UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 502

Lake Level Response to Climate in Minnesota

by

Filiz Dadaser-Celik

and

Heinz G. Stefan

Prepared for
Legislative Citizens Committee on Minnesota Resources
St. Paul, Minnesota

December 2007
Minneapolis, Minnesota

Abstract

We are interested in the variability of lake levels in Minnesota, and the relationship between lake levels and climate. We analyzed historical water levels in 25 Minnesota lakes. Eight were landlocked lakes and seventeen were flow-through lakes. The data were daily values, but substantial gaps existed. The longest record reached back to 1906 (Lake Minnetonka and Upper Prior Lake in Scott County). We determined statistical parameters such as mean annual lake levels and seasonal variations of the historical lake water levels. Linear regression and Mann-Kendall test were used to evaluate the presence of trends in daily, mean annual, spring (May) and fall (October) water levels.

The majority of the 25 lakes showed rising water levels in the last century (1906 to 2007). The strongest upward trend was observed in a landlocked lake (Lake Belle Taine in Hubbard County) where the rate was 0.030 m/yr. The second largest increase was observed in a flow-through lake (Marion Lake in Dakota County) with a rate of 0.024 m/yr. Swan Lake (in Nicollet County) and Swan Lake (in Itasca County) were the only lakes that showed a falling trend with a rate of -0.011 and -0.002 m/yr, respectively.

The analysis also showed that lake levels have been increasing in most of the 25 lakes in the last 20-years (1987-2006). One landlocked lake and eight flow-through lakes showed their strongest upward trends in the last 20 years. Five of the eight landlocked lakes and eleven of the seventeen flow-through lakes reached their highest recorded levels after 1990. Upward trends in recorded lake water levels were found in both spring and fall in the majority of the 25 lakes analyzed.

We also attempted to understand how Minnesota lake levels have responded to climate changes in the past. Correlation coefficients were calculated between annual lake water levels and mean annual climate variables. The correlation of water levels with precipitation was moderate, and the correlation with dew point and air temperatures was very weak. 48- and 36-month antecedent precipitation was the strongest indicator of average water levels. Multivariate regression analysis of lake levels did not improve the lake level predictions. Numerical indicators for ground water and surface water in- and out-flows appear necessary for further improvement.

The correlation between mean annual water levels was strongest among lakes in the same climate regions and weakest among lakes in distant climate regions. Lake levels in the same Minnesota climate region (with identical precipitation and temperatures) had correlation coefficients as high as 0.78, while those in distant regions were not correlated. The average correlation coefficients among annual water levels in all lakes were 0.43 for the eight landlocked lakes and 0.41 for the seventeen flow-through lakes.

Overall, the analyses showed that changes have occurred in lake levels in Minnesota in the last century and in the last 20 years. The majority of the lakes have rising lake levels. The correlation between climate parameters and lake levels was weak. The consistency of water level variations in lakes of the same region is perhaps the strongest indicator of a climate effect. If the trends continue, lakes included in this study may experience significant water level increase by 2050.

Table of contents

1. INTRODUCTION

In the 1930, during a sequence of warm and dry years, Lake Minnetonka water levels fell to their lowest recorded elevations. Currently Lake Superior is approaching a record low level. At other times lake levels have been above normal levels. We wish to analyze the variability of lake levels in Minnesota, and to examine if there is a relationship with specific climate parameters.

Lake levels show seasonal and long-term fluctuations in response to lake water inputs and outputs. Water inputs to a typical Minnesota lake are by surface runoff (I), precipitation (P), and ground-water inflow (GI); water losses are by surface outflow (O), evaporation (E), and ground-water outflow (GO). The difference between water input and loss rates over a specific time period (Δt) determines the change in lake water volume and hence water level. If all flows are expressed per unit surface area of a lake in units of mm/year, the water level change is given by a water balance equation (Eq. 1) as:

$$\Delta L/\Delta t = P - E + I - O + GI - GO \qquad \text{(Eq. 1)}$$

The complexity of hydrologic processes that control each of the terms in Eq. 1 provides a challenge when the relationship between lake water levels and climate is to be explored. Changes in climatic variables, such as air temperature, relative humidity, and precipitation, can affect all water budget components directly or indirectly, and cause fluctuations in water levels (IPCC, 2001). Although a change in lake water levels can be an indicator of climate change - because of its dependence on precipitation and evaporation - it can also have other causes such as anthropogenic changes in land and water uses. Changes in surface and ground-water flows due to changes in land use or land cover, water diversions and ground-water pumping can affect lake water levels strongly. Outlet control structures can be the most important determinant of level in a regulated lake or impoundment (reservoir).

Although individual water budget components of a lake can provide a picture of the changes in climatic and hydrologic factors over time, it is not always easy to quantify them. For example the identification and measurement of multiple tributaries to a lake can require an extensive amount of time and effort: Sub-watersheds have to be delineated, and runoff from them has to be gauged or modeled. Overland flow may have to be specified. There is usually only one natural outflow from a lake, but multiple man-made withdrawal points may exist. A stage/discharge relationship is required to quantify the outflow rate at any time. Ground-water inflow and/or outflow depends on the hydrogeology of a lake setting, and field or model studies are required to develop at least estimates of the ground-water components in a lake water budget (Winter 1997). Fellows and Brezonik (1980) used a direct measurement technique to estimate seepage from Florida lakes with consolidated sediments and found that shoreline length relative to surface area was related to the relative importance of seepage. In many lake water budget studies, it has been common practice to estimate ground-water flow as the residual of the surface water components (e.g., Watson et al. 2001), or to omit the ground-water components altogether. In a regional assessment of multiple lakes, calculating water balances becomes even more challenging.

The magnitude of errors and uncertainties in lake water budgets is often underestimated. According to a very thorough study by Winter (1981) in New England, South Dakota, and California lakes, errors in measurement and regionalization create significant uncertainties in lake water balances. For example, the error in precipitation inflows can be up to 30% in annual water budgets and 42% in monthly water budgets (Table 1). Ground-water components can include errors over 100%, when estimated as the residual of the water budget (Winter 1981).

Table 1. Errors (percent) in estimation of water budget components with commonly used methodology (reproduced from Winter 1981).

Water Balance Component	**Source of Error**	**Annual Water Balance**	**Monthly Water Balance**
Precipitation	Gage	2	2
	Placement	5	5
	Areal averaging	10	15
	Gage density	13	20
Evaporation	NWS Class A Pan	10	10
	Pan to lake coefficient	15	50
	Areal averaging	15	15
Stream Flow In/Out	Current meter measurement	5/5	5/5
	Stage discharge relationship	20/10	30/10
	Channel bias	5/5	5/5

Mann and McBride (1972) investigated the hydrologic balance of Lake Sallie, in Minnesota. The lake is connected to Detroit Lake and has a significant amount of surface water outflow. Ground-water inflow was determined from flow nets based on weekly measurements in 32 observation wells in the watershed and compared to the residual of the surface-water budget. Based on the precision and adequacy of the data used, 5% error was found in precipitation, surface-water inflow, surface-water outflow, and change in storage components, 10% error was found in evaporation and 30% error was present in ground-water inflow.

The objective of our study is to analyze historical data of lake levels in Minnesota and to explore if and how lake level changes are related to climate. Because lake levels are affected by many factors, the relationship is expected to be strongest when precipitation and evaporation are the most prominent components of the water balance (Eq.1). Levels of “landlocked” (endorheic or closed-basin) lakes with no surface water outflow and stable ground-water levels, can be good indicators of weather (short-term) or climate (long-term). On the other hand, water levels of regulated water bodies with large surface water inflows and outflows such as the Mississippi River impoundments behind Dams 1 to 26 are not expected to be indicators of climate change. Many Minnesota lakes are of glacial origin and hence “natural”, but have been fitted with small dams and gates as water level control structures. Such “flow-through” or exorheic lakes, may handle a large range of surface water inflows without an apparent response in water levels. Only exceptionally large floods may cause a water level rise because most control structures operate under a specific stage-discharge relationship. In extended or exceptionally dry weather periods, the water level response of exorheic lakes will be more apparent.

In this study, we analyzed water levels recorded in 8 landlocked lakes and 17 flow-through lakes in Minnesota to identify changes and climate connections in the last century. We examined the full records and 20-year periods of the records to identify long-term and short-term trends in water levels. We also examined the relationships between water levels and climatic variables such as precipitation, air temperature, and dew point temperature.

2. PREVIOUS STUDIES OF LAKE LEVELS IN THE U.S./ MINNESOTA

Lake level trends in 11 northern Wisconsin headwater lakes of the LTER (Long-Term Ecological Research Program) (Trout Bog, Crystal Bog, Crystal Lake, Big Muskellunge Lake, Sparkling Lake, Allequash Lake, Trout Lake) and in five southern Wisconsin lakes (Fish Lake,

Lake Mendota, Lake Wingra and Lake Monona) were investigated by Magnuson et al. (2006). Both increasing and decreasing trends were found in the water levels recorded. For example, water levels in Lake Mendota increased by 2.2 cm/decade from 1916 to 2001. Fish Lake showed a rising trend of 73.3 cm/decade from 1966 to 2001. Water levels in Buffalo Lake increased about 3.7 cm/decade from 1943 to 1988. The increase in Fish Lake was found to be related to long-term increases in precipitation and ground-water recharge. The increase in water levels of Lake Mendota was due to a combination of climatic and land use changes (i.e., increases in intense rainfall events and impervious surfaces in the watershed) and water regulation practices. For the 1984-2001 period, water levels in Allequash Lake decreased by 16.5 cm/decade due to water level regulation practices.

Changnon (2004) evaluated the water level fluctuations observed and recorded in Lakes Superior, Michigan-Huron and Erie from 1861 to 2001. The analysis showed that during the 1923-1938 and 1973-2001 periods, climatic changes caused exceptional water level fluctuations in lake levels. After the 1923-1938 period, all lakes except Lake Superior experienced increasing water levels. The cause of this trend was explained to be the wetter and cooler weather conditions in the basins of Lakes Michigan-Huron and Erie since 1935-1940. During the same time period, air temperature increased and precipitation remained stable in the Lake Superior Basin.

Devils Lake, a natural closed-basin lake in northeastern North Dakota, showed a 24.5 ft (7.35 m) water level increase from 1993 to 1999 and was only 13 ft (3.9 m) below its natural spill elevation to the Sheyenne River in 2000 (Wiche and Vecchia 2000). The water level increase was consistent with increases in precipitation since 1990s and a slight decrease in annual average air temperatures since 1980s. Since 2000, the water level in Devils Lake has continued to remain high and reached 24.6 ft (7.38m) above its 1993 level in 2005 (Anonymous 2005).

Brown (1985) investigated the factors that caused an 11 ft (3.3m) rise in water levels in another closed basin lake, Big Marine Lake, Washington County, MN from 1938 to 1983. The analysis showed that increased precipitation and groundwater recharge were responsible for the increase in water levels.

Christensen and Bergman (2005) investigated water level fluctuations in Long Lost Lake, Clearwater County, MN between 1939 and 2001 and reported that they were caused by changes in precipitation, which showed similar fluctuations during the same time period.

Vining (2003) calculated the evaporative losses from three regulated lakes, Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota for the 1931-2001 period, and found a downward trend in evaporation rates. The author argued that the trend could be due to drought conditions in the mid 1930s and wet conditions in the late 1990s.

In summary, most of these studies confirm the expectation that lake water level rise is correlated with a precipitation increase; a decrease in evaporation rate which depends on climate parameters such as dew point and wind speed may be a significant contributing factor. In regulated lakes the relationship between lake level and climate parameters is less evident.

3. CLIMATE OF MINNESOTA

3.1. Seasonal and geographic climate parameter distributions

Climatic and hydrologic parameters have been recorded in Minnesota over approximately a century. Precipitation, air temperature, dew point temperature and pan evaporation are climatic parameters of particular interest for a lake level study. An example of the seasonal distribution of these parameters is given in Figure 1. The precipitation, air temperature, and dew point were recorded at the Minneapolis/St. Paul Airport (downtown Minneapolis prior to 1938) and pan evaporation data were collected at the St. Paul Climatological Observatory. Monthly precipitation is highest in June and about two-thirds of the total annual precipitation occurs between May and September. Average annual precipitation for the 1891-2006 period was 700 mm (27.5 in). Pan evaporation is highest during July and about twice as large as precipitation from May to September. Average pan evaporation for May-September was 857 mm (33.7 in) for the period 1972-2006. Average daily air temperature between 1891 and 2006 was 7.3°C (45.2°F). Average daily temperature from June to September was 20.2°C (68.4°F), highest in July 22.9°C (73.2°F). Dew point temperature followed the same seasonal pattern as air temperature.

Precipitation and mean daily temperature data collected at International Falls, Detroit Lakes, and Fairmont (Figure 2) were assembled to illustrate geographic differences in these parameters throughout Minnesota. Data was available for the 1948-2006, 1896-2006, and 1931-2006 periods, respectively. International Falls is located on the northern Minnesota border with Canada at 49^{o} latitude, Detroit Lakes is located in the western portion of central Minnesota, and Fairmont is in south-eastern Minnesota between 44^{o} and 45^{o} latitude. Air temperature and precipitation increase going towards southern Minnesota (Figure 2). Average annual air temperature was 2.8°C (37.1°F), 4.2°C (39.5 °F), 7.3°C (45.2 °F), and 7.6°C (45.8 °F) at International Falls, Detroit Lakes, Minneapolis and Fairmont, respectively. Average annual precipitation was 617 mm (24.3 in), 630 mm (24.8 in), 700 mm (27.6 in), and 761 mm (30.0 in) at those same locations, respectively.

