An assessment of long-term trends in hydrologic components and implications for water levels in Lake Superior

Homayoun Motiee and Edward McBean

ABSTRACT

The combination of climate change and natural periodicities in meteorological variables are demonstrating significant impacts on the water resources of Lake Superior within the Laurentian Great Lakes system of North America. Statistical analyses of long-term records are used to demonstrate how changes over time may be interpreted very differently, depending upon the timeframe over which the analyses are made. Non-linear regression modelling shows that, while increasing trends in overland and overlake precipitation, flows and runoff occurred during the first decades of the twentieth century, very different trends are apparent for the period 1970–2005. For this latter period, increasing rates of air overlake temperature and lake evaporation are occurring but all other parameters are demonstrating decreasing trends. The result is a decline in water levels in Lake Superior at the rate of approximately 1 cm per year over the last 35 years. The results are used to show that to avoid decreasing water levels in Lake Superior, the discharge through St Mary's River must be decreased to approximately one-half the long-term annual average, the results of which will have dramatic implications for ships' cargo levels and hydroelectric energy generation.

Key words | climate change, drought, Great Lakes, Lake Superior, Mann–Kendall, regression modelling

Homayoun Motiee (corresponding author)
Water Eng. Faculty, Power and Water University of Technology (PWUT),
Tehran,
Iran
and
University of Guelph,
Guelph,
Canada
E-mail: *hmotiee@uoguelph.ca*

Edward McBean
School of Engineering,
University of Guelph,
Guelph N1G 2W1,
Canada

INTRODUCTION

Recent studies indicate there are substantial impacts of climate change influencing water resources (e.g. IPCC 2007). The consequences may include changes in hydrologic parameters and adjustments in the frequency and magnitude of hydrologic extremes. For example, recent measurements on lakes around the world show that a significant number of lakes are experiencing decreasing water levels. Some lakes have dried out completely due to a combination of these changes plus mismanagement of water resources (e.g. Hamoun Lake in southeast of Iran; Partow 2003). Lake Oroomiyeh in northwest Iran, with a surface of 5,800 km^2 (the second-most saline lake in the world) is demonstrating significant declines in surface levels. In 2008, the depth of water in Lake Oroomiyeh was 2 m less than the long-term average and the volume is estimated to have decreased to one-third (Zargar 2008). Another dramatic example is the Aral Sea, landlocked in Central Asia, with a drainage basin of 1.8 million km^2. Due to mismanagement and drought, the water levels in the Aral Sea have decreased by 23 m (Micklin 2006). Its surface area has decreased by 74%, its volume by 90% and the salinity has increased from 10 to more than 100 $g\,L^{-1}$.

Water level decreases in lakes around the world have been reported by many researchers (e.g. Micklin 2006; Leon 2008; Zargar 2008). At least three of the Great Lakes of North America (Superior, Michigan and Huron) are demonstrating decreased water levels (USACE 2008). The reasons for the decrease of water levels in Lake Superior,

doi: 10.2166/nh.2009.061

the biggest lake in the immense hydrologic system of the Great Lakes, are examined herein. Also shown are how the timeframes used in the analyses influence the determination of trends.

LAURENTIAN GREAT LAKES OF NORTH AMERICA

The Laurentian Great Lakes of North America, namely Lakes Superior, Huron, Michigan, Erie and Ontario, represent some of the most important water resources in the world. They provide water for more than fifty million people in eastern North America. Combined, the Great Lakes and their connecting channels comprise the largest freshwater system on earth (see Figure 1), holding approximately 20% of the world's fresh surface water supply (de Loë & Kreutzwiser 2000; GLIN 2005). Furthermore, the Great Lakes and their connecting channels are essential water and power-generating resources that support extensive economic and urban development throughout the region.

As an indication of the enormous size of the Great Lakes, the estimated cumulative volume of the five lakes is 6×10^{15} (six quadrillion) gallons (equal to 22,700 km^3) which is sufficient water to flood the entire continent of North America to an average depth of 1 m (Hunter & Croley 1993). However, although massive in terms of volume, since the water surface area is 244,000 km^2 (USEPA 2005) and the Great Lakes basin has only a drainage area of 770,000 km^2 (Croley 1990), it follows that the Great Lakes drain land areas only twice that of their surface area.

