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

Project Report No. 506

Lake Evaporation Response to Climate in Minnesota

by

Filiz Dadaser-Celik

and

Heinz G. Stefan

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

March 2008
Minneapolis, Minnesota

Abstract

In this report we analyze the variability of water losses by evaporation from lake surfaces in Minnesota, and trends in lake evaporation for the period 1964 – 2005. Daily evaporation rates were estimated using a mass-transfer equation with recorded daily weather data as input. The weather data came from six Class A weather stations (International Falls, Duluth, Minneaplis/St. Paul, LaCrosse, WI, Sioux Falls, SD, and Fargo, ND). Annual (Jan-Dec) lake evaporation ignoring lake ice-covers and annual evaporation for the actual open-water season were computed from the daily values. Trends in annual evaporation over the periods 1964 – 2005 and 1986 – 2005 were determined using a linear regression method. The trend analysis was repeated for annual water availability (precipitation minus evaporation). Finally correlation coefficients between annual average water levels of 25 Minnesota lakes, and annual evaporation or annual water availability were calculated.

In the last 40 years (1964 – 2005), annual average open-water season evaporation ranged from 580 to 747 mm/yr (22.8 to 29.4 in/yr) at the six locations. The trend over the 1964 – 2005 period was upward (rising) at three stations (International Falls, Duluth, and Sioux Falls), and downward (falling) at three stations (Fargo, Minneapolis, and La Crosse). The strongest upward trend in evaporation (0.64 mm/yr) was for Duluth and the strongest downward trend (-1.65 mm/yr) for La Crosse. Annual evaporation for the 12-month (Jan-Dec) period, i.e., disregarding ice covers, was from 79 mm/yr (3.1 in/yr) to 140 mm/yr (5.5in/yr) higher than annual evaporation computed for the open-water season at the six locations.

In the last 20-years (1986–2005) annual open-water season evaporation had a decreasing trend at five of the six locations. The decreasing trends were stronger than for the 1964 – 2005 period and ranged from -0.69 for International Falls and Minneapolis to -1.57mm/yr for La Crosse. The only positive trend was 1.09mm/yr for Sioux Falls.

Annual average measured precipitation for the 1964 – 2005 period at the six locations ranged from 536mm/yr to 812 mm/yr (21.1 in/yr to 32.0 in/yr) and showed a rising trend at four of the six stations (International Falls and Duluth were the exceptions). For the 1986 – 2005 period precipitation showed an increasing trend at all stations except Duluth and La Crosse.

Water availability, calculated as the difference between annual open-water season precipitation and annual open-water evaporation, showed upward trends at all stations from 1964 to 2005. The trends ranged from 0.05mm/yr for Duluth to 4.27mm/yr for Fargo. From 1986 to 2005 five locations showed an upward trend and one a downward trend in water availability. The five upward trends were much stronger than for the 1964 – 2005 period, ranging from 0.58mm/yr for La Crosse to 15.06 mm/yr for Fargo. The only downward trend was -2.67mm/yr for Duluth.

Overall, the analysis showed that positive and negative trends in lake evaporation have occurred in Minnesota in the last 40 years. Trends in measured precipitation during the same time period were stronger and upwards. As a result, water availability in Minnesota also has an upward trend. No strong correlation between lake levels, annual evaporation rates or annual water availability was found, but the increase in water availability can explain the observed water level increases in 25 Minnesota lakes.

TABLE OF CONTENTS

1. INTRODUCTION

About a foot of water is lost annually by evaporation from Minnesota lakes, more in the south and less in the north. In this report we examine lake evaporation in Minnesota in the last four decades and relate this information to climate and observed lake water levels. Trends are of particular interest.

Precipitation and evaporation are the amounts of water received and emitted at a lake's surface. They are component of a lake's water budget which also includes surface inflow from the watershed, surface outflow from a lake to a stream, seepage and ground-water recharge from a lake, and storage resulting in lake level change. The water budget of a lake can be stated as:

$$\Delta L/\Delta t = P - E + I - O + GI - GO \qquad (1)$$

In Equation (1), P refers to precipitation on the lake surface, E is evaporation from the lake surface, I is surface runoff from a watershed into a lake, GI is ground-water inflow, and GO is ground-water outflow. All water budget components can be expressed as flow per unit surface area of a lake, e.g., in units of mm/yr. L is the water level in mm and Δt is a time interval, typically one year.

Changes in Minnesota's climate (recorded weather) in recent years have increased the concern for changes in annual evaporation rates and the consequences for lake levels and water availability from lakes. Seeley (2003) reported that Minnesota is now having warmer winters, higher minimum air temperatures, higher frequency of tropical dew points, and greater annual precipitation. Air temperature and precipitation showed rising trends of 2 – 3°C/100 years and 5-10%/100 years , respectively, from 1900 to 1994 (Gleick, 2000). Effects of a changing climate have already been identified in some of Minnesota's water resources (Changnon and Kunkel, 1995; Johnson and Stefan, 2006; Novotny and Stefan, 2007). Although evaporation is one of the most important parameters affecting water resources in Minnesota, no studies of changes in this parameter have yet been conducted.

Mean annual lake evaporation and mean summer evaporation in the United States including Minnesota are given in Figures 1 and 2. The maps were developed by a Minnesota hydrologist (Adolph Meyer) and published in 1942. Meyer (1942) conducted extensive studies on lake evaporation in Minnesota, and developed an evaporation equation that we will use. In Meyer's studies (Meyer 1942), mean annual lake evaporation in Minnesota was in the range 559 - 914 mm (22 - 40 in), while mean summer evaporation was in the range 508 - 889 mm (20 - 35 in). Evaporation rates vary with geographic location and increase from north to south. According to an unpublished report prepared by the National Climatic Data Center (NCDC), annual lake evaporation in Minnesota ranges from 508 mm (20 in) at the northeast corner to 889 mm (35 in) at the southwest corner (NCDC, unpublished report). Pan evaporation varies from 762 mm (30 in) to 1270 mm (50 in)(NCDC, unpublished report) .

Another noteworthy study on lake evaporation in Minnesota was conducted by Sturrock, Rosenberry, and Winter (1992) on Williams Lake in central Minnesota. In this study evaporation from May to September for the 1982 – 1986 period was estimated using both energy budget and mass-transfer methods. Evaporation for the May – September period was found to be 419 mm (16.5 in) with the energy balance method and 427 mm (16.8 in) with the mass transfer method (Sturrock et al., 1992).

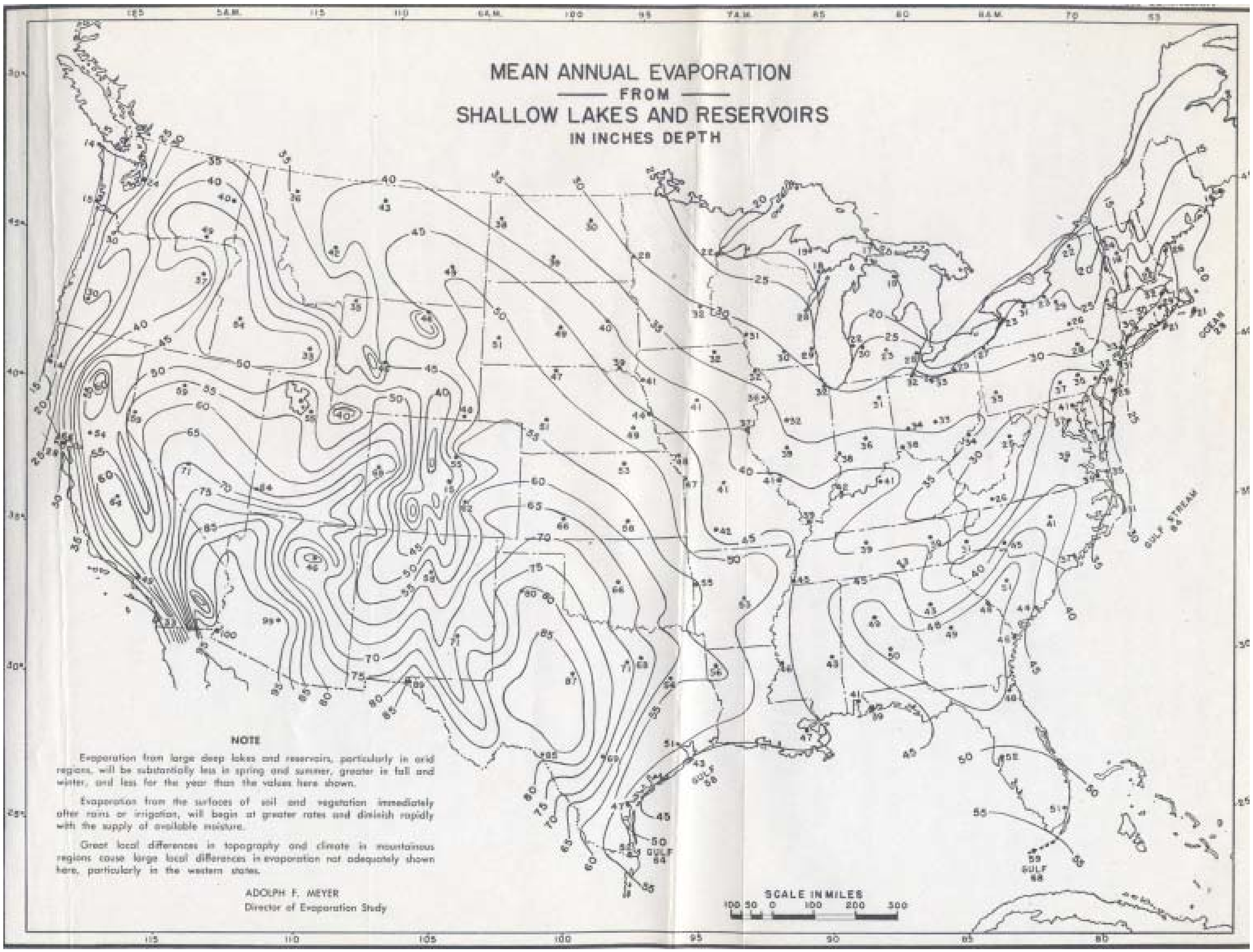

Figure 1.Mean annual lake evaporation in the U.S. (Meyer, 1942).

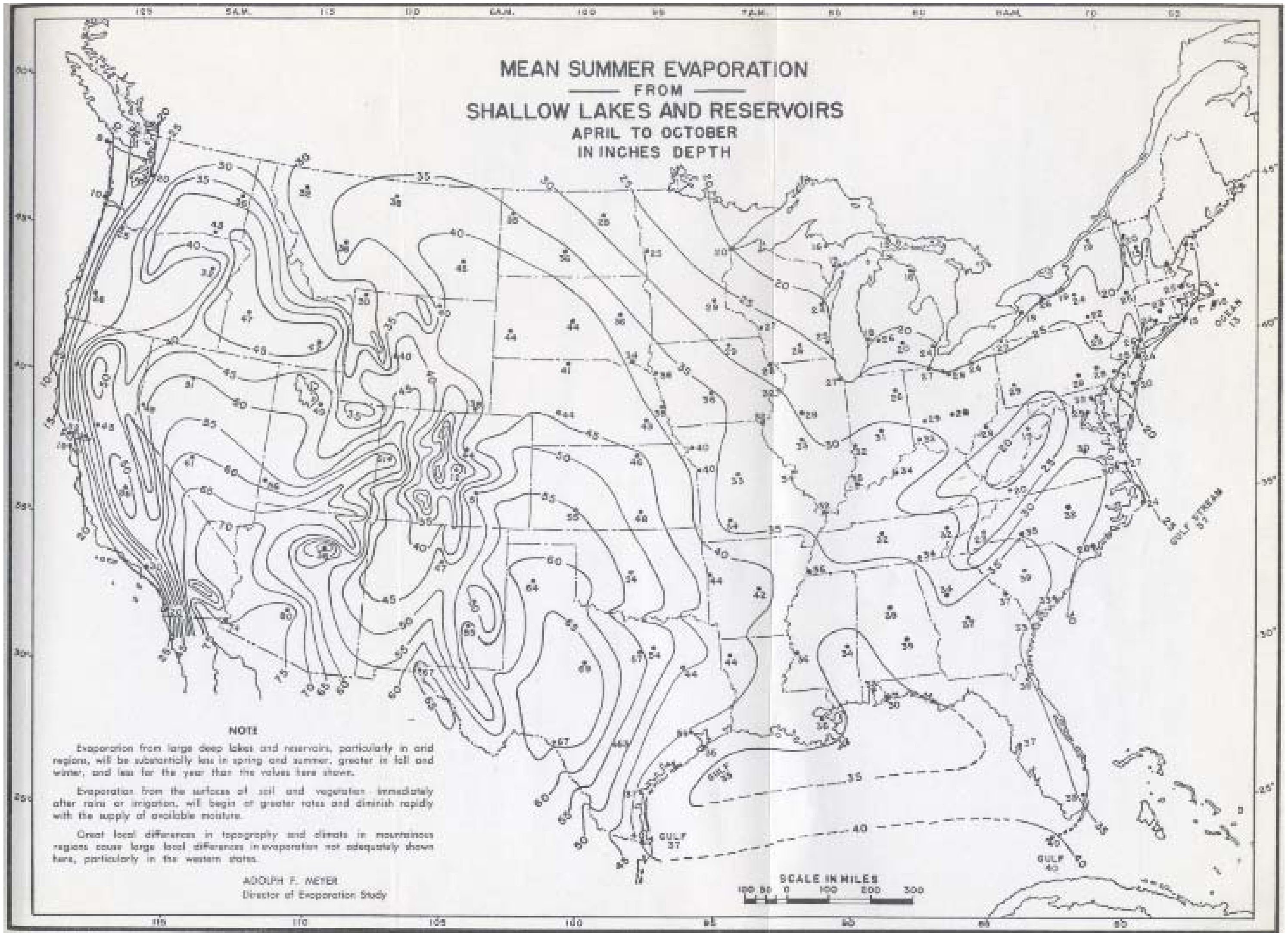

Figure 2.Mean summer lake evaporation in the U.S. (Meyer, 1942).

Direct measurements of evaporation (pan evaporation) are available for recent years only at two locations in Minnesota, and only for the summer months (May to September) (http://www.climate.umn.edu). Based on these data, average annual summer pan evaporation in Minneapolis was 857 mm (33.7 in) with a standard deviation of 112 mm (4.4 in) for the period 1972 – 2006. In Waseca, it was 917 mm (36.1 in) with a standard deviation of 9.7 mm (3.8 in) for the period of 1964 – 2002. Pan evaporation is generally higher than lake evaporation for a number of reasons, and a pan coefficient on the order 0.6 to 0.9 has to be applied to pan evaporation to obtain lake evaporation (Winter, 1981). If a pan coefficient of 0.7 is used, annual summer lake evaporation in Minneapolis and Waseca correspond to 560 mm (23.6 in) and 642 mm (25.3 in), respectively.

By comparison mean annual precipitation was 752 mm (29.61 in) in Minneapolis (1972 – 2006) and 875 mm (34.43 in) in Waseca (1964 – 2002). Pan evaporation measured in Minneapolis (May-September, 1972 – 2006) and Waseca (May-September, 1964 – 2002) has decreased at a rate (trend) of -5.08 mm/yr (-0.20 in/yr; significant at the 0.01 level) and -1.27 mm/yr (0.05 in/yr; significant at the 0.5 level), respectively. These results are at best representative of southern Minnesota because of the high climate variability throughout the state. Measurements of pan evaporation in northern Minnesota are not available.

The downward trend in measured pan evaporation at two Minnesota locations contradicts projections for evaporation rates due to climatic change (warming). Rising air temperatures are thought to stimulate evaporation in the future (Kling et al., 2003). Annual lake evaporation was estimated to increase by 20% (112 to 183 mm/yr or 4.5 to 7.2 in/yr) for a 4°F warmer climate in Minnesota (Anonymous, 1997). Simulations of lake temperature changes based on heat budgets under a 2xCO2 climate scenario in Minnesota (Table 1) showed an increase in evaporative heat fluxes corresponding to approximately 200mm/yr (7.9 in/yr) of water (Figure 3) (Fang and Stefan, 1999).