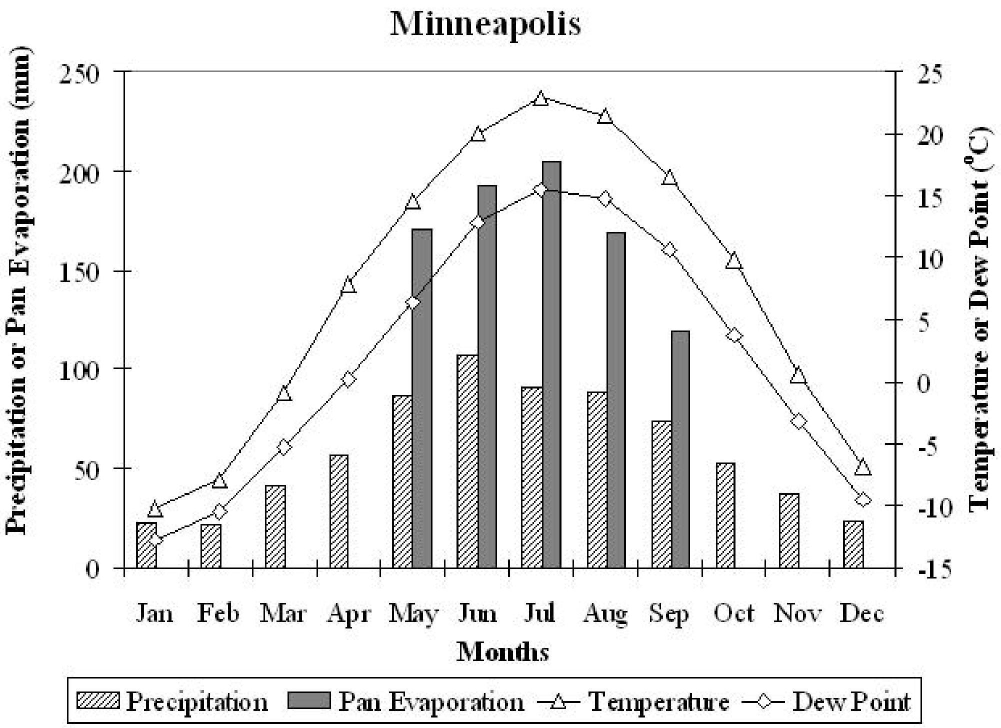

Figure 1. Average monthly precipitation, pan evaporation, air temperature and dew point temperature at Minneapolis/St. Paul, MN (1 in = 25.4 mm and °F = 1.8 x °C + 32) (data from: http://www.climate.umn.edu/ and http://www.ncdc.noaa.gov/oa/ncdc.html).

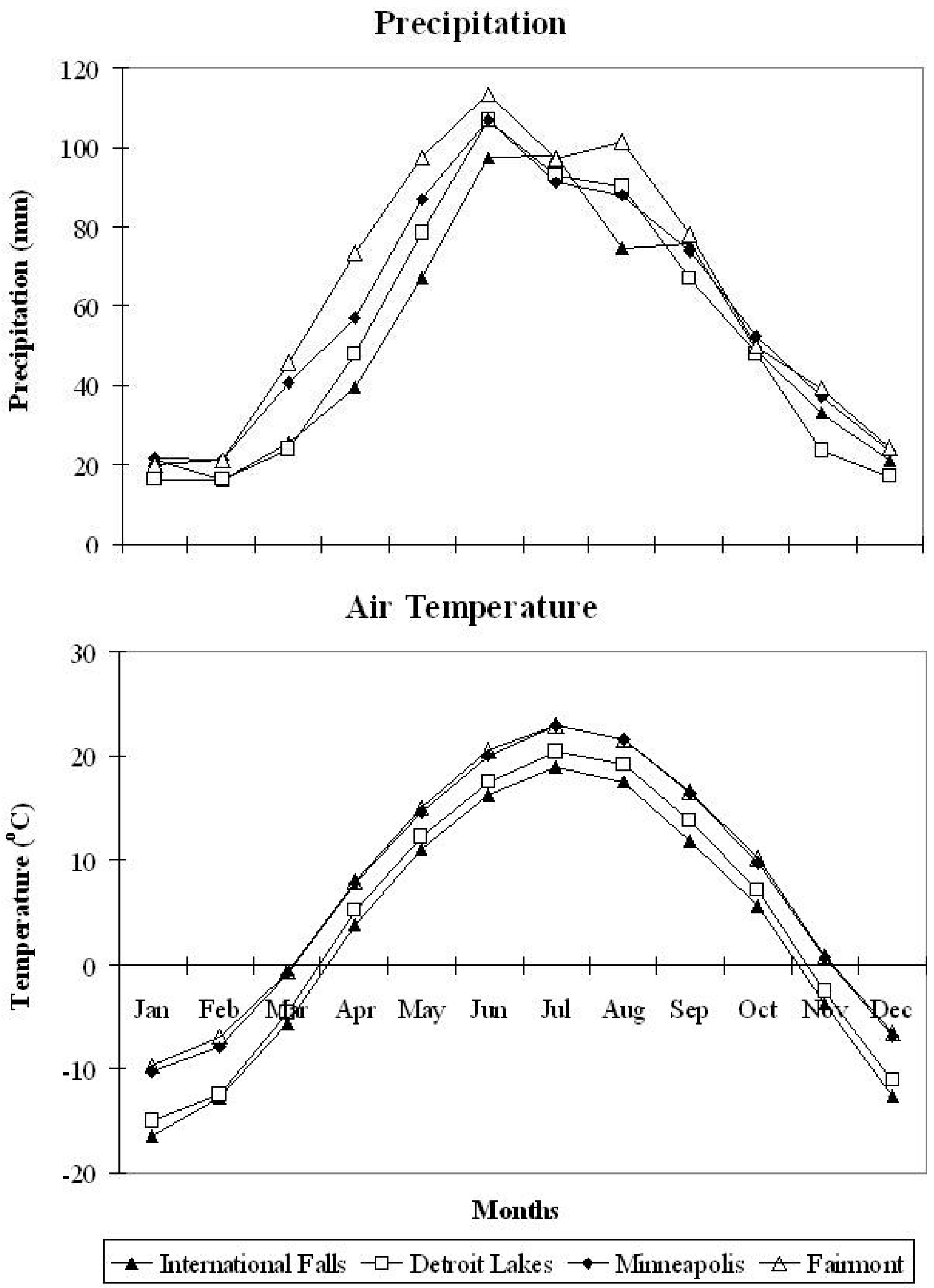

Figure 2. Average monthly precipitation and air temperature at International Falls, Detroit Lakes, Minneapolis, and Fairmont, MN (1 in = 25.4 mm and ^{o}F = 1.8 x ^{o}C + 32) (data from: http://www.ncdc.noaa.gov/oa/ncdc.html).

3.2. Observed climatic and hydrologic changes in Minnesota

Seeley (2003) found that Minnesota is now having warmer winters, higher minimum temperature, higher frequency of tropical dew points, and greater annual precipitation.

Air temperature and precipitation showed raising trends of 2-3 °C/100 years and 5-10%/100 years , respectively, in Minnesota, from 1900 to 1994 (Gleick 2000). The average precipitation and daily temperature in Detroit Lakes, MN and Minneapolis, MN for the1903-1922 and 1987-2006 periods are given in Figure 3. Annual average precipitation increased about 24 mm (0.94 in from 25.47 to 26.41 in) and 25 mm (0.97 in from 29.04 to 30.01 in) in Detroit Lakes and Minneapolis, respectively. Precipitation increased particularly during spring and fall in Detroit Lakes and during summer in Minneapolis. Average annual temperature also increased 2.34 °C (4.21 °F from 38.04 to 42.25 °F) in Detroit Lakes and 1.03 °C (1.9 °F from 44.5 to 46.4 °F) in Minneapolis. Average daily temperatures in all months in Detroit Lakes and all months except October in Minneapolis became higher.

Pan evaporation data were available for only two locations in Minnesota: Minneapolis (1972-2006) and Waseca (1964-2002). Despite the increases in air temperatures, pan evaporation rates in both locations showed decreasing trends for the given periods. The trend was -6.21 mm/yr (0.25 in/yr) for Minneapolis and -0.99 mm/yr (0.04 in/yr) for Waseca.

The effects of a changing climate have been observed in Minnesota’s water resources. Changnon and Kunkel (1995) found upward trends in flood flows that occur in the warm-season (May-November) and in the cold-season (December-April). Heavy-precipitation events in Minnesota (e.g., 7-day precipitation events qualifying at the 1-yr recurrence level) from 1921 to 1985 according to Changnon and Kunkel (1995). Johnson and Stefan (2006) found earlier ice-out dates and later ice-in dates in Minnesota lakes. They also showed that first stream runoff due to snowmelt is occurring earlier and stream temperatures are rising. They concluded that all these changes are well correlated with air temperatures. Novotny and Stefan (2007) found significant trends in seven stream-flow statistics including mean annual flow, peak and low flows, high and extreme flow days, and strong correlations between mean annual stream flows and total annual precipitation.

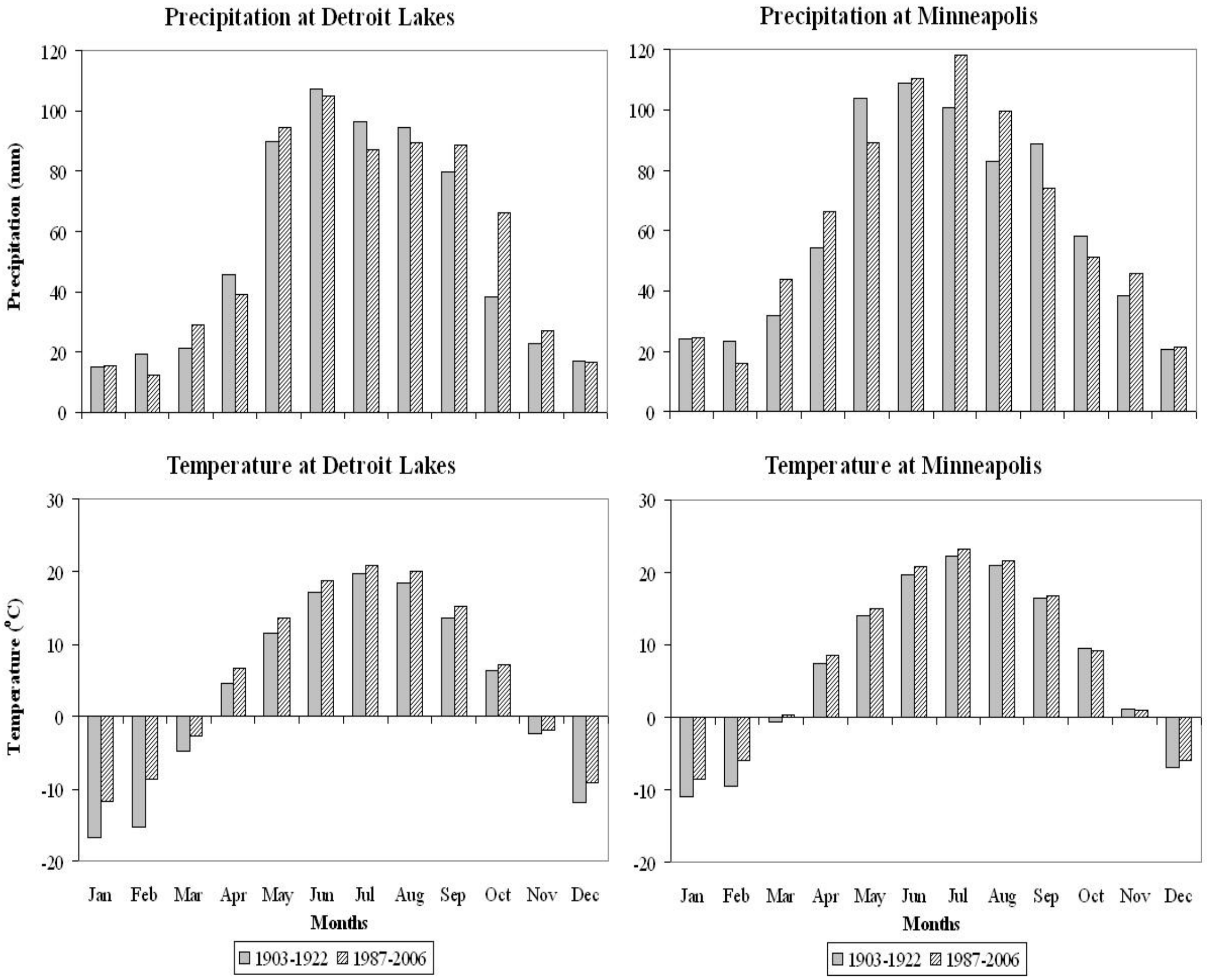

Figure 3. Average monthly precipitation air and temperature at Detroit Lakes and Minneapolis, MN for 1903-1922 and 1987-2006 (data from: http://www.ncdc.noaa.gov/oa/ncdc.html).

4. LAKE SELECTION FROM MINNESOTA LAKE LEVEL DATA BASE

In this study we evaluated lake levels in Minnesota. There are 11,842 lakes in Minnesota greater than 10 acres in surface area. Unfortunately long-term measurements of water levels are not available for most of these lakes**.** We obtained the data on lake levels from the Department of Natural Resources (DNR) website. These DNR lake level data are daily visual readings on a lake gauge collected mostly by volunteers who participate in the Lake Level Minnesota program. Currently, the DNR's Division of Waters has a record of water levels (10 or more readings) for about 4000 lakes (DNR-Waters 2005).