As a result of the above, while there are enormous volumes of water in the Great Lakes, the relatively modest contributing drainage area translates to enormous retention times as summarized in Table 1. Lake retention time (also called the residence time of lake water, or the water age or flushing time) is the time that the volume of water takes in a lake to exit through its outlet (Shaw *et al.* 1993). It is calculated by dividing the lake volume by either the mean rate of inflow of all tributaries plus direct precipitation, or by the mean rate of outflow (ideally including evaporation

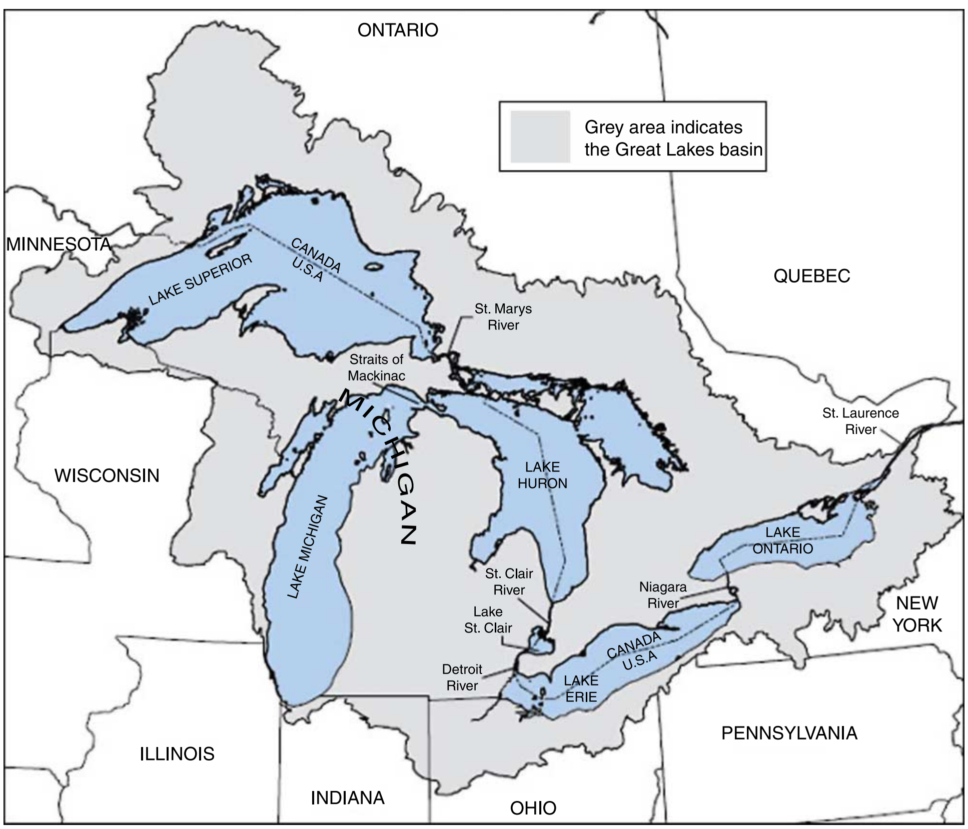

Figure 1 | The Great Lakes basin in North America.

Table 1 | Retention times for the Great Lakes (USEPA 2005)

Lake name	Retention time (years)
Superior	191
Michigan	99
Huron	22
Erie	2.6
Ontario	6

and seepage). Hence, while the dimensions of the Great Lakes imply that they might support the diversion of large quantities of water out of the watershed, any changes arising from climate change and/or water diversions from the Lakes may create long-term repercussions on water levels and water budgets. The above indicates the importance of understanding the influences of drought or climate change on the Lakes. Specifically, the lengthy record of historical data for the Great Lakes provides the opportunity to assess long-term stresses acting on the Lakes. Since global climate changes may be underway, this provides the opportunity to assess long-term changes in precipitation, runoff, evaporation and flows in terms of the water budget for the Great Lakes.

According to Neff & Nicholas (2005), "Fluctuations in the Great Lakes water level arise from natural parameters and human activities. Levels on the Great Lakes depend on their storage capacity, outflow characteristics of the outlet channels, operating procedures of the regulatory structures, and the amount of water supply received by each lake". Therefore, fluctuations of water levels in the Great Lakes are a challenge for people living and working near their shores. Rising and falling lake levels affect shipping, hydroelectric energy generation, recreational boating, water supply and damage to the coastline through flooding and erosion. It may be possible to minimize the damage resulting from fluctuating lake levels by understanding the causes of these fluctuations and developing effective management practices.

