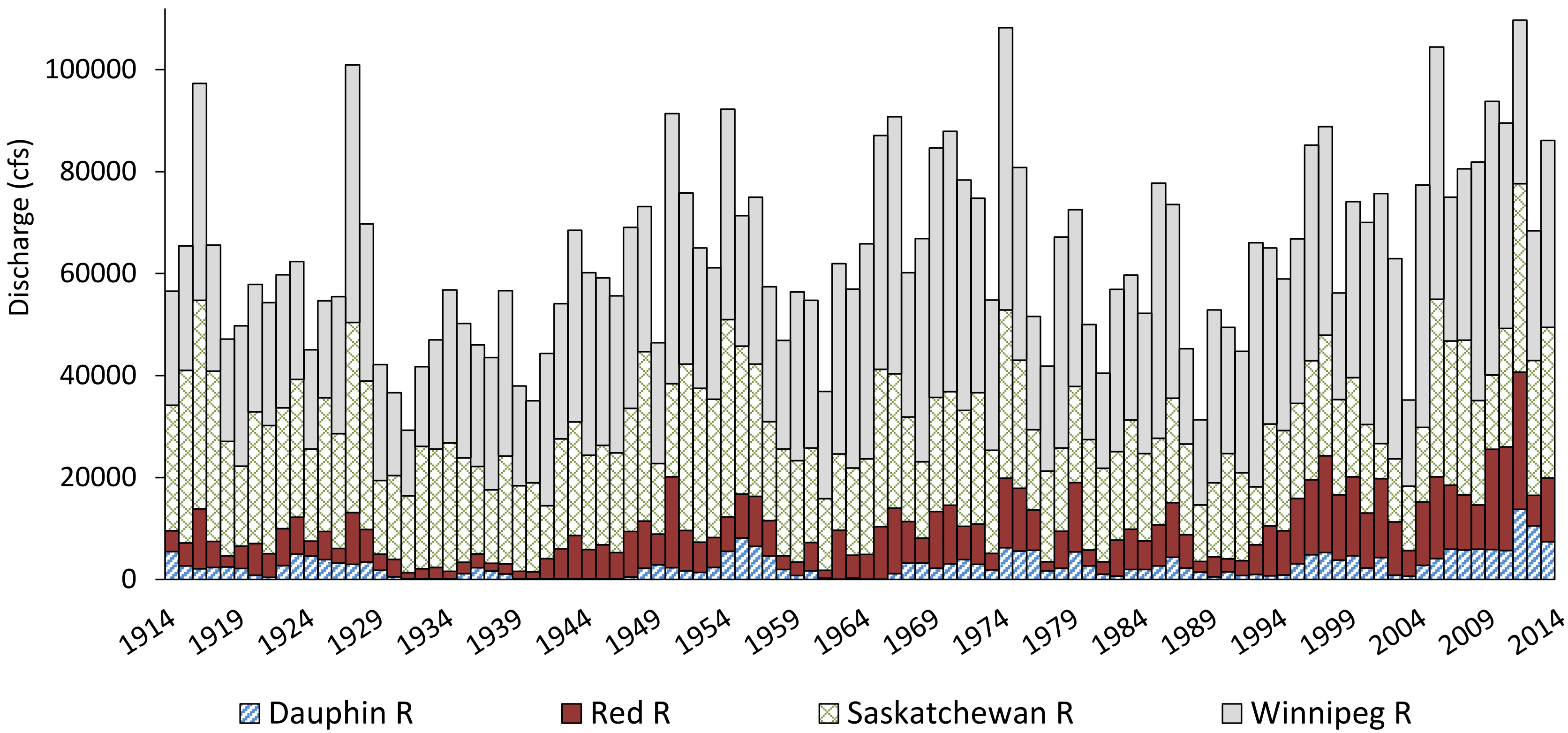

Figure 5. Annual mean discharge of the four major tributaries of Lake Winnipeg.

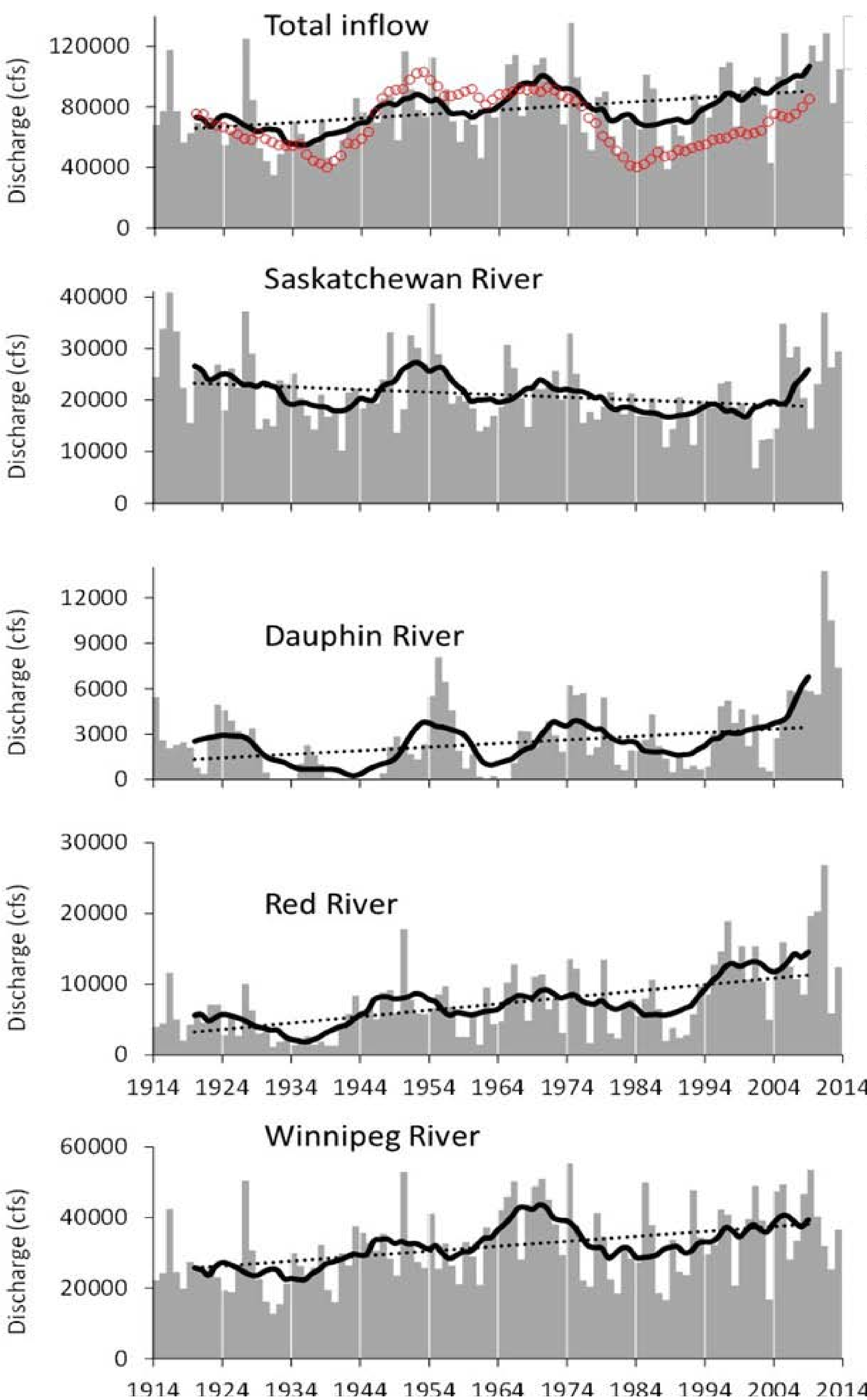

Figure 6. Annual mean discharge (grey columns) and 10-y running mean discharge (solid black line) records for the four major Lake Winnipeg tributaries. Upper panel shows the total inflow (solid black line) and the inverted Pacific Decadal Oscillation (PDO, red circles) climate index. Dashed lines indicate the apparent linear trend over the period 1914–2013.

Inter-annual and multi-decadal variability

At the scale of decadal mean discharge, since 1914 there have been four relatively wet periods separated by three drier ones as indicated by total inflow to Lake Winnipeg (Figure 6). Drier periods have recurred at 20–30 year intervals in the 20th century; the last of these was in the late 1980s/early 1990s—about 25 years ago. Although at the scale of the Lake Winnipeg watershed, true droughts tend to be local events, these have apparently been sufficiently in phase across Lake Winnipeg tributary watersheds that the total inflow retains multi-decadal patterns in the discharge of individual major tributaries. The strong coincidence of a similar pattern in the Pacific Decadal Oscillation (PDO) suggests that hemispheric-scale forcing underlies this pattern (upper panel in Figure 6).

The PDO index describes a pattern of sea surface east-west differences of sea surface temperature in the Pacific Ocean with a period of the order of 20–30 years. Numerous studies have linked inter-annual and multi-decadal variability in North American climate with Pacific Ocean climate (e.g. Latif and Barnett, 1994; Gershunov et al. 1999; Nigam et al., 1999). That is very much how one might interpret the relationship between total Lake Winnipeg inflow and the PDO illustrated in the top panel of Figure 6. With the PDO inverted, local maxima in the early 1950s and 1970s, and minima in the late 1930s, early 1960s and mid-late 1980s approximately match corresponding wet and dry phases in the pattern of inflow to Lake Winnipeg. The PDO has been falling since about 1984, and flow into to Lake Winnipeg increasing.

This relationship puts quasi-periodic oscillations of discharge in tributaries of Lake Winnipeg clearly in the domain of a well-known, but poorly understood drought cycle common to the Canadian Prairies and the United States western plains. Unfortunately, it may be of little value as a predictive tool. Indeed, in one study, Newman et al. (2003) argue that the PDO, and the interactions of the PDO with the better known El-Nino Southern Pacific Oscillation, are essentially unpredictable. While this may not forever be the case, apparently it is so for the time being.

However, whether the watershed is in a wet or a dry phase is not a reliable indicator of the total annual inflow in any individual year. Certainly, the highest annual mean tributary discharges have all occurred in wet periods, but a low inflow year can occur in even the wettest periods. The 3rd lowest total annual inflow to Lake Winnipeg occurred in 2003, when the watershed was well into a sustained high flow period. That is, although through the 20th century one could count on a series of mostly high flow years continuing through a decade or so, one could never have predicted the next year's discharge with great certainty.

Long term trends

Dotted lines in Figure 6 show linear discharge trends over the century. Determining the significance of these trends is beyond the scope of this report. However, there are published statistical analyses of discharge trends for several of the Lake Winnipeg tributary watersheds.