Table 1. 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

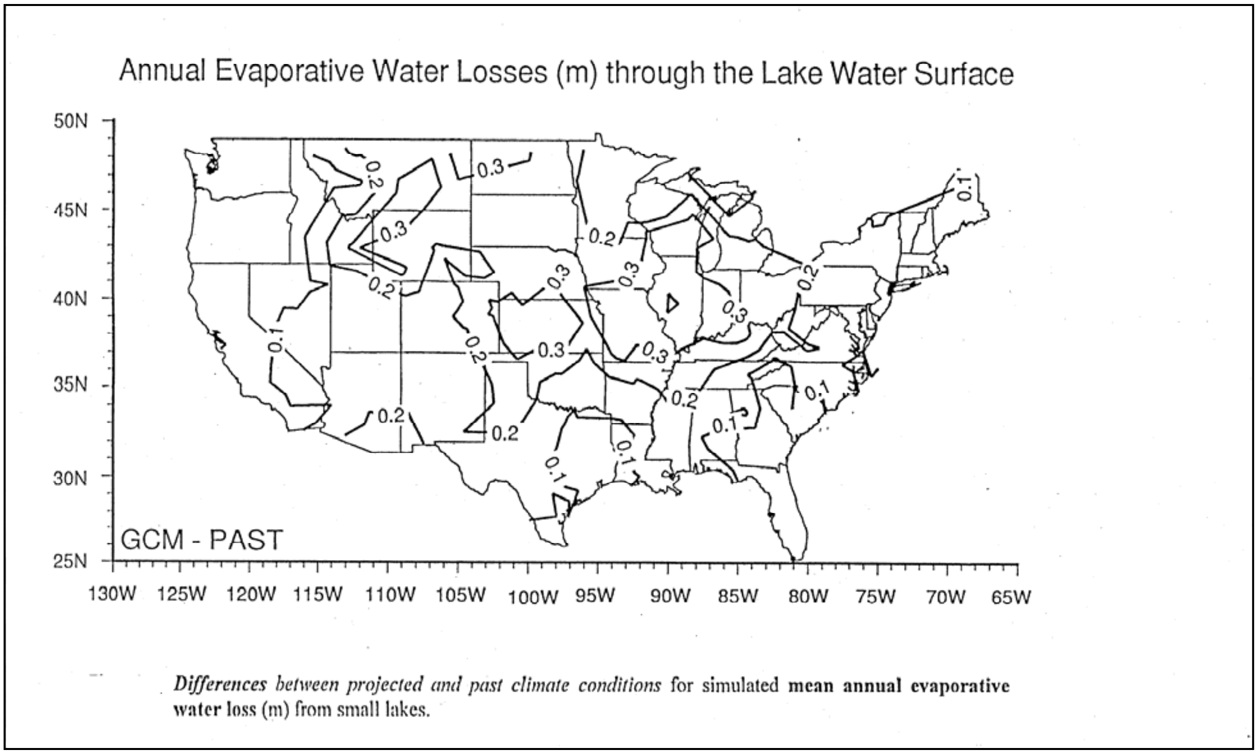

Figure 3. Projected changes in mean annual evaporative water loss (m) from small lakes under 2xCO2 scenario (reproduced from (Fang and Stefan, 1999) (1 in = 0.0254 m).

The impact of changed evaporative water losses from a lake can be mitigated by the other water budget components in equation (1). For example, precipitation is projected to increase in Minnesota. The increase can be about 15% in summer, fall and winter with no change in spring (Anonymous, 1997). Lower lake levels due to increased evaporative water losses can be prevented by increased precipitation. The difference between increases in precipitation and increases in evaporation in Minnesota, therefore, will be an important factor to control the future state of the lakes in Minnesota.

In this study, we will calculate annual evaporation rates from water surfaces during 40 years of changing Minnesota climate conditions. We will use weather data recorded at six locations in and around Minnesota for the 1964 – 2005 and 1986 – 2005 periods, and four different evaporation equations. We will then determine the linear trends in the calculated annual evaporation rates.

For comparison we will also examine the trends in precipitation at the same locations, and trends in the difference between precipitation and evaporation, i.e. net water input through the surface of lakes (water availability). To be able to understand the relationships between evaporation rates and lake levels, we will correlate the calculated annual net water input through the surface of lakes with observed lake levels.

2. METHODS

2.1. Estimation of Daily Evaporation

Evaporation from a water surface can be determined by several methods based on different principles (Chow, 1964; Winter, 1981). Methods used include (1) measurement in evaporation pans, (2) the water budget method, (3) the energy budget method, and (4) aerodynamic methods (e.g., eddy correlation, gradient or mass transfer method). Most of these methods require extensive data collection. For example, to use the energy budget method, all energy fluxes to and from a lake, e.g., incoming and reflected solar radiation, and the change in heat energy stored within the lake have to be estimated. The water budget method requires estimation of water inputs and outputs for a lake. Overland flow and ground-water inflow and outflow can be difficult to determine because of uncertainties in watershed characteristics, ground-water/surface-water relationships, etc. The pan evaporation method is a straightforward method, but the accurate estimation of pan coefficient is very difficult (Winter, 1981). In this study, we chose to use an aerodynamic mass transfer method because most of the data required by this equation are climatic data that are available from weather stations. We also had no water temperature time series data that were long enough to use the more accurate energy balance equation. Mass transfer methods have been shown to be useful in estimating lake evaporation with sufficient accuracy (Singh and Xu, 1997a).

The mass transfer method for estimating evaporation is based on the principles developed by Dalton (1802). According to Dalton, the evaporation rate from a water surface depends on the difference between the water-vapor pressure at the evaporating surface (e_o) and the water vapor pressure in the air above that surface (e_a) and on wind speed (u) above the water surface. A general equation based on Dalton's principles is provided as equation (2) and a general equation for estimating wind function, f(u), is given as equation (3).

$$E = f(u)(e_o - e_a) \tag{2}$$

$$f(u) = a + Nu^n \tag{3}$$

Parameters in equations (2) and (3), i.e., a, N, n, were estimated by calibrating equation (2) with climatic data at specific locations. The equations obtained in this way by numerous investigators can be found in the hydrological literature (e.g., Chow 1964). An evaluation and generalization of most commonly used empirical equations is provided in Singh and Yu (1997). Singh and Yu concluded that empirical equations can provide satisfactory estimation of evaporation if parameter values were estimated by calibration with local climatic data. However, transfer of parameter values from other regions (even within a small region with similar climatic characteristics) can significantly affect the reliability of the evaporation estimates.

In this study, sufficient historical data were not available to estimate parameter values for different regions of Minnesota. Therefore, we had to transfer parameter values from other studies. To show the degree of uncertainty in evaporation values estimated by different parameter values, we calculated evaporation with four different empirical equations. These equations were the Meyer equation, Lake Hefner equation, Rohwer equation, and Ryan & Harleman equation. The first three of these equations have been commonly used to estimate evaporation from lakes in the United States (Chow, 1964). The fourth equation provides a different perspective, because it was originally developed for estimating water losses from heated water bodies, e.g., cooling ponds, rather than natural water bodies. Below we provide a brief discussion and explanation of these equations.

The Meyer equation (equation (4)) (Meyer, 1942) was developed to estimate evaporative water losses from lakes. Meyer was a hydrologist based in Minnesota and the equation was originally developed for Minnesota conditions. In equation (4), E refers to evaporation rate (in/day), e_o is the saturation vapor pressure (in Hg) at mean water temperature, e_a is the vapor pressure (in Hg) of the air measured at 7.6 m (25 ft) above the water surface, u is the wind speed (mph) measured at 7.6 m (25 ft) above the water surface, and C is an empirical constant. C was determined to be 0.33 for daily evaporation from Lake Minnetonka when climate data from the Minneapolis/St. Paul Airport were used as input.

$$E = C(e_o - e_a)(1 + \frac{u}{10}) \tag{4}$$

The Lake Hefner equation (Marciano and Harbeck, 1954) was developed for a water-supply reservoir (Lake Hefner) located near Oklahoma City, OK. In equation (5), E is again the evaporation rate (in/day), e_o is saturation vapor pressure (mb) at the water temperature and e_a is vapor pressure (mb) of the air, and u is the mean daily wind speed (mph). To develop this equation Marciano and Harbeck used wind speed and relative humidity data from the nearest airport (13 miles away), and water-surface temperatures were measured.

$$E = 0.00177u(e_o - e_a) \tag{5}$$

The Rohwer equation (Rohwer, 1931) is provided in equation (6). In equation (6) E is evaporation (in/day), e_o and e_a are saturation vapor pressure (mb) at the mean water temperature and vapor pressure (mb) of the air, respectively, and u is the wind speed (mph) measured at the water surface. P is air pressure in Pa.

$$E = 0.771(1.465 - 0.0186P)(0.44 + 0.118u)(e_s - e_a) \tag{6}$$

The Ryan & Harleman equation (equation (7)) was developed to estimate evaporation from heated water bodies. In that case, both forced (wind driven) convection and free (buoyancy driven) convection effectively control evaporation rates, while for natural water bodies forced convection is the dominant factor. In equation (7), Q_e is evaporative heat flux (W/m^2), ΔQ_v is virtual temperature difference (^0C), u is the wind speed measured at 2 m (m/s) and, e_o and e_a are saturation vapor pressure at the water surface and vapor pressure of the air (mb), respectively.

$$Q_e = (2.7\Delta Q_v^{1/3} + 3.1u)(e_s - e_z) \tag{7}$$

ΔQ_v can be calculated with equation (8), where T_w is water temperature (^oC), T_a is air temperature (^oC), and P is air pressure (mb).

$$\Delta Q_v = T_w(1+0.378\frac{e_s}{P}) - T_a(1+0.378\frac{e_a}{P}) \tag{8}$$

Evaporation can be found by dividing Q_e by latent heat of vaporization (L_v) (equation (9)). L_v is nearly constant. A relationship with water temperature used by (Stefan et al., 1980) is given in equation (10).

$$E = \frac{Q_e}{L_v} \tag{9}$$

$$L_v = 597.5 - 0.592T_w \tag{10}$$

Saturation vapor pressure and vapor pressure of the air were estimated using equations (11) and (12), respectively. In these equations, e_o and e_a are in millibars, T is in ^oC and T_d is dew point temperature in ^oC.

$$e_o = 6.11\times 10^{\frac{7.5\times Tw}{237.7+Tw}} \tag{11}$$

$$e_a = 6.11\times 10^{\frac{7.5\times T_d}{237.7+T_d}} \tag{12}$$

Because daily water temperature measurements were not available, we used equilibrium temperature, T_e, as a substitute for surface water temperature (T_w). T_e was calculated using the equation (13) developed by Edinger et al. (1968).

$$T_e = T_d + \frac{H_s}{K} \tag{13}$$

In equation (13), H_s is the shortwave solar radiation in (W/m^2) and K is the bulk surface heat exchange coefficient ($W/m^2/^oC^1$). K can be calculated from equation (14), where β is an approximation of the slope of the saturation pressure vs. water temperature curve (mm $Hg/^oC$) and f(u) is a function ($W/m^2/mmHg^{-1}$) of wind speed u (m/s)

$$K = 4.5 + 0.05T + \beta f(u) + 0.47 f(u) \tag{14}$$

β and f(u) can be calculate with equations (15) and (16).

$$f(u) = 9.2 + 0.46u^2 \tag{15}$$

$$\beta = 0.35 + 0.15T_m + 0.0012T_m^2 \tag{16}$$

In equation (17), the mean temperature T_m is calculated as:

$$T_m = \frac{T + T_d}{2} \tag{17}$$

As explained by Singh and Xu (1997b), the mass-transfer based evaporation equations are most sensitive to the vapor pressure difference, which is affected by water temperature and air temperature measurements. Because we did not have long time series of actual measured water temperature data, we used equilibrium temperatures in our calculations. The equilibrium temperature is by definition the water temperature that a water body with no thermal inertia, i.e., zero depth, assumes instantaneously under a given set of weather (climate) conditions. The equations to evaluate equilibrium temperature are based on the heat flux balance at a water surface. Water temperatures of water bodies of finite depth generally lag in temperature behind the equilibrium temperature. That means that the water temperatures we used are good estimates for very shallow water, but are too low in spring and too high in fall for water bodies of greater depth. We evaluated the sensitivity of the calculated evaporation values to changes in equilibrium temperature. The approach and the results of the sensitivity analysis are presented in Appendix 1. The sensitivity analysis shows how much water temperatures deviate from equilibrium temperatures as the lake water depth increases.

2.2. Climate Data Input

The climate data (air temperature, dew point temperature, and wind speed) required for the evaporation computations came from six weather stations (Figure 4). The stations chosen are on the boundaries of Minnesota. Geographic variability is therefore well-covered. Although we wanted to include some stations inside Minnesota (i.e., Bemidji, Brainerd, Detroit Lakes and St. Cloud), climate data for those stations were not available for long enough period of time (they were available after mid-1990s). The climate data included in this analysis were obtained from the State Climatology Office. Shortwave solar radiation data required for estimating daily equilibrium temperatures were obtained from the National Solar Radiation Database (http://rredc.nrel.gov/solar/old_data/nsrdb/). Daily climate data from 1964 to 2005 were used in the analysis. Prior to 1964, daily climate data for some parameters (e.g., wind speed) were unavailable. The 40-year period was deemed long enough to detect trends due to global climate change. Daily precipitation data were available for a longer period (prior to 1950 to 2005)

Figure 4. Location of weather stations used in this study

2.3. Estimation of Annual Evaporation/Ice Cover Effects

Annual evaporation from lakes will first be calculated by accumulating the daily evaporation values from January 1 to December 31.

During the winter months most Minnesota lakes are covered by ice. We therefore calculated separately the annual evaporation for the natural open-water period to estimate the actual amount of water lost from lakes. For the ice-cover period we assumed that no water was evaporated, even though a small amount of water transfers from lake ice and snow covers to the atmosphere, i.e. the water loss by ablation of snow and ice covers during the ice cover period was neglected. The most important water loss from a lake to the atmosphere in winter is not in the form of water vapor but most likely as snow drift blown from lake ice covers on to the land. This would be particularly important for lakes with a large surface area, i.e. wind fetch. Although snow removal from lake surfaces by wind can be easily observed, not much data seems to have been collected on this phenomenon. Snow accumulation in a suburb was reported to be substantially larger than on a lake in the Twin Cities area (Stefanovic, 2000)

To calculate annual evaporation for the open-water season, we ignored evaporation calculated for the ice-cover period. The ice-cover periods on northern and southern Minnesota lakes are significantly different (average ice-in and ice-out dates for Minnesota lakes are given in Appendix 2) According to Johnson and Stefan (2004) the average lake ice-out date in Minnesota varies from April 1 at 44.3^{o} latitude to May 1 at 48.6^{o} latitude. In the same study, ice-in dates were found to vary from November 12 at 47.0^{o} latitude to December 8 at 47.2^{o} latitude. The effect of latitude is not as apparent in recorded ice-in dates as in ice-out dates, because in addition to latitude lake depth has a strong effect on ice-in (Williams et al., 2004). Based on recorded ice-in and ice-out dates, the ice-cover period was assumed to be from November to May at northern locations (Fargo, International Falls, and Duluth) and December to April for southern stations (Sioux Falls, Minneapolis, and La Crosse). The bulk of the annual evaporation occurs in summer and only a small fraction in winter (Meyer, 1942). A precise estimation of the ice cover period is therefore not necessary.

2.4. Estimation of Trends in Evaporation

Trends in evaporation, precipitation and water availability (annual precipitation minus open-water evaporation) were estimated using a linear regression. Water availability was calculated in two ways:

1) as the difference between measured total annual precipitation and open-water evaporation, which is based on the assumptions that (a) water loss from snow and ice covers of lakes will not

be significant during ice-cover periods and (b) snowfall on an ice or snow covered lake will accumulate and be entirely captured by the lake as snowmelt. It should be noted that during warm weather periods in winter a lake's snow cover can be melted from below by heat conducted from the lake water through the ice cover or by radiative and conductive heat input from the atmosphere. The resulting snowmelt water accumulates between the snow cover and the lake ice cover, and freezes to "white ice" on the top of the existing lake ice cover when cold weather sets in.

2) as the difference between precipitation during the natural open-water period and open-water evaporation. This procedure is based on the assumption (a) that snowfall will not accumulate on a lake ice cover, but will be blown away by wind, and (b) water loss from the ice/snow surface of a lake is negligible.

It is likely that case (1) is more appropriate for wind sheltered, i.e. small lake surrounded by significant vegetation (trees) or buildings, while case (2) is representative of a lake with large surface areas and lack of wind sheltering.

2.5. Correlation of lake levels with evaporation

Correlation coefficients between water levels recorded in 25 Minnesota Lakes (8 landlocked and 17 flow-through lakes) and calculated annual evaporation or water availability (precipitation minus evaporation) were calculated. The names, locations and characteristics of the lakes included in this study are provided in Appendix 3.