Lake Superior

Lake Superior is the deepest of the Great Lakes (Figure 2) with an average depth of 147 m. It is also the coldest and the cleanest of the lakes in the Great Lakes ecosystem

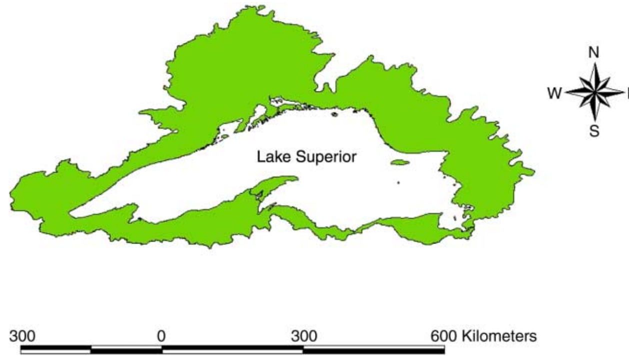

Figure 2 | Lake Superior and its surrounding watersheds.

(Hunter & Croley 1993). According to the GLIN (2005), the total area of the Lake Superior Basin is 208,980 km^2 and it has the largest surface area of any freshwater lake in the world, encompassing 82,097 km^2, (hence 39% of its entire drainage area), a shoreline of 4,393 km and 12,232 km^3 of water volume (Table 2).

As a result of Lake Superior's large surface area and position at the headwaters of the Great Lakes ecosystem, rain/snowfall represents the largest sources of input directly to the Lake. The 335 tributary rivers and streams that drain into the Lake from the surrounding watershed represent the second-largest source of water. One result of this combination of physical characteristics is that retention time of water in the Lake is very large, between 173 and 191 years (USEPA 2005). Water leaves Lake Superior through

Table 2 | Physical characteristics of Lake Superior (GLIN 2005)

Length (km)	563
Breadth (km)	257
Depth (m)	149 average (maximum: 406)
Shoreline length (km)	4,393 (including islands)
Volume (km^3)	12,232
Water surface area (km^2)	82,097
Retention/replacement time (years)	191
Outlet	St Mary's River to Lake Huron
Drainage basin area (km^2)	127,700
Surface water elevation (m a.s.l.)	183
Population	444,000 (US), 229,000 (Canada)

evaporation and regulated discharge via St Mary's River. According to USACE (2008), "for Lake Superior, 40% of the water volume exiting the lake leaves through evaporation and 60% leaves through the St Mary's River".

According to LaMP (2008), climate change is anticipated to impact the Great Lakes and Lake Superior in many dimensions including: shorter winters, increasing the warmth of annual average temperatures from 2°C to almost 4°C (Kling *et al.* 2003), more frequent extreme heat events and a fall in the duration of lake ice cover as air and water temperatures rise; increasing frequency of heavy precipitation events, both rain and snow, and a reduction of future lake levels as winter ice coverage decreases; continuing reduction in the duration of winter ice cover, changes of the timing of stream flows because of earlier ice break-up and earlier peaks in spring runoff; and increasing incidence of extreme events such as severe storms and floods.

Of enormous concern is that Lake Superior has recently dropped to its lowest water level in 81 years. Figure 3 demonstrates the water level in recent years (2006–2008), showing two values of maximum (at the top) and minimum (at the bottom) of water level for every month in a period 1918–2007. Two curves of recorded values (solid line) and average values (the dashed line) are indicated. As illustrated in this figure, the recorded values curve in 2006–2008 are substantially below the average value curve. According to USACE (2008), Lake Superior's water level in March 2008 was 30 cm lower than its monthly long-term average. Further, the average water temperature of Lake Superior has risen by 3°C since 1979, which indicates an increase in evaporative loss from the Lake (Cauchon 2007).

Water level changes have impacted on shipping. For example, for every 2.5 cm Lake Superior drops, about 2.0 km^3 (529 billion gallons) of water are displaced. For every decrease of 2.5 cm in depth, cargo ships must reduce their loads by 50 to 270 tons, therefore providing less cargo for the same amount of shipping time (Hall & Stuntz 2007).

Historical data assembly

Since long-term datasets for the Great Lakes exist, assessment of the long-term hydrologic variables for Lake Superior is feasible (Quinn & Kelley 1983). For the Great Lakes, mean monthly and mean annual overlake air temperature and evaporation data are available for the period 1948–2005 (NOAA 2007). For the streamflows, according to Croley *et al.* (2004), lake outflows are determined by direct measurement (for Lakes Superior and Ontario), stage-discharge relationships (for Lakes Michigan, Huron and St Clair) or a combination (Lake Erie), and are considered accurate to within 5%. Allan & Hinz (2004) employed the data of a total of 425 gages (259 in US, 166 in Ontario) for the characterization of flow regimes of rivers of the Great Lakes basin.