We first focused on closed or landlocked lakes because they have no surface water outflows and are therefore better indicators of climatic changes due to a strong dependence of water levels on water inflows and evaporation (IPCC, 2001). A list of landlocked lakes in Minnesota was obtained from DNR. However, after examination of water-level data, we decided to include all lakes in the analysis because most landlocked lakes did not have long-term records. Although records were available for a significant number of flow-through lakes, their water levels are often controlled by DNR by outlet dams. This means that water levels observed in flow-through lakes are not as reliable as those observed in landlocked lakes.

We followed three steps (criteria) to select lakes for our analysis. We first developed a list of lakes where data collection had started prior to 1957 and extended up to at least 2005. We looked for daily lake level records. All lake-level records had gaps, i.e., the data were non-continuous. In the second step, we therefore identified 40 lakes (20 landlocked lakes and 20 lakes with surface outlets), which provided the longest and most continuous records. In the third step, we selected the lakes which provide at least one data from at least 40 years. Final set of lakes selected for study contained 8 landlocked lakes (Table 2) and 17 flow-through lakes (Table

3). Landlocked lakes had water elevations in the range of 270 – 460 m (900 – 1,500 ft) and flow-though lakes had water elevations in the range of 270 – 550 m (900 – 1,800 ft). Other characteristics of the lakes included in this study are provided in Tables 2 and 3, and their locations are shown in Figure 4.

Period of data record and number of daily lake level data were also provided in Tables 2 and 3, which can provide an idea about the magnitude of the gaps in data. Flow-through lakes had longer and more continuous records than the landlocked lakes. Data from Lake Minnetonka was available for the period 1906-2006 and were mostly continuous (data were available about 50% of the days included in the analysis). Lake Swan (Itaska) and Lake Vermilion had comparatively shorter records but more continuous data (available for about 58% and 68% of the days, respectively) than Lake Minnetonka. Other flow-though lakes had records available in the range of 9-27%. The average data availability for flow-through lakes was 22%. The most continuous record available for landlocked lakes was from Lake Belle Taine (11%) and most sparse data was available for Swan Lake (Nicollet) (1%). The average data availability for landlocked lakes was about 7%. Most records were collected from April to October in both landlocked and flow-though lakes. Landlocked lakes Island and Otter Tail and flow-though lakes Birch, Minnetonka, Mud, Peltier, Swan and Vermilion also had significant amounts of data from the November-March period. Multi-year gaps were present in records of lakes other than Lakes Birch, Height of Land, Minnetonka, Peltier, Pelican, Swan and Vermilion.

Table 2. Landlocked lakes selected for study.

No	Lake ID	Lake name	Location (County)	Period of record	Number of daily lake level data	Surface area (ha)	Littoral area (ha)	Max. depth (m)
1	29014600	Belle Taine	Hubbard	07/20/1935 to 05/18/2007	2,936	480	312	17
2	40012400	Emily	Le Sueur	12/28/1940 to 04/17/2007	1,442	95	67	11
3	62007500	Island	Ramsey	01/01/1924 to 06/30/2006	2,041	24	24	3
4	29015000	Little Sand	Hubbard	05/11/1956 to 05/18/2007	1,828	156	60	24
5	31057100	Loon	Itasca	02/01/1955 to 05/22/2007	1,278	94	19	21
6	56024200	Otter Tail	Otter Tail	07/18/1919 to 04/27/2007	3,004	5,559	2,620	37
7	58006700	Sturgeon	Pine	06/22/1945 to 05/02/2007	575	691	201	12
8	11030400	Swan	Nicollet	11/22/1946 to 04/17/2007	299	3,785	N/A	3

Table 3. Flow-through lakes selected for study.

No	Lake ID	Lake name	Location (County)	Period of record	Number of daily lake level data	Surface area (ha)	Littoral area (ha)	Max. depth (m)
1	41004300	Benton	Lincoln	07/31/1947 to 04/17/2007	2,325	1,157	1,157	3
2	62002400	Birch	Ramsey	06/04/1930 to 04/13/2007	2,537	N/A	N/A	N/A
3	3038100	Detroit	Becker	08/25/1943 to 05/17/2007	3,625	1,249	767	27
4	18029800	East Fox	Crow Wing	04/22/1937 to 05/15/2007	2,401	97	41	20
5	30013600	Green	Isanti	06/22/1937 to 04/20/2007	2,407	325	145	9
6	3019500	Height of Land	Becker	03/24/1938 to 05/16/2007	3,004	1,426	1,292	6
7	19002600	Marion	Dakota	05/03/1946 to 04/16/2007	2,963	227	184	6
8	27013300	Minnetonka	Hennepin	05/30/1906 to 04/18/2007	18,616	5,672	2,369	34
9	61013000	Minnewaska	Pope	05/29/1935 to 04/25/2007	2,860	2,880	867	10
10	34015800	Mud	Kandiyohi	12/02/1945 to 04/26/2007	3,735	939	939	4
11	18030800	Pelican	Crow Wing	11/29/1933 to 05/04/2007	3,125	3,342	1,584	32
12	2000400	Peltier	Anoka	04/02/1951 to 04/10/2007	5,584	188	167	5
13	56014100	Rush	Otter Tail	06/26/1934 to 04/27/2007	3,195	2,162	1,347	21
14	51004600	Shetek	Murray	11/05/1926 to 04/13/2007	3,245	1,456	1,456	3
15	31006700	Swan	Itasca	09/21/1937 to 05/31/2007	14,881	1,001	205	20
16	70007200	Upper Prior	Scott	04/04/1906 to 04/05/2007	4,188	143	133	15
17	69037800	Vermilion	St Louis	10/03/1950 to 05/31/2007	14,097	16,426	6,077	23

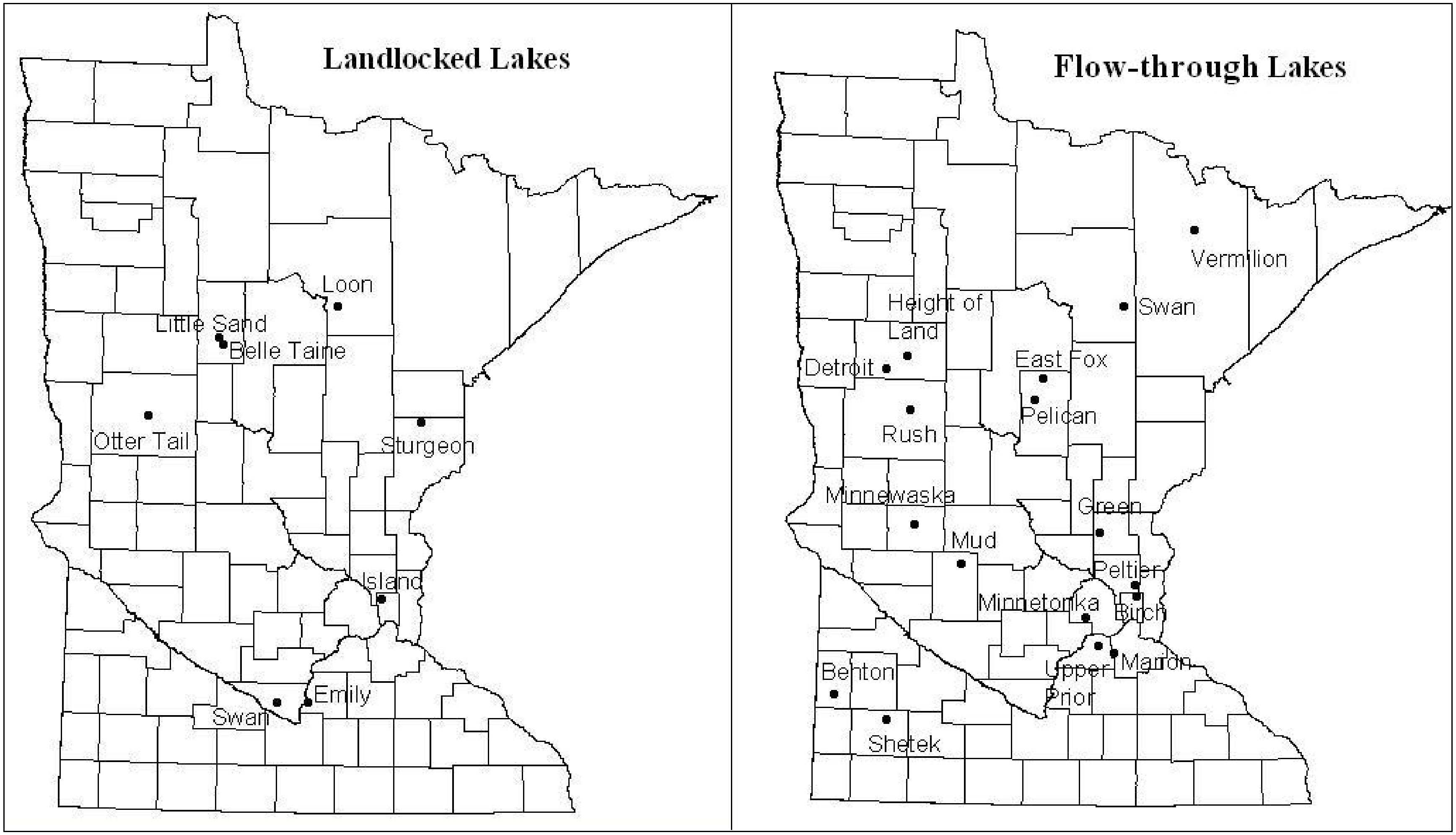

Figure 4. Location of lakes selected for study.

5. METHODS OF ANALYSIS

In this study we analyze records of lake levels and climate parameters to determine a) statistical characteristics of Minnesota lake levels, b) trends in Minnesota lake levels, and c) relationship between lake levels and climate parameters.

5.1. Statistical characteristics

The standard parameters (means, standard deviations, maxima and minima, ranges, etc.) were determined for lake levels at daily and annual timescales for the full records, 20-year periods and selected months.

5.2. Trend Estimation

We used linear regression to test the trends in daily water levels. Although daily time series had significant amounts of missing data, linear regression provided meaningful estimates of trends in lake water levels. Linear regression was used because it provides a good visual presentation (Svensson et al. 2005). We accepted that the linear trends are significant when $p<0.01$.

The Mann-Kendall test (Mann 1945, Kendall 1975) was used to test trends in annual average lake levels, spring lake levels (May), and fall lake levels (October).

The Mann-Kendall test is a non-parametric test which has been used widely for detection of trends in hydrologic data (e.g., Lins and Slack 1999, Abdul Aziz and Burn 2006, Cengiz and Kahya 2006, Novotny and Stefan 2007). The first step in this test is the estimation of the test statistic, S:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \qquad \text{(Eq 2)}$$

In Eq. 2, x denotes the data values, n denotes the length of the record and the sgn function is defined as:

$$\mathrm{sgn}(\theta) = \begin{cases} 1 \; if \; \theta > 0 \\ 0 \; if \; \theta = 0 \\ -1 if \; \theta < 0 \end{cases} \qquad \text{(Eq 3)}$$

The S statistic is normally distributed when n>0. Mean (μ) and variance (σ) of S are given in Eqs. 4 and 5.

$$\mu = 0 \qquad \text{(Eq 4)}$$

$$\sigma = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \qquad \text{(Eq 5)}$$

where t_i is the number of ties of extent i.

A test statistic Z is estimated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\sigma}} \; if \; S > 0 \\ 0 \quad if \; S = 0 \\ \frac{S+1}{\sqrt{\sigma}} \; if \; S < 0 \end{cases} \qquad \text{(Eq 6)}$$

We accepted that Z is significant when p<0.01.

We also estimated Sen’s slope (Sen 1968) for these parameters. Sen’s slope provides a measure of the slope if a trend is present in data. It is also a non-parametric method and works well with time series with missing data. Sen’s slope can be found as the median of the slopes calculated from all pairs of values in the data series using Eq. 7.

$$Q_i = \frac{x_j - x_k}{j-k} \text{ for } i=1 \text{ to } N \qquad \text{(Eg 7)}$$

In Eq. 7, N is the number of data pairs, x_j and x_k are the data values at times j and k, respectively, where j is greater than k.

5.3. Correlations of lake levels with climate parameters

Correlation coefficients were calculated to explore the relationships between water levels and climate variables. Climatic variables that are directly related to water levels include precipitation, air temperature, dew point temperature, wind speed, solar radiation, and pan evaporation. Precipitation is not only a direct input to a lake, but also affects surface and ground-water flows. Several other variables determine jointly the amount of evaporation from a lake, which is often the most significant water loss component in the lake water balance. In this study we included only precipitation, air temperature and dew point temperature in the correlation analysis considering that solar radiation is directly related to air temperature and changes in average wind speed are small compared to the changes in other variables. We could not use pan evaporation data (which is a direct measure of evaporation from the lakes) in the correlation analysis because pan evaporation data were available only for two locations (Minneapolis and Waseca) for a short time period (1972-2006 and 1964-2002) and on a monthly time scale.