3. RESULTS

3.1. Statistics of Daily Lake Evaporation in Minnesota

Daily evaporation rates at the six weather stations were calculated by the Meyer, Lake Hefner, Rohwer, and Ryan & Harleman equations with daily weather data for the 1964 – 2005 period as input. Examples of daily evaporation values for the month of July are given in Figures 5a and 5b. These figures were obtained by averaging daily evaporation values calculated by four equations for every July day from 1964 to 2005. Average daily evaporation values for July were in the range 3.5 - 6 mm/day (0.14 - 0.24 in/day). The Meyer equation gave the highest estimates for all stations and the Lake Hefner equation the lowest. Variations in daily evaporation in July were in the range 0.15 - 0.30 mm/day (0.006 - 0.012 in/day). Mean daily evaporation rates for

July calculated with the Meyer equation varied between 4.4 and 6.7 mm/day (0.17 and 0.26 in/day) for the six weather stations. The Lake Hefner equation gave mean annual evaporation rates from 3.1 to 4.9 mm/day (0.12 to 0.19 in/day); the Rohwer equation predicted values in the range from 3.9 to 5.5 mm/day (0.15 to 0.22 in/day), and the Ryan & Harleman equation gave values in the range from 3.6 to 6.6 mm/day (0.14 to 0.26 in/day).

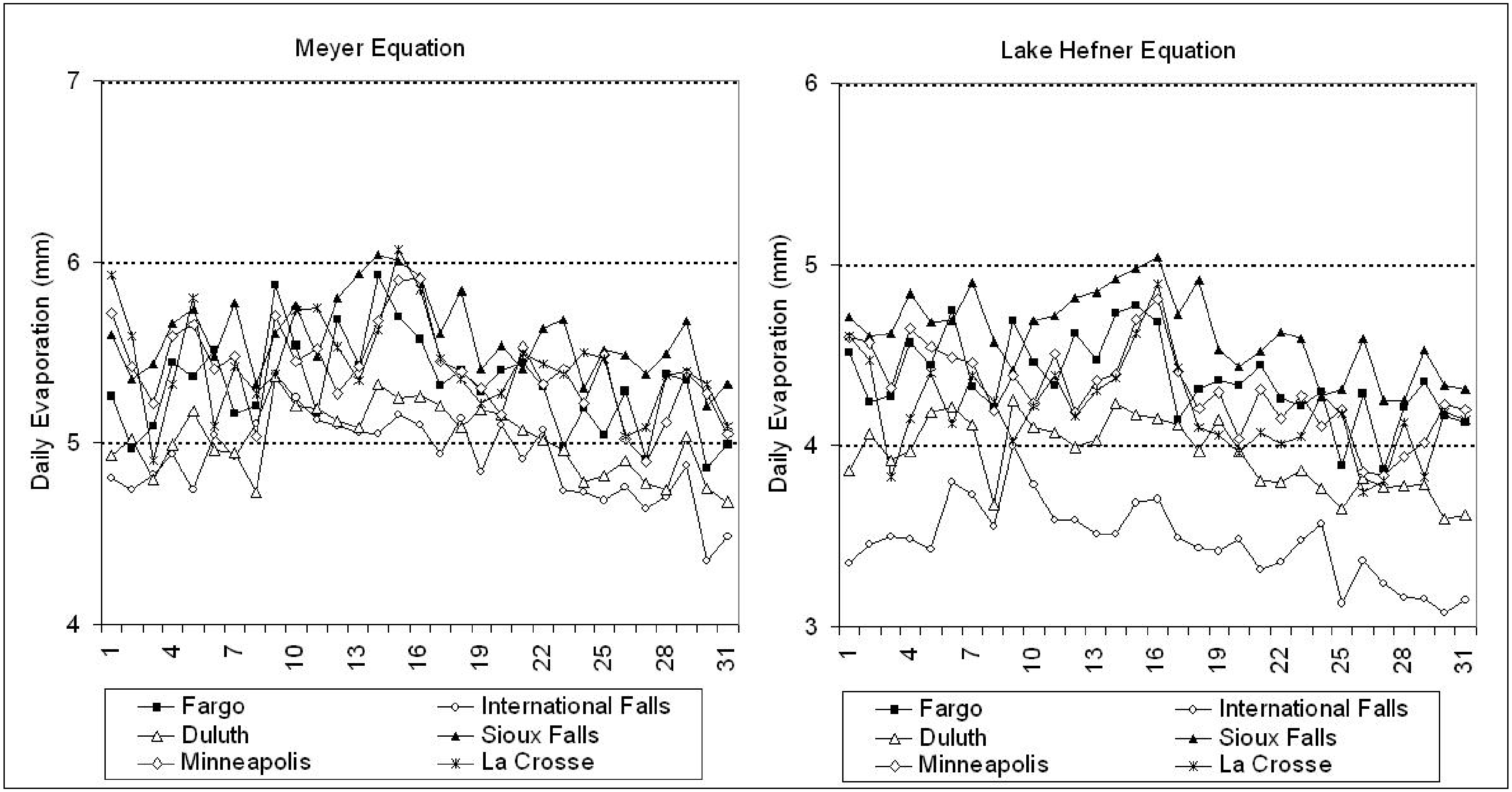

Figure 5a. Average daily evaporation for July calculated using the Meyer and Lake Hefner equations (1 in = 25.4 mm).

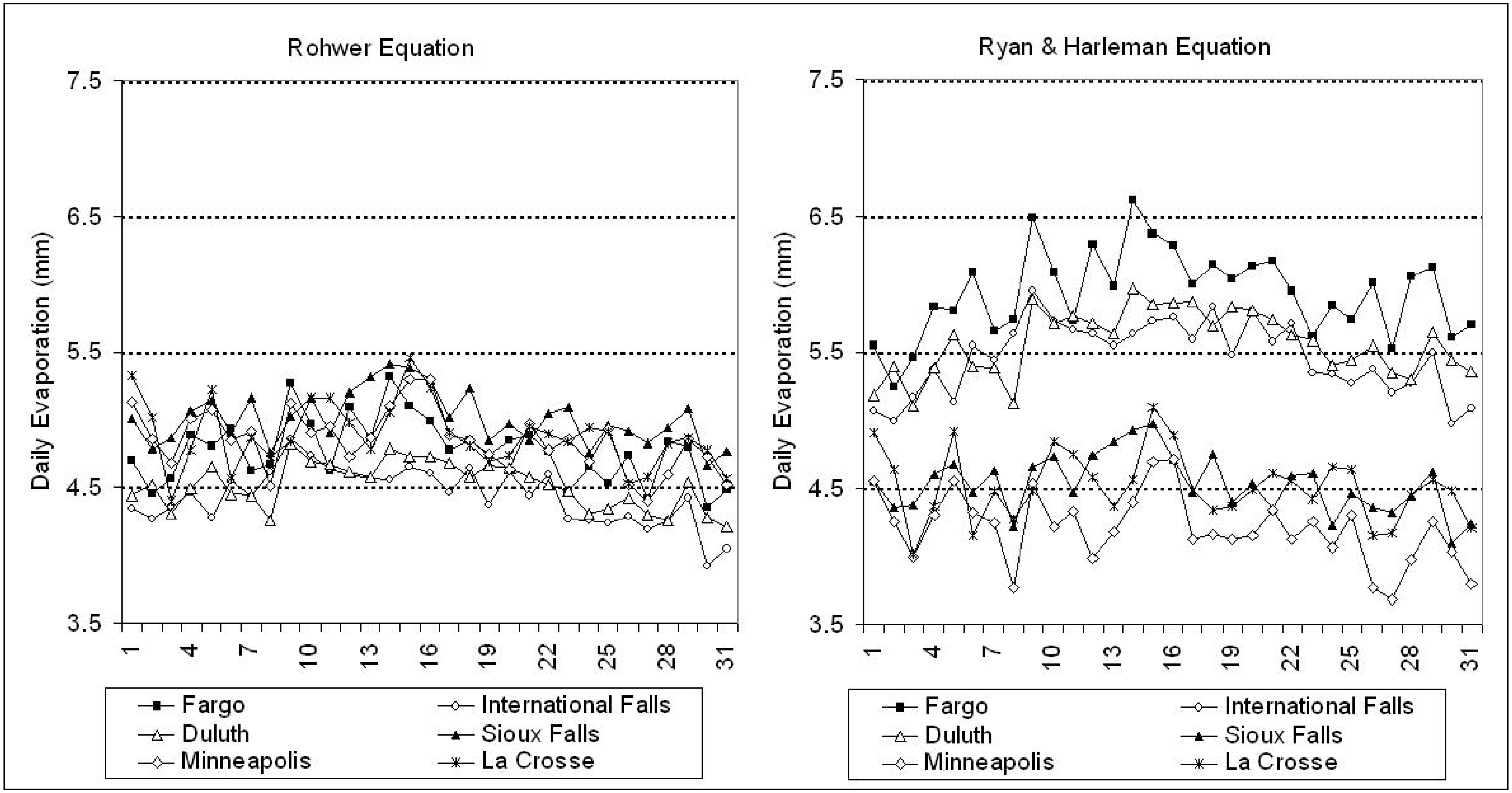

Figure 5b. Average daily evaporation for July calculated using the Rohwer and Ryan & Harleman equations (1 in = 25.4 mm).

3.2. Statistics of Monthly Lake Evaporation in Minnesota

Monthly evaporation values were obtained from computed daily values. A plot of monthly evaporation values is given in Figures 6a and 6b. Figure 6 was obtained by averaging daily evaporation values calculated by the four equations for every month from 1964 to 2005. Monthly evaporation values calculated with the Meyer, Lake Hefner, and Rohwer equations showed similar seasonal fluctuations for all six climate stations. Monthly evaporation values were consistently lowest at International Falls and highest at La Crosse. This geographic difference is expected and matches the gradients shown in Figures 1 and 2. Results were not quite as consistent when the Ryan & Harleman equation was used.

All equations predicted the occurrence of peak monthly evaporation in July. Variations in the monthly evaporation by latitude can be seen in Figures 6a and 6b, one panel for each equation used. The geographic range of computed July evaporation values was 134 - 160 mm (5.3 - 6.3 in) when the Meyer equation was used, 103 - 130 mm (4.1 - 5.2 in) for the Lake Hefner equation, 132 - 144 mm (5.2 - 5.7).for the Rohwer equation, and 123 - 179 mm (4.8 - 7.1 in) when the Ryan & Harleman equation was used.

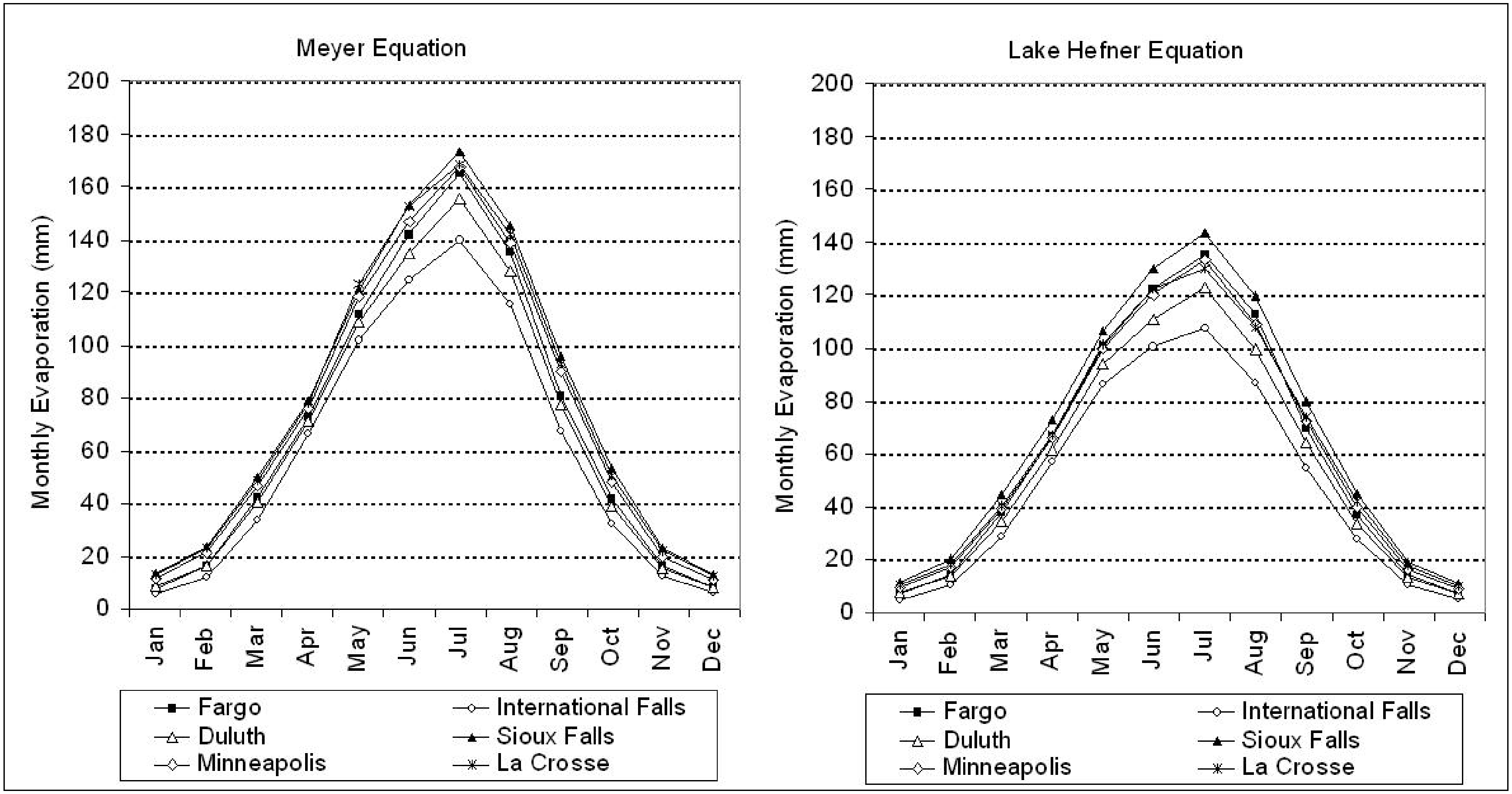

Figure 6a. Average monthly evaporation calculated using the Meyer and Lake Hefner equations (1 in = 25.4 mm).

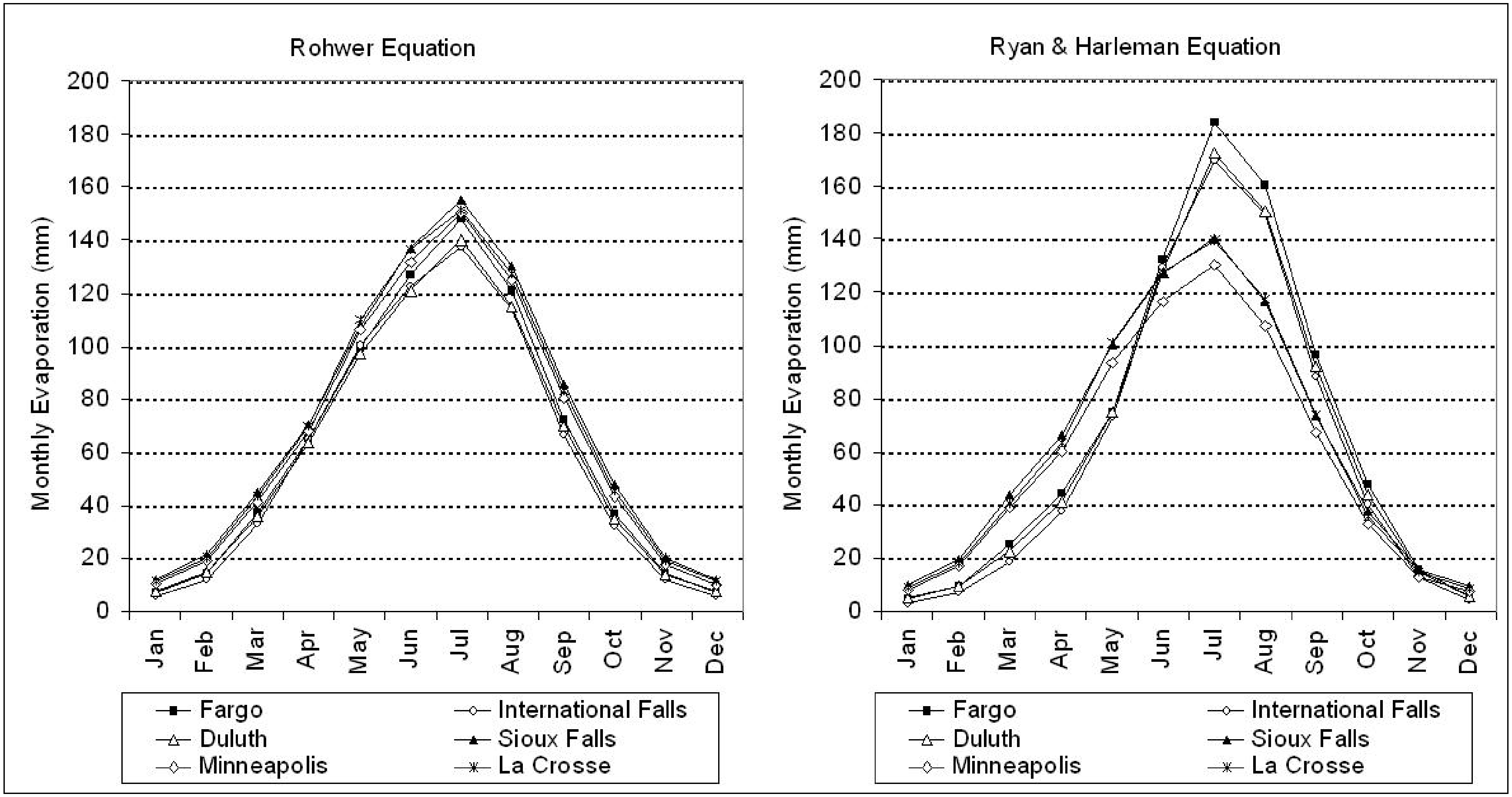

Figure 6b. Average monthly evaporation calculated using the Rohwer and Ryan & Harleman equations (1 in = 25.4 mm).