Mean monthly and mean annual data series for overland and overlake precipitation, evaporation, air overlake temperature, runoff from surrounding lands, water levels of Lake Superior and the flow data for St Mary's River were obtained from the Great Lakes Environmental Research Laboratory (GLERL) of the National Organization for Atmospheric Administration (NOAA 2007). Station data for the US were obtained from the National Climatic Data Center and station data for Canada were obtained from Atmospheric Environment Service. These data have been spatially weighted using the modified Theissen weighting approach (Assel *et al.* 1995; Croley *et al.* 2004). With the exception of evaporation and air overlake temperature, available from 1948, all other time series data were available for the period of 1900–2005.

It should be mentioned that runoff from the drainage basin is based on tributary river streamflow records which are published by GLERL (Neff & Killian 2003). Runoff to the Great Lakes includes all water entering the lakes through rivers, streams and direct overland flow. Runoff from rivers and streams is calculated by considering runoff from gauged and ungauged portions of each Great Lake basin.

According to Neff & Killian (2003), "Runoff from gaged portions of the Great Lakes Basin is calculated using stage data collected at gaging stations located throughout the Basin. These stage data are compared to stage-discharge relationships developed and maintained for each station and streamflow is estimated. Streamflow data are reported by the US Geological Survey (USGS) and the Water Resources Branch of Environment Canada (EC), but neither agency provides estimates of runoff in ungaged areas".