St. George (2006) demonstrated that at stations in the Winnipeg River watershed, increasing discharge over the century was significant for both regulated and unregulated tributaries—meaning that the change was unlikely to be due to regulation. He concluded that annual mean discharge in the watershed had increased by 58% from 1924 to 2003, and that this was driven by statistically significant increases in the months of November through April (60–110% increases, $p = 0.05$). He found no significant changes in the summer months.

Studies by Novotny and Stefan (2007) and Ehsanzadeh *et al.* (2011) both demonstrate that discharge the Red River at Emerson has increased significantly since early in the 20th century—Novotny and Stefan for the period 1913–2002, and Ehsanzadeh *et al.* for the period 1913–2008. At Emerson, the average discharge of the Red River over the last two decades (1994–2013) was more than 3X the discharge in the first decade of record (1912–1921). In fact, it was 80% higher than in any 20-year period ending before 1994. Ehsanzadeh et al. (2011) also studied the record Assiniboine River and concluded that it showed no significant trend in century long record of annual mean flows. It is likely, then, that the significant trend in Red River discharge is due mainly to increased runoff in the watershed south of Winnipeg. In this interpretation, the very high Assiniboine River discharge in 2011 remains anomalous, at least for the time being.

In contrast to the Winnipeg and Red Rivers, in the last decade of the 20th century, the mean discharge of the Saskatchewan River was 33% lower than the average over the first decade of record (1912–1921). However, the 4th and 5th highest flow years on record (2011 and 2005 respectively) have occurred since then. Altogether, the period 2005 to 2013 includes 6 years in the top 22 flow years on record. Thus, the apparent downward trend observed through the 20th century, while not reversed, has certainly been reduced by high flows in this century.

Most of the Saskatchewan River's discharge is generated in Alberta. In a study for Alberta Environment, Seneka (2004) found that the decrease in discharge of the North Saskatchewan River was significant over the century. However, in the South Saskatchewan watershed there is only weak evidence of climate-forced decreases in river discharge. A recent Alberta study calculated that 30% of the median natural flow in the South Saskatchewan watershed was lost annually due to reservoir operations, irrigation and other such operations (AMEC 2009). After "naturalizing" flow to correct for these increases in consumptive use, Seneka (2004) found no additional significant decrease in discharge in the century-long record at in the South Saskatchewan River at Medicine Hat. On the other hand, in an attempt to distinguish climate forcing from consumptive use, Rood et al. (2005) selected headwater stations with minimal upstream human impact, and found significantly decreasing discharge in near century-long records for 4 of 5 South Saskatchewan River tributaries.

In summary, the discharges of the Winnipeg and Red Rivers have been demonstrated to have increased significantly since early in the 20th century. In contrast, the annual discharge of the Saskatchewan River has decreased, although the trend has been interrupted by some very high flows in the last few years. While the increasing discharge in the Winnipeg and Red Rivers is associated with changing climate, or specifically with significantly increased precipitation over the watersheds since the early 20th century, climate is only part of the explanation for decreasing flows in the Saskatchewan River. Losses to irrigation and other consumptive uses has contributed measurably. Although there is some evidence of a long term increase in discharge of the Dauphin River into Lake Winnipeg (Figure 6), to my knowledge, no statistical analysis of this trend has been published. In total, the inflow to Lake Winnipeg has increased through the century, though the change has clearly not been linear. Rather, there have been a series of relatively high flow periods separated by drier periods, with the peak decadal mean flow in each high flow period exceeding the last. The historical record begins and ends in two of the wetter periods. The peak decadal mean inflow so far in the current one is 107,000 cfs, almost 50% higher than the peak of 73,000 cfs in the relatively wet period at the beginning of the 20th century.

Relative contribution of the major tributaries

Due to differing trends in annual discharge, the relative contribution of the four major tributaries to Lake Winnipeg has changed through the period of record. Of the four, the Dauphin River contributes least inflow, averaging 3% over the century (Table 3). Two of the highest annual inflow contributions, 9% in 1976 and 11% in 2011, are associated with diversion of water from the Assiniboine River through Lake Manitoba, although another, 9% in 1955, was not. Although contributions of the Winnipeg River to annual inflow to Lake Winnipeg ranged from 29–54% over the century, there has been no major trend; it averaged 36% of total inflow through the first two decades of the period of record, and has averaged 40% over the last two. On the other hand, the century-long decline in Saskatchewan River discharge has meant that its contribution to total inflow has dropped from an average of 37% over the first two decades of record down to 22% over the last two. This was roughly balanced by the increase in Red River discharge, from 7% through the first two decades to 14% through the last two.

Table 2. Relative (%) annual discharge contributions of the four major tributaries to inflow to Lake Winnipeg from 1914–2013.

	Saskatchewan River	**Dauphin River**	**Red River**	**Winnipeg River**
Mean	28	3	9	40
Minimum	7	0.1	2	29
Maximum	49	9	19	54

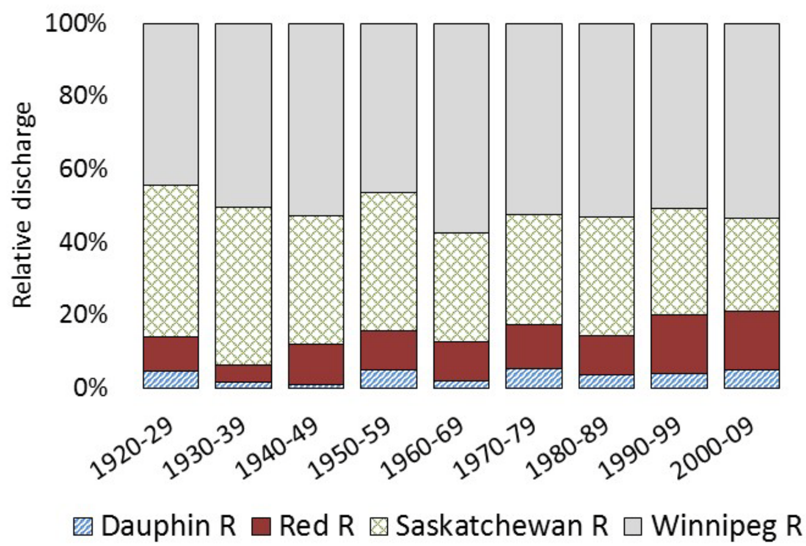

Figure 7. Relative (%) decadal discharge contributions of the four major tributaries to inflow to Lake Winnipeg from 1914–2013.

Winds

Winds superimpose abrupt changes on average lake level, whether or not the lake is regulated. In the case of Lake Winnipeg, persistent northerly or southerly winds drag water away from the upwind end of the lake, and pile it against the downwind end. The resulting short-term (hours or days) increase in water level at the downwind end of the lake is called setup.

It is well understood that setup in the south basin of Lake Winnipeg is caused by sustained northerly wind events. Setup in Lake Winnipeg has been modeled as a function of wind energy and basin geometry by both Einarsson and Lowe (1968) and Hamblin (1976). The relationship is demonstrated graphically in Figure 8 which shows increasing southward inter-basin flow with increasingly strong antecedent northerly winds. Southward winds of 20–25 mph (32–40 km/h in Figure 8) sustained for 24 h would force an average flow of 350,000 cfs (10,000 cu m/s in Figure 8) southward through the Narrows. They would raise the 3980 km^2 south of the Narrows by an average of 0.7 ft. The extreme value at the lower right of Figure 8 represents a one day increase in mean water level at Gimli of 1.7 ft forced by sustained 35 mph winds from the north. Because the south basin itself would be tilted from north to south, a 1–2 ft increase in daily mean level measured at Gimli may manifest as a setup of 4 or more feet at the south shore.

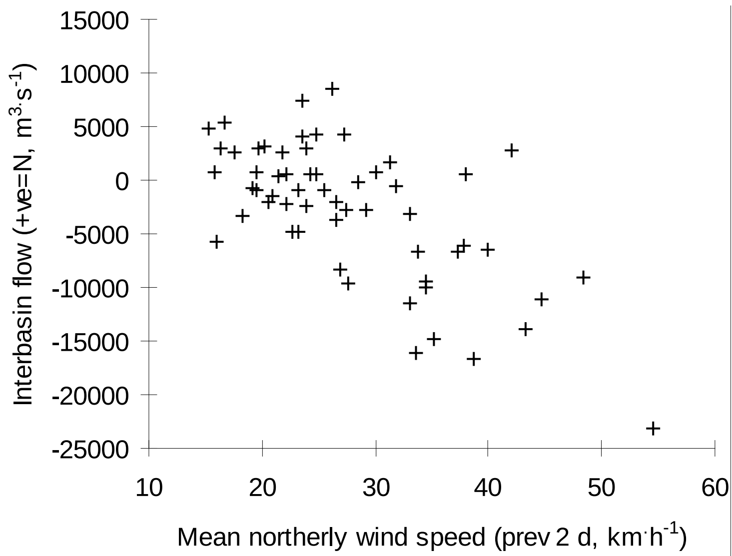

Figure 8. Flow through the Lake Winnipeg Narrows as a function of northerly winds. Flow was calculated as the product of daily changes in the level of the south basin X the area of the south basin. Wind speed is the average over the two days previous to the flow. Data is shown only for events when the mean 2-day antecedent wind direction was between 330^o-30^o (i.e. northerly). (Reproduced from McCullough, 2001).

Analyses of century-long wind records are fraught with uncertainty due to changing instrumentation through time. They may also be affected by poorly recorded changes near anemometer towers, including construction or demolition of buildings nearby, relocation of towers to avoid effects of such construction, or growth or clearing of adjacent forest canopy. In relation to wind effects on Lake Winnipeg, where the overarching concern with wind is how it may superimpose setup on the average water level it is more practical to analyze the record of the effect—setup—rather than of the cause—winds.

In Figure 9, long term daily mean lake level records are used to examine century-long trends and variability in setup. Specifically, a setup event is defined for this purpose as a water level increase of one foot or more compared to the median level over the previous week, recorded at Gimli (July 1966–present) or Winnipeg Beach (1914–July 1966). For clarity, setup so-defined will be referred to as "daily mean setup". While this century-long record of abrupt increases in daily mean water level can be used an index of frequency, trends and variability in setup, it underestimates both the range from trough to peak in the hourly level record, and the peak level achieved during each setup event. Figure 9 shows hourly and daily observations from a sample water level record. Peak hourly water levels generally ranged from a few inches to a little over a foot higher than peak daily levels. Finally, the record at Gimli also underestimates peak levels farther south in the basin, and especially along the south shore.