Because several climate parameters influence a lake's water balance, single variable regression is not the best approach for the analysis of lake levels in relation to climate. We pursued a multiple variable regression analysis by first examining the basic deterministic relationships between climate parameters and the water budget components. We then formulated appropriate regression equations, and finally estimated parameter values by analysis of the data. If Eq. 1 is rewritten, we obtain the following equation. The components labeled 1,2,3,4, and 5 on the right-hand side of Eq. 8, denote precipitation, evaporation, surface runoff, surface outflow, and net ground-water flow, respectively.

$$(\Delta L / \Delta t)\ A = \underset{\mathbf{1}}{[p\ A]} - \underset{\mathbf{2}}{[N\ (R_w T_a - T_d) W]} + \underset{\mathbf{3}}{[p\ C\ A_b]} - \underset{\mathbf{4}}{[K\ w\ (L - L_b)^{3/2}]} + \underset{\mathbf{5}}{T\ W_a\ (L - L_a)/d} \qquad \text{(Eq 8)}$$

where

A = lake surface area, m^2

p = rainfall intensity, m/d

W = wind speed above water surface (m/s)

T_a = air temperature

T_d = dewpoint temperature

R_w = the ratio of water temperature to air temperature (assumed to be 0.82 from stream water/air temperature relationships)

C =runoff coefficient, (dimensionless)

A_b = basin area = m^2

K = weir coefficient

w = outflow channel width, m

L = lake water level, m

L_b = water level at which outflow starts, m

T = transmissivity

W_a= aquifer width, m

L= water level at the lake, m

L_a = ground-water level at distance d

d = horizontal distance, m

Because no information on the parameters in terms 3, 4, and 5 was readily available for most lakes, we formulated the final equation as below and estimated coefficients X and Y.

$$(\Delta L / \Delta t) = X\ [p] - Y[(R_w T_a - T_d) W] \qquad \text{(Eq 9)}$$

6. RESULTS

6.1. Statistics of daily water level records of 25 Minnesota lakes

The recorded daily water levels for the lakes investigated have been plotted in Figure 5 for landlocked lakes and in Figure 6 for the flow-through lakes. The period of record is given in Table 1 and reached back to at least 1957 for all lakes, and as far as 1919 (Otter Tail) for landlocked lakes and 1906 (Minnetonka) for flow-through lakes.

One can see in Figures 5 and 6 that there were significant reversals in lake water levels within the period of record. All landlocked lakes whose records went back to the period 1930-1940 had their lowest water levels between 1930 and 1940 (Table 4). Six of the 10 flow-though lakes whose records start earlier than 1940 had their lowest water levels also between 1930 and 1940 (Table 5). The highest water levels in five of the landlocked lakes and 11 of the flow-through lakes were recorded after 1990 (Tables 4 and 5).

All but three lakes showed at least 1 m fluctuation over their entire record (Tables 4 and 5). The largest fluctuation over the entire record in landlocked lakes was observed in Lake Belle Taine (4.38 m) and the largest fluctuation in flow-through lakes was in Marion Lake (4.03 m). Although histogram of daily lake levels could provide us information about the distribution of water levels, we could not prepare histograms, since significant amounts of data were missing and majority of the data were collected during certain periods (April-October).

Table 4. Highest and lowest recorded lake levels and their dates for landlocked lakes

Lake Name	Highest Recorded Level (m)	Date of Highest Recorded Level	Lowest Recorded Level (m)	Date of Lowest Recorded Level	Range of fluctuations for entire record (m)
Belle Taine	435.79	6/14/2001	431.42	11/4/1936	4.37
Emily	296.83	7/1/1993	294.59	12/28/1940	2.24
Island	288.87	8/11/1993	286.02	8/1/1931	2.85
Little Sand	435.82	6/14/2001	434.76	10/8/1976	1.06
Loon	389.52	5/12/1980	388.42	7/29/1975	1.10
Otter Tail	403.04	5/16/1999	401.63	12/18/1934	1.41
Sturgeon	326.17	10/10/1986	324.94	9/15/1977	1.23
Swan (Nic)	299.41	5/5/1969	296.48	8/17/1989	2.93

Table 5. Highest and lowest recorded lake levels and their dates for flow-through lakes

Lake Name	Highest Recorded Level (m)	Date of Highest Recorded Level	Lowest Recorded Level	Date of Lowest Recorded Level	Range of fluctuations for entire record (m)
Benton	533.40	4/16/1993	531.58	4/18/1977	1.82
Birch	280.81	4/17/1952	278.63	6/4/1930	2.18
Detroit	407.15	6/28/1998	406.40	9/13/1970	0.75
East Fox	384.33	6/9/2005	383.51	8/10/1976	0.82
Green	281.79	5/1/2001	280.29	7/25/1958	1.50
Height of Land	443.88	8/6/1993	442.52	2/20/1940	1.36
Marion	300.08	7/6/1993	296.06	5/25/1964	4.02
Minnetonka	283.62	9/7/2002	280.96	12/13/1937	2.66
Minnewaska	347.37	6/2/1972	344.32	5/29/1935	3.05
Mud	367.41	9/20/1991	365.18	12/2/1945	2.23
Pelican	368.13	6/26/2001	366.74	3/13/1935	1.39
Peltier	270.24	7/3/1975	267.30	2/2/1960	2.94
Rush	403.58	8/31/1993	402.40	1/26/1944	1.18
Shetek	453.20	4/10/1969	450.86	11/21/1952	2.34
Swan (Itasca)	407.94	5/15/1950	406.52	9/19/1944	1.42
Upper Prior	276.05	7/20/1983	272.33	10/25/1940	3.72
Vermilion	414.30	5/28/2001	413.33	11/16/1976	0.97

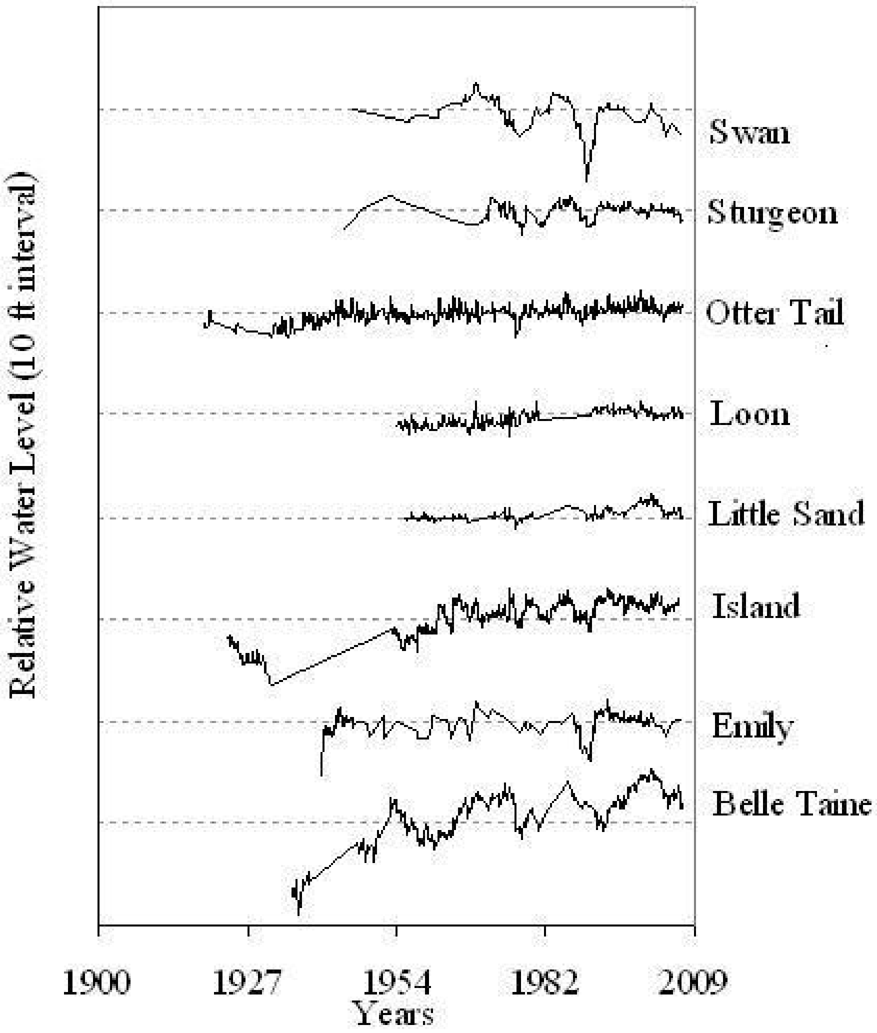

Figure 5. Daily water level data in landlocked lakes (10ft = 3.28m).

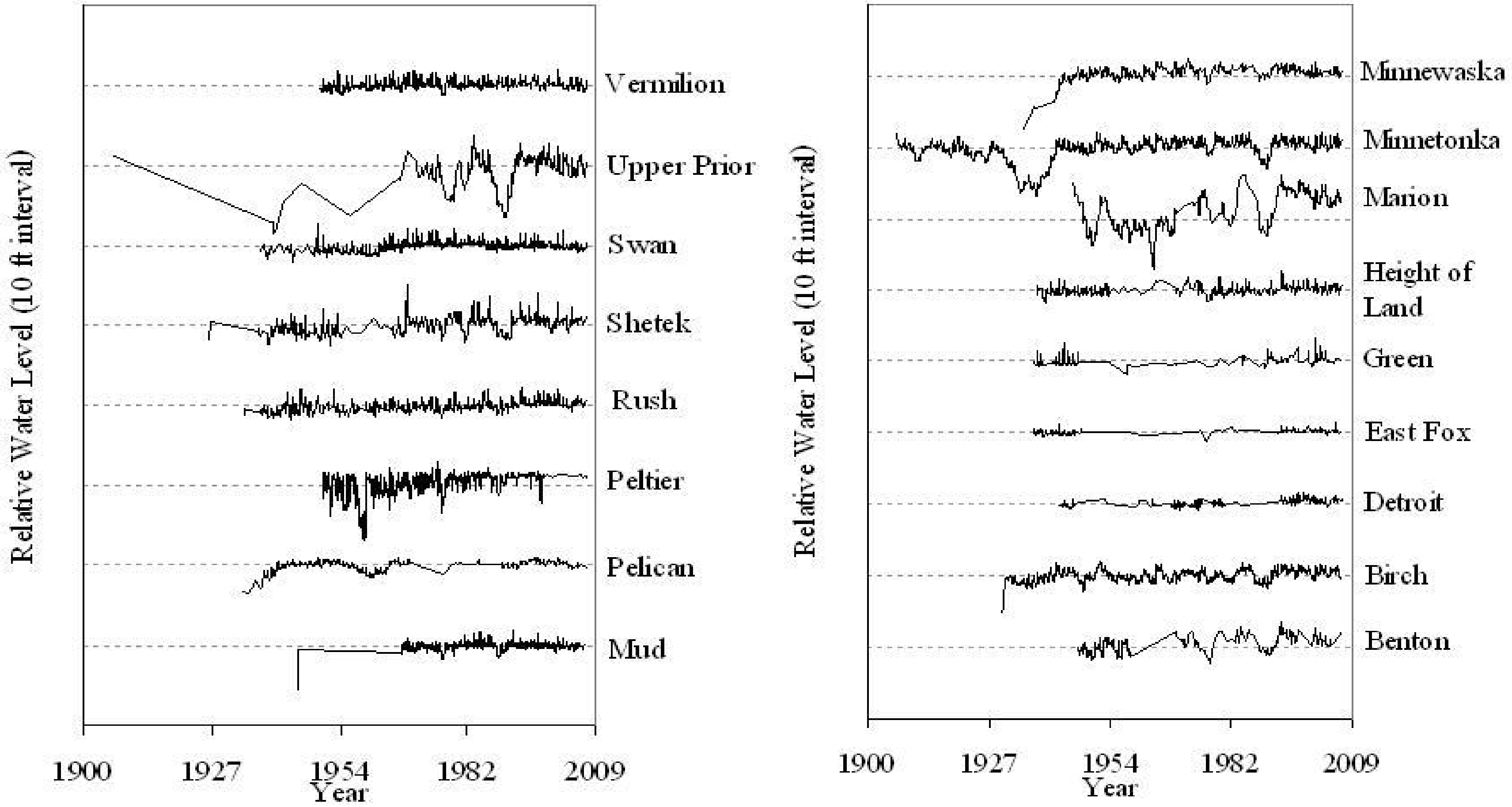

Figure 6. Daily water level data in flow-through lakes (10ft = 3.28m).

6.2. Seasonal water level fluctuations in 25 Minnesota lakes

Water levels in Minnesota's lakes typically rise during spring and early summer, then fall during mid-summer and early fall, and remain low and stable during winter (Rosenberry et al. 1997). The rise in early spring is due to snowmelt and spring rainfall as well as lack of evaporation due to low lake and temperatures. During mid summer and early fall, precipitation has usually been low and evaporation has been high due to dry air and high water temperatures. During winter, ice covers and low air temperatures inhibit evaporation and precipitation is in the form of snow.

The eight landlocked lakes included in this study showed the seasonal pattern described by Rosenberry (Figure 7). In the 8 landlocked lakes peak water levels occurred between May and July (five in May). Water levels decreased during fall, and minimum water levels in landlocked lakes occurred between November and February. The seasonal patterns in all lakes were similar.

Water levels in 17 flow-through lakes seem to peak about one month earlier in the season (Figure 8) than in landlocked lakes. Flow-through lakes reach their highest water levels between April and July (seven in April, only one in July). The minimum water levels in flow-through lakes are observed between October and March (13 between Dec and Feb).

The values plotted in Figures 7 and 8 are monthly averages over the period of record. Average standard deviations of average monthly lake levels from the record mean were in the range of 0.18-0.81 m (0.60-2.66 ft with an average of 1.31 ft) for landlocked lakes and 0.06-0.79 m (0.21-2.60 ft with an average of 0.87 ft) for flow-through lakes. The medians of average standard deviations were in the range of 0.19-0.83 m (0.61-2.73 ft) and 0.06-0.79 m (0.21-2.58 ft), respectively. These results indicate that landlocked lakes had larger fluctuations in monthly lake levels from year to year than flow-through lakes. This is not unexpected. Largest standard deviations were observed in Lake Belle Taine (landlocked) and Lake Marion (flow-through).

Average annual (water year) fluctuations in most landlocked and flow-through lakes were calculated by DNR (DNR-Waters 2005) and are given in Table 6. The average of annual fluctuations was 0.35 m for landlocked lakes and 0.45 m for flow-through lakes, i.e. the selected flow-through lakes show larger fluctuations in water levels than landlocked lakes in a water year. The largest annual fluctuation in landlocked and in flow-through lakes were observed in Island Lake (0.46 m) in Upper Prior Lake (0.70 m), respectively.