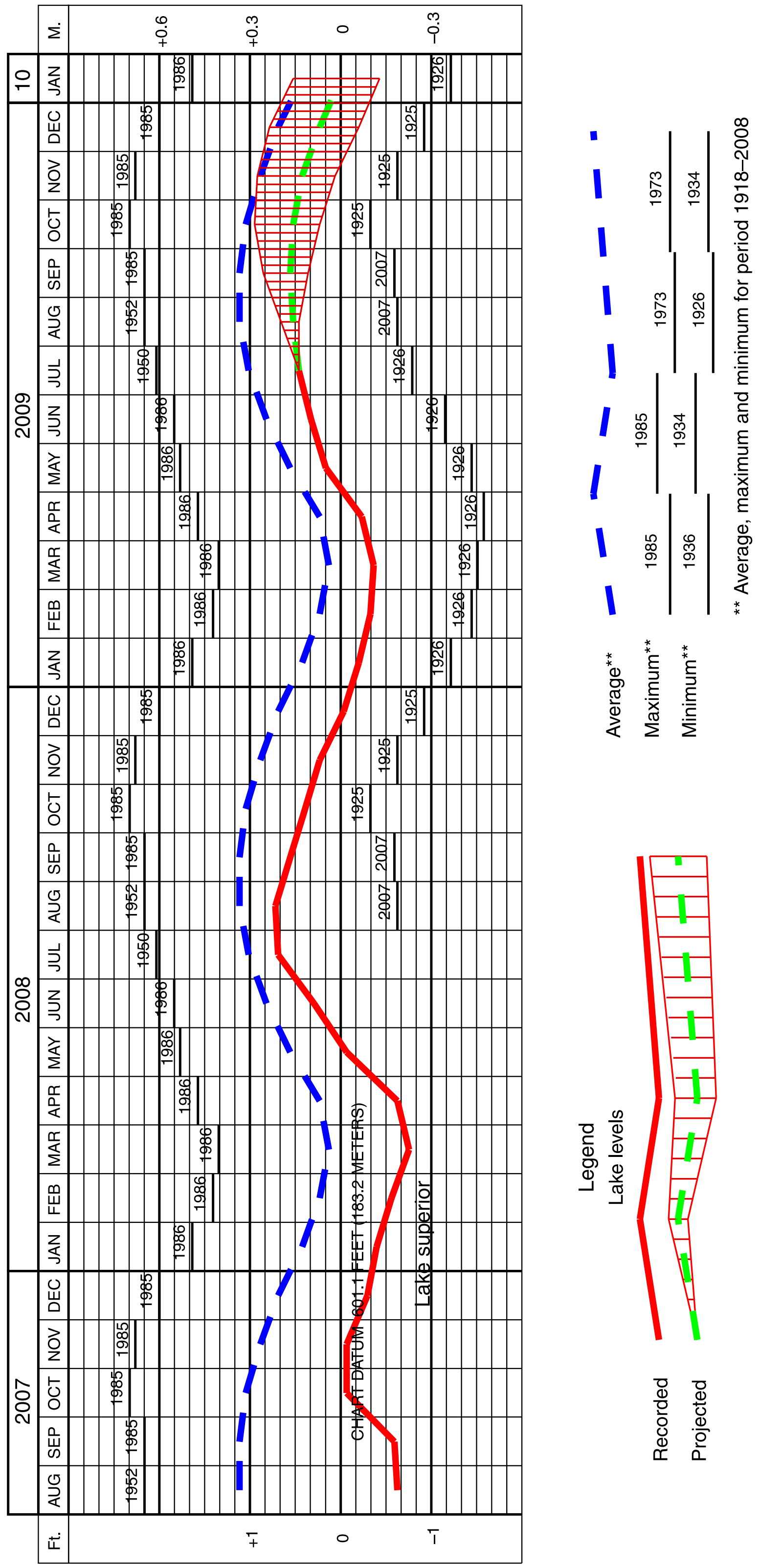

Figure 3 | Graph of water level in Lake Superior from 2006–2008 (USACE 2008).

TREND CHARACTERIZATION METHODOLOGY

Mann–Kendall test

The non-parametric Mann–Kendall test may be used to detect trends that are monotonic but not necessarily linear. The null hypothesis in the Mann–Kendall test is that the data are independent and randomly ordered. The Mann–Kendall test does not require the assumption of normality and only provides the direction, but not the magnitude, of significant trends (Kendall 1955; Helsel & Hirsch 1992).

The Mann–Kendall procedure was applied to the time series of annual precipitation, evaporation, air overlake temperature, flow, runoff and water level. The computational procedure for the Mann–Kendall test considers the time series of n data points and T_i and T_j are two subsets of data where $i = 1, 2, 3, \ldots, n-1$ and $j = i+1, i+2, i+3, \ldots, n$. Each data point T_i is used as a reference point and is compared with all the T_j data points such that:

$$\mathrm{sign}(T) = \begin{cases} 1 & \text{for} \quad T_j > T_i \\ 0 & \text{for} \quad T_j = T_i \\ -1 & \text{for} \quad T_j < T_i \end{cases} \tag{1}$$

The Mann–Kendall S-statistic is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sign}(T_j - T_i) \tag{2}$$

and the variance for the S-statistic is defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{3}$$

in which t_i denotes the number of ties to extent i. All these parameters are discussed in detail by Kendall (1955, chapter 5). The summation term in Equation (3) is only used if the data series contains tied values. The test statistic Z_s is calculated as:

$$Z_s = \begin{cases} (S-1)/\sigma & \text{for} \quad S > 0 \\ 0 & \text{for} \quad S = 0 \\ (S+1)/\sigma & \text{for} \quad S < 0 \end{cases} \tag{4}$$

and follows a standard normal distribution. Equation (4) is useful for record lengths greater than 10 and if the amount of 'tied' data is low (Kendall 1955). The test statistic Z_s is used as a measure of significance of trend. In fact, this test statistic is used to test the null hypothesis, H_0. If $|Z_s|$ is greater than $Z_{\alpha/2}$, where α represents the chosen significance level (e.g. 5% with $Z_{0.025} = 1.96$), then the null hypothesis is invalid implying that the trend is significant.

Regression model test

One of the most useful parametric models to detect trends is linear regression. The model for Y (e.g. precipitation) may be described by:

$$Y = aX + b \tag{5}$$

where X is time (years), a is slope coefficient and b is least-square estimate of the intercept.

The slope coefficient indicates the annual average rate of change in the hydrologic characteristic. If the slope is statistically significantly different from zero, the interpretation is that it is entirely reasonable to assume that there is a real change occurring over time, as inferred from the data. The sign of the slope defines the direction of the trend of the variable: increasing if the sign is positive and decreasing if the sign is negative.

Normality of the data

The method of linear regression requires the assumptions of normality of residuals, constant variance and true linearity of relationship (Helsel & Hirsch 1992). As well, many statistical analyses require that the data come from normally distributed populations. The normal distribution is the most common statistical distribution because approximate normality arises naturally in many physical, biological and social measurement situations. With testing using Minitab 15 software, the Ryan–Joiner (R–J) test was employed to evaluate the normality of the data series which is similar to the Shapiro–Wilk normality test (Wolstenholme 1999).

The Ryan–Joiner test assesses normality by calculating the correlation between the data and the normal scores of the data. If the correlation coefficient is near unity, the population is likely to be normal. The R–J statistic assesses the strength of this correlation; if it falls below the appropriate critical value, the null hypothesis of population normality is rejected.

In this regard, checking the normality of the data was accomplished using the R–J method. The R–J coefficient is compared to a coefficient, Ca, and if the R–J coefficient is greater than Ca then the null hypothesis of normality cannot be rejected. The coefficient of Ca depends on the number of the data points and the significance levels of α (Devore 2004).