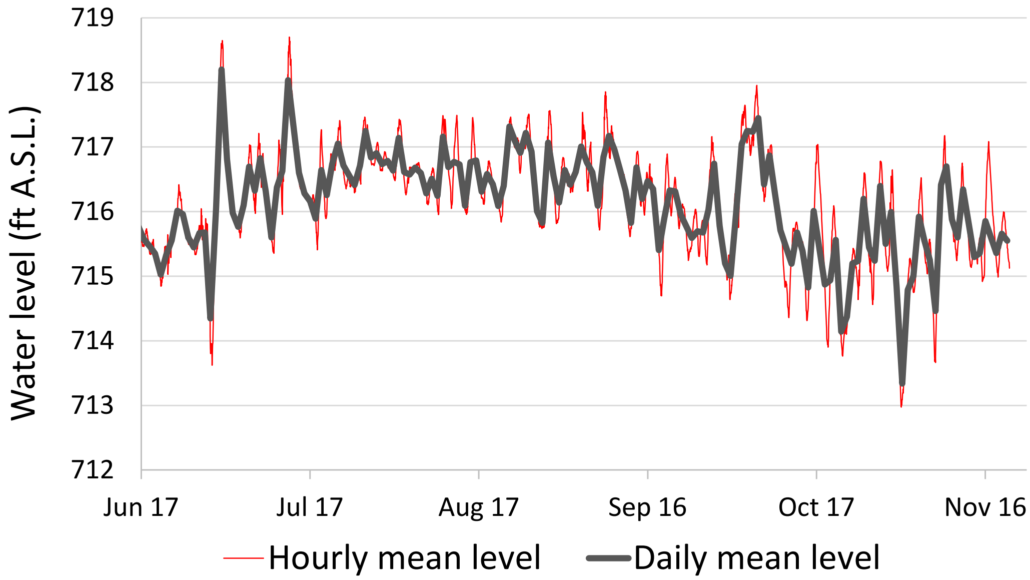

Figure 9. Hourly and daily mean water level recorded at Gimli from June 17 to November 20, 1914.

There was an average of 11 daily mean setup events >1 ft each summer from 1920 to 2010. About two-thirds of these occurred in autumn and this distribution does not appear to have changed throughout the century (Figure 10). There were only 71 daily mean setup events > 2 ft over the whole 90 y record. Most of these also occurred in autumn, although there is more variability, and therefore less predictability, in the distributions of larger events. We can reasonably infer from this data that strong northerly winds are more frequent in autumn than earlier in the open water season, since these drive setup in the south basin. This supports the common perception that storms on Lake Winnipeg are more frequent in autumn than earlier in the summer. The similar distributions among the three 30-year averaging periods in Figure 10A indicates this has not changed over the last century.

Since the early 20th century, the annual maximum setup in the south basin has decreased slightly, but the change is small compared to the inter-annual variability (Figure 11). The frequency of daily mean setup events > 1 ft has also decreased, but also only modestly, from about 10/year early in the 20th century (except for the first five years which are anomalously high compared to the rest of the record) down to about 8/year in the first decade of this century. The record is marked by multi-decadal variability similar to that seen in precipitation records for the watershed. This presumably reflects oscillations between one- to two-decade long periods with more and less frequent strong wind events.

Since setup events in the south basin are caused by persistent, strong northerly winds, they are accompanied storm waves capable of eroding banks and damaging structures along the shore. The most destructive storms result when high setup is superimposed on already high water. The lake was higher than average in both the 1970s and 2000s, but on average, fewer and smaller than average setup events added to these high levels. On the other hand, in the 1950s, high water was accompanied by a high frequency of relatively high setup events. Overall, though, there is no obvious shared historical pattern or trend in windiness and high water.

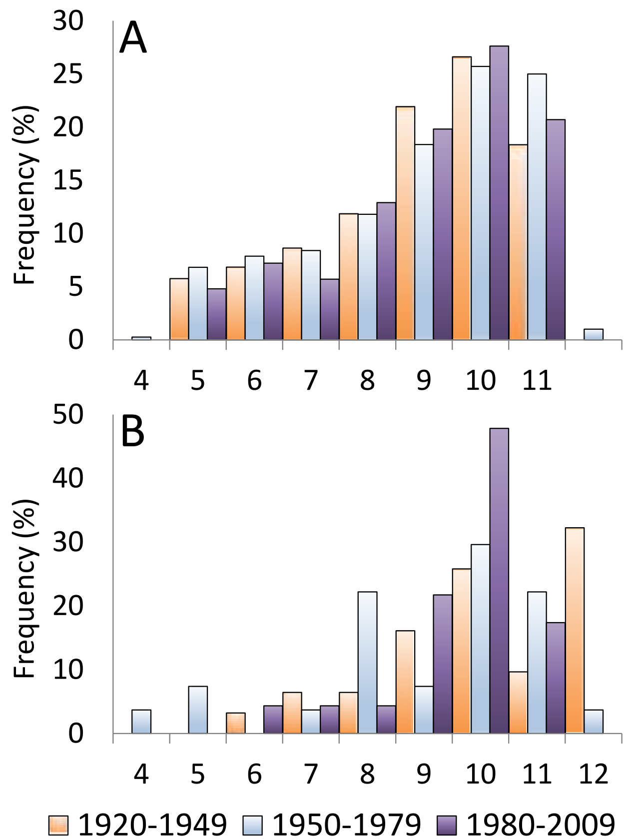

Figure 10. Monthly frequency of setup events in the south basin of Lake Winnipeg, where a setup event is defined as an increase from one day to the next of >1 ft (B) and >2 ft (C) in the daily mean level of the south basin of Lake Winnipeg at Gimli (or before 1966, at Winnipeg Beach). Months: 4 = April to 12 = December.

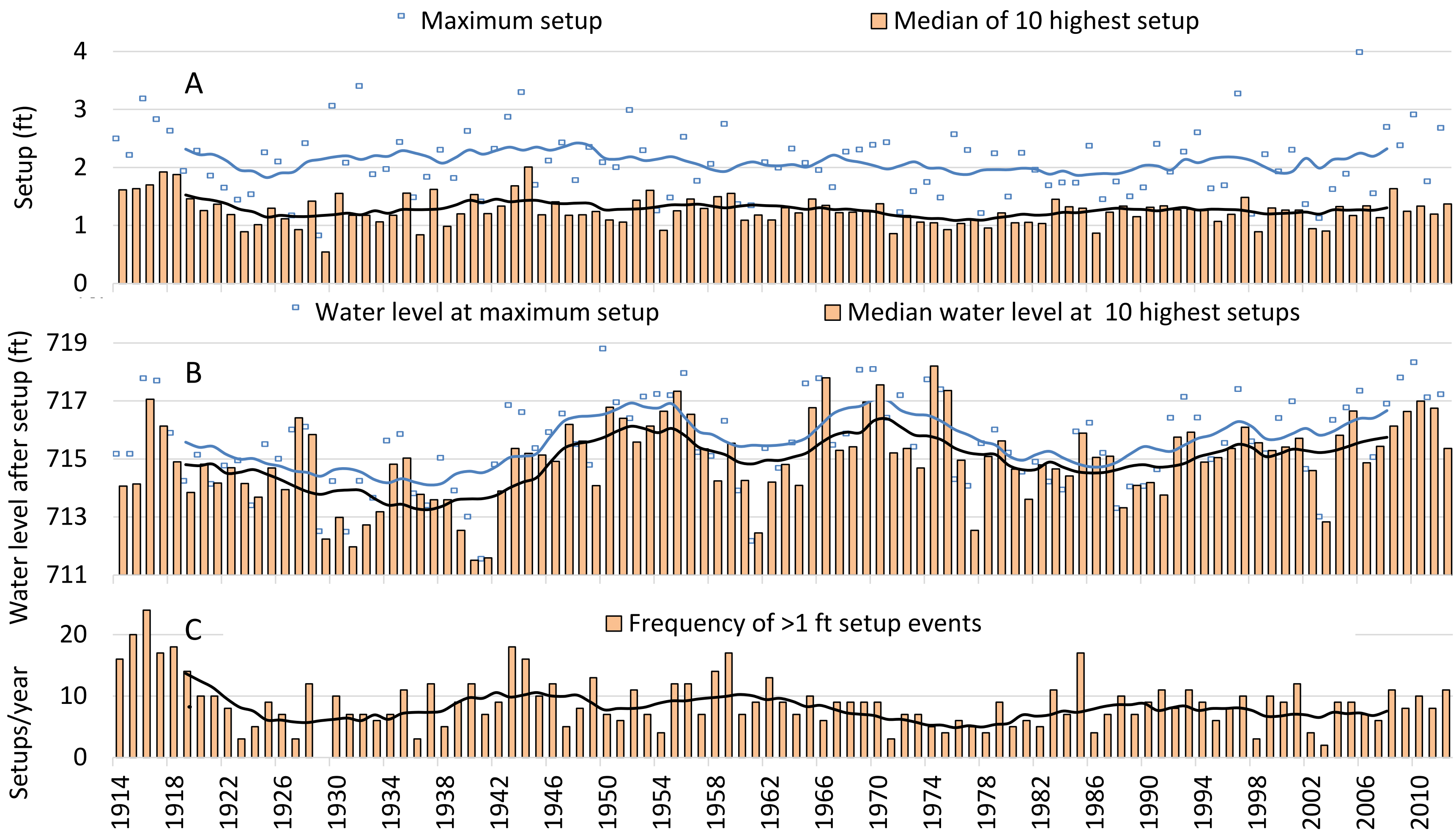

Figure 11. A. Setup events as indicated by daily change in water level recorded at Gimli (or at Winnipeg Beach before 1966). Each setup event is defined as the increase in daily mean water level compared to the median water level through the previous week. Both the highest annual setup and the median water level increase for the 10 largest setup events each year are shown. B. Water level at Gimli on the date of each setup event recorded in panel A. C. Frequency of setup > 1 ft above the previous weekly median water level. Solid lines are 10-year running means; dotted lines are linear trends.

Modeled 21st century climate

Temperature

Twenty-first century monthly mean water temperature for Lake Winnipeg was modeled by McCullough (2011) using output from version 3 of the Canadian Global Climate Model (CGCM3) under a range of forcing emission scenarios developed by the Intergovernmental Panel on Climate Change. The scenarios selected describe evolution of greenhouse gas concentrations and aerosol loadings in response to varying population growth, economic development and technological change over the next century. Under the strongest forcing scenario, the CGCM3 predicts that mean midsummer air temperature over Lake Winnipeg will increase by 2.4^{o}C over the first half of the 21st century and another 2.0^{o}C in the second half of the century. Under the weakest forcing scenario, it predicts a mean midsummer increase almost as great in the first half of the century, 2.0^{o}C, but only 0.3^{o}C more in the second half.