3.3. Statistics of Annual (Jan-Dec) Evaporation in Minnesota

Annual (Jan to Dec) evaporation was obtained as the sum of the daily values. Annual evaporation varied, as to be expected, by location and from year to year (Figures 7a and 7b). The four equations gave somewhat different results. Annual (Jan-Dec) evaporation values estimated by the Meyer Equation were consistently higher than values obtained from the other three equations. The Lake Hefner, the Rohwer, and the Ryan & Harleman equations provided similar results. Mean annual evaporation rates for the period 1994 – 2005 calculated with the Meyer equation varied between 781 and 942 mm/yr (30.8 and 37.1 in/yr) for the six locations investigated. The Lake Hefner equation gave mean annual evaporation rates from 579 to 802 mm/yr (22.8 to 31.6 in/yr); the Rohwer equation predicted values in the range from 704 to 843 mm/yr (27.7 to 33.2 in/yr), and the Ryan & Harleman equation gave values in the range from 692 to 800 mm/yr (27.2 to 31.5 in/yr).

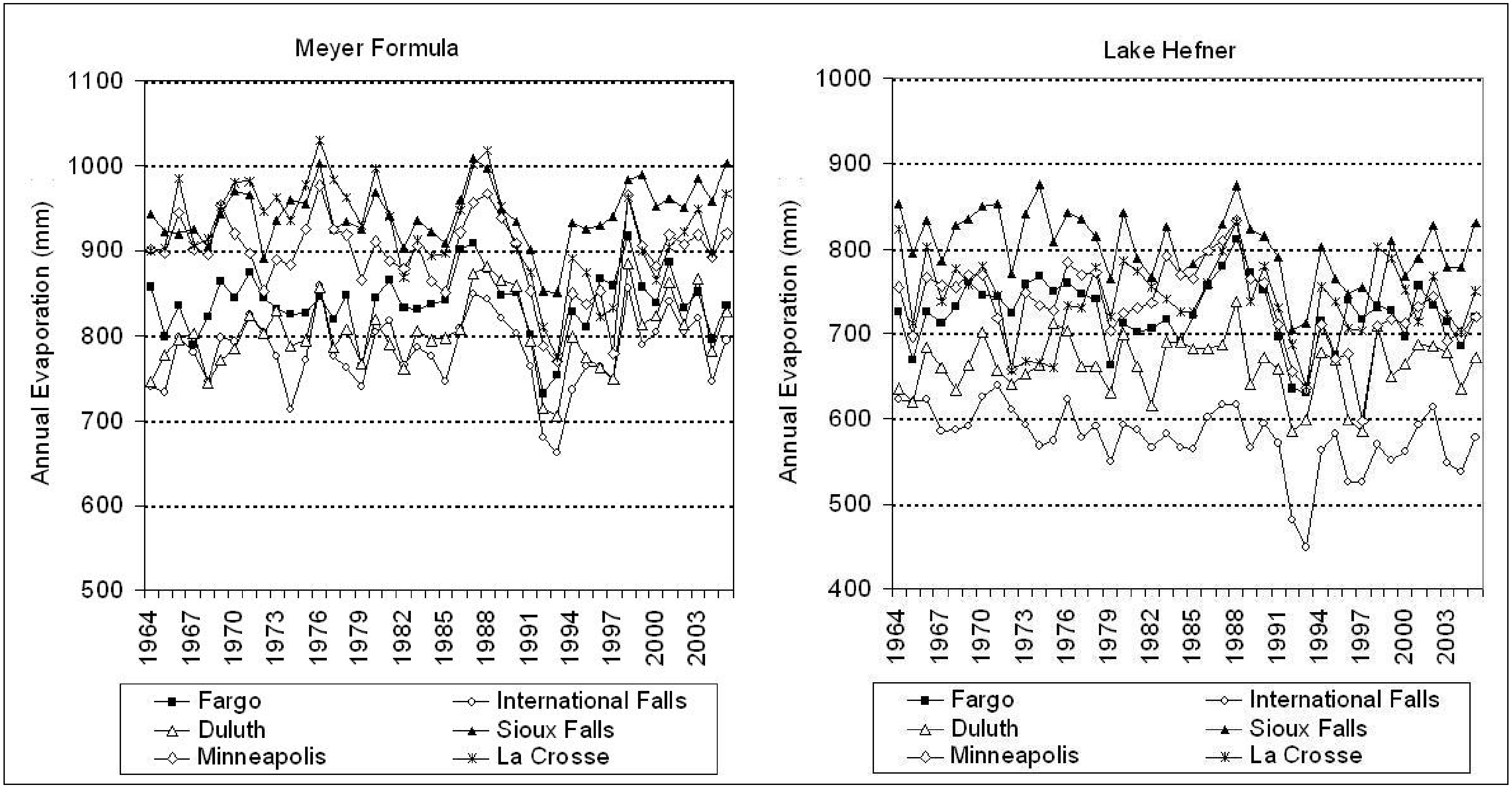

Figure 7a. Annual evaporation (Jan – Dec) from 1964 to 2005 calculated using the Meyer and Lake Hefner equations (1 in = 25.4 mm).

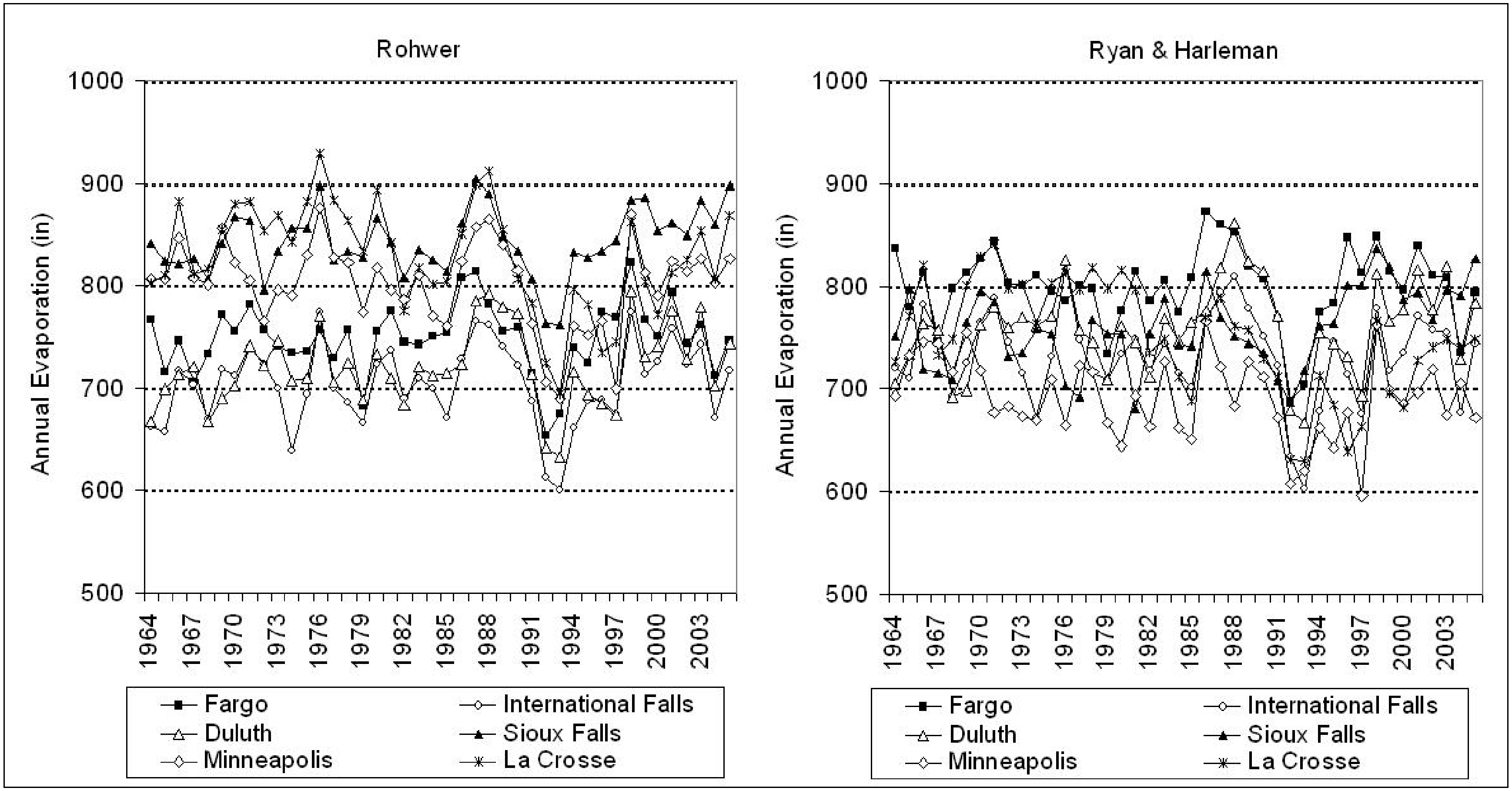

Figure 7b. Annual evaporation (Jan – Dec) from 1964 to 2005 calculated using the Rohwer and Ryan & Harleman equations (1 in = 25.4 mm).

When the values obtained with the four equations were averaged for every year and plotted against time, Figure 8 was obtained. Statistics of the time-series for the period 1964 – 2005 in Figure 8 are given in Table 2. According to Table 2 mean annual evaporation rates varied going from north to south. This is in agreement with Figures 1 and 2. The absolute values in Figures 1 are about the same as those in Table 2 for central Minnesota, but the gradient from north to south in Figure 1 is stronger than in Table2.

Standard deviation of mean annual evaporation does not seem related to latitude (Table 2), but the extreme values (minimum and maximum annual evaporation in the 1964 – 2005 period show a weak dependence on latitude.

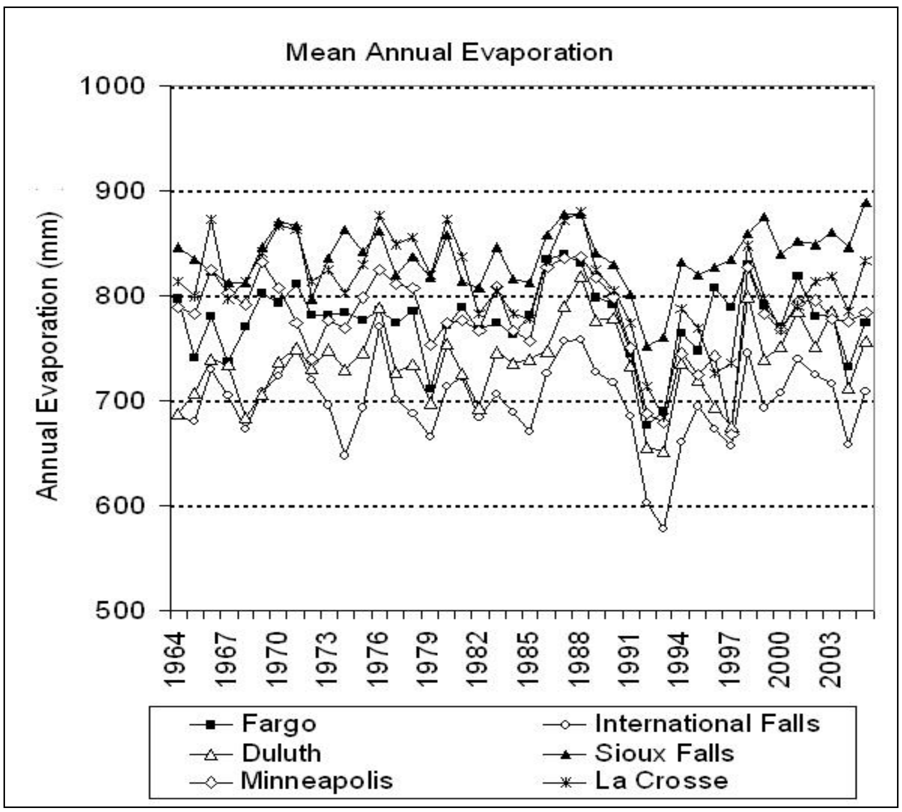

Figure 8. Mean annual evaporation calculated for six locations. Average values obtained by four equations are used.

Table 2. Statistics of annual (Jan-Dec) evaporation in mm/yr (in/yr) for 1964 – 2005. Values obtained by the four equations are averaged (1 in = 25.4 mm).

Location	Mean	Stand. Dev.	Minimum	Maximum
International Falls	699 (27.5)	38 (1.5)	579 (22.8)	770 (30.3)
Duluth	736 (29.0)	37 (1.4)	652 (25.7)	819 (32.2)
Fargo, ND	778 (30.6)	34 (1.3)	678 (26.7)	841 (33.1)
Minneapolis	780 (30.7)	40 (1.6)	668 (26.3)	838 (33.0)
La Crosse, WI	811 (31.9)	45 (1.8)	685 (27.0)	881 (34.7)
Sioux Falls, SD	837 (33.0)	29 (1.1)	752 (29.6)	889 (35.0)

According to Figure 8, the maximum of annual evaporation occurred in the years 1987 – 1988 for all stations except for International Falls and Sioux Falls. The minimum of annual evaporation for all stations occurred in the 1992 – 1993 period. 1987 – 1988 is recalled as an extremely dry period with very low river flows and lake stages. 1992 – 1993 was a wet period.

The periods of extreme evaporation also appear aligned with the periods of extreme annual air temperatures in Minnesota (Figure 9). Maximum annual average air temperature in Minnesota was observed in 1987 and minimum annual average air temperature in 1996. Overall the correlation between annual evaporation and annual average air temperature is not strong. Correlation coefficients varied from 0.12 to 0.38. The highest correlation was found for Duluth and the lowest for La Crosse.

The statistics (mean and standard deviation) of annual (Jan – Dec) evaporation rates obtained by individual equations are given in Table 3.