Evaluation of the results

There are different ways to evaluate the significance of the results such as confidence limits at 95% levels, R-square and P-value. All these values were calculated in the evaluation of trend lines. The 95% confidence interval of the slope is a range of values, as is the 95% confidence interval of the intercept. Linear regression can also combine these uncertainties to graph a 95% confidence interval of the regression line. The best-fit line is solid, and the 95% confidence interval is shown by two curves surrounding the best-fit line in the figures which follow.

For a population with a sample size n, the confidence interval (CI) was calculated by the procedure outlined in Devore (2004):

$$\hat{Y} \pm t_{(\alpha/2,n-2)} S_{\hat{Y}} \quad (6)$$

where $\hat{Y}$ is the mean value of observations, $S_{\hat{Y}}$ the estimated standard deviation of the statistic $\hat{Y}$ and $t_{(\alpha/2,n-2)}$ is a critical value for a 95% confidence level.

The plotting of the confidence interval for the regression line shows that the CI is centred at the mean of X, namely X_{mean}, and extends out to each side by an amount that depends on the confidence level with a hyperbolic form (Devore 2004). It should be noted that in the presence of autocorrelation, the confidence intervals of the slope of the regression line may widen significantly. Therefore, a slope that is statistically significant under the hypothesis of uncorrelated data may become ‘not significantly different from zero’ if correlation is properly taken into account.

Of additional interest is the prediction of a variable for some future time, and estimation of an interval of plausible values for the value of Y associated with a future value of X. This is possible with the calculation of prediction intervals rather than a confidence interval (Devore 2004). The P value is a probability with a value ranging from 0–1; when P is less than 0.05, for example, it shows that the trend is significant at 5% level. The smaller the value of P, the more significant is the trend (Helsel & Hirsch 1992).

R-square (R^2) or the square of the correlation coefficient is a fraction between 0.0 and 1.0 (dimensionless) where a value approaching zero means there is minimal correlation between X and Y; when R^2 approaches 1.0, the correlation is high.

Autocorrelation function coefficient

According to Marco *et al.* (1993), “hydrologic time series are generally autocorrelated”. Autocorrelation is defined as the correlation of a time series with its own past and future values separated by k lag time units (k is equal to unity in this research).

Autocorrelation in some series, such as streamflows, usually arises from the effects of surface, soil and groundwater storage. Conversely, annual precipitation is usually not statistically significantly correlated.

Baren (1994) and Montanari *et al.* (1996) indicated that autocorrelation has an influence on the width of the confidence intervals where high autocorrelation results in increased magnitudes of confidence limits. This means a slope that is statistically significant under the hypothesis of uncorrelated data may become ‘not significantly different from zero’ if autocorrelation is properly accounted for (Baren 1994).

In addition, the autocorrelation coefficient may influence the results obtained from the Mann–Kendall test. Hamed & Ramachandra (1998) state that “The null hypothesis for the Mann–Kendall test is that the data are independent and randomly ordered, i.e. there is no trend or serial correlation structure among the observations”. However, in many situations of hydrology and climatology, observed data are autocorrelated. Cox & Stuart (1955) indicate that “positive autocorrelation among the observations would increase the chance of a significant answer, even in the absence of a trend”.

For this research MiniTab-15 was used for calculation of the autocorrelation, trend lines, statistical values such as confidence intervals and plotting of the figures.

RESULTS OF THE HYDROLOGIC TREND TESTS

The tests with different periods of time equal to 105 years (1900–2005) and 35 years (1970–2005) were completed. The trend characterizations show that the last decades of the 20th century demonstrate decreasing slopes, and yet the 105-year trend characterizations are statistically significant showing increasing trends. These findings, as described in more detail below, demonstrate that results are dependent upon the timeframe over which the analyses are completed.

Historical period trends 1900–2005

The results of time series for the period 1900–2005 by the two statistical methods are as follows.

The Mann–Kendall test

The existence of positive trends for four parameters (of five possible), namely overlake precipitation, overland precipitation, runoff and flow in St Mary's River, is demonstrated. However, for water level there is a negative trend. For overlake and overland precipitation, there is a small positive autocorrelation function (ACF) of 0.03 and 0.17, respectively. For flows, runoff and water levels, the ACFs are 0.55, 0.50 and 0.70, respectively.

For overlake precipitation, overland precipitation and runoff, the value of Z_s are 2.70, 5.90 and 4.20. This is greater than $Z_{0.025}$, indicating evidence of a statistically significant trend at 5% level. Meanwhile, for flows at St Mary's River the value of Z_s is 1.60, less than $Z_{0.025}$, but there is statistical evidence of a positive trend with a 10% level. The water level trend with a Z_s equals -1.40, implying a negative trend for water levels at 10% significance level (Table 3a).