Under any of the modeled forcing scenarios, midsummer surface water temperature would rise in Lake Winnipeg by 1.9–2.5^{o}C in both basins through the first half of this century (McCullough 2011). Under the strongest forcing scenario, they would rise a further 2.0^{o}C by the late 21st century; with reduction of fossil fuel use, only a further 0.5^{o}C. Such warming is predicted to advance breakup by 4–6 days in the south basin, and a week in the north, by the mid-21st century. By the end of the century, it would be about week and a half earlier in the south, and two weeks earlier in the north. Ice would form almost a week later in both basins by the mid-21st century, and as much as two weeks later by the end of the century.

One of the most comprehensive studies to date of the vulnerability of Canadian society to climate change was published by Natural Resources Canada in 2009. The study utilized output from seven global climate models forced by seven greenhouse gas emission scenarios set out by the International Panel on Climate Change. These scenarios range from a 21st century in which there is global conversion to predominantly non-fossil fuels to a fossil fuel intensive future, with various scenarios representing different assumptions about variables such as population growth and economic indicators. It is currently considered best climate forecasting practice to acknowledge these many uncertainties by considering the median and range of output of multiple models and scenarios.

In a chapter contributed to this National Resources Canada study, Sauchyn and Kulshreshtha (2009) discuss climate change in the Prairie Provinces. They predict median temperature increases over the Lake Winnipeg watershed of about 3^{o}C by the 2050s and 5^{o}C by the 2080s. These are somewhat higher than the ranges predicted by McCullough (2011) and would develop modestly higher mid-summer lake temperatures, as well as a longer open water period than was predicted in a single model (CGCM3) three-scenario study.

Table 3. Temperature (^oC) and precipitation (%) changes predicted for grasslands and forest regions in the Canadian Prairie Provinces. (After Figures 8a and 8b in Sauchyn and Kulshreshtha 2008).

		Temperature		Precipitation	
		Grasslands	Forest	Grasslands	Forest
Winter	**2050s**	3.8	3.9	13	16
Spring	**2050s**	3.2	2.8	17	12
Summer	**2050s**	3.1	2.8	-4	4
Autumn	**2050s**	2.8	2.7	2	8
Annual	**2050s**	3.2	2.8	5	11
Annual	**2080s**	5	4.8	11	12

Precipitation

For the grasslands regions of the Prairie Provinces, Sauchyn and Kulshreshtha (2009) predict a 5% increase in precipitation by the mid-21st century, and 11% by the 2080s. For the forested regions they predict a large increase earlier, 11% by mid-century (Table 3) with little further change thereafter. However, they predict larger increases in winter and spring in both regions—12–16% by mid-century, with smaller or negative changes in summer and autumn.

Winter snowmelt and spring rains contribute disproportionately to annual flow of streams in northern latitude, plains watersheds, that is, in Lake Winnipeg tributary streams. Over the century, April-May discharge has contributed 40–60% of the annual discharge of the Red River. The spring freshet contributes even more of the annual discharge in smaller streams—a long term average of 70% in the La Salle River, southwest of Winnipeg, for instance. Consequently, large increases in winter and spring precipitation in the future may supply larger total flow to Lake Winnipeg in spite the smaller or even negative change in summer and autumn precipitation.

Runoff and river discharge

Figure 12 shows global runoff predicted for the mid-21st century (Milly et al., 2005). The watershed of Lake Winnipeg straddles a boundary between higher mid-21st century precipitation to the east and north, and lower to the southwest. Milly et al. (2005) predict an average 5–20% increase in a band stretching from the Winnipeg River watershed across Lake Winnipeg into the Pas region in northern Manitoba. Over most of the Assiniboine and Saskatchewan River watersheds, they foresee no change, with as many models predicting reduced runoff as not.

In general, local model studies show a similar pattern, except that increased runoff may be more widespread, reaching westward at least as far as the Assiniboine River watershed. From predicted warmer and shorter winters, Sauchyn and Kulshreshtha (2008) infer reduced snow accumulation and, because prairie streams are dominated by the spring freshet, less runoff as well. They argue that in larger rivers, continued glacial retreat will also reduce summer and autumn flow. Pomeroy et al. (2009) report that climate change will reduce flow of the South

Saskatchewan at Lake Diefenbaker by 8.5% by the 2050s, though the ensemble of models tested gave predictions ranging from an increase of 8% to a decrease of 22%. In the model, average decreases in the foothills tributaries were partially compensated by runoff increases in the prairie.

This is at odds with other runoff modeling results. Clair et al. (1998) used hydrological models to predict that a doubling of carbon dioxide in the atmosphere would cause a 117% increase in average runoff over the Prairies, although they did caution that model validation was not as successful for prairie watersheds as for other ecosystems in Canada. However, a more recent study returned similar figures for two prairie watersheds. Shrestha et al. (2012) used hydrological modeling of output from four global climate models to predict a 15–60% increase in runoff driven by an 11–17% increase in precipitation over the upper Assiniboine River watershed in eastern Saskatchewan, and a 9.2–46% increase in runoff driven by an 6.6–14% increase in precipitation over the Morris River watershed southwest of Winnipeg.

This may in part be because winter snowmelt and spring rains contribute disproportionately to annual flow of streams in northern latitude, plains watersheds, that is, in Lake Winnipeg tributary streams. Over the century, April-May discharge has contributed 40–60% of the annual discharge of the Red River. The spring freshet contributes even more of the annual discharge in smaller streams—a long term average of 70% in the La Salle River, southwest of Winnipeg, for instance. Contrary to the argument of Sauchyn and Kulshreshtha (2008) large increases in winter and spring precipitation in the future may supply more total flow to Lake Winnipeg in spite of the shorter snow accumulation time, and the smaller or even negative change in summer and autumn precipitation. This would help explain the increasing runoff through the coming century predicted by Clair et al. (1998) and Shrestha et al. (2012).

These may seem to be very great increases in runoff given the modest predicted precipitation change. However, consider that in a prairie watershed, a one inch rain after a long dry spell may be absorbed into the soil or fill local, ephemeral wetlands, and have little effect on downstream flow, while runoff from the same one inch of rain in a wet year, with soil saturated and wetlands brimming, may swell the same stream to flood stage. Figure 13 shows river discharge as a function of precipitation for western and eastern tributaries of the Red River, and the southern and northern reaches of the Winnipeg River watershed. Annual mean river discharge and annual precipitation were re-grouped into consecutive 3-year means to minimize variability due to unknown differences in storage. Following the trend line for the eastern tributaries of the Red River, for example, a 20% increase in precipitation in the watershed, from 550 to 660 mm/y, more than doubles stream flow, from 50 to 110 mm/y. This result is not unfamiliar to hydrologists. Rannie (1998) referred to two studies that show the effect of such disproportional response to increasing precipitation—one in Wilson Creek (on the Manitoba escarpment) where 10-20% increases in precipitation resulted in 57–90% increases in stream flow, and another for the Souris-Red-Rainy River region (the U.S. portion of the Lake Winnipeg watershed) where a 10% increase in precipitation produced a 68% increase in stream flow.

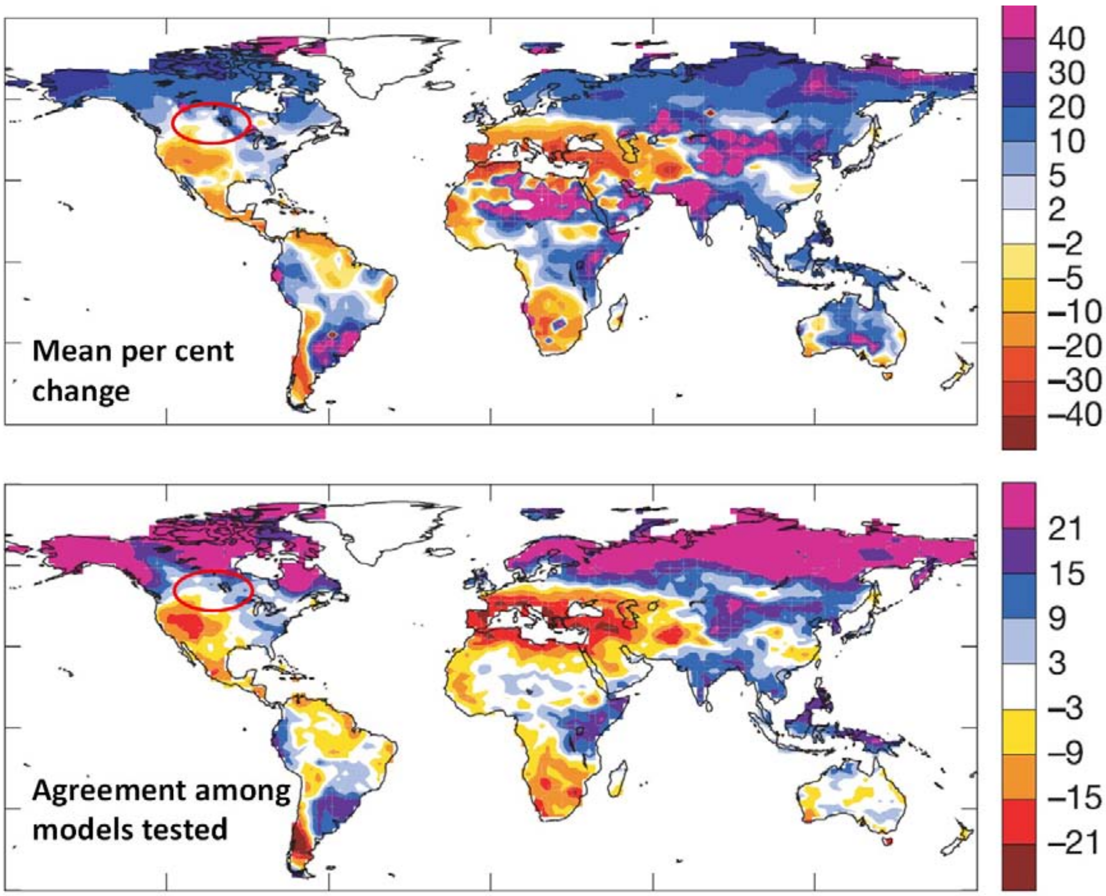

Figure 12. Percent change in runoff in 2041–2050 compared to average runoff from 1900–1970. Lake Winnipeg watershed is indicated by red ellipses. 21 climate scenario/climate model ensembles were run; the agreement among models is the number of combinations that predicted increases minus the number that predicted decreases. Reproduced from Milly et al. (2005).