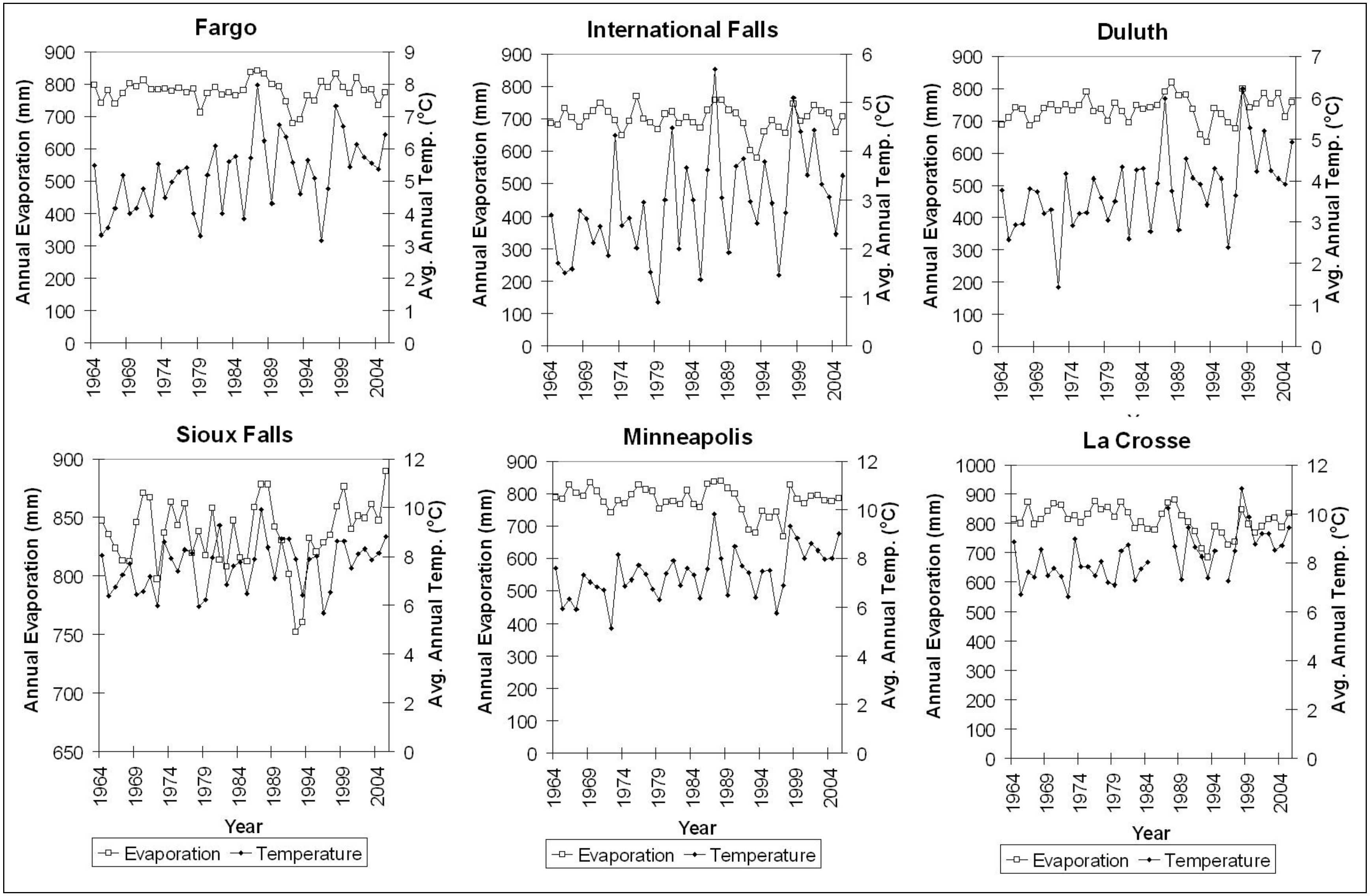

Figure 9. Annual evaporation vs. annual average air temperature at six locations.

Table 3. Statistics of annual (Jan – Dec) evaporation in mm/yr (in/yr) calculated with four evaporation equations for 1964 – 2005.

Equation	Statistic	Meyer	Lake Hefner	Rohwer	Ryan & Harleman
International Falls	Mean	781 (30.7)	579 (22.8)	704 (27.7)	733 (28.9)
	Std. Dev.	44 (1.7)	38 (1.5)	40 (1.6)	44 (1.7)
Duluth	Mean	803 (31.6)	662 (26.1)	721 (28.4)	760 (29.9)
	Std. Dev.	42 (1.7)	35 (1.6)	39 (1.5)	43 (1.7)
Fargo, ND	Mean	838 (33.0)	725 (28.5)	750 (29.5)	800 (31.5)
	Std. Dev.	38 (1.5)	37 (1.5)	34 (1.3)	38 (1.5)
Minneapolis	Mean	895 (35.2)	732 (28.8)	802 (31.6)	692 (27.2)
	Std. Dev.	47 (1.9)	48 (1.6)	42 (1.3)	39 (1.5)
La Crosse, WI	Mean	925 (36.4)	741 (29.2)	829 (32.6)	750 (29.5)
	Std. Dev.	56 (2.2)	45 (1.8)	52 (2.0)	55 (2.2)
Sioux Falls, SD	Mean	942 (37.1)	802 (31.6)	843 (33.2)	759 (29.9)
	Std. Dev.	36 (1.4)	41 (1.6))	32 (1.3)	39 (1.5)

All equations, except the Ryan & Harleman equation showed that the highest mean annual evaporation rate was at Sioux Falls and the lowest was at International Falls. The three northern locations (Fargo, International Falls, and Duluth) had lower mean annual evaporation rates than the three southern locations (Sioux Falls, Minneapolis, and La Crosse). Evaporation rates calculated with the Ryan & Harleman equation deviated from those obtained by the other three equations, possibly because the Ryan & Harleman equation was developed with data from heated water bodies such as cooling water ponds of power plants and warm springs, not natural lakes.

3.4. Statistics of Annual Natural Open-Water Evaporation in Minnesota: Effects of Ice Cover

Mean annual evaporation rates for the period 1964 – 2005, calculated for the **natural open-water period,** i.e. excluding the ice-cover period, were from 71 to 163 mm/yr (2.8 to 6.4

in/yr) lower than the calculated total annual evaporation from Jan to Dec. Mean annual evaporation rates for a natural open-water season, i.e. averages obtained from the four equations are plotted in Figure 10. The statistics of these values are given in Table 4. Averages of annual open-water evaporation rates obtained by individual equations are provided in Table 5.

Comparing the values in Tables 2 for the Jan-Dec period and in Table 4 for the open-water period leads to very similar conclusions. The same holds true for a comparison of Table 3 and Table 5. The geographic distribution of the mean annual evaporation rates for the open-water period resembles that for the full year (Jan to Dec). The highest and lowest annual open-water evaporation values were calculated for the southernmost and the northernmost locations, i.e. Sioux Falls and International Falls, respectively, when the Meyer, Lake Hefner, and Rohwer equations were used. The Ryan & Harleman equation deviated from that result.

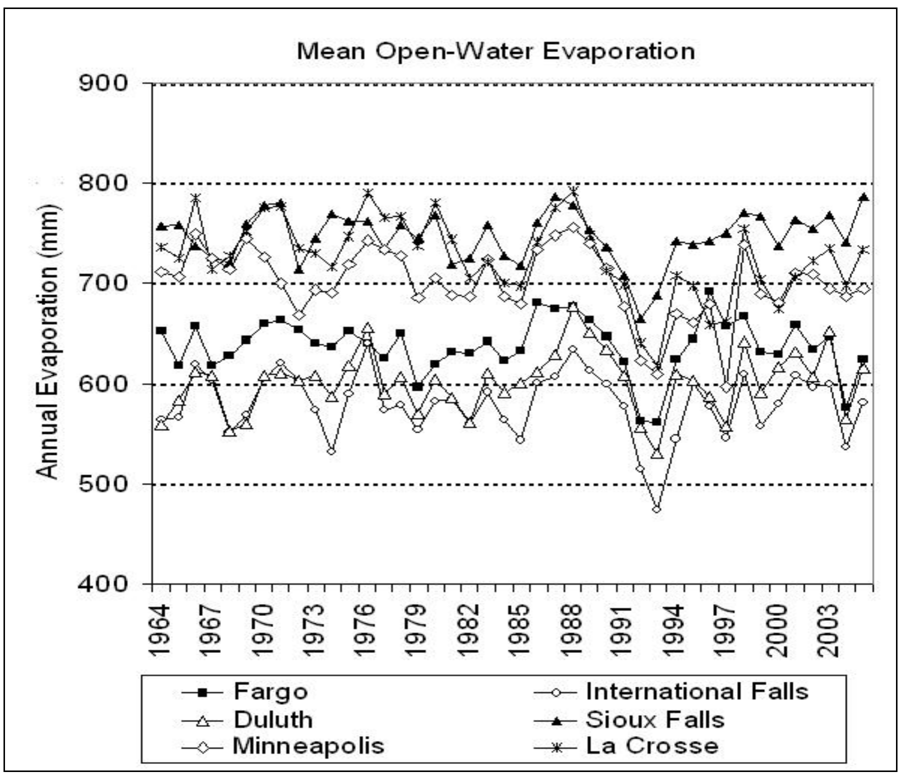

Figure 10. Annual natural open-water evaporation at 6 locations for 1964 – 2005. Values obtained by the four equations are averaged.

Table 4. Statistics of annual open-water evaporation in mm/yr (in/yr) for 1964 – 2005. Values obtained by the four equations for the natural open-water season are averaged.

Location	Mean	Stand. Dev.	Minimum	Maximum
International Falls	580 (22.8)	33 (1.3)	474 (18.7)	642 (25.3)
Duluth	602 (23.7)	31 (1.2)	531 (29.9)	678 (26.7)
Fargo. ND	638 (25.1)	28 (1.1)	561 (22.1)	693 (27.3)
Minneapolis	701 (27.6)	36 (1.4)	597 (23.5)	756 (29.8)
La Crosse, WI	727 (28.6)	40 (1.6)	619 (24.4)	793 (31.2)
Sioux Falls, SD	747 (29.4)	26 (1.0)	666 (26.2)	788 (31.0)

Table 5. Statistics of annual open-water evaporation in mm/yr (in/yr) calculated with four evaporation equations for 1964 – 2005.

Equation	Statistic	Meyer	Lake Hefner	Rohwer	Ryan and Harleman
International Falls	Mean	634 (25.0)	463 (18.2)	572 (22.5)	650 (25.6)
	Std. Dev.	36 (1.4)	31 (1.2)	33 (1.3)	41 (1.6)
Duluth	Mean	643 (25.3)	524 (20.6)	578 (22.8)	662 (26.1)
	Std. Dev.	35 (1.4)	28 (1.1)	32 (1.2)	39 (1.5)
Fargo, ND	Mean	676 (26.6)	578 (22.7)	605 (23.8)	696 (27.4)
	Std. Dev.	29 (1.1)	31 (1.2)	26 (1.0)	34 (1.4)
Minneapolis	Mean	805 (31.7)	657 (25.9)	722 (28.4)	621 (24.4)
	Std. Dev.	43 (1.7)	43 (1.7)	38 (1.5)	35 (1.4)
La Crosse, WI	Mean	829 (32.6)	662 (26.1)	744 (26.5)	674 (26.5)
	Std. Dev.	50 (2.0)	40 (1.6)	47 (1.9)	49 (1.9)
Sioux Falls, SD	Mean	843 (33.2)	716 (28.2)	754 (29.7)	677 (26.7)
	Std. Dev.	31 (1.2)	37 (1.5)	29 (1.1)	36 (1.4)

3.5. Trends in Annual (Jan-Dec), Open-Water and Peak Monthly (July) Evaporation in Minnesota

We examined the trends in evaporation for the 1964 – 2005 and 1986 – 2005 periods by using linear regression. In this trend estimation we used the evaporation values calculated by the Meyer equation. Although the Meyer equation provided somewhat higher results than the other three equations, we chose to use it for the trend analysis because (1) parameters of the Meyer equation were developed and tested with data from a Minnesota lake (Lake Minnetonka) -mass-transfer equations are expected to provide better estimates if parameters are obtained by calibration with local data-, and (2) the results obtained by the Meyer equation agree well with lake evaporation estimates for the Minnesota region (NCDC).

The a**nnual (Jan-Dec) evaporation** for the 1964 – 2005 period showed an increasing trend at four of the six locations investigated (Table 6). La Crosse and Minneapolis showed a decreasing trend. Only the trend for La Crosse was significant at the 0.05 level; trends for Duluth, Minneapolis and Sioux Falls were significant at the 0.5 level. The long-term trends were obviously weak, and are not readily apparent in Figure 7. The annual (Jan-Dec) evaporation for the more recent 1986 – 2005 period showed a decreasing trend (Table 6). These trends were negative, except for Sioux Falls. All trends were significant near the 0.5 level. It therefore appears that the trends over the 40-year and 20-year periods are reversed, but not significant. Even the strongest trends in the calculated annual evaporation were not hugely different. The extreme values were found for La Crosse (-1.7mm/yr; -0.065 in/yr) for the 1964 – 2005 period and for Sioux Falls (1.2mm/yr; 0.046 in/yr) for the 1986 – 2005 period.

The statistics of annual evaporation rates calculated by the Meyer equation for the two periods (1964 – 2005 and 1986 – 2005) are summarized in Table 7. Average annual evaporation rates were higher during the 1986 – 2005 period than the 1964 – 2005 period for four stations, except Minneapolis and LaCrosse. Standard deviations of mean annual evaporation rates were higher for the 1986 – 2005 period than the 1964 – 2005 period for all stations.

Overall the results suggest that evaporation became more variable in the last 20-year period, but that no significant trend can be established.

Annual open-water evaporation from 1964 to 2005 showed no conclusive trends. (Table 6). From 1986 to 2005 all stations, except Sioux Falls, showed a negative trend. The trends for Fargo, Sioux Falls, and La Crosse were significant at the 0.5 level. The strongest trends in both time periods were observed at La Crosse (-0.065 and -0.062 in/yr, respectively). Means and standard deviations of annual open-water evaporation values for the two periods showed similar geographic distributions as the annual (Jan-Dec) evaporation (Table 7).

Table 6. Trends in annual evaporation, open-water evaporation, and peak monthly evaporation calculated by linear regression on values from the Meyer equation (1 in=25.4 mm).

		1964 – 2005			1986 – 2005		
Location	Trend And Sig.	Annual Evap. (mm/yr)	Open Water Evap. (mm/yr)	Peak Monthly Evap. (mm/mo)	Annual Evap. (mm/yr)	Open Water Evap. (mm/yr)	Peak Monthly Evap. (mm/mo)
International Falls	Trend	0.30	0.13	0.08	-0.05	-0.69	0.53
	Sig.	0.58	0.79	0.56	0.98	0.69	0.35
Duluth	Trend	0.84	0.64	0.13	-0.25	-1.07	0.25
	Sig.	0.13	0.16	0.46	0.90	0.52	0.67
Fargo, ND	Trend	0.23	-0.03	-0.03	-0.89	-1.32	0.33
	Sig.	0.63	0.93	0.90	0.64	0.39	0.54
Minneapolis	Trend	-0.81	-0.99	-0.25	-0.20	-0.69	0.30
	Sig.	0.18	0.07	0.15	0.93	0.75	0.63
La Crosse, WI	Trend	-1.65	-1.65	-0.30	-1.17	-1.57	-0.13
	Sig.	0.02	0.01	0.04	0.65	0.48	0.84
Sioux Falls, SD	Trend	0.56	0.23	0.03	1.63	1.09	0.36
	Sig.	0.22	0.56	0.79	0.35	0.47	0.50

Maximum (peak) monthly evaporation occurred in July. From 1964 to 2005 it had a decreasing trend for Fargo, Minneapolis, and La Crosse and an increasing trend for International Falls, Duluth, and Sioux Falls (Table 6). Only the trend for La Crosse was significant at the 0.05 level, while all others were near the 0.5 level. From 1986 to 2005, peak monthly evaporation showed an upward trend at all stations except La Crosse (Table 7). The trends were significant near the 0.5 level. The strongest trend in July evaporation was obtained for La Crosse for the

1964 – 2005 period (-0.012 in/month) and in Sioux Falls for the 1986 – 2005 period (0.021 in/month).