The regression test

The R–J method shows that the data series are Gaussian with values equal to 0.993, 0.995, 0.994, 0.997 and 0.984 for overlake precipitation, overland precipitation, flow of St Mary's River, runoff and water level parameters, respectively. The coefficient of Ca for the data series over 105 years and a significance level of 5% is equal 0.975 (Devore 2004). Consequently, all data can be assumed to be normally distributed.

The long-term overlake and overland precipitation, flow, runoff and water level data (1900–2005) for Lake

Table 3a | Autocorrelation function coefficient (AFC) and Mann–Kendall coefficient for hydrologic parameters of Lake Superior (1900–2005)

	ACF	Z_s (Mann–Kendall test)	Significance level
Precipitation overlake	0.03	2.70	YES (positive at 5% level)
Precipitation over land	0.17	5.90	YES (positive at 5% level)
Flow of St Mary's River	0.55	1.60	YES (positive at 10% level)
Runoff from watershed	0.50	4.20	YES (positive at 5% level)
Water level	0.70	−1.4	YES (negative at 10% level)

Table 3b | Regression statistics for hydrologic parameters of Lake Superior (1900–2005)

	Regression equation	Slope with 95% confidence limits	P-value	R-square	Normality test (R–J)
Precipitation over lake	$Y = 0.81\ X - 822.8$	0.81 ± 0.54	0.003	0.081	0.993
Precipitation over land	$Y = 1.41\ X - 1{,}993$	1.41 ± 0.50	0.00002	0.24	0.995
Flow of St Mary's River	$Y = 2.06\ X - 1{,}905$	2.06 ± 1.98	0.056	0.03	0.994
Runoff from watershed	$Y = 1.826\ X - 3{,}085$	1.82 ± 0.74	0.0001	0.22	0.997
Water level	$Y = -0.0005\ X + 184.7$	-0.0005 ± 0.0009	0.26	0.015	0.984