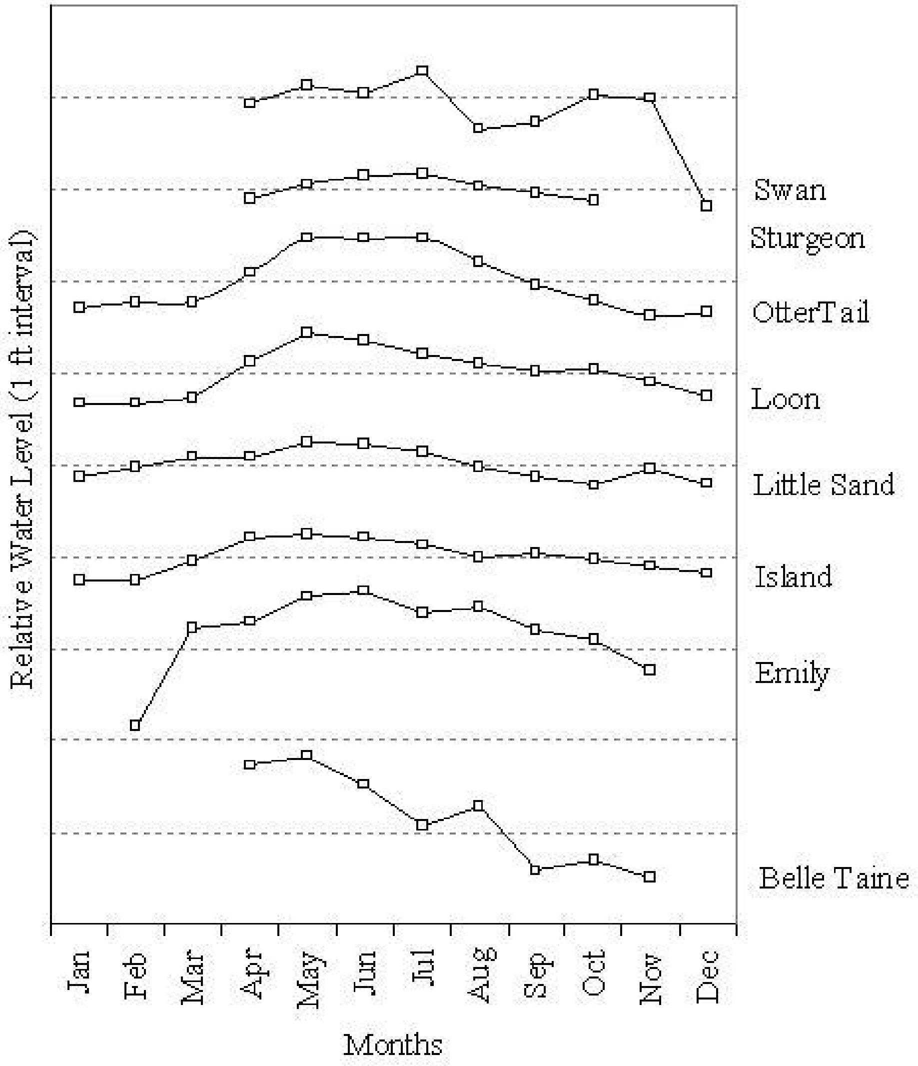

Figure 7. Seasonal water level fluctuations in eight landlocked Minnesota lakes (1 ft = 0.305 m)

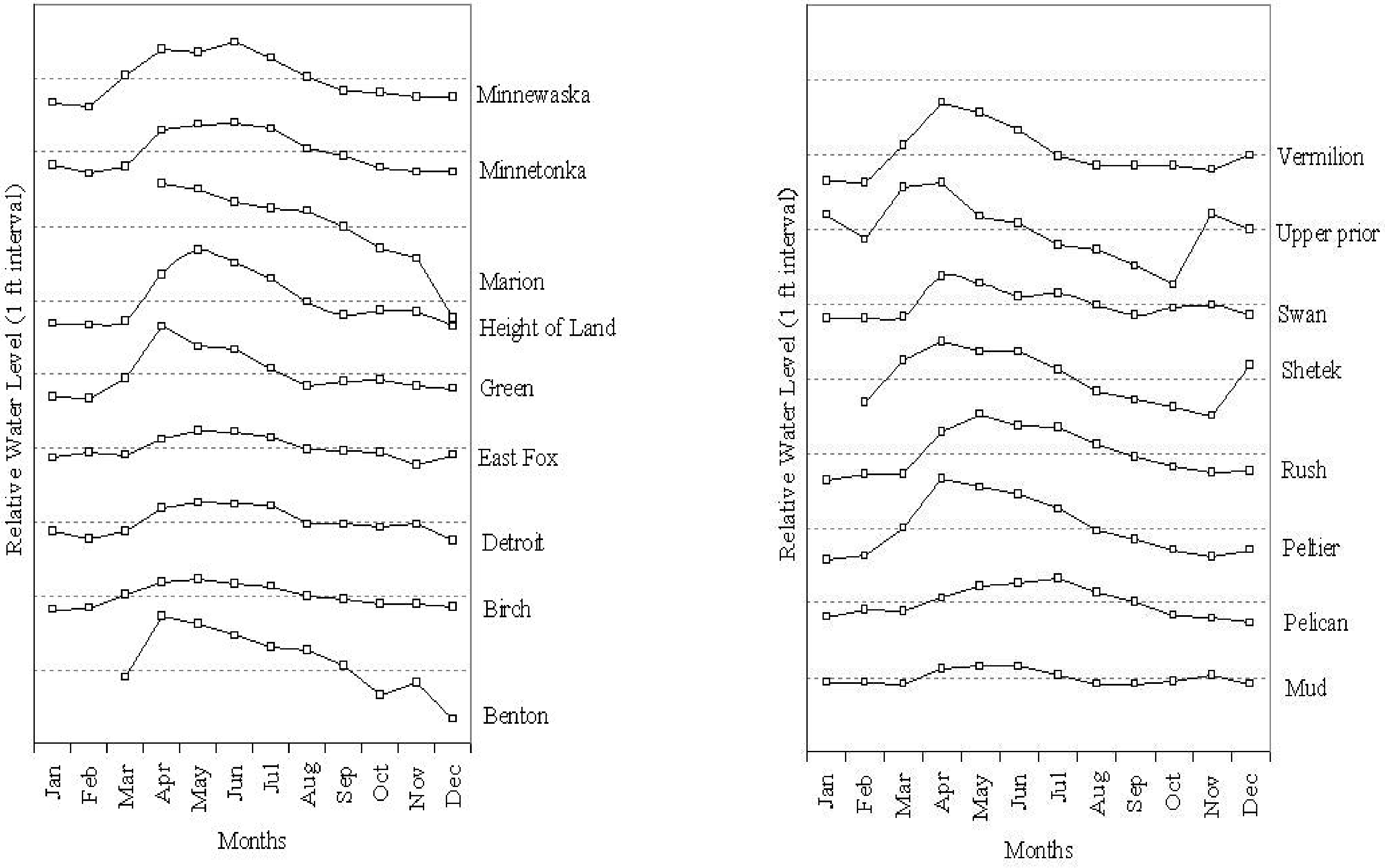

Figure 8. Seasonal water level fluctuations in 17 flow-through lakes in Minnesota. (1 ft = 0.305m)

Table.6. Range and average of annual water level fluctuations in landlocked and flow-through lakes (from DNR-Waters, 2005)

Landlocked Lakes				**Flow-through Lakes**			
Lake name	**Average annual fluctuation (m)**	**Maximum annual fluctuation (m)**	**Number of water years**	**Lake name**	**Average annual fluctuation (m)**	**Maximum annual fluctuation (m)**	**Number of water years**
Belle Taine	0.41	4.38	51	Benton	0.46	1.82	30
Emily	-			Birch	0.41	2.17	75
Island	0.43	2.84	59	Detroit	0.29	0.74	26
Little Sand	0.22	1.06	31	East Fox	0.17	0.71	24
Loon	0.31	1.10	40	Green	0.46	1.50	22
Otter Tail	0.43	1.41	75	Height of Land	0.46	1.36	47
Sturgeon	0.27	1.23	28	Marion	0.63	4.03	46
Swan (Nic)	-			Minnetonka	0.45	2.66	99
				Minnewaska	-		
				Mud	0.40	2.23	37
				Pelican	0.26	1.39	48
				Peltier	-		
				Rush	0.46	1.18	65
				Shetek	0.62	2.34	55
				Swan (Itasca)	0.46	1.42	56
				Upper Prior	0.70	3.72	33
				Vermilion	0.48	0.97	54
Average	**0.35**	**2.00**		**Average**	**0.45**	**1.88**	

6.3. Trends of daily water levels in 25 Minnesota lakes

There are thousands of lakes in Minnesota. We only had long enough records for 25 of these lakes, a very small sample indeed. Trends in these 25 lakes were estimated by applying a linear regression method to the entire water level records, and to the last 20-year segment (i.e.,1987-2007) of the record. The complete period of record for each lake is given in Table 1 and reached back to at least 1957 for all lakes, and as far as 1919 (Otter Tail) for landlocked lakes and 1906 (Minnetonka) for flow-through lakes. The trends in the last twenty years of record (1987-2007) are of particular interest for the study of climate change effects on lake levels.

All of the 8 landlocked lakes, except Swan Lake in Nicollet County had a rising water level trend in the long-term, i.e., over the period of record. In the last 20 years (1987-2006) all landlocked lakes, except Emily and Loon, showed rising lake level trends also (Table 7). The calculated trends for all landlocked lakes, except Sturgeon Lake, were significant at the 0.01 level. Swan Lake and Lake Emily, located in close proximity show water level patterns in the last 20 years that are somewhat different from the long-term pattern (Figure 5 and Table 6).

All of the 17 flow-through lakes investigated, except Swan Lake (Itasca), showed rising water levels (increasing trends) throughout their period of record (Table 8). With the exception of Detroit Lake, Height of Land Lake and Lake Minnewaska all flow-through lakes also showed increasing lake level trends in the last 20 years.

Of the 8 landlocked lakes Belle Taine in Hubbard County had by far the strongest upward water level trend (0.033 m/yr) and an even faster rise (0.054 m/yr) in the last 20 years. Marion Lake was the flow-through lake which stood out with the strongest increasing lake level trends trend (0.023 m/yr for the period of record, and 0.040 m/yr for the last 20 years). By comparison, the medians of the trends over the period of record were 0.007 m/yr and 0.004 m/yr for the landlocked and flow-through lakes, respectively; medians for the last twenty years (1987-2007) were 0.005m/yr and 0.002 m/yr landlocked and flow-through lakes, respectively. It would therefore appear that the data indicate a rising lake level trend both over the long-term (period of record) and over the last 20 years (1987-2007) and that the median rise in lake water level for both the long-term and the most recent 20-year period is on the order of 5 mm/yr.

Table 7. Trends of daily water levels (m/year) in landlocked lakes

Lake name	Trend for period of record	Trend for 1987-2007
Belle Taine	0.033*	0.054*
Emily	0.004*	-0.004
Island	0.022*	0.017*
Little Sand	0.007*	0.007*
Loon	0.008*	-0.012*
Otter Tail	0.006*	0.003*
Sturgeon	0.002	0.000
Swan (Nicollet)	-0.019*	0.030*

* significant at the 0.01 level

Table 8. Trends of daily water levels (m/year) in flow-through lakes

Lake name	Trend for period of record	Trend for 1987-2007
Benton	0.008*	0.031*
Birch	0.003*	0.023*
Detroit	0.004*	-0.005*
East Fox	0.001*	0.000
Green	0.003*	0.020* (I)
Height of Land	0.002*	-0.004
Marion	0.023*	0.040*
Minnetonka	0.010*	0.029*
Minnewaska	0.010*	-0.005*
Mud	0.001*	0.000
Pelican	0.002*	0.002 (I)
Peltier	0.016*	0.001
Rush	0.005*	0.009*
Shetek	0.005*	0.015*
Swan (Itasca)	-0.002*	0.000
Upper Prior	0.018*	0.049*
Vermilion	0.003*	0.000

* significant at the 0.01 level

(I) data not available at the start and/or end of the time period

6.4. Trends of average annual water levels in 25 Minnesota lakes

Annual average lake levels were calculated by averaging the daily data available for each year. The data were therefore considerably reduced in size. The annual values were calculated because averaging could reduce the effect of missing data on the results. It could, however, also introduce a bias if seasonal patterns and data gaps existed.

The trends in annual average lake water levels were tested with the Mann-Kendall test (Test Z) and Sen's slope was also calculated. The trends derived from the daily lake level data and from the mean annual lake levels would be expected to be similar.

Five of the 8 landlocked lakes (Emily, Sturgeon and Swan (Nicollet) are the exceptions) showed an increasing trend significant at the 0.01 level (Table 9). No significant trend was found for the three lakes. The direction of the trends and the magnitude of the trends (Sen's slope) were found to be similar to the trends obtained from linear regression of the daily water level data (Table 9)

Table 9. Trends of annual average water levels in landlocked lakes

Lake name	Years of record	Test Z	Sen's Slope (m/yr)
Belle Taine	58	6.63*	0.030
Emily	54	1.16	0.002
Island	61	6.73*	0.020
Little Sand	42	5.03*	0.007
Loon	44	6.06*	0.009
Otter Tail	82	7.71*	0.007
Sturgeon	42	0.82	0.003
Swan (Nic)	44	-2.43	-0.012

*significant at the 0.01 level.