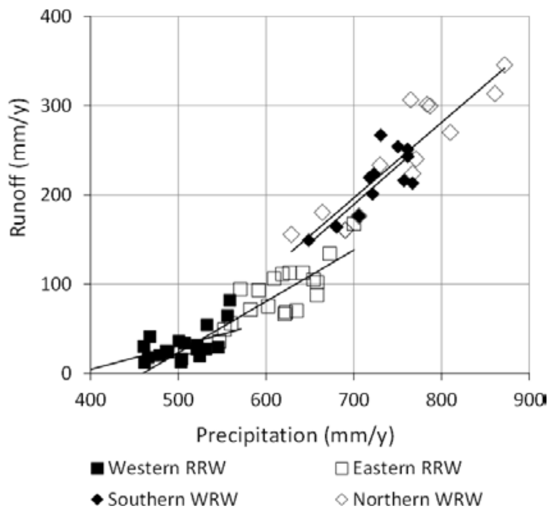

Figure 13. River discharge response to precipitation in the eastern and western Red (RRW) and southern and northern Winnipeg River (WRW) watersheds. Discharge is expressed as mm depth equivalent over the watershed. Points are consecutive 3-year averages of precipitation and discharge, to minimize the effect of storage changes in each watershed.

Lake level

Over the last century, Lake Winnipeg has gone through three extended relatively low water periods. The two lowest years on record occurred in 1941 and 1942 (Figure 14). They were preceded a few years earlier by the three next lowest years, 1930, 1931 and 1932. These years bracket the driest decade on record for both the Winnipeg and Red River watersheds (Figure 6). In high water periods between dry spells, the lake rose to successively higher decadal mean levels—in the late 1910s/early 1920s, late 1940s/early 1950s, and late 1960s/early 1970s. The two highest years on record, 1974 and 1972 fall in the highest flow decade for the Winnipeg River watershed, and the 2nd highest in the Red. These two southeastern watersheds have supplied roughly half the total inflow to Lake Winnipeg over the century, so that multi-decadal climate patterns there tend to drive the multi-decadal patterns in lake level record. However, although the current decade (the fourth high water period in the century) has seen the highest decadal mean inflow on record (Figure 6), this is not the highest decade on record in terms of water level (Figure 14). The decadal mean level from 2002–2011 was 713.99 ft MSL. Without regulation, it would have been 715.1 ft ASL, just 0.1 ft less than the peak decadal mean level in the early 1970s, and over 2 ft higher than the decadal mean level at the beginning of the period of record—713.0 ft ASL from 1913–1922.

Nielsen (1998) estimated that the water level of the south basin of Lake Winnipeg is rising about 0.7 ft/century due to differential isostatic rebound.*[1] That is, as much as 0.7 ft of the 2 ft increase in unregulated decadal mean level of the lake since the early 20th century can be accounted for by a geological process. As will be shown below, the remaining increase of roughly a foot and a half can be ascribed to higher runoff from the watershed, a climate-driven process.

In spite of swings between periods of predominantly high or low inflow from the watershed, and resulting periods of predominantly high or low water levels, individual low inflow/low level years can occur anytime in the record. For example, as previously mentioned, in a period when the total inflow to Lake Winnipeg was approaching the record high decadal mean, the inflow to the lake in 2003 was the 3rd lowest on record. As a direct consequence, the peak water level reached in 2003 was the 5th lowest on record (Figure 14).

*[1] Isostatic rebound is the elastic rise of the earth's crust after being depressed by the weight of continental glaciers. Because it is closer to the center of glaciation, rebound is faster at the outlet of Lake Winnipeg than at the south end of the lake. As the northern outlet sill rises relative to the south end, so lake water rises relative to the south shores. Because the Two Mile Outlet Channel is deeper than the natural outlet at Warren's Landing, the effect of differential rebound is removed as a factor determining lake level, in any reasonable future planning horizon.

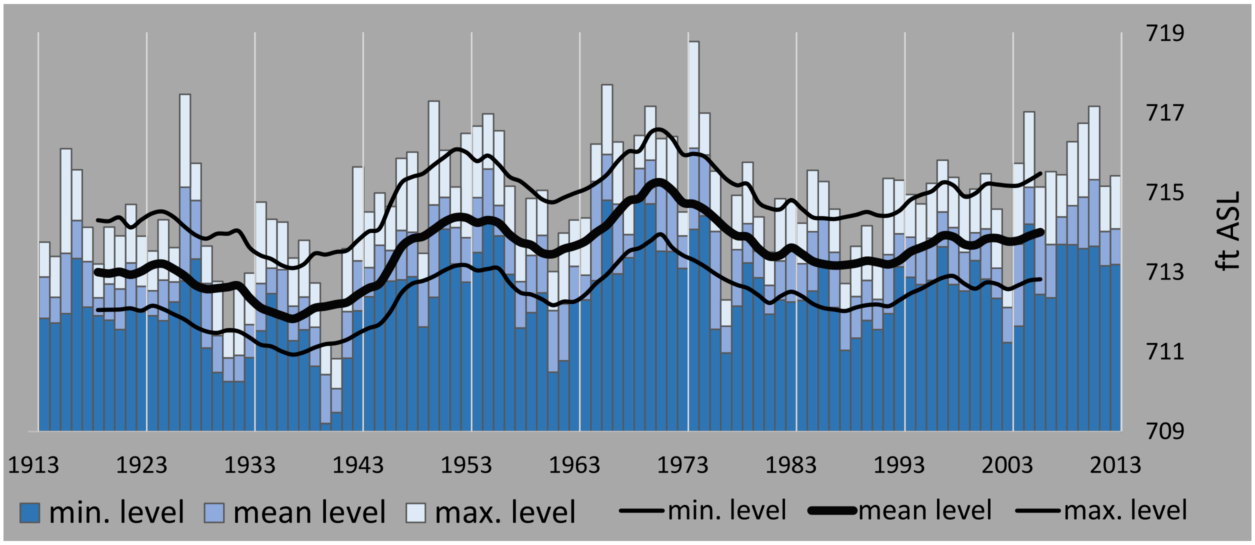

Figure 14. Annual and 10-year running minimum, mean and maximum water level in Lake Winnipeg. Calculated from averages of 3-day mean levels at two stations—Berens River and Gimli (or Grand Beach before 1966)—to remove the effect of wind setup in daily observations at individual stations.

One must also bear in mind that the seasonal range in a single year often exceeds the difference between-years within wet or dry periods, and between successive high and low water periods. The highest decadal average water level was only 3.4 ft higher than the lowest. Over the century-long record, the seasonal range (here defined as the difference between annual maximum and minimum levels, with setup excluded from the record as described elsewhere in this document) has averaged 0.8 ft, and has been as high as 4.9 ft. There is only a weak overall correlation between total inflow and annual lake level range, but in the period before lake level regulation, the 3 greatest intra-annual seasonal ranges, all greater than 4.6 ft, were recorded in the three highest total inflow years, 1974, 1927 and 1950 (in descending order of total inflow; Figures 7 and 14). Although regulation has tended to constrict seasonal variability in water level, the greatest intra-annual range since 1978 is still a considerable 4.1 ft (in 2004, when the lake was recovering from very low water in 2003).

Although there is only weak correlation between the annual *mean* lake level and annual mean inflow, the annual *peak* lake level can be reasonably well-estimated as a function of the mean inflow in the previous year (which sets the late winter stage) and the peak inflow in the current year (which determines the rise in spring and summer). This is illustrated in Figure 15. Annual peak levels were determined for a lake level record with setup removed as described in the methods section. "Estimated peak lake level" was determined by a polynomial regression on 1) the mean inflow for the 12-month period from April of the previous year to March of the current year, and 2) the highest monthly mean inflow in the current year. Estimated peak levels are compared with observed peak levels in Figure 14. For the pre-regulation period (1914–1971) for years with no missing days in the level record, the polynomial regression estimates 90% of the variance in observed annual peak lake level ($r^2 = 0.90$, $p = 0.000$, $n = 24$). Below 715 ft MSL, the regression estimates peak level as accurately for regulated (1978–2013) as for unregulated (1914–1971) conditions, indicating that below 715 ft MSL, regulation has had little effect on peak levels. However, due to the operating license requirement to maximize outflow when necessary to maintain maximum levels below 715 ft MSL, regulation clearly reduced what would have been higher peak lake levels at least for those years with estimated peak levels near or above 716 ft MSL (to the right of 716 ft MSL in Figure 15). The two points on the far right represent 1997 and 2011, in the summers after the 12th and 11th highest April-to-March inflow on record, and during the years with the 4th and 3rd highest monthly inflow, respectively. Without regulation, it is likely that the lake would have peaked at 718 ft MSL in 1997 and again in 2011, almost a foot higher than it actually peaked in 2011 (upper square at right in Figure 15), and two or more feet higher than it peaked in 1997 (lower square at right).

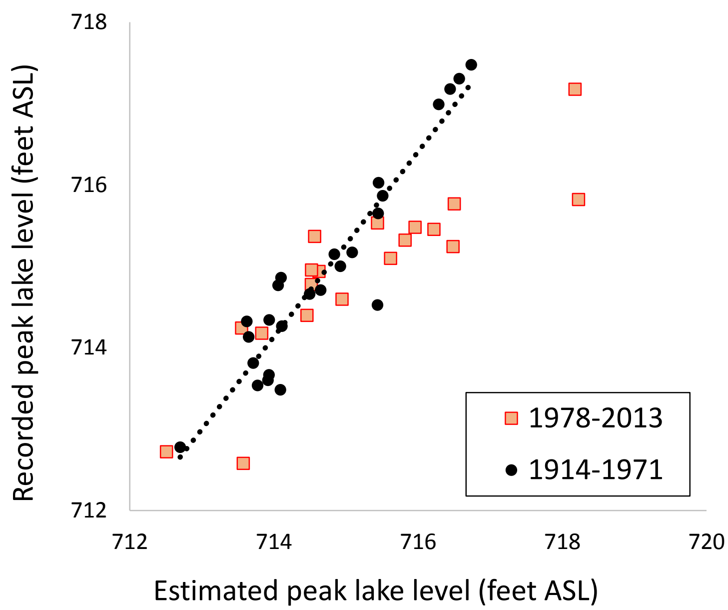

Figure 15. Influence of inflow on annual peak lake level. Points represent setup-free levels as described in the methods section. "Estimated peak lake level"s were estimated from inflow data as described in the text.

Figure 16 compares the observed record of water level in Lake Winnipeg with levels modeled using the record of monthly total inflow to the lake and a constructed record of monthly outflow. Outflow was determined using stage-discharge curves for the natural, Warrens Landing outlet that are readily calculated using pre-regulation lake level and Nelson River discharge records. Details are described in McCullough et al. (2102). In Figure 16, annual mean historical level and modeled, unregulated level are indicated by heavy grey and red lines, respectively. Two pairs of lines bounding the annual means indicate the range due to seasonal, intra-year fluctuations in the setup-free record, and the potential effect of setup superimposed on the setup-free level record in the south basin. Variability is defined as 2X the annual standard deviation of setup-free daily levels for each year, measured at two stations—Berens River, and either Gimli or Winnipeg Beach. The additional range due to setup in the south basin is defined as the setup-free variability plus/minus 2X the standard deviation of daily setup as described elsewhere in this document. Because setup is defined as the difference between the daily mean level and the median level in the preceding week, it may be either positive or negative, and thus also defines a lower bound to the range of probably levels.