Table 7. Mean and standard deviation of annual (Jan – Dec) and open-water evaporation in mm/yr (in/yr) for the periods 1964 – 2005 and 1986 – 2005 from the Meyer equation

		Annual Evaporation		Annual Open-Water Evaporation	
Location	Statistic	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Mean	781 (30.7)	785 (30.1)	634 (25.0)	637 (25.1)
	Std. Dev.	44 (1.7)	53 (2.1)	36 (1.4)	41 (1.6)
Duluth	Mean	803 (31.6)	813 (32.0)	643 (25.3)	653 (25.7)
	Std. Dev.	42 (1.7)	54 (2.1)	35 (1.4)	41 (1.6)
Fargo, ND	Mean	838 (33.0)	843 (33.2)	676 (26.6)	678 (26.7)
	Std. Dev.	38 (1.5)	48 (1.9)	29 (1.1)	38 (1.5)
Minneapolis	Mean	895 (35.2)	887 (34.9)	805 (31.7)	796 (31.3)
	Std. Dev.	47 (1.9)	60 (2.3)	43 (1.7)	53 (2.1)
La Crosse, WI	Mean	925 (36.4)	904 (35.6)	829 (32.6)	809 (31.8)
	Std. Dev.	56 (2.2)	64 (2.5)	50 (2.0)	56 (2.2)
Sioux Falls, SD	Mean	942 (37.1)	948 (37.3)	843 (33.2)	845 (33.3)
	Std. Dev.	36 (1.4)	43 (1.7)	31 (1.2)	38 (1.5)

To summarize, all three parameters (i.e., annual (Jan-Dec), open-water, and peak monthly evaporation) had an upward trend at International Falls, Duluth, and Sioux Falls and a downward trend at Minneapolis and La Crosse for the period 1964 – 2005. In recent years (1986 – 2005), there has been a change in direction of annual and open-water evaporation trends for International Falls and Duluth and peak monthly evaporation trend for Minneapolis. The trends at all other locations have remained the same, although their magnitudes have changed. For example, the magnitude of annual and open-water evaporation trends has decreased for Minneapolis and La Crosse in recent years, but increased for Sioux Falls.

3.6. Statistics and Trends of Annual Precipitation in Minnesota

Precipitation is considered in this study because the difference between annual evaporation and annual precipitation gives the net water loss through a lake's surface. To maintain a stable lake level the net loss of water through a lake's surface has to be made up by surface runoff from the watershed into a lake or by a net groundwater input.

Annual precipitation time series at the six locations Figure 4 have been plotted in Figure 11. The lowest annual precipitation for the 1964 – 2005 period was observed at Fargo with an average rate of 536 mm/yr (21.1 in/yr). The highest annual precipitation was observed at La Crosse with an average rate of 812 mm/yr (32.0 in/yr). The highest variation in annual precipitation was at Minneapolis (standard deviation was 154 mm/yr or 6.1 in/yr) and the lowest variation was at International Falls (standard deviation was 91 mm/yr or 3.6). Both annual (Jan-Dec) and annual open-water season precipitation were higher during the 1986 – 2005 period than the 1964 – 2005 period for all stations except International Falls (Table 8).

Table 8. Mean and standard deviation of annual (Jan – Dec) and open-water season precipitation in mm/yr (in/yr) for the periods 1964 – 2005 and 1986 – 2005 .

		Annual (Jan-Dec) Precipitation		Annual Open-Water Precipitation	
Location	Statistic	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Mean	616 (24.3)	599 (23.6)	466 (18.3)	461 (18.1)
	Std. Dev.	91 (3.6)	93 (3.7)	77 (3.0)	81 (3.2)
Duluth	Mean	786 (31.0)	792 (31.2)	551 (21.7)	567 (22.3)
	Std. Dev.	133 (5.2)	139 (5.5)	110 (4.3)	117 (4.6)
Fargo, ND	Mean	535 (21.1)	572 (22.5)	395 (15.6)	431 (17.0)
	Std. Dev.	131 (5.1)	136 (5.3)	115 (4.5)	118 (4.6)
Minneapolis	Mean	751 (29.6)	774 (30.5)	633 (24.9)	669 (26.3)
	Std. Dev.	154 (6.1)	130 (5.1)	148 (5.8)	129 (5.1)
La Crosse, WI	Mean	812 (32.0)	837 (32.9)	678 (26.7)	696 (27.4)
	Std. Dev.	151 (5.9)	145 (5.7)	143 (5.6)	125 (4.9)
Sioux Falls, SD	Mean	632 (24.9)	656 (25.8)	547 (21.6)	575 (22.6)
	Std. Dev.	148 (5.8)	149 (5.9)	132 (5.2)	136 (5.4)

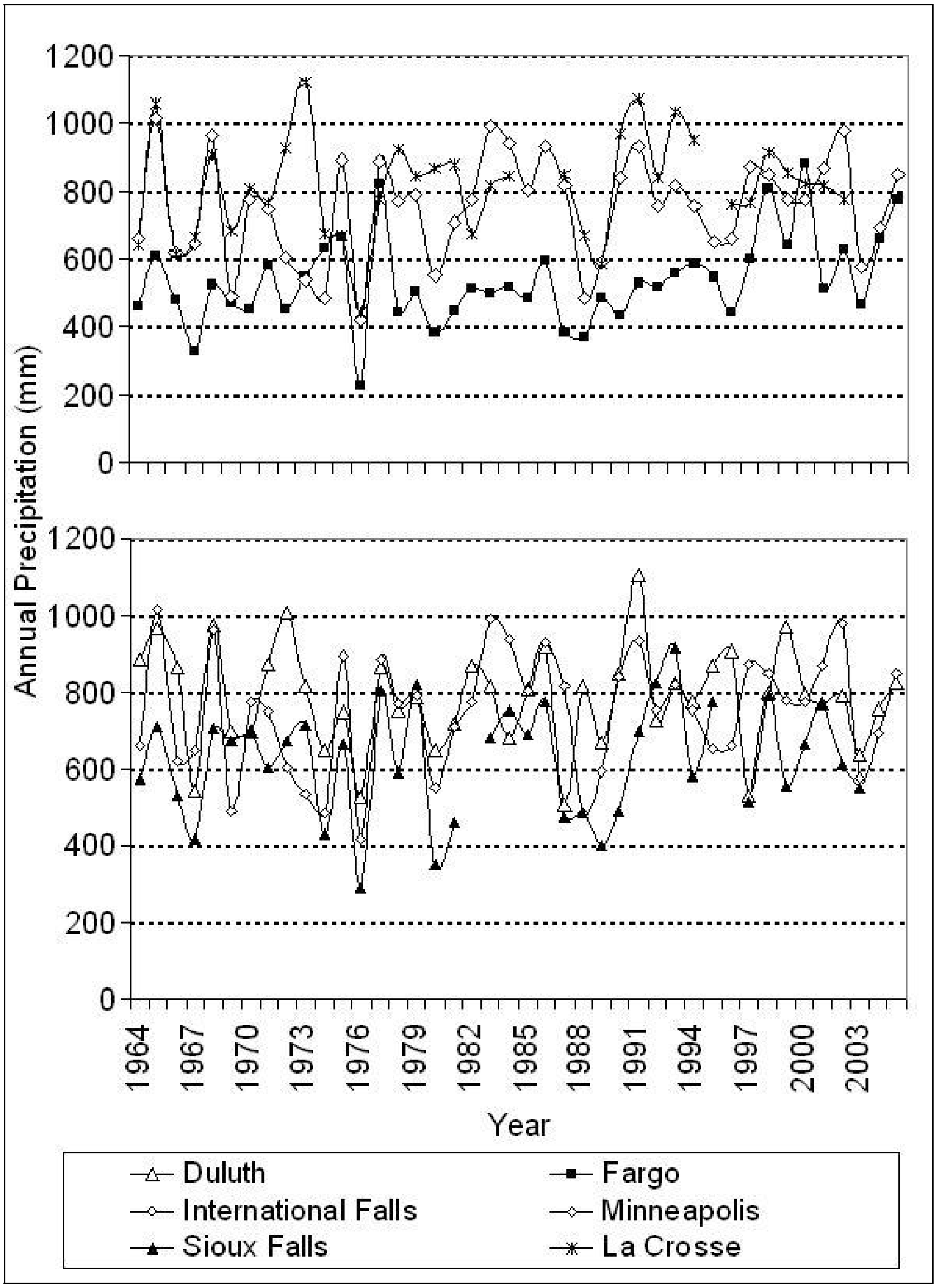

Figure 11. Annual precipitation at six weather stations.

Trends in precipitation were analyzed for the 1964 – 2005 and 1986 – 2005 periods (Table 9). For the 1964 – 2005 period, precipitation at the three southern locations, i.e. Sioux Falls, La Crosse, Minneapolis, as well as Fargo had an upward trend. Only the trend for Fargo was significant at the 0.05 level. Trends at all other locations, except International Falls, were significant at the 0.5 level (Table 9).

For the more recent 1986 – 2005 period, precipitation at all stations, except La Crosse and Duluth, showed an upward trend. The trend for Fargo was significant at the 0.05 level and the trends at the other stations, except Duluth, were significant at the 0.5 level (Table 9).

Table 9. Trends in precipitation (mm/yr) for 1964 – 2005 and 1986 – 2005.

Location	Period	1964 – 2005	1986 – 2005
International Falls	Trend	-0.84	5.10
	Sig.	0.47	0.16
Duluth	Trend	-0.44	-1.10
	Sig.	0.80	0.84
Fargo, ND	Trend	3.89	13.18
	Sig.	0.02	0.01
Minneapolis	Trend	2.47	1.78
	Sig.	0.21	0.73
La Crosse, WI	Trend	1.70	-1.53
	Sig.	0.39	0.78
Sioux Falls, SD	Trend	2.61	7.20
	Sig.	0.17	0.22

3.7. Statistics and Trends of Annual Water Availability (Precipitation minus Evaporation)

Annual water availability is defined as precipitation minus evaporation through a lake surface. Water availability is calculated as a) annual precipitation minus annual open-water evaporation, and b) annual open-water season precipitation minus open-water evaporation. This dual approach is used because in the winter months when lakes are ice-covered and precipitation is in the form of snow, the water gains and losses are more difficult to quantify then for the summer months. Under the scenario (a) the water availability is maximum, i.e. winter precipitation is retained in its entirety as an input to the lake. There is no water loss by snow blown away from the lake surface onto land, or by ablation of snow and ice from the frozen lake surface. Under scenario (b) the water availability is a minimum because winter precipitation is ignored entirely, i.e. snow fall on a lake surface is blown away by the wind or evaporated. It is likely that scenario (a) matches conditions on small, wind-sheltered lakes better, while scenario (b) may be more appropriate for lakes with large wind-exposed fetches.

Table 10 provides the statistics of water availability for the six stations. The values in Table 10 are the differences between measured precipitation (Table 8) and calculated annual evaporation (Table 7). All are annual values averaged over the indicated period. According to Table 10, water availability (for scenarios (a) and (b)) in all stations except International Falls and Duluth was higher in the last 20 years (1986 – 2005). Water availability at International Falls showed a slight decrease in the 1986 – 2005 period. Water availability at Duluth calculated with scenario (a) showed a slight decrease and water availability calculated with scenario (b) showed an increase in the last 20 years.

Annual water availability has a negative value for most years at all six locations because evaporation tends to exceed precipitation. This water deficit has to be made up by surface runoff from the watershed into a lake or by a net groundwater input if a stable lake level is to be maintained.

Table 10. Mean and standard deviation of annual water availability in mm/yr (in/yr) for the periods 1964 – 2005 and 1986 – 2005 . Water availability is calculated as a) annual precipitation minus annual open-water season evaporation, and b) annual open-water season precipitation minus annual open-water season evaporation.

		Precipitation - Open-Water Evaporation		Open-Water Precipitation - Open-Water Evaporation	
Location	Statistic	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Mean	-18 (-0.7)	-39 (-1.5)	-168(-6.6)	-177 (-7.0)
	Std. Dev.	106 (4.2)	106 (4.2)	92 (3.6)	93 (3.6)
Duluth	Mean	256 (10.1)	253 (10.0)	21 (0.8)	28 (1.1)
	Std. Dev.	141 (5.6)	147 (5.8)	118 (4.7)	128 (5.1)
Fargo, ND	Mean	-140 (-5.5)	-107 (-4.2)	-281 (-11.0)	-248 (-9.7)
	Std. Dev.	138 (5.4)	147 (5.8)	121 (4.8)	131 (5.2)
Minneapolis	Mean	-54 (-2.1)	-22 (-0.9)	-173 (-6.8)	-127 (-5.0)
	Std. Dev.	171 (6.7)	151 (5.9)	166 (6.5)	153 (6.0)
La Crosse, WI	Mean	-16 (-0.6)	30 (1.3)	-150 (-5.9)	-110 (-4.3)
	Std. Dev.	167 (6.6)	153 (6.0)	167 (6.6)	153 (6.0)
Sioux Falls, SD	Mean	-212 (-8.3)	-190 (-7.5)	-308 (-12.1)	-294 (-11.6)
	Std. Dev.	164 (6.4)	170 (6.7)	171 (6.7)	204 (8.0)

Trends in annual water availability are given in Table 11. For the period 1964 – 2005, annual water availability – calculated as annual precipitation minus annual open-water evaporation – showed an upward trend, i.e. a smaller annual water deficit at the lake surface, for Fargo, Minneapolis, Sioux Falls, and La Crosse. The trend calculated for Fargo was significant at the 0.05 level, all others were significant at the 0.5 level. Annual water availability for International Falls and Duluth showed a decreasing trend. For International Falls this trend was significant at the 0.5 level; for Duluth the trend was not significant.

For the period 1986 – 2005, water availability trends were upward for International Falls, Fargo, Minneapolis, and Sioux Falls (Table 11). Trends for Fargo were significant at the 0.05 level; trends for International Falls, Minneapolis, and Sioux Falls were significant at the 0.5

level. Annual water availability had an upward trend for Duluth, but a downward trend for La Crosse.

For the period 1964 – 2005, annual water availability – calculated as the difference between open-water precipitation minus open-water evaporation – showed increasing trends at all stations (Table 11). The trends for Fargo and Minneapolis were significant at the 0.05 level, and the trends for La Crosse and Sioux Falls at the 0.5 level. The trends for International Falls and Duluth were near zero, but the other four ranged from 1.6 to 4.3 mm/yr.

For the period 1986 – 2005, annual water availability for the open-water season (Table 11) showed an upward trend at all locations, except Duluth. The trends for Fargo and Sioux Falls were significant at the 0.05 level, the trend for International Falls at the 0.5 level. The strongest trend was at Fargo (15.1mm/yr).

Table 11. Trends (mm/yr) in annual water availability. Water availability is calculated as a) annual precipitation minus annual open-water evaporation, and b) annual open-water season precipitation minus annual open-water evaporation.

		Precipitation - Open-Water Evaporation		Open-Water Precipitation - Open-Water Evaporation	
Location	Trend Sig.	1964 – 2005	1986 – 2005	1964 – 2005	1986 – 2005
International Falls	Trend	-0.96	5.77	0.18	6.76
	Sig.	0.48	0.17	0.88	0.06
Duluth	Trend	-0.98	-0.22	0.05	-2.67
	Sig.	0.59	0.97	0.97	0.61
Fargo, ND	Trend	3.93	14.50	4.27	15.06
	Sig.	0.02	0.01	0.00	0.00
Minneapolis	Trend	3.45	2.47	4.17	2.29
	Sig.	0.11	0.68	0.05	0.71
La Crosse, WI	Trend	3.68	1.89	3.23	0.58
	Sig.	0.09	0.78	0.13	0.93
Sioux Falls, SD	Trend	2.37	6.09	1.63	5.04
	Sig.	0.27	0.37	0.47	0.54

3.8. Correlations of lake levels with evaporation or water availability

In a previous study (Dadaser-Celik and Stefan 2007) historical lake levels recorded in 25 Minnesota lakes were analyzed and correlated with climate parameters. That study can be extended by examining the lake level correlations with evaporation or water availability at the water surface. It is a logical step forward although it still does not include inflows from the watershed or groundwater interaction of a lake.

The correlation coefficients between observed annual average water levels of 8 landlocked and 17 flow-through lakes and computed annual evaporation, annual open-water evaporation, and annual water availability were calculated (Tables 12 and 13). Evaporation and water availability values were taken from one of the six weather stations (Figure 4) nearest the lake. The correlation between lake levels and evaporation would be expected to be negative (higher evaporation = lower lake levels); while the correlation with water availability would be expected to be positive (more net water input = higher lake levels).

The correlation coefficients in Tables 12 and 13 are very low indicating that evaporation alone is not a predictor of lake levels. Water levels correlated slightly better with annual water availability, but it also cannot be used as a sole predictor variable. As to be expected lake levels of 22 out of 25 lakes (88%) had a negative correlation with evaporation, but even the best correlation coefficients was only -0.47. The correlation between lake levels and water availability at the lake surface was positive for 24 of 25 lakes (96%), but the highest correlation coefficient was only 0.66. For **landlocked lakes** the average correlation coefficients were poorer than for **flow-through lakes**, especially for evaporation. The reason for this is unknown, but it can be speculated that the interaction of landlocked lakes with groundwater is so dominant that evaporation becomes fairly negligible.

Table 12. Correlations coefficients of observed water levels in 8 landlocked lakes with calculated evaporation or water availability.