Table 10. Trends of annual average water levels in flow-through lakes

Lake name	**Years of record**	**Test Z**	**Sen's Slope (m/yr)**
Benton	49	3.09*	0.008
Birch	78	3.56*	0.004
Detroit	41	3.88*	0.004
East Fox	47	3.83*	0.001
Green	49	3.34*	0.004
Height of Land	66	3.01*	0.002
Marion	59	4.24*	0.024
Minnewaska	69	4.31*	0.004
Minnetonka	102	5.63*	0.005
Mud	41	1.74	0.001
Pelican	64	3.44*	0.003
Peltier	56	5.68*	0.008
Rush	72	5.21*	0.005
Shetek	70	5.16*	0.007
Swan (Itasca)	71	3.61*	0.003
Upper Prior	44	2.56	0.015
Vermilion	58	3.96*	0.003

* significant at 0.01 level.

All flow-through lakes showed a rising trend for lake water levels (Table 10). For 15 of the 17 lakes investigated the trend was significant at the 0.01 level. Except for Swan Lake (Itasca), the annual (Table 10) and the daily lake level data (Table 8) gave the same directions and similar magnitudes for the trends in lake levels. The medians of the trends are 0.002 m/yr and 0.001 mm/yr for the landlocked and the flow-through lakes, respectively.

6.5. Trends of May and October water levels in 25 Minnesota lakes

We have already determined trends of Minnesota lake levels in the previous sections. The data were daily and mean annual lake levels. Knowing the seasonal lake level cycles we can also determine trends in the highest and lowest annual lake levels. Based on the previous section we selected the May and October lake levels for this analysis, and the results were as follows.

A positive trend in May water levels was observed in seven of the eight landlocked lakes studied (five lakes had significant trends), but not in Swan (Nicollet) (Table 11). Positive trends in May water levels were also observed in all of the flow-through lakes, except Lake Vermilion (Table 12). Seven flow-through lakes had significant positive trends.

A positive trend in October lake levels was observed in six of landlocked lakes, but not in Sturgeon and Swan (Table 11). The positive trends were significant for all lakes, except Lake Emily. A positive trend in October water levels was also observed in all flow-through lakes, except Mud Lake (Table 12). Eight of the positive trends were significant.

The magnitude of these trends in May and October water levels concurs with those given in Tables 4 to 9 except for lakes Sturgeon, Mud and Vermilion. All three lakes showed a positive trend in daily/annual average lake water levels when the full record was used, but the trend was negative for data for the months of May and October. This is an odd result, because a similarity in trends would be expected over the long term.

Table 11. Trends of May and October water levels in landlocked lakes

	May		**October**	
Lake name	**Test Z**	**Sen’s slope (m/yr)**	**Test Z**	**Sen’s Slope (m/yr)**
Belle Taine	5.24*	0.080	5.35*	0.092
Emily	1.58	0.015	0.42	0.004
Island	3.72*	0.038	6.35*	0.068
Little Sand	4.48*	0.020	3.81*	0.019
Loon	4.16*	0.024	4.05*	0.027
OtterTail	2.94*	0.015	4.61*	0.017
Sturgeon	0.00	0.000	-1.21	-0.021
Swan (Nic)	-0.95	-0.038	-0.67	-0.041

* significant at the 0.01 level

Table 12. Trends of May and October water levels in flow-through lakes

	May		October	
Lake name	**Test-Z**	**Sen's slope (m/yr)**	**Test Z**	**Sen's Slope (m/yr)**
Benton	2.01	0.023	2.31	0.017
Birch	2.89*	0.011	3.89*	0.016
Detroit	3.64*	0.010	2.90*	0.015
East Fox	1.54	0.002	1.78	0.005
Green	0.51	0.003	2.20	0.007
Height of Land	2.23	0.009	1.39	0.004
Marion	3.46*	0.072	2.85*	0.067
Minnetonka	4.72*	0.015	4.35*	0.013
Minnewaska	2.51	0.011	3.40*	0.015
Mud	0.55	0.001	-0.47	-0.001
Pelican	1.93	0.006	1.30	0.005
Peltier	3.85*	0.015	4.26*	0.040
Rush	3.91*	0.015	3.92*	0.014
Shetek	3.42*	0.019	2.99*	0.020
Swan	1.39	0.005	1.72	0.009
Upper Prior	0.54	0.020	1.60	0.043
Vermillion	-0.76	-0.003	1.84	0.007

*significant at the 0.01 level

6.6. Recent trends in water levels in 25 Minnesota lakes

Climate is never stationary (IPCC) and hence lake levels can be expected to be continuously changing. We are concerned especially with lake level changes in the last 20 years (1987-2007). Information presented in the forgoing sections can be summarized as follows:

1) A majority of the 25 lakes studied showed significant positive trends, i.e. increasing lake levels in the past 20 years.
2) There is no indication of a uniform change in trends in the last 20years of record for the 8 landlocked lakes. Compared to the full record length, trends in the past 20 years reversed in 3 of the 8 landlocked lakes studied, accelerated in one lake, and remained about the same in the in the remaining 4 lakes (Table 6).
3) There is also no indication of a uniform change in trends in the last 20years of record for the 17 flow-through lakes. A comparison of water level trends in flow-through lakes in the last 20-year period to trends in the full record (Table 7) shows that 4 lakes reversed trends, 8 accelerated trends, 3 had about the same trends, and 2 lakes had reduced water level trends in recent years compared to the long-term record.
4) Summarizing points 1), 2) and 3) above: there is a weak positive trend in the water levels of the 25 lakes studied, but there is no conclusive evidence for an acceleration of the positive trend.
5) The remaining question is: How long can the positive trend continue, and where will it end?

7. CORRELATIONS OF LAKE LEVELS AND CLIMATE PARAMETERS

7.1. Correlation among lake levels

Climate is a common determinant of lake levels on a regional scale. When several lakes are studied in a region, synchronous fluctuations in lake characteristics or similar long-term patterns can be indicators of climatic change (Magnuson et al. 2006).

If lake water levels are driven predominantly by weather (climate), we would expect lake levels to be strongly correlated with each other, although watershed parameters (topography, land cover and soil characteristics) and hydrogeological parameters would weaken the correlation. The time scale and geographic scale are factors in the correlation because in small lakes with large watersheds water levels will change faster and by more than in large lakes with small watersheds, i.e. ratios such as (lake surface area)/(watershed surface area), (seepage flowrate/precipitation) and (surface runoff/precipitation), for example, will influence the correlation. To avoid the shortest timescales of hydrologic processes we examined correlations among annual average water levels of our 25 lakes in Minnesota.

For landlocked lakes (Table 13), the strongest correlation was observed between water levels of Lake Belle Taine and Little Sand Lake (correlation coefficient = 0.83). Given the diversity of geology, land-use and climate in Minnesota, this is to be expected because the two lakes are located in the same climate region (Division 2 in Table 13). The average correlation coefficient for pairs of landlocked lakes located in the same climate region was 0.50 (0.64 for Division 2, 0.34 for Division 6, 0.52 for Division 8).The average of the correlation coefficients between water levels in any two landlocked lakes, located in any region of Minnesota, was 0.43. Water levels in lakes located in distant climate regions of Minnesota (Appendix 1), e.g., one lake in the central north (Division 2) and the other in the central south (Division 8) had an average correlation coefficient of 0.11, i.e. no correlation. Swan Lake (Nicollet) and Loon Lake in this Division 2/8 set even had a negative correlation coefficient (-0.4). All the others were positive (Table 13).

The strongest relationship among flow-through lakes was observed between Lake Minnetonka and Lake Minnewaska (0.87) (Table 14). All pairs of lakes were positively correlated except for Swan Lake (Itasca) and Detroit Lake which are in very different climate regions. The average of the correlation coefficients of water levels in all pairs of flow-through lakes was 0.41. Water levels in flow-through lakes of the same climate region had an average correlation coefficient of 0.46 (0.33 for Division 1, 0.46 for Division 4, 0.37 for Division 5, 0.47 for Division 6, and 0.67 for Division 7). Water levels in flow-through lakes of very different climate regions (e.g., 1,2, 3 and 7,8, and 9) had an average correlation coefficient of 0.35. The affect of lake location on correlation coefficients can be observed for Division 7. The average correlation coefficient between water levels of Divisions 1 and 7 was 0.31, 0.44 for Divisions 2-7 and 0.40 for Divisions 3-7 although the correlation coefficient between water levels of lakes located in Division 7 (Lakes Benton and Shetek) was 0.67.

Table 13. Correlation of water levels for landlocked lakes

Lake Name	**Belle Taine**	**Emily**	**Island**	**Little Sand**	**Loon**	**Otter Tail**	**Sturgeon**	**Swan**
Climate Division	2	8	6	2	2	4	6	8
Correlation coefficients								
Belle Taine	1.00							
Emily	0.26	1.00						
Island	0.52	0.44	1.00					
Little Sand	0.83	0.34	0.50	1.00				
Loon	0.50	0.25	0.68	0.60	1.00			
Otter Tail	0.76	0.58	0.80	0.70	0.64	1.00		
Sturgeon	0.39	0.43	0.34	0.51	0.33	0.44	1.00	
Swan (Nicollet)	0.10	0.52	0.22	0.10	-0.40	0.16	0.40	1.00

Table 14. Correlation of water levels for flow-through lakes

Lake Name	**Benton**	**Birch**	**Detroit**	**East Fox**	**Green**	**Height of Land**	**Marion**	**Minnetonka**	**Minnewaska**	**Mud**	**Pelican**	**Peltier**	**Rush**	**Shetek**	**Swan**	**Upper Prior**	**Vermillion**
Climate Divisions	7	6	1	6	6	1	9	6	4	5	6	6	4	7	2	5	3
Benton	1.00																
Birch	0.54	1.00															
Detroit	0.10	0.34	1.00														
East Fox	0.40	0.19	0.44	1.00													
Green	0.47	0.60	0.48	0.38	1.00												
Height of Land	0.54	0.36	0.33	0.59	0.30	1.00											
Marion	0.64	0.65	0.38	0.25	0.58	0.25	1.00										
Minnetonka	0.69	0.57	0.35	0.21	0.35	0.30	0.53	1.00									
Minnewaska	0.75	0.44	0.24	0.19	0.32	0.36	0.43	0.87	1.00								
Mud	0.45	0.03	0.32	0.31	0.21	0.21	0.35	0.25	0.51	1.00							
Pelican	0.51	0.57	0.19	0.38	0.51	0.34	0.43	0.79	0.81	0.12	1.00						
Peltier	0.40	0.31	0.20	0.32	0.61	0.13	0.49	0.39	0.38	0.43	0.40	1.00					
Rush	0.50	0.58	0.61	0.49	0.57	0.54	0.59	0.60	0.46	0.32	0.56	0.44	1.00				
Shetek	0.67	0.45	0.30	0.42	0.46	0.30	0.54	0.53	0.43	0.37	0.22	0.41	0.52	1.00			
Swan (Itasca)	0.40	0.23	-0.09	0.30	0.18	0.29	0.35	0.44	0.47	0.40	0.41	0.50	0.42	0.48	1.00		
Upper Prior	0.61	0.59	0.37	0.28	0.46	0.40	0.78	0.76	0.47	0.37	0.51	0.27	0.58	0.66	0.39	1.00	
Vermilion	0.35	0.11	0.04	0.51	0.36	0.44	0.30	0.19	0.36	0.14	0.26	0.48	0.46	0.46	0.47	0.17	1.00

7.2. Correlations of mean annual lake levels with mean annual climate parameters

To address the possible causes of lake level changes more explicitly we examined correlations between lake level changes and climate parameters, especially precipitation, air temperature and dew point temperature. A correlation between long-term lake water levels and long-term precipitation averages is expected and has been found in several studies discussed and referenced earlier. Precipitation not only provides direct water input through the lake water surface, but it is also the source of water input to lakes by surface runoff and/or groundwater flow. Air temperature, dew point temperature, and wind speed are directly related to evaporative water losses, and therefore also reasonable climate parameters to include in the analysis.

We first examined the correlation of average water levels with annual and antecedent precipitation data. Annual precipitation refers to the total precipitation from January to December (12 months) in the same year with water level measurement. We used fairly long time periods for antecedent precipitation because lake level responses are cumulative in time. The correlations coefficients of annual average water levels in the 8 landlocked lakes and the annual precipitation were in the range of 0.12-0.53, and the average was 0.27 (Table 15).

Table 15. Correlation of annual average water levels with precipitation in landlocked lakes

Lake name	**Annual precipitation**	**24-month antecedent precipitation**	**36-month antecedent precipitation**	**48-month antecedent precipitation**	**60-month antecedent precipitation**
Belle Taine	0.22	0.46	0.64	0.72	0.78
Emily	0.16	0.54	0.56	0.51	0.49
Island	0.39	0.62	0.67	0.67	0.67
Little Sand	0.35	0.55	0.65	0.67	0.69
Loon	0.23	0.41	0.35	0.40	0.37
Otter Tail	0.53	0.72	0.78	0.79	0.79
Sturgeon	0.15	0.47	0.55	0.64	0.55
Swan	0.12	0.37	0.46	0.49	0.41
Average	**0.27**	**0.52**	**0.58**	**0.61**	**0.59**

Table 16. Correlation of annual average water levels with precipitation in flow-through lakes

Lake name	Annual precipitation	24-month antecedent precipitation	36-month antecedent precipitation	48-month antecedent precipitation	60-month antecedent precipitation
Benton	0.32	0.67	0.74	0.71	0.67
Birch	0.48	0.72	0.72	0.68	0.61
Detroit	0.38	0.47	0.51	0.47	0.46
East Fox	0.49	0.37	0.43	0.46	0.41
Green	0.39	0.56	0.68	0.58	0.59
Height of Land	0.41	0.46	0.50	0.45	0.44
Marion	0.26	0.57	0.72	0.75	0.76
Minnetonka	0.34	0.55	0.62	0.64	0.65
Minnewaska	0.22	0.48	0.56	0.65	0.69
Mud	0.31	0.33	0.31	0.24	0.17
Pelican	0.38	0.62	0.69	0.75	0.79
Peltier	0.44	0.47	0.47	0.48	0.46
Rush	0.36	0.49	0.59	0.56	0.58
Shetek	0.42	0.60	0.57	0.55	0.48
Swan	0.25	0.36	0.33	0.20	0.38
Upper Prior	0.06	0.36	0.47	0.52	0.52
Vermilion	0.33	0.35	0.24	0.26	0.17
Average	**0.34**	**0.50**	**0.54**	**0.53**	**0.52**

The correlation coefficients of annual average water levels of 17 flow-through lakes and annual precipitation was in the range of 0.06-0.49 with an average of 0.34 (Table 16). Water levels in landlocked lakes had the highest average correlation with 48-month antecedent precipitation (0.61), while water levels of flow-through lakes were correlated best with 36-

month antecedent precipitation (0.54). Although high correlation with antecedent precipitation was observed for some lakes, in general the correlation of water levels with antecedent precipitation was moderate for both landlocked and flow-through lakes. Long-term rather than short-term (i.e., annual or 12-month) precipitation was more effective in determination of water levels in lakes.