There are two approximations underlying Figure 16. First, confidence limits for prediction of the mean are not shown. 95% confidence bounds on the modeled lake level are roughly ±0.9 ft (S.E. = 0.41 ft, n = 144, based on estimated-minus-observed monthly mean water levels for a selected pre-regulation period, 1960–1971). It must be understood that the bounds shown in Figure 16 indicate potential, not real annual maxima and minima. The outlet stage-discharge curve used to model the annual mean level of the lake is based on pre-regulation records of monthly mean levels and discharges, and is not sufficiently precise to make useful estimates of weekly mean water levels, let alone daily means. The method based on historical variation of weekly mean levels and of setup events was devised to put reasonable bounds around the modeled annual mean levels that would have obtained under unregulated conditions—i.e. the bounds shown in Chart B of Figure 16. These show potential maximum and minimum setup-free daily mean water levels, and potential maximum and minimum daily mean levels including setup in the south basin. They are based on the assumption that annual variability of weekly mean levels and of setup events would have been the same without regulation. This may be a conservative assumption with regard to intra-year variability of weekly mean levels, which are probably influenced by regulation, but it is very reasonable in terms of setup events, which are due entirely to winds and therefore independent of lake level controls at the outlet.

In any case, this method does appear to describe the range about the annual mean reasonably well compared to the historical record (Figure 16A; dotted lines show the annual maximum and minimum levels measured in the south basin). For example, the highest daily mean level since 1960, 719.51 ft MSL, recorded in late July 1974, was only 0.1 ft higher than the peak level of 719.41 ft MSL estimated as the sum of annual mean level + 2X the standard deviation of weekly mean levels + 2X the standard deviation of setup (see Figure 16A). The method underestimates the minimum level in 2004, by over 1 ft. However, the lowest observed level over the period shown in Figure 16, is also reasonably represented: 710.05 ft MSL recorded in August 1977, compared with the estimated potential minimum level of 710.35 ft MSL (Figure 16A).

Figure 16 reveals that regulation has had distinct, different effects on annual mean lake level in relatively dry compared to relatively wet periods. In the drier 1980s/early 1990s, the annual mean lake level tended to be increased by regulation (Figure 16) and the seasonal peak was shifted from May or June to late summer or fall (Figure 17). In the wetter years since 1996, the annual mean level has tended to be reduced—by a foot or more since 2005—but the timing of the spring peak was not shifted.

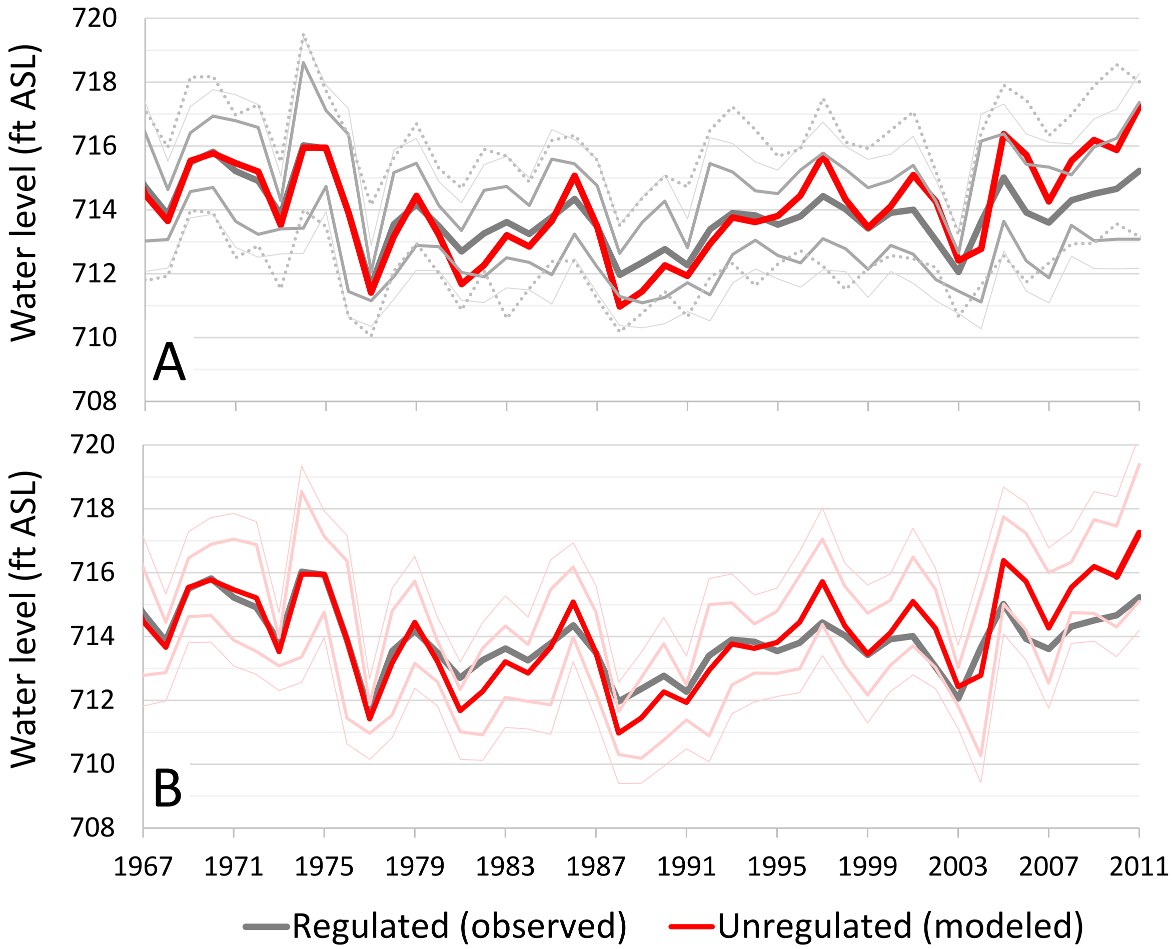

Figure 16. Historical and modeled, unregulated Lake Winnipeg annual mean levels. A: Historical, observed annual mean level (heaviest grey line) with potential maximum and minimum weekly and daily level, as defined elsewhere in this document, indicated by inner and outer lighter grey lines. Dotted lines show the observed annual minimum and maximum water level measured at Gimli (or Winnipeg Beach before 1966). B: Modeled, unregulated levels with potential maxima and minima indicated as in Chart A.

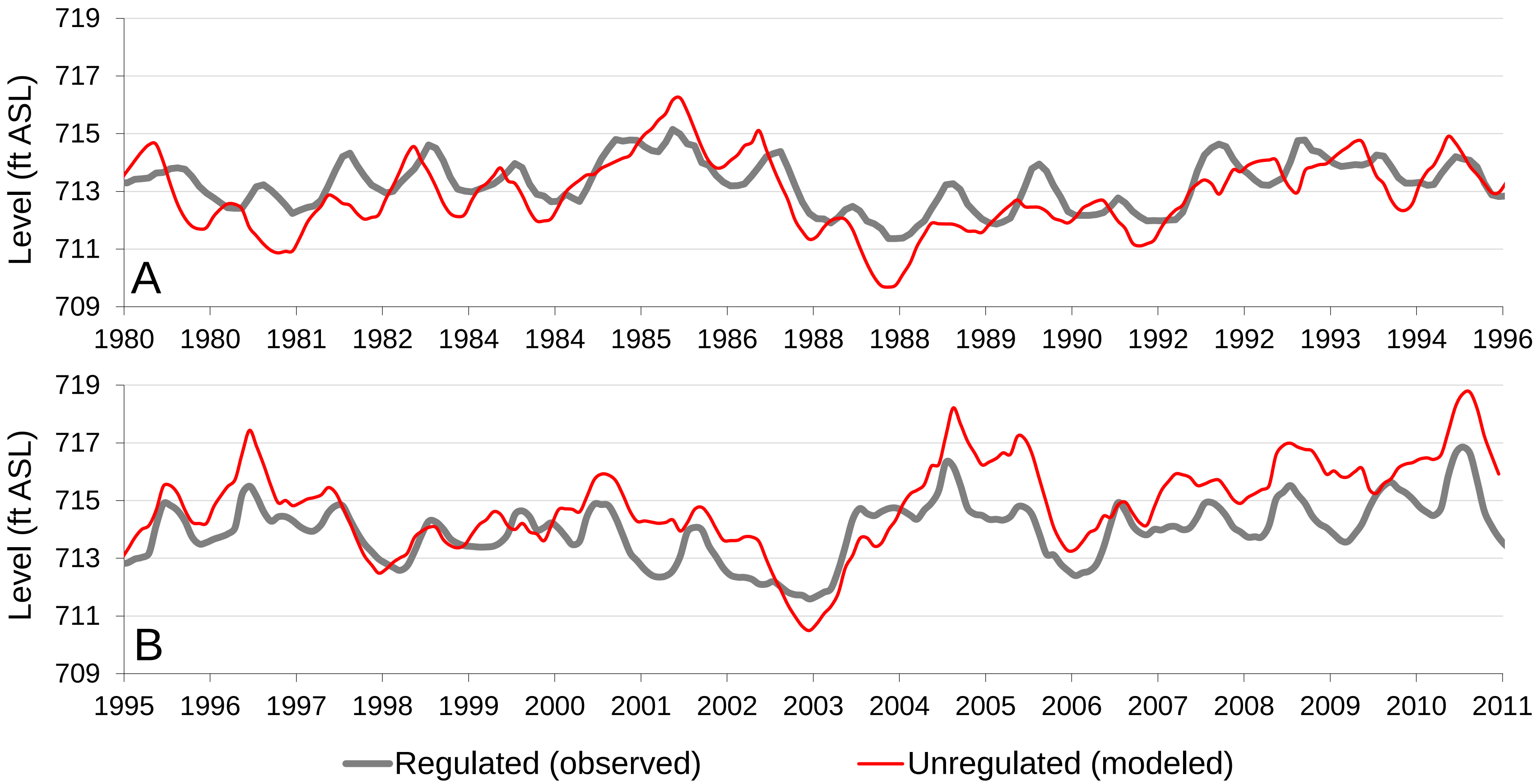

Figure 17. Historical and modeled, unregulated Lake Winnipeg monthly mean levels.