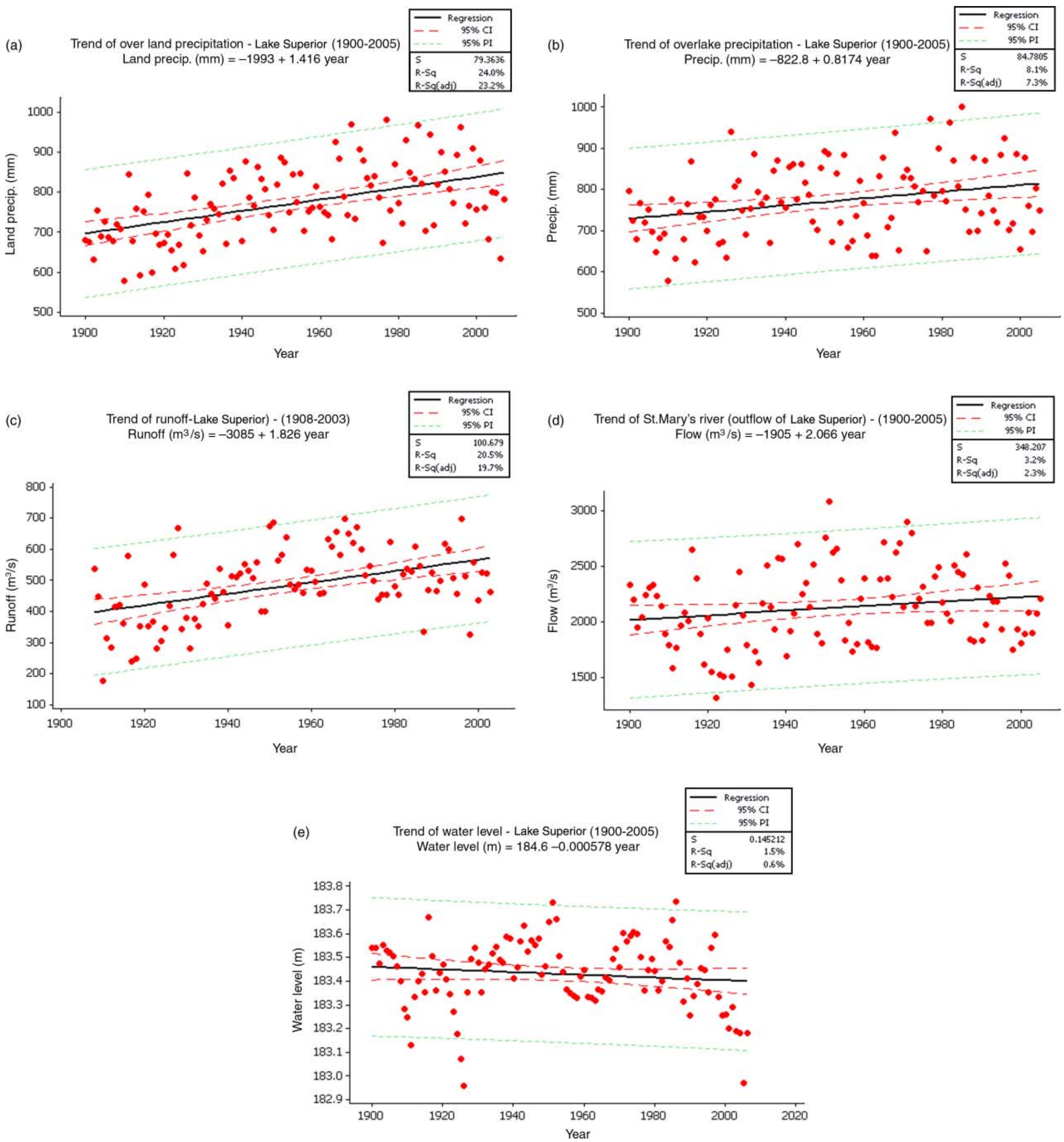

Figure 4 | Trends for average annual (a) land precipitation, (b) overlake precipitation, (c) runoff, (d) outflow and (e) water level for Lake Superior (1900–2005).

Superior are plotted as average annual parameters versus time in Figure 4(a–e), respectively. The slopes of the trend lines are demonstrated by the statistical test results listed in Tables 3a and 3b as highly significant from both the regression modelling and from the Mann–Kendall statistics (for all parameters except water levels, as summarized in Table 3b). Hence, on the basis of the period 1900–2005, increasing trends are present for all parameters except water level. Interpretation of the statistical coefficients implies the following.

1. Since the P-value for the slope in overlake and overland precipitation and runoff are very low, there is statistical significance at 5% level.
2. The 95% confidence limits of slope for overlake precipitation (0.81 ± 0.54), overland precipitation (1.41 ± 0.50), flow of St Mary's River (2.06 ± 1.98) and runoff (1.82 ± 0.74) do not include a value of zero for slope, indicating there is statistical significance at 5% level. It is noted that since evaporation data were only available for the period 1950–2005, no trend has been calculated for this parameter in the period 1900–2005.

Historical period trends 1970–2005

Table 4 illustrates the magnitudes of hydrologic parameters for the period 1970–2005. The results of data series in this period, analyzed by two statistical methods are as follows.

The Mann–Kendall test

The existence of a positive trend only for evaporation and negative trends for all other parameters is demonstrated. Overlake and overland precipitation show the decreasing trends with 10% level of significance with negative autocorrelations of value −0.23 and −0.18, respectively. For flow, runoff, evaporation, air Overlake temperature and water levels, positive autocorrelations of value 0.31, 0.1, 0.03, 0.26 and 0.70, respectively, are obtained. The positive autocorrelation in the two periods of 1900–2005 and 1970–2005 would increase the chance of a significant answer; however, the relatively high value of autocorrelation (0.7) can affect the interval confidence and the uncertainty of the results.

For overlake and overland precipitation, the values of Z_s are −1.60 and −1.70, respectively, and their absolute magnitudes are less than $Z_{0.025}$. On the contrary, for flow of St Mary's River, runoff, evaporation, air overlake temperature and water level, the values of Z_s are −2.20, −2.25, 2.26, 2.90 and −4.70, respectively. Their absolute magnitudes are greater than $Z_{0.025}$, showing there is an increasing trend for evaporation and a decreasing trend with a 5% significance level for the other parameters (Table 5a).

The regression test

The R–J method shows that the data series are normally distributed with the values of coefficient equal to 0.99, 0.996, 0.98, 0.98, 0.98, 0.98, 0.99 for overlake precipitation, overland precipitation, flow of St Mary's River, runoff, evaporation, air overlake temperature and water level parameters, respectively (Table 5b). The coefficient of Ca for data over 35 years and a significance level of 5% is equal to 0.97 (Devore 2004). As a result, all data are normally distributed because the R–J coefficients for all series are greater than Ca, and hence the null hypothesis of normality cannot be rejected.

The overlake and overland precipitation, flow, runoff, evaporation and water level data for the period (1970–2005) for Lake Superior are plotted as