We identified 10 years with highest and lowest water levels for all lakes and conducted a correlation analysis to understand if extremely high and low water levels in lakes are related to annual and antecedent precipitation. Although the analyses provided higher correlations with precipitation for some lakes (e.g., Lake Emily and Lake Minnetonka), the results were not consistent for all lakes. Some lakes (e.g., Lake Otter Tail and Lake Height of Land) showed very low (even negative) correlations with precipitation. Overall average correlation values were very low (on the order of 0.10s-0.30s for landlocked lakes and 0.10s-0.20s for flow-through lakes). These results may suggest that extreme water levels are probably due to a combination of climatic factors rather than changes in precipitation patterns.

We also examined the correlations between annual average water levels of lakes and annual, May-October and June-August average air temperature and annual average dew point, May-October and June August dew point data. The air temperature data used in the analysis are average air temperature for appropriate climate divisions. Dew point data was obtained from the weather stations (if available) closest to the each lake. We did not include average antecedent air temperature and dew point temperature in the analyses, because the change from one year to another was low for these parameters. Correlation coefficients between annual average water levels of landlocked lakes and annual average air temperature were in the range of -0.33-0.50 with an average of 0.14 (Table 17). The correlations of water levels with May-

October and June-August average air temperatures provided average correlation coefficients of -0.07 and -0.02 (Table 17). Correlation coefficients between annual average water levels of flow-through lakes and annual average air temperature were in the range of -0.16-0.52 with an average of 0.09 (Table 18). The correlations of water levels with May-October and June-August average air temperatures provided average correlation coefficients of -0.07 and -0.08 (Table 18). Correlation coefficients of extremely high and low water levels with air temperature were also very low. The correlation coefficients calculated for both landlocked lakes and flow-through lakes are much lower than expected and show that there is almost no correlation between average annual water levels and air temperatures.

Correlation coefficients between annual average water levels of landlocked lakes and annual average dew point temperatures were in the range of 0.09-0.62 with an average of 0.34. The correlations of annual average water levels of flow-through lakes with annual average dew point temperatures provided average correlation coefficients of in the range of -0.08 and 0.50 with an average of 0.21. Correlation coefficients of extremely high and low water levels with dew point temperatures were also very low (average correlation coefficients were lower that 0.25 for both landlocked and flow-through lakes). Although correlations of water levels with dew point temperatures seem to be stronger than correlations with air temperatures, they are still weak to come to a conclusion that changes in dew point temperatures are responsible for lake level changes.

Table 17. Correlation of annual average water levels with air and dew point temperatures for landlocked lakes.

Lake name	**Corr. with annual average air temp.**	**Corr. with May-October average air temp.**	**Corr. with June-August average air temp.**	**Corr. with annual average dew point**	**Corr. with May-October average dew point**	**Corr. with June-August average dew point**
Belle Taine	0.40	-0.08	-0.05	0.41	0.14	0.23
Emily	-0.10	-0.27	-0.14			
Island	0.15	0.20	0.14	0.07	0.06	0.00
Little Sand	0.50	0.06	0.16	0.62	0.36	0.35
Loon	0.35	0.00	-0.02	0.45	0.23	0.23
Otter Tail	-0.03	-0.21	-0.25	0.36	0.32	0.22
Sturgeon	0.14	0.09	0.13	0.22	0.06	0.15
Swan	-0.33	-0.33	-0.13			
Average	**0.14**	**-0.07**	**-0.02**	**0.36**	**0.20**	**0.20**

Table 18. Correlation of annual average water levels with air and dew point temperatures for flow-through lakes.

Lake name	Corr. with annual average air temp.	Corr. with May-October average air temp.	Corr. with June-August average air temp.	Corr. with annual average dew point	Corr. with May-October average dew point	Corr. with June-August average dew point
Benton	-0.09	-0.34	-0.15	0.39	0.34	0.38
Birch	0.06	-0.21	-0.23	0.18	0.07	0.11
Detroit	0.52	0.38	0.20	0.50	0.34	0.30
East Fox	0.21	0.18	0.07	0.39	0.34	0.37
Green	0.28	0.14	0.23	0.36	0.23	0.44
Height of Land	-0.07	-0.16	-0.11	0.17	0.27	0.29
Marion	0.31	-0.02	0.03			
Minnetonka	0.09	-0.14	-0.20	0.12	0.05	0.03
Minnewaska	0.10	-0.14	-0.25	-0.03	0.06	-0.04
Mud	0.23	0.26	0.10	0.18	0.13	0.19
Pelican	0.18	-0.14	-0.23	0.15	-0.06	0.21
Peltier	0.09	-0.12	-0.12	0.11	0.05	-0.01
Rush	-0.08	-0.28	-0.24	0.23	0.26	0.09
Shetek	-0.16	-0.19	-0.16	0.44	0.49	0.37
Swan	-0.09	-0.10	-0.09	-0.08	-0.02	0.03
Upper Prior	0.13	-0.03	-0.01	0.28	0.13	0.08
Vermilion	-0.14	-0.33	-0.25	-0.01	0.30	-0.03
Average	**0.09**	**-0.07**	**-0.08**	**0.21**	**0.19**	**0.17**

7.3. Correlations of May lake levels with antecedent precipitation

To moved closer to a process-oriented analysis we correlated the high lake water levels after snowmelt (May) with the antecedent 6-month to 60-month total precipitation. The results are shown in Tables 19 and 20.

The correlations coefficients of May water levels in the 8 landlocked lakes and the 12-month antecedent precipitation were in the range of 0.12-0.68, and the average was 0.47 (Table 19). These are disappointingly low values indicating only a weak correlation with antecedent annual precipitation. The correlation coefficients with 6-month antecedent precipitation were even lower, with a range of -0.12 to 0.46 and an average of 0.22 (Table 19). The best correlation was obtained with 36-month antecedent precipitation. The correlation coefficient range was 0.38 to 0.70 with an average of 0.63 (Table 19).

The correlation coefficients between May lake levels in the 17 flow-through lakes and the 12-month antecedent precipitation were in the range of 0.19-0.71, with an average of 0.48 (Table 20). The correlation coefficients with 6-month antecedent precipitation were again significantly lower, with a range of 0.01-0.64 and an average of only 0.32. The best correlation of May lake levels was obtained with12-month and 24-month precipitation. The correlation coefficient range for 12-month and 24-month antecedent precipitation was 0.19 to 0.71 and 0.10 to 0.74, respectively, with an average of 0.48 (Table 20).

Table 19. Correlation coefficient of May water levels in landlocked lakes with antecedent precipitation.

Lake name	**Corr. with 6-month antec. precip.**	**Corr. with 12-month antec. precip.**	**Corr. with 24-month antec. precip.**	**Corr. with 36-month antec. precip.**	**Corr. with 48-month antec. precip**	**Corr. with 60-month antec. precip**
Belle Taine	0.10	0.36	0.56	0.78	0.75	0.78
Emily	0.37	0.56	0.63	0.52	0.52	0.36
Island	0.46	0.60	0.68	0.66	0.69	0.67
Little Sand	0.32	0.44	0.61	0.69	0.65	0.68
Loon	-0.07	0.12	0.36	0.38	0.33	0.29
OtterTail	0.38	0.60	0.67	0.67	0.72	0.72
Sturgeon	-0.12	0.38	0.64	0.74	0.71	0.55
Swan (Nic)	0.32	0.68	0.65	0.60	0.58	0.55
Average	**0.22**	**0.47**	**0.60**	**0.63**	**0.62**	**0.57**

Table 20. Correlation coefficient of May water levels in flow-through lakes with antecedent precipitation.

Lake name	Corr. with 6-month antec. precip.	Corr. with 12-month antec. precip.	Corr. with 24-month antec. precip.	Corr. with 36-month antec. precip.	Corr. with 48-month antec. precip	Corr. with 60-month antec. precip
Benton	0.36	0.71	0.74	0.69	0.64	0.52
Birch	0.35	0.67	0.66	0.62	0.56	0.47
Detroit	0.42	0.54	0.63	0.63	0.28	0.30
East Fox	0.48	0.19	0.10	0.07	0.19	0.22
Green	0.60	0.55	0.27	0.42	0.30	0.10
Height of Land	0.45	0.57	0.49	0.39	0.17	0.20
Marion	0.19	0.52	0.66	0.73	0.75	0.76
Minnetonka	0.08	0.44	0.55	0.59	0.59	0.60
Minnewasha	0.01	0.27	0.49	0.49	0.51	0.52
Mud	0.41	0.36	0.33	0.19	0.22	0.17
Pelican	0.03	0.37	0.52	0.57	0.60	0.62
Peltier	0.35	0.30	0.31	0.34	0.32	0.36
Rush	0.36	0.48	0.41	0.39	0.47	0.49
Shetek	0.38	0.61	0.62	0.54	0.16	0.14
Swan	0.30	0.46	0.36	0.21	0.45	0.42
Upper prior	0.01	0.50	0.54	0.62	0.54	0.42
Vermillion	0.64	0.59	0.50	0.35	0.27	0.23
Average	**0.32**	**0.48**	**0.48**	**0.46**	**0.41**	**0.38**

7.4. Correlations of October lake levels with antecedent air and dew point temperatures

The correlations coefficients of October water levels in landlocked lakes with antecedent May-October air temperatures were in the range from -0.38 to 0.25 with an average of -0.11 (Table 21). The negative correlation is plausible since warmer air temperatures are likely to lead to more evaporation, but the correlation coefficient is very weak. The correlation coefficients of October lake levels with June-August air temperatures, i.e., for a shorter period, were even poorer with a range from -0.43 to 0.33, and an average of -0.06.

Dew point temperature is a better measure of evaporation potential than air temperature. For landlocked lakes the correlation coefficients of October water levels with June-August dew point temperatures ranged from 0.07 to 0.42 with an average of 0.26. The June-August period covers the 3 months with the largest evaporative water losses. The positive correlation is meaningful because a higher dew point is associated with less evaporation, hence higher lake levels. The correlation was in the range of 0.11-0.47 with an average of 0.36 when May-October dew point temperatures were chosen (Table 21).

For flow-thorough lakes, the correlations coefficients of October water levels with May-October air temperatures ranged from -0.28 to 0.43 with an average of -0.10 (Table 22). The correlation coefficients of October water levels with June-August air temperatures was in the range from -0.40 to 0.30 with an average of -0.11. The correlation coefficients of October water levels with June-August dew point temperature ranged between -0.24 and 0.50 with an average of 0.15. It improved to a range from -0.27 to 0.67 with an average of 0.19 when May-October dew point temperatures were chosen.

Table 21. Correlation coefficient of October water levels in landlocked lakes with air and dew point temperatures.

Lake name	**Corr. with May-October average air temp.**	**Corr. with June-August average air temp.**	**Corr. with May-October average dew point**	**Corr. with June-August average dew point**
Belle Taine	-0.13	-0.08	0.47	0.18
Emily	-0.24	-0.29		
Island	0.25	0.13	0.17	0.16
Little Sand	0.06	0.33	0.63	0.40
Loon	0.16	0.04	0.42	0.31
OtterTail	-0.38	-0.43	0.38	0.42
Sturgeon	-0.21	0.05	0.11	0.07
Swan	-0.35	-0.26		
Average	**-0.11**	**-0.06**	**0.36**	**0.26**

Table 22. Correlation coefficient of October water levels in flow-through lakes with air and dew point temperatures.

Lake name	Corr. with May-October average air temp.	Corr. with June-August average air temp.	Corr. with May-October average dew point	Corr. with June-August average dew point
Benton	-0.15	0.20	0.37	0.50
Birch	-0.24	-0.25	0.16	0.16
Detroit	0.43	0.24	0.38	0.29
East Fox	-0.04	-0.10	0.08	-0.24
Green	0.03	0.30	-0.16	0.49
Height of Land	-0.21	-0.29	0.46	0.27
Marion	-0.10	-0.04		
Minnetonka	-0.22	-0.25	0.11	0.05
Minnewasha	-0.03	-0.13	0.20	0.11
Mud	-0.28	-0.40	-0.12	0.12
Pelican	-0.16	-0.05	-0.07	0.22
Peltier	-0.14	-0.27	0.14	-0.02
Rush	-0.28	-0.24	0.36	0.21
Shetek	-0.03	-0.16	0.67	0.35
Swan	0.00	-0.08	0.08	0.04
Upper Prior	-0.20	-0.10	0.00	0.17
Vermillion	0.16	0.77	-0.27	0.27
Average	-0.10	-0.11	0.15	0.19

7.5. Multivariate regression of lake levels with climate variables

We estimated parameter values X and Y in Eq 9 for selected lakes (lakes which have the most continuous records) and selected time periods (where continuous data are available). We used both daily and monthly average values to estimate the parameters. Our multi-variate regression did not provide a significant improvement of the results obtained by single variable regression (correlation). The value obtained for variable X (which denotes the correlation with precipitation) was almost the same as the correlation coefficient obtained from single variable regression. We found a weak positive correlation with the evaporation term (low and positive Y value) although we expected a strong negative correlation. One reason that explains these unexpected results could be omission of surface water and ground water inflow, surface water outflow components. Lake water budgets are the result of complex interactions of multiple variables and cannot be well explained with selective variables in most cases.