By the terms of annually renewed interim licenses, Lake Winnipeg has been operated as a multi-use reservoir. Manitoba Hydro has been licensed manage outflow and lake levels, within the range of 711 to 715 ft MSL, to store water as needed from the spring or early summer peak, when electricity demand is relatively low, and release it through the following winter, when demand is higher. Whenever water levels exceeds 715 ft, they are required to maximize outflow until the level returns to the licensed range.

Both precipitation and tributary discharge are at or nearing century-long peaks in the southeastern watershed of Lake Winnipeg, as is the total tributary inflow to the lake. We may be in the midst of one of several 10–20 year wet periods in the century-long climate record, in which case we may soon return to drier conditions in the watershed and lower water supply to the lake. If so, then it may return to the lower level regime that characterized the 1980s, with few water level excursions beyond 715 ft MSL. However, both historical, 20th Century climate trends and predictions from climate change literature indicate that inflow to Lake Winnipeg is likely to increase through the 21st Century. Historically, each succeeding wet period has generated higher decadal mean total inflow into Lake Winnipeg. If we entering an era of gradually increasing precipitation and runoff from the watershed, it will become increasingly difficult to maintain the lake below 715 ft MSL.

References

AMEC Earth and Environmental. 2009. South Saskatchewan River Basin in Alberta Water Supply Study. Prepared for Alberta Agriculture and Rural Development.

Clair, T.A., J. Ehrman and K. Higuchi. 1998. Changes to the runoff of Canadian ecozones under a doubled CO2 atmosphere. Canadian J. of Fisheries and Aquatic Sciences 55:2462–2477.

Ehsanzadeh, E., van der Kamp, G., Spence, C. 2011. The impact of climatic variability and change in the hydroclimatology of Lake Winnipeg watershed. Hydrol. Process. DOI: 10.1002/hyp.8327.

Einarsson, E. and A.B. Lowe. 1968. Seiches and setup on Lake Winnipeg. Limnology and Oceanography. V.13, No.2, p.257-271.

Gershunov, A., T. Barnett and D. Cayan, 1999: North Pacific interdecadal oscillation seen as factor in ENSO-related North American climate anomalies. EOS, 80, 25-30.

Hamblin, P.F. 1976. Seiches, circulation, and storm surges of an Ice-free Lake Winnipeg. Journal of the Fisheries Research Board of Canada. V.33, p. 2377-2391.

Latif, M. and T.P. Barnett, 1994: Causes of decadal climate variability over the north Pacific and North America. Science 266, 634-637.

McCullough, G.K. 2001. Organic Carbon, Nitrogen and Phosphorous Fluxes in Rivers Flowing into and out of Lake Winnipeg. Report to the Department of Fisheries and Oceans, Winnipeg, Canada. iv+46 pp.+appendix.

McCullough, G.K. 2011. Climate Change. Section 9.5 in L. Levesque and E. Page, State of Lake Winnipeg 1999–2007. Environment Canada/Manitoba Water Stewardship Report. viii + 209 p. http://www.gov.mb.ca/conservation/waterstewardship/water_quality/state_lk_winnipeg_report/pdf/state_of_lake_winnipeg_rpt_technical_high_resolution.pdf

McCullough, G.K., S.J. Page, R.H. Hesslein, M.P. Stainton, H.J. Kling, A. Salki, D.G. Barber. 2012. Hydrological forcing of a recent trophic surge in Lake Winnipeg. J. of Great Lakes Research. 38:95-105.

Milly, P.C.D., K.A. Dunne and A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. 438(17):347–350.

Nielsen, E. 1998. Lake Winnipeg coastal submergence over the last three centuries. J. Paleolimnology 19:335-342.

New, M., M. Hulme, M. and P.D. Jones, 2000. Representing twentieth century space-time climate variability. Part 2: development of 1901-96 monthly grids of terrestrial surface climate. Journal of Climate 13, 2217-2238

Newman, M. G.P. Compo and M. Alexander. 2003. ENSO-forced variability of the Pacific Decadal Oscillation. Journal of Climate 16(23):3853–3857.

Nigam, S., M. Barlow, and E. H. Berbery, 1999: Analysis Links Pacific Decadal Variability to Drought and Streamflow in the United States. EOS, Transactions, American Geophysical Union, Vol 80, No. 51, Dec 21 1999.

Novotny, E.V., Stefan, H.G. 2007. Stream flow in Minnesota: Indicator of climate change. J. of Hydrol. 334:319–333.

Pomeroy, J.W., X. Fang and B. Williams. 2009. Impacts of Climate Change on Saskatchewan's Water Resources. University of Saskatchewan Centre for Hydrology Report No. 6. http://www.usask.ca/hydrology/reports/CHRpt06_Impacts-Climate-Change-Sask-Water-Resources_Apr09.pdf

Pomeroy, J.W., K. Shook, X. Fang, S. Duanski, C. Westbrook and T. Brown. 2014. Improving and Testing the Prairie Hydrological Model at Smith Creek Research Basin. University of Saskatchewan Centre for Hydrology Report No. 14. http://www.usask.ca/hydrology/reports/CHRpt14_PHM_SCRB.pdf

Province of Manitoba. 1970. Interim License for the Regulation of Water Levels for Water Power Purposes: Lakes Winnipeg, Playgreen and Kiskittogisu.

https://www.hydro.mb.ca/corporate/water_regimes/lake_wpg_regulation/Appendix_1_Interim_Water_Power_Act_Licences_for_LWR_and_Jenpeg.pdf

Rood, S.B., G.M. Samuelson, J.K. Weber and K.A. Wywrot. 2005. Twentieth Century decline in stream flows from the hydrographic apex of North America. J. Hydrology 306:215–233.

Sauchyn, D., and S. Kulshreshtha. 2008. Prairies, in From Impacts to Adaptation: Canada in a Changing climate 2007, ed. D.S. Lemmen, F.J. Warren, J. Lacroix and E. Bush. Government of Canada, Ottawa, ON p. 275-328. http://www.nrcan.gc.ca/environment/resources/publications/impacts-adaptation/reports/assessments/2008/10253

Seneka, M. 2004. Trends in historical Annual flows for Major Rivers in Alberta. Prepared for Alberta Environment, February, 2004.

Shrestha, R.R., Y.B. Dibike, T.D. Prowse. 2012. Modelling of climate-induced hydrologic changes in the Lake Winnipeg watershed. J. Great Lakes Research 38(3):83–94.

Skinner, W.R. and D.W. Gullett. 1993. Trends of daily maximum and minimum temperature in Canada during the past century. Climatological Bulletin 63–77.

St. George, S. 2006. Streamflow in the Winnipeg River basin, Canada: Trends, extremes and climate linkages. J. of Hydrol. 332(3-4):396–411.

Appendix 1

Meteorological and hydrometric stations information.

Table A1. Meteorological stations used for precipitation time series chart.

Province/State	Station Identification	Station Name	Longitude	Latitude
SW Alberta				
AB	3034480	MEDICINE HAT A	-110.72	50.02
AB	3031400	CARWAY	-113.37	49.00
AB	3034720	MOUNTAIN VIEW	-113.63	49.13
N. Saskatchewan				
SK	4048520	WASECA	-109.50	53.10
SK	4057120	SASKATOON A	-106.62	52.23
SK	4056240	PRINCE ALBERT A	-105.68	53.22
S. Saskatchewan				
SK	4019040	YELLOW GRASS	-104.17	49.80
SK	4016560	REGINA A	-104.67	50.43
SK	4013480	INDIAN HEAD CDA	-103.67	50.53
S. Manitoba, N. North Dakota				
MB	5021848	Morden CDA	-98.08	49.18
ND	324958	LANGDON EXPERIMENT STN	-98.33	48.75
ND	323594	GRAFTON	-97.42	48.42
S. Dakota, W. Minnesota				
MN	215638	MORRIS WC EXP STATION	-95.88	45.58
SD	395536	MILBANK 2SSW	-96.63	45.20
MN	215400	MILAN 1NW	-95.93	45.13
NW Ontario				
ON	6037775	SIOUX LOOKOUT A	-91.90	50.12
ON	6034075	KENORA A	-94.37	49.78

Table A2. Water Survey of Canada hydrometric station information.

Station Number	Station Name	Period of record	Latitude	Longitude	Drainage Area (km2)
05KL001	SASKATCHEWAN R AT GRAND RAPIDS	1909-2011	53.164	-99.349	406000
05KJ001	SASKATCHEWAN R AT THE PAS	2002-2013	53.838	-101.209	347000
05GG001	N SASKATCHEWAN R AT PRINCE ALBERT	1962-1987	53.203	-105.772	131000
05HG001	S SASKATCHEWAN R AT SASKATOON	2011-2013	52.141	-106.644	141000
05LM006	DAUPHIN R NEAR DAUPHIN R	2002-2013	52.002	-98.330	82300
05LM001	FAIRFORD R NEAR FAIRFORD	2002-2013	51.587	-98.712	79800
05LK002	LAKE MANITOBA AT STEEP ROCK	1923-2014	51.444	-98.803	
05LL003	LAKE MANITOBA AT DELTA	1914-1969	50.188	-98.317	
05OJ010	RED R NEAR LOCKPORT	1962-2008	50.108	-96.932	287000
05OJ005	RED R AT SELKIRK	2008-2013	50.146	-96.865	287000
05OC001	RED R AT EMERSON	1956-1996	49.009	-97.215	102000
05MJ001	ASSINIBOINE R AT HEADINGLEY	1956-1991	49.868	-97.405	162000
05PF069	WINNIPEG R AT PINE FALLS GEN. STN	1987-2011	50.568	-96.178	136000
05PF063	WINNIPEG R AT SLAVE FALLS	1907-2011	50.225	-95.571	126000
05PF051	WINNIPEG R ABOVE BOUNDARY FALLS	1928-1955	50.212	-95.092	126000
05RD005	LAKE WINNIPEG AT BERENS R	1914-2013	52.353	-97.022	
05RE003	LAKE WINNIPEG AT GEORGE ISLAND	1983-2013	52.818	-97.620	
05RF001	LAKE WINNIPEG AT MONTREAL POINT	1969-2011	53.625	-97.844	
05SA003	LAKE WINNIPEG AT VICTORIA BEACH	1959-2013	50.695	-96.562	
05SB001	LAKE WINNIPEG AT WINNIPEG BEACH	1913-1966	50.506	-96.965	
05SB006	LAKE WINNIPEG AT GIMLI	1966-2013	50.631	-96.982	
05SD001	LAKE WINNIPEG AT PINE DOCK	1958-2013	51.640	-96.803	
05SD002	LAKE WINNIPEG AT MATHESON ISLAND	1957-2013	51.724	-96.915	
05SG001	LAKE WINNIPEG AT MISSION POINT	1953-2013	53.191	-99.212	

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Resumé

Education

- Ph.D. 2006. Department of Environment and Geography, University of Manitoba. Dissertation: "Circulation of Terrestrial Runoff and its Suspended Load in a large Tropical Lake: A Study of Processes and Effects near the Mouth of the Linthipe River in Lake Malawi". My thesis demonstrates how dilution and sedimentation in the plunge region at the mouth of a river quickly reduce initial density differences between river and lake to control how deeply underflow will sink in a stratified tropical lake before lifting from the bottom and spreading horizontally as interflow. It describes the significance of this process to primary productivity in Lake Malawi.