Lake Name	Jan – Dec Evaporation	Open-Water Evaporation	Maximum Water Availability[1]	Minimum Water Availability[2]
Belle Taine	0.42	0.35	0.23	0.28
Emily	-0.36	-0.36	0.03	0.02
Island	-0.37	-0.37	0.34	0.34
Little Sand	0.30	0.16	0.41	0.45
Loon	-0.07	-0.12	0.30	0.37
Otter Tail	-0.06	-0.03	0.37	0.42
Sturgeon	-0.34	-0.37	0.28	0.31
Swan	-0.21	-0.19	0.15	0.10
Average	**-0.08**	**-0.12**	**0.26**	**0.29**

[1] annual precipitation – annual open-water evaporation

[2] annual open-water precipitation – annual open-water evaporation

Table 13. Correlations coefficients of observed water levels in 17 flow-through lakes with calculated evaporation and water availability.

Lake Name	Jan – Dec Evaporation	Open-Water Evaporation	Maximum Water Availability[1]	Minimum Water Availability[2]
Benton	-0.18	-0.12	0.24	-0.04
Birch	-0.39	-0.41	0.38	0.38
Detroit	0.16	0.12	0.46	0.50
East Fox	-0.29	-0.34	0.53	0.53
Green	-0.44	-0.44	0.40	0.41
Height of Land	-0.14	-0.06	0.27	0.30
Marion	-0.32	-0.36	0.26	0.28
Minnetonka	-0.37	-0.39	0.35	0.33
Minnewaska	-0.19	-0.05	-0.09	-0.06

Mud	-0.41	-0.47	0.66	0.64
Pelican	-0.31	-0.32	0.23	0.20
Peltier	-0.41	-0.45	0.48	0.52
Rush	-0.12	-0.09	0.40	0.40
Shetek	-0.19	-0.12	0.56	0.09
Swan	-0.37	-0.40	0.11	0.09
Upper Prior	-0.27	-0.32	0.23	0.20
Vermillion	-0.29	-0.33	0.38	0.42
Average	**-0.27**	**-0.27**	**0.34**	**0.31**

[1] annual precipitation – annual open-water evaporation [2] annual open-water precipitation – annual open-water evaporation

We also calculated the correlation coefficients between lake levels in October and evaporation during the summer (June-August and May-October) (Tables 14 and 15). May-October evaporation had a higher average correlation coefficient than June-August evaporation. Correlation coefficients of October water levels with May-October evaporation were negative, as to be expected for 22 out of 25 lakes (88 %), but the best value was only -0.64, and the average only -0.22 and -0.27 for **landlocked and flow-through lakes**, respectively.

Table 14. Correlation coefficients of observed October water levels in 8 landlocked lakes with calculated summer evaporation.

Lake Name	June-August Evaporation	May-October Evaporation
Belle Taine	0.45	0.32
Emily	-0.56	-0.64
Island	-0.44	-0.48
Little Sand	0.10	0.00
Loon	-0.21	-0.14
Otter Tail	-0.13	-0.19
Sturgeon	-0.06	-0.27
Swan	-0.30	-0.38
Average	**-0.14**	**-0.22**

Table 15. Correlation coefficients of observed October water levels in 17 flow-through lakes with calculated summer evaporation.

Lake Name	June-August Evaporation	May-October Evaporation
Benton	0.29	-0.01
Birch	-0.40	-0.49
Detroit	0.03	0.15
East Fox	0.02	-0.13
Green	-0.02	-0.24
Height of Land	-0.12	-0.10
Marion	-0.55	-0.53
Minnetonka	-0.42	-0.52
Minnewasha	-0.14	-0.11
Mud	-0.51	-0.50
Pelican	-0.04	-0.12
Peltier	-0.41	-0.47
Rush	-0.21	-0.18
Shetek	-0.23	-0.21
Swan	-0.34	-0.35
Upper prior	-0.49	-0.57
Vermillion	-0.34	-0.26
Average	**-0.23**	**-0.27**

In summary, these results show that the correlation between lake water levels and evaporation and water availability is low. This is attributed to the fact that surface water inflow from the watershed of a lake and groundwater interactions (Eq.1) affect lake water levels at least as much or more than evaporation and precipitation on the lake surface. The obvious conclusion is that for most lake water budgets surface water runoff from the watershed must be considered.

4. SUMMARY & CONCLUSIONS

Lake evaporation can be measured as pan evaporation or computed from relationships with climate parameters. We reviewed measured pan evaporation data and computed evaporation rates from Minnesota lakes by using daily weather data recorded at six Class A weather stations (Figure 4) from 1964 to 2005. Daily evaporation at these stations was estimated using mass-transfer equations named after Meyer, Lake Hefner, Rohwer, and Ryan and Harleman. Results were analyzed individually or as averages.

Trends in evaporation and water availability (precipitation minus evaporation) were calculated using linear regression. We also compared results for the full period of record (1964 – 2005) with results for the recent 20 years (1986 – 2005). For the trend analysis we selected the Meyer equation as most appropriate for Minnesota conditions.

We examined the correlation coefficients between annual average water levels of 25 previously analyzed Minnesota lakes (Dadaser-Celik and Stefan (2007) and annual evaporation or water availability. Eight lakes were landlocked and 17 flow-through lakes.

The results can be summarized as follows:

1) July is the month with the highest evaporation from lake surfaces in Minnesota. Daily evaporation from Minnesota lakes in July is on average 4.4 – 6.7 mm/day (0.17 – 0.26 in/day). Monthly evaporation in July varied in the range 134 – 160 mm (5.3 – 6.3 in).
2) Annual evaporation from Minnesota lakes ranged from 781 to 942 mm/yr (30.8 to 37.1 in/yr). To obtain these results, daily values calculated by the Meyer equation for six locations were averaged for the 1964 – 2005 period. The lowest evaporation occurs when Minnesota lakes are ice-covered.
3) The open-water season evaporation showed no consistent trend in the 1964 – 2005 period (Table 6). Three locations (International Falls, Duluth and Sioux Falls) had a weakly rising trend (0.13 to 0.64 mm/yr), and the other three locations (Fargo, Minneapolis and La Crosse) had a weakly falling trend (-0.03 to -1.65 mm/yr).
4) Over the last 20 years (1986 – 2005), the open-water season evaporation trends became slightly more negative. Five of the six locations had negative trends from -0.69 to -1.57mm/yr. The exception was Sioux Falls with a positive trend of 1.09mm/yr (Table 6).

5) Annual average precipitation at the six locations ranged from 536mm/yr to 812 mm/yr (21.1 in/yr to 32.0 in/yr) in the 1964 – 2005 period. Annual precipitation showed a rising trend at four of the six locations (International Falls and Duluth were the exceptions) from 1964 to 2005. Increasing trends were in the range of 1.70 to 3.85 mm/yr, while the strongest decreasing trend was -0.84 mm/yr (Table 8).

6) Over the last 20 years (1986 – 2005), the annual precipitation also showed a rising trend at four of the six locations (Duluth and La Crosse were the exceptions). Increasing trends were in the range of 1.78 to 13.18 mm/yr, while the strongest decreasing trend was –1.53 mm/yr (Table 8).

7) Water availability had trends similar to precipitation for the period 1964 – 2005. The strongest upward trend was found for Fargo with a rate of 3.93 mm/yr and the strongest negative trend for Duluth with a rate of -0.98 mm/yr. For the last 20 years (1986 – 2005) water availability had a stronger upward trend (e.g., 14.5 mm/yr in Fargo) than for the 40-year period (1964 – 2005).

8) Water availability during the open-water period – calculated as annual open-water season precipitation minus annual open-water evaporation – increased at all six locations from 1964 to 2005 (Table 9). The strongest rise was at Fargo with a rate of 4.27 mm/yr.

9) From 1986 to 2006, water availability during open-water periods showed even stronger rising trends for all locations, except Duluth. The strongest upward trend was again at Fargo (15.06mm/yr). Duluth had a downward trend of -2.67mm/yr.

We have also attempted to understand how Minnesota lake levels have responded to climate in the past 40 year, and evaporation is an important component of this investigation. Correlation coefficients between annual lake water levels and annual evaporation or annual water availability were, however, very weak. Similarly weak were correlation coefficients between lake levels in October and evaporation from May to October.

Overall, the analysis shows that lake evaporation in Minnesota in the last 40 and the last 20 years has had trends that were not strong enough to form a conclusion about evaporation changes. Evaporation seems to have become more variable from year to year in the last 20 years. By comparison trends in precipitation during the same time periods were positive and much stronger than trends in evaporation. As a result, upward trends in annual water availability exist in the state of Minnesota. That is mostly good news.

Although we did not find strong correlations between lake levels and evaporation and water availability, increases in water availability can perhaps explain the increased observed water levels of 25 lakes, which we analyzed before (Dadaser-Celik and Stefan 2007).

ACKNOWLEDGEMENTS

Funding for this study was provided by the Environmental and Natural Resources Trust Fund as recommended by the Legislative-Citizens Commission on Minnesota Resources (LCCMR), St Paul, Minnesota. The grant was coordinated by Lucinda Johnson from the Natural Resources Research Institute, University of Minnesota 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

Anonymous, 1997. Climate Change and Minnesota. EPA 230-F-97-008w, United States Environmental Protection Agency (EPA), Office of Policy, Planning and Evaluation, Washington, D.C.

Changnon, S.A. and Kunkel, K.E., 1995. Climate-related fluctuations in Midwestern Floods During 1921-1985. Journal of Water Resources Planning and Management, 121(4): 326-334.

Chow, V.T., 1964. Handbook of Applied Hydrology. McGraw-Hill Book Company, New York, NY, USA.

Dadaser-Celik, F. and Stefan, H.G., 2007. Lake level response to climate in Minnesota., University of Minnesota, St. Anthony Falls Laboratory, Report No: 502., Minneapolis, MN.

Dalton, J., 1802. Experimental essays on evaporation. Machester Literary Philosophical Society Proceedings, 5: 536-602.

Edinger, J.E., Brady, D.K. and Geyer, J.C., 1968. The response of water temperatures to meteorological conditions. Water Resources Research, 4(5): 1137-1143.

Fang, X. and Stefan, H.G., 1999. Projections of climate change effects on water temperature characteristics of small lakes in the contiguous U.S. Climatic Change, 42: 377-412.

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 Stefan, H.G., 2004. Indicators of climate warming in water resources data from Minnesota, St. Antony Falls Laboratory, University of Minnesota, Minneapolis, MN, USA.

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

Kling, G.W. et al., 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.

Marciano, J.J. and Harbeck, G.E., 1954. Mass-transfer studies. In: USGS (Editor), Water-Loss Investigations: Lake Hefner Studies, Technical Report. United States Geological Survey, Washington, D.C., pp. 46-70.

Meyer, A.F., 1942. Evaporation From Lakes and Reservoirs: A Study Based on Fifth Years' Weather Bureau Records. Minnesota Resources Commission, St. Paul, MN.

NCDC, Climate of Minnesota, National Climatic Data Center (NCDC), Available at http://www5.ncdc.noaa.gov/climatenormals/clim60/states/Clim_MN_01.pdf (accessed February 22, 2008).

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

Rohwer, C., 1931. Evaporation from free water surfaces, U.S. Department of Agriculture, Washington, D.C., USA.

Seeley, M., 2003. Climate trends: what are some implications for Minnesota's air and water resources?

Singh, V.P. and Xu, C.-Y., 1997a. Evaluation and Generalization of 13 Mass-Transfer Equations for Determining Free Water Evaporation. Hydrological Processes, 11(3): 311-323.

Singh, V.P. and Xu, C.-Y., 1997b. Sensitivity of mass transfer-based evaporation equations to errors in daily and monthly input data. Hydrological Processes, 11(11): 1465-1473.

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

Stefan, H.G., Gulliver, J., Hahn, M.G. and Fu, A.Y., 1980. Water temperature dynamics in experimental field channels: Analysis and modeling, St. Antony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN, USA.

Stefanovic, 2000. personal communication.

Sturrock, A.M., Winter, T.C. and Rosenberry, D.O., 1992. Energy budget evaporation from Willams Lake: A closed lake in North Central Minnesota. Water Resources Research, 28(6): 1605-1617.

Williams, G., Layman, K.L. and Stefan, H.G., 2004. Dependence of lake ice covers on climatic, geographic and batyhmetric variables. Cold Regions Science and Technology, 40: 145-164.

Winter, T.C., 1981. Uncertainties in Estimating the Water Balance of Lakes. Water Resources Bulletin, 17(1): 82-115.

APPENDIX 1. Sensitivity of evaporation to water temperature assumption

In the sensitivity analysis, we estimated average daily lake water water temperatures by solving equation A1.1

$$\frac{dT}{dt} = \frac{K(T_e - T_w)}{\rho Ch} \qquad \text{(A1.1)}$$

In Equation A1.1, T_w is water surface temperature (^oC), t is time (day), K is the bulk surface heat exchange coefficient ($W/m^2/C$), T_e is the equilibrium temperature (^oC), ρ is density of water (1,000 kg/m^3), C is the heat capacity of water (4,186 $J/kg/^oC$), and h is the surface mixed layer depth (m) of a lake. Daily T_e and K values were obtained by using the climatic data and equations provided by Edinger (1974) as explained in the Methods section. Equation A1.1 was solved numerically for T_w for mixed layer depths of 0, 1.0, 5.0, and 20.0 m.

Average daily and average monthly water temperatures corresponding to different mixed layer depths are shown on Figures A1.1 and A1.2, respectively, for the year 1964. As can be seen, daily water temperatures become more dynamic when mixed depth is decreased (Figure A1.1). Day to day temperature fluctuations are highest when mixed layer depths are 0 and 1 m and small when mixed water depths are 5 and 20 m. The peak water temperatures decrease and the timing of peaks is delayed as mixed layer depths increase (Figures A.1 and A.2). Average annual surface water temperatures for mixed layer depths of 0, 1, 5 and 20 m were 8.4 ^oC (47.2 ^oF), 8.0 ^oC (46.4 ^oF), 8.6 ^oC (47.2 ^oF), and 9.1 ^oC (48.4 ^oF), respectively, under 1964 climate conditions. This is a fairly narrow range. In our evaporation estimates/calculations we used the water temperatures for 0 m mixed layer depth, which is within 0.7^oC of the other values.

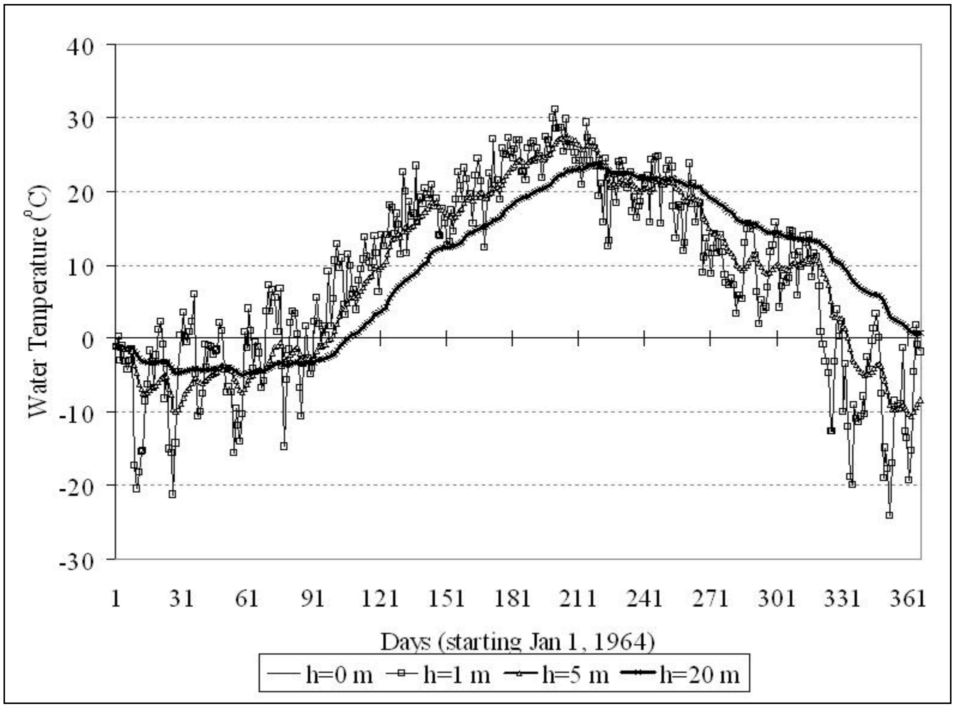

Figure A1.1. Daily water temperatures for the year 1964 corresponding to mixed water depths of 0, 1, 5 and 20 m.