8. PROJECTIONS FOR MINNESOTA CLIMATE AND LAKE LEVELS

8.1. Projections of climatic and hydrologic changes in Minnesota

It is projected that air temperature and precipitation in Minnesota will continue to increase in the next century (Kling et al. 2003). Based on the results from the United Kingdom Hadley Centre's climate model (HadCM2) and projections of the Intergovernmental Panel on Climate Change (IPCC), the increase in air temperature is expected in all seasons around 2.2 oC (4°F with a range of 2 to 7°F) (Anonymous 1997). Precipitation is projected to increase by about 15% in summer, fall and winter and to remain mostly stable for spring (Anonymous 1997). Along with these changes, evaporation is projected to increase, which will affect the amount of runoff to the lakes and streams and infiltration to ground water (Kling et al. 2003). Lake evaporation could increase by 20% (102 to 178 mm or 4 to 7 inches) for a 4°F warmer climate (Anonymous 1997). Increased water losses by evaporation could decrease lake levels but increased precipitation could compensate for the additional losses. The difference between increases in precipitation and increases in evaporation is projected to remain the same or become positive in fall, winter and spring and negative in summer in the next century (Kling et al. 2003).

In previous simulations of lake temperatures in Minnesota, Stefan et al. (1998) used the a 2xCO2 climate scenario relative to past climate (1955-1979) shown in Table 23. The values came from GCM simulations of the Canadian Climate Center.

Table 23. Weather parameter increments and ratios for Minnesota. Values were obtained from the Canadian Climate Center General Circulation Model (CCC GCM) for a 2xCO2 climate scenario (Stefan et al. 1998).

Month	Air temperature (^{o}C)[a]	Solar radiation ratio[b]	Wind speed ratio[b]	Specific humidity ratio[b]	Precipitation ratio[b]
Jan	8.17	0.94	1.08	1.85	1.23
Feb	8.5	0.92	1.1	1.94	1.26
Mar	4.37	0.95	0.88	1.53	1.22
Apr	5.76	0.95	1.01	1.78	1.5
May	5.39	0.97	0.97	1.46	1.05
Jun	4.27	0.96	0.85	1.32	0.99
Jul	3.54	0.96	0.8	1.23	0.87
Aug	5.24	0.99	0.83	1.35	0.87
Sep	4.51	0.99	0.9	1.29	0.79
Oct	2.71	0.98	1.01	1.19	0.96
Nov	2.9	1.01	1.02	1.29	0.96
Dec	4.38	1	0.91	1.25	0.97
Average	4.98	0.97	0.95	1.46	1.06

a Increment = 2xCO2 CCC GCM output – 1xCO2 CCC GCM output

b Ratio = 2xCO2 CCC GCM output divided by 1xCO2 CCC GCM output

8.2. Projections of lake level changes in Minnesota

Despite the increase in average global temperature and projections that show evaporation rates will increase in the future, Peterson et al. (1995) found a downward trend in pan evaporation rates over most of the United States and former Soviet Union over the last century. According to Roderick (2002), these decreases are caused by a decrease in solar radiation due to increasing cloud cover and aerosol concentrations. If pan evaporation rates continue to decrease or stay stable, lake levels can be expected to become higher due to increased precipitation.

Our analysis of the water level records from 25 lakes leads to the conclusion that there is a weak positive trend in the water levels of the 25 lakes studied, but there is no conclusive evidence for an acceleration of the positive trend. Increasing trends can be due to climatic factors (i.e., increasing precipitation and decreasing evaporation rates) or non-climatic factors (i.e., land-use changes).

If the current trends in lake levels continue, we may expect 0.08-0.75 m increase in water levels in landlocked lakes and 0.03-0.60 m increase in flow-through lakes included in this study in the next 23 years. Water levels of Lake Swan (Nicollet), which is the only lake with a negative trend, can decrease by 0.30 m by 2030. The change in water levels in some lakes (e.g., Lake Belle Taine with 0.75 m and Lake Marion with 0.60 m increase) can be very significant.

9. SUMMARY AND CONCLUSIONS

We analyzed historical water levels in 25 Minnesota lakes. Eight were landlocked lakes and seventeen were flow-through lakes. The data were daily values, but substantial gaps existed. The longest record reached back to 1906 (Lake Minnetonka and Upper Prior Lake in Scott County). We determined statistical parameters such as annual mean values and seasonal variations of the historical lake water levels. Linear regression and Mann-Kendall test were used to evaluate the presence of trends in daily, mean annual, spring (May) and fall (October) water levels.

The majority of the 25 lakes showed increasing trends (rising water levels) in the last century (1906 to 2007) (Tables 1 and 2). The strongest upward trend was observed in a landlocked lake (Lake Belle Taine in Hubbard County) where the rate was 0.030 m/yr. The second largest increase was observed in a flow-through lake (Marion Lake in Dakota County) with a rate of 0.024 m/yr. Swan Lake (in Nicollet County) was the only landlocked lake that showed a falling trend with a rate of 0.011 m/yr. Swan Lake (in Itasca County) was the only landlocked lake that had a negative trend (0.002 m/yr) in daily water levels, but it showed a positive trend when annual average water levels were used.

The analysis also showed that lake levels have been increasing in most of the 25 lakes in the last 20-years (1987-2006). One landlocked lake and eight flow-through lakes showed their strongest upward trends in the last 20 years. Five of the eight landlocked lakes and eleven of the seventeen flow-through lakes reached their highest recorded levels after 1990. Upward trends in recorded lake water levels were found in both spring (May) and fall (October) in the majority of the 25 lakes analyzed.

We also attempted to understand how Minnesota lake levels have responded to climate changes. Correlation coefficients were calculated between annual lake water levels and mean annual climate variables such as precipitation, dew point and air temperature.

The correlation of water levels with precipitation was moderate while correlations of water levels with dew point and air temperatures were weak. The correlation coefficients of average water levels were largest with 48- and 36-month antecedent precipitation for landlocked lakes and flow-through lakes, respectively. A multivariate regression of lake levels did not provide a significant improvement of the correlations probably due to the omission of significant components in the water budget equation such as groundwater and surface water flows.

The correlation between mean annual lake levels was strongest among lakes in the same climate regions and weakest among lakes in distant climate regions. Some lakes in the same Minnesota climate region (with similar precipitation and temperature characteristics) had correlation coefficients of 0.78, while those in distant regions had low and even negative correlation coefficients. The average of the correlation coefficients among water levels in all lakes was 0.43 for the eight landlocked lakes and 0.41 for the seventeen flow-through lakes investigated.

Overall, analyses of the lake levels showed that changes have been observed in lake levels in Minnesota in the last century and in the last 20 years. The majority of the lakes showed an upward trend (rising lake levels). However, the correlation between climate parameters and lake levels was weak. The regional consistency in lake level responses is perhaps the strongest indicator of a climate effect. If the trends continue, lakes included in this study may experience water level increase up to 0.75 m by 2030.

ACKNOWLEDGEMENTS

This study was conducted with funding from the Minnesota Citizens Committee on Minnesota Resources, St Paul, Minnesota, to the University of Minnesota. The grant was coordinated by Lucinda Johnson from the Natural Resources Research Institute in Duluth.

The lake level data used in this study came from a database of the Minnesota Department of Natural Resources in St. Paul. Weather data were extracted from the database of the State Climatologist Office. We thank these institutions and individuals for their help and co-operation.

REFERENCES

Abdul Aziz, O. and D. Burn. 2006. Trends and variability in the hydrological regime of the mackenzie river basin. Journal of Hydrology: 282–294.

Anonymous. 1997. Climate Change and Minnesota. United States Environmental Protection Agency (EPA), Office of Policy, Planning and Evaluation, Washington, D.C.

Anonymous. 2005. Devils Lake Quick Facts. Pages Available at: http://www.swc.state.nd.us/4dlink9/4dcgi/GetContentPDF/PB-206/DL_Quick_Facts.pdf.

Brown, R. G. 1985. Hydrologic Factors Affecting Lake-Level Fluctuations in Big Marine Lake, Washington County, Minnesota. U.S. Geological Survey Water Resources Investigations Report 85-4176, Denver, CO.

Cengiz, T. M. and E. Kahya. 2006. Türkiye göl su seviyelerinin egilim ve harmonik analizi (Trends and first harmonic analysis of Turkish lake levels). Istanbul Teknik Universitesi Dergisi (Istanbul Technical University Journal) 5: 215-224.

Changnon, S. A. 2004. Temporal behaviour of levels of the Great Lakes and Climate Variability. Journal of Great Lakes Research 30: 184-200.

Changnon, S. A. and K. E. Kunkel. 1995. Climate-related fluctuations in Midwestern Floods During 1921-1985. Journal of Water Resources Planning and Management 121: 326-334.

Christensen, V. G. and A. L. Bergman. 2005. Hydrologic Conditions and Lake-Level Fluctuations at Long Lost Lake, 1939–2004, White Earth Indian Reservation, Clearwater County. U.S. Geological Survey Scientific Investigations Report 2005–5181, Reston, VI.

DNR-Waters. 2005. Water year data summary, 2003 and 2004. Minnesota Department of Natural Resources, St. Paul, MN.

Fellows, C. R. and P. L. Brezonik. 1980. Seepage flow into Florida Lakes. Water Resources Bulletin 16: 635-641.

Gleick, P. G. 2000. Water - The Potential Consequences of Climate Variability and Change. Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA.

Johnson, S. L. and H. G. Stefan. 2006. Indicators of climatewarming in Minnesota: Lake ice covers and snowmelt runoff. Climatic Change 75: 421–453.

Kendall, M. G. 1975. Rank Correlation Methods, Griffin, London.

Kling, G. W., K. Hayhoe, L. B. Johnson, J. J. Magnuson, S. Polasky, B. J. Robinson, M. M. Wander, D. J. Wuebbles, D. R. Zak, R. L. Lindroth, S. C. Moser, and M. L. Wilson. 2003. Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems. The Union of Concerned Scientists, Cambridge, MA and The Ecological Society of America, Washington, D.C.

Lins, H. F. and J. R. Slack. 1999. Stream flow trends in the United States. Geophysical Research Letters 26: 227-230.

Magnuson, J. J., B. J. Benson, J. D. Lenters, and D. M. Robertson. 2006. Climate-driven variability and change. p 123-150. *In* J. J. Magnuson, T. K. Kratz, and B. J. Benson (ed) Long-Term Dynamics of Lakes in the Landscape: Long-Term Ecological Research on North Temperate Lakes. Oxford University Press, New York, NY.

Mann, H. B. 1945. Non-Parametric tests against trend. Econometrica 13: 245–259.

Mann, W. B. and M. S. McBride. 1972. The hydrologic balance of Lake Sallie, Becker County, Minnesota. Pages 189-191. U.S. Geological Survey Professional Paper, 800-D.

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

Peterson, T. C., V. S. Golubev, and P. Y. Grolsman. 1995. Evaporation losing its strength. Nature 377.

Roderick, M. L. and G. D. Farquhar. 2002. The Cause of Decreased Pan Evaporation over the Past 50 Years. Science 298: 1410-1411.

Rosenberry, D. O., T. C. Winter, D. A. Merk, G. H. Leavesley, and L. D. Beaver. 1997. Hydrology of the Shingobee River Headwaters Area. p 19-24. *In* T. C. Winter (ed.) Hydrological and biogeochemical research in the Shingobee River Headwaters Area, north-central Minnesota. U.S. Geological Survey Water Investigations Report 96-4215, Denver, CO.

Seeley, M. 2003. Climate trends: what are some implications for Minnesota’s air and water resources? Pages Available from http://www.pca.state.mn.us/air/pubs/climatechange-seeley-1103.pdf.

Sen, P. K. 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of American Statistical Association 39: 1379-1389.

Stefan, H. G., X. Fang, and M. Hondzo. 1998. Simulated climate change effects on year-round water temperatures in temperate zone lakes. Climatic Change 40: 547–576.

Svensson, C., Z. W. Kundzewicz, and T. Mauer. 2005. Trend detection in river flow series: 2. Flood and low-flow index series. Hydrological Sciences 50: 811-824.

Vining, K. C. 2003. Estimation of Monthly Evaporation from Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota, 1931-

2001. U.S. Geological Survey Water-Resources Investigations Report 03-4282, Bismarck, ND.

Watson, B. J., L. H. Motz, and M. D. Annable. 2001. Water Budget and Vertical Conductance for Magnolia Lake. Journal of Hydrologic Engineering, American Society of Civil Engineers, 6: 208-216.

Wiche, G. J. and A. V. Vecchia. 2000. Climatology, Hydrology, and Simulation of an Emergency Outlet, Devils Lake Basin, North Dakota. USGS.

Winter, T. C. 1981. Uncertainties in Estimating the Water Balance of Lakes. Water Resources Bulletin 17: 82-115.

Winter, T. C., ed. 1997. Hydrological and biogeochemical research in the Shingobee River Headwaters Area, north-central Minnesota. U.S. Geological Survey, Denver, CO.

Appendix: Minnesota climate divisions and counties.

http://www.cpc.noaa.gov/products/analysis_monitoring/regional_monitoring/CLIMDIVS/minnesota.gif