- MA. 1999. Department of Geography, University of Manitoba. Dissertation: "Determining Precision of Aquatic Turbidity Measurement by NOAA–N Series AVHRR" I compared reflectance recorded from 1985–1998 by five NOAA satellites with Secchi transparency and beam transmission data from Environment Canada cruises on Lake Erie. I concluded that reflectance data from this satellites series is a stable proxy measure of the historic turbidity record in large lakes.

- B.Sc. 1971. Department of Earth Sciences, University of Manitoba.

Awards

- Lake Winnipeg Foundation Alexander Bajkov Award for “outstanding efforts to protect and restore Lake Winnipeg and its watershed”.
- University of Manitoba Distinguished Dissertation Award for “groundbreaking, novel contributions to his academic discipline", 2006
- Department of Geography Thomas Weir Award for Outstanding Master's Thesis (University of Manitoba) 1999
- University of Manitoba Graduate Fellowship (Duff Roblin Fellow), 1998–2002.

Scientific affiliations

- Member of the International Association of Great Lakes Researchers

Public service

- Member of the Manitoba Water Services Board (2002–2009) sharing oversight responsibility for more than $35M annually of government spending on potable and waste water treatment in Manitoba
- Member of the Science Advisory Council of the Lake Winnipeg Foundation (2011-present)

Employment history:

2008–present: Post-doctoral fellow (2008–2010) and Research Associate (2010–present) with the Centre for Earth Observations Science, Department of Environment and Geography, University of Manitoba

- Responsible for research into freshwater/marine interactions in Hudson Bay. Led four oceanographic expeditions in the Churchill and Nelson River estuaries, participated in helicopter surveys of the Nelson River offshore plume under ice, and participated in four oceanographic expeditions across Hudson Bay (Science Chief of Mission on one).
- Since 2011: also conducting ongoing research into dynamics of multi-year ice in the Beaufort Sea

2001–2009: Private Consultant

- Climate and nutrient loading studies in Lake Winnipeg watershed. Remote sensing of surface temperature, suspended solids and chlorophyll-a, and for algal species discrimination in Lake Winnipeg. Primarily through contracts with the Centre for Earth Observations Science, University of Manitoba, funded by GRIP grants from the Canada Space Agency, Government of Canada.

1996–2006: Student

1976–1996: Geomorphologist and hydrologist
Fisheries and Oceans Canada

1973–1976: Resource Analyst
Garry Hilderman and Associates, Landscape Architects and Planners

1972–1973: Geomorphologist

Publications

- **Highlighted, refereed primary publications**

Barber, D.G., G.K. McCullough, D. Babb, A.S. Komarov, L.M. Candlish, J.V. Lukovich, M. Asplin, S. Prinsenberg, I. Dmitrenko and S. Rysgaard. 2014. Climate change and ice hazards in the Beaufort Sea. Elementa 2:000025

McCullough, G.K., S.J. Page, R.H. Hesslein, M.P. Stainton, H.J. Kling, A. Salki, D.G. Barber. 2012. Hydrological forcing of a recent trophic surge in Lake Winnipeg. *J. of Great Lakes Research.* 38:95-105.

Schindler, D.W., R.E. Hecky, McCullough, G.K. 2012. The rapid eutrophication of Lake Winnipeg: Greening under global change. *J. of Great Lakes Research.* 38:6-13.

McCullough, G.K., and D. Barber. 2006. The effect of suspended solids loading from the Linthipe River on light in Lake Malawi. *J. Great Lakes Res*. 33:466–482.

McCullough, G.K., D. Barber and P.M. Cooley. 2006. The vertical distribution of runoff and its suspended load in Lake Malawi. *J. Great Lakes Res*. 33:449–465.

McCullough, G.K. 1998. The contribution of forest litterfall to phosphorous inputs into Lake 239, Experimental Lakes Area, Northwestern Ontario. Pp. 159-168 in: M.K. Brewin and D.M.A. Monita (Technical Coordinators) *Proceedings of the Forest–Fish Conference: Land Management Practises Affecting Aquatic Ecosystems*, Calgary, Canada, 1–4 May, 1996. Canadian Forestry Service, Northern Forestry Centre Information Report NOR-X-356.

Newbury, R.W. and G.K. McCullough. 1984. Shoreline erosion and restabilization in the Southern Indian Lake reservoir. *Can. J. Fish. and Aquat. Sci.* Vol. 41, No. 4, pp. 558-566.

Hecky, R.E. and G.K. McCullough. 1984. Effect of impoundment and diversion on the sediment budget and nearshore sedimentation of Southern Indian Lake. *Can. J. Fish. and Aquat. Sci.* Vol. 41, No. 4, pp. 567-578.

- **Other refereed primary publications**

Guéguen, C. M.A. Granskog, G.K. McCullough, D.G. Barber. 2011. Characterisaton of colored dissolved organic matter in Hudson Bay and Hudson Strait using parallel factor analysis. J. Marine Systems 88:423–433.

Wang, R., G.K. McCullough, G.G. Gunn, K. Hochheim, A. Dorostkar, K. Sydor, D. Barber. 2011. An observational study of ice effects on estuarine variability. Continental Shelf Research 47:67-77.

Kling, H.J., S.B. Watson, G.K. McCullough and M.P. Stainton. 2011. Bloom development and phytoplankton succession in Lake Winnipeg: a comparison of historical records with recent data. J. Aquatic Ecosystem Health and Management. 14(2):219–224.

Ribbink, A.J., D.G. Barber, H.A. Bootsma, R.G. Brook, P.M. Cooley, R.E. Hecky, H.J. Kidd, H.J. Kling, G.K. McCullough, and F.X. Mkanda. 2001. The Lake Malawi/Niassa/Nyasa biodiversity conservation programme: science in a socio-economic context. Annales de la Musée royal de l'Afrique Centrale (Tervuren) 288: 28-59.

Paterson, M.J., D. Findlay, K. Beaty, W. Findlay, E.U. Schindler, M. Stainton, G. McCullough. 1997. Changes in the planktonic food web of a new experimental reservoir. Can. J. Fish. and Aquat. Sci. Vol. 54, pp. 1088-1102.

Mouchot, M.-C., T. Alfoldi, D. de Lisle, G. McCullough. 1991. Monitoring the water bodies of the Mackenzie Delta by remote sensing methods. Arctic. Vol. 44, Supp. 1, pp. 21-28.

Mouchot, M.-C., G. McCullough, A. Fabbri, O. Dupont, C. Kushigbor. 1989. Application de la morphologie mathématique a l'étude des reseaux hydrologiques complexes. Télédétection et gestion des ressources, Vol. VI, Bernier, Bonn et Gagnon [Eds.], L'Association Québécoise de Télédétection. pp. 51-71.

Newbury, R.W., G.K. McCullough and R.E. Hecky. 1984. The Southern Indian Lake impoundment and Churchill River diversion. Can. J. Fish. and Aquat. Sci. Vol. 41, No. 4, pp. 548-557.

Newbury, R.W. and G.K. McCullough. 1983. Shoreline erosion and restablilization in a permafrost affected impoundment. In: Proceedings of the 4th International Conference on Permafrost. National Academy Press, Washington, D.C., U.S.A. pp. 918-922.

- **Technical and data reports**

McCullough, G.K. 2011. Climate change. Section 9.5 in L. Lévesque and E. Page (Ed.) *State of Lake Winnipeg: 1999 to 2007*. Environment Canada and Manitoba Water Stewardship Report.

McCullough, G.K. and L. Lévesque. 2011. Thermal regime. Section 5.0 in L. Lévesque and E. Page (Ed.) *State of Lake Winnipeg: 1999 to 2007*. Environment Canada and Manitoba Water Stewardship Report.

McCullough, G.K. and L. Lévesque. 2011. Total suspended solids. Section 5.3 in L. Lévesque and E. Page (Ed.) *State of Lake Winnipeg: 1999 to 2007*. Environment Canada and Manitoba Water Stewardship Report.

Armstrong, N. and G.K. McCullough. 2011. Nutrient loading to Lake Winnipeg. Section 7.0 in L. Lévesque and E. Page (Ed.) *State of Lake Winnipeg: 1999 to 2007*. Environment Canada and Manitoba Water Stewardship Report

Watson, S., H. Kling, G.K. McCullough, M. Stainton. 2011. Bloom Development and Phytoplankton Succession in Lake Winnipeg: A Comparison of Historical Records with Recent

(2003 to 2007) Data. Section 9.1 in L. Lévesque and E. Page (Ed.) *State of Lake Winnipeg: 1999 to 2007*. Environment Canada and Manitoba Water Stewardship Report.

McCullough, G.K. 2008. *Using Remote Sensing Methods to Determine the Contribution of Cyanobacteria to Plankton Biomass in Lake Winnipeg*. Report to the Canadian Department of Fisheries and Oceans, Freshwater Institute, Winnipeg.

McCullough, G.K. 2007. *MERIS/MODIS Prediction of Chlorophyll in Lake Winnipeg.* Report to the Canadian Department of Fisheries and Oceans, Institute of Ocean Sciences, Nanaimo, British Columbia. iv + 46 p.

McCullough, G.K. 2007. *Assessment of bbe Fluoroprobe for algal taxonomic discrimination in Lake Winnipeg.* Report to the Canadian Department of Fisheries and Oceans Freshwater Institute, Winnipeg, Manitoba. Iv+24 pp.

McCullough, G.K. 2003. *Surface Water Temperature and Break-up and Freeze-up of the Ice Cover on Lake Winnipeg.* Report to the Department of Fisheries and Oceans, Freshwater Institute, Winnipeg, Canada. iv+42 pp.

McCullough, G.K. 2001. *Organic Carbon, Nitrogen and Phosphorous Fluxes in Rivers Flowing into and out of Lake Winnipeg.* Report to the Department of Fisheries and Oceans, Winnipeg, Canada. iv+46 pp.+appendix.

McCullough, G.K., K. Hocheim and P.M. Cooley. 2001. *Retrospective Study of Suspended Sediment Patterns on Lake Winnipeg using NOAA AVHRR Satellite Imagery.* Report to the Department of Fisheries and Oceans, Winnipeg, Canada. v+72 pp.+4 appendices.

+earlier reports available on request.