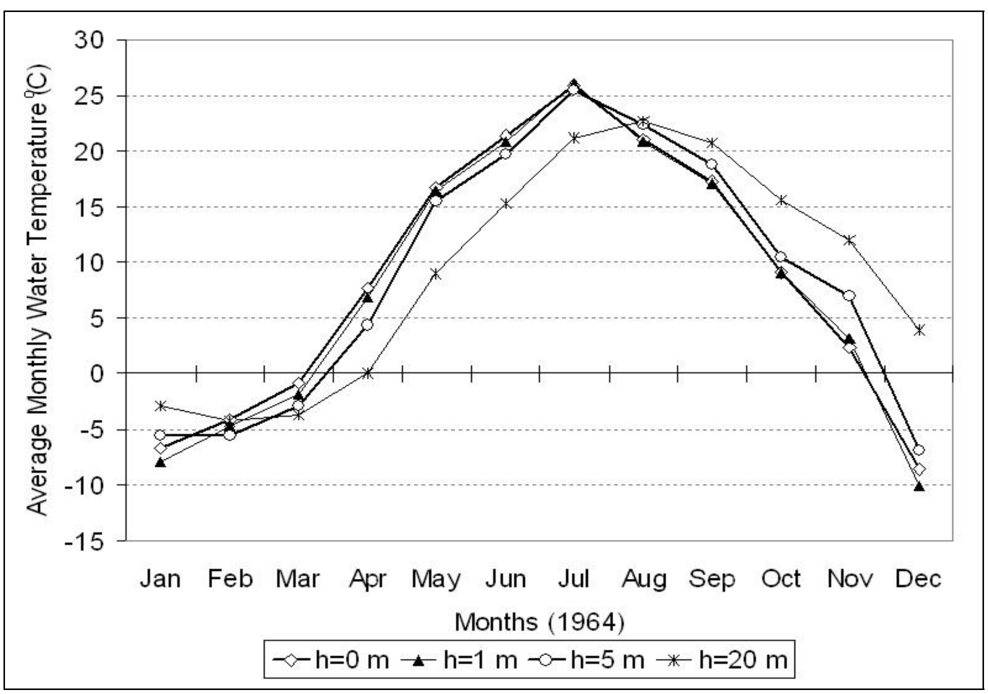

Figure A1.2. Average monthly water temperatures for the year 1964 corresponding to mixed layer depths of 0, 1, 5 and 20 m.

The annual evaporation values calculated with the Meyer equation corresponding to different mixed water depths are provided in Figure A1.3. As expected, annual evaporation decreased as mixed water depth increased because the surface water remained colder. Average annual evaporation values for the 1964 – 2005 period corresponding to mixed water depths of 0, 1, 5 and 20 m were 895 mm (35.2 in), 851 mm (33.5 in), 840 mm (33.1 in), and 767 mm (30.2 in), respectively. Mixed layer depths in Minnesota's dimictic lakes are typically from 2 to 5 m in summer, when evaporation is at a maximum. Evaporation values for those depths given in Figure A1.3 are on the order of 5 to 8% lower than those for 0m mixed layer depth. Absolute evaporation estimates may be too high by this fraction, but trends would not be much affected.

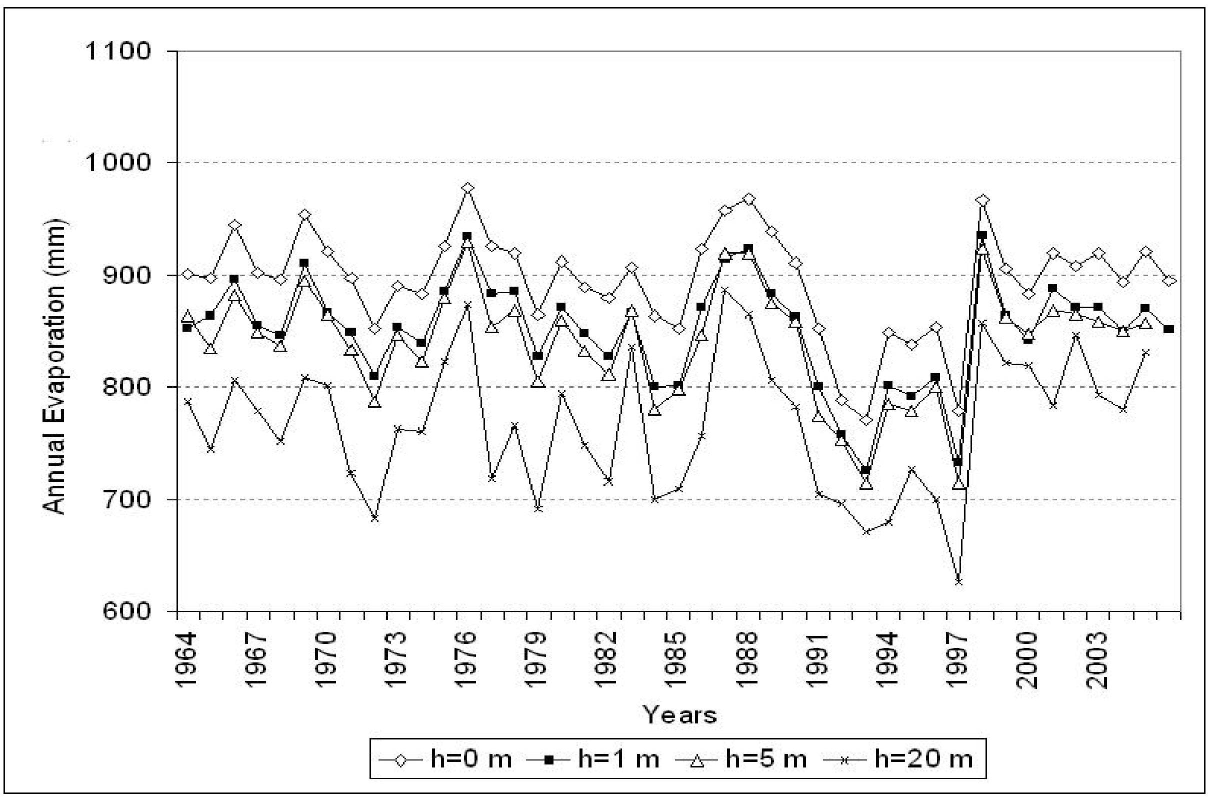

Figure A1.3. Annual evaporation calculated with water temperatures estimated for mixed layer depths of 0, 1, 5, and 20 m.

APPENDIX 2. Average Ice-out and Ice-in dates for Minnesota Lakes

Ice-out and ice-in dates for Minnesota lakes are shown in Figures A2.1 and A2.2. The data cover the latitudes over which the state of Minnesota extends. The data are averages of many years of record (Johnson and Stefan 2006). Ice-out date data show less scatter because ice-out is more directly correlated with climate variables some of which are strongly dependent on latitude. Ice out depends also on climate, but in addition has a strong dependence on average lake depth which is not accounted for in the data plot.

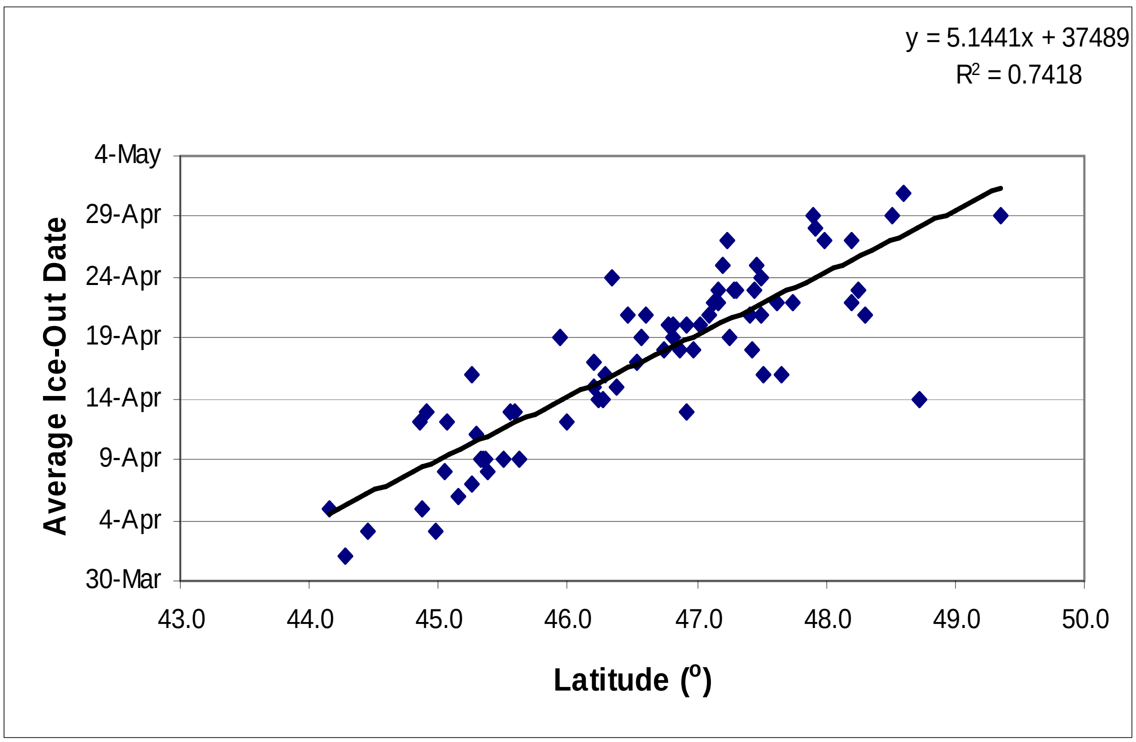

Figure A2.1. Average ice-out dates for Minnesota lakes (Johnson and Stefan, 2006)

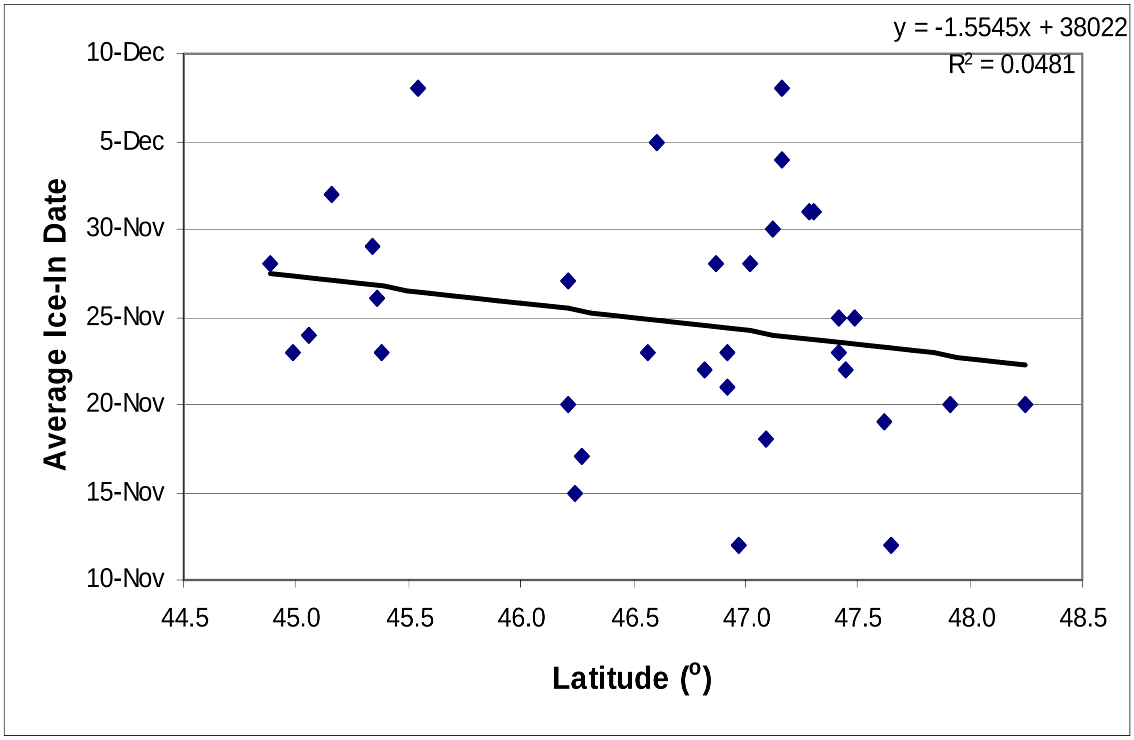

Figure A2.2. Average ice-in dates for Minnesota lakes (Johnson and Stefan, 2006)

APPENDIX 3. Names, locations, and characteristics of Minnesota lakes included in this study

The names and locations of the lakes included in the lake level study (Dadasser-Celik and Stefan 2007) are given in Figure A3.1. The lake characteristics are listed on Table A3.1.

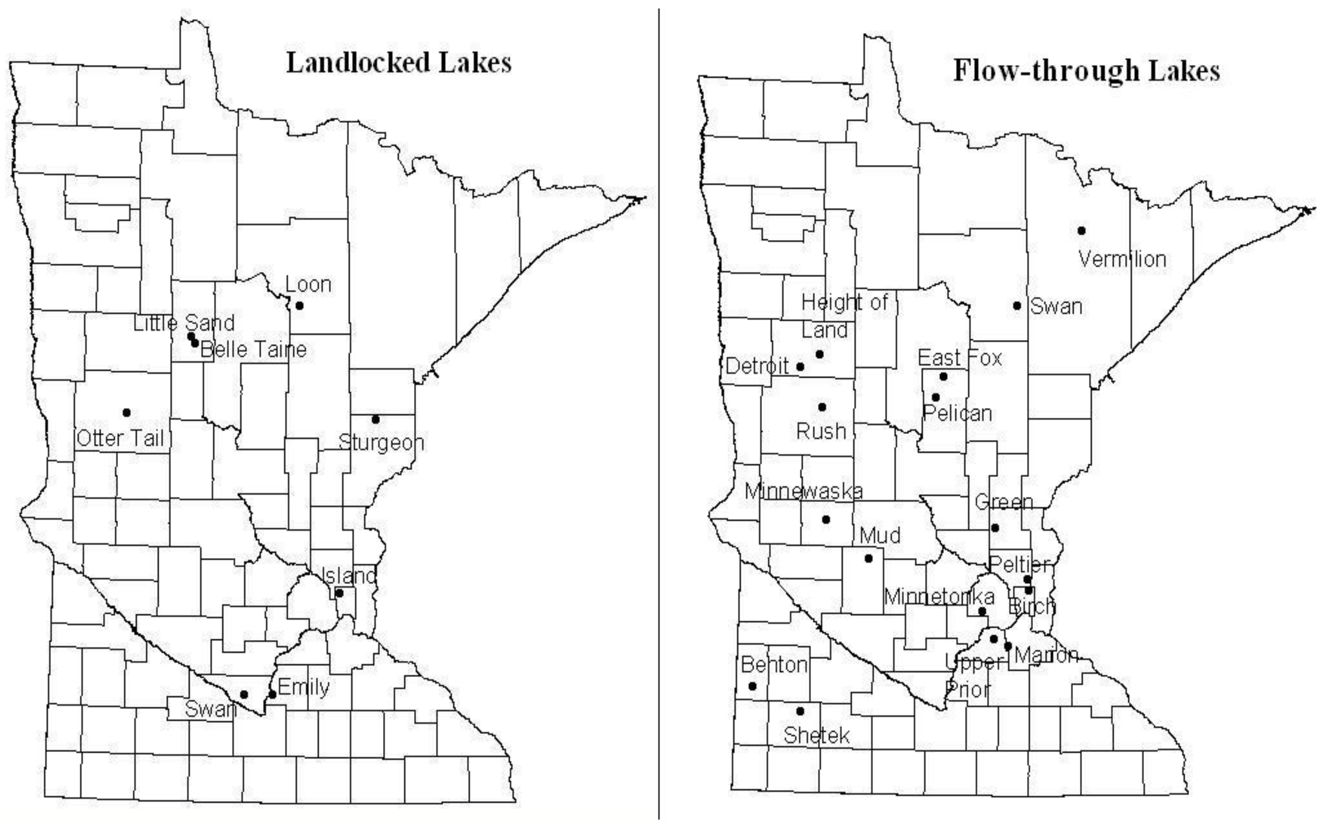

Figure A3.1.Locations and names of Minnesota lakes included in the lake level study (Dadasser-Celik and Stefan 2007)

Table A3.1. Landlocked lakes included in this 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 A3.2. Flow-through lakes included in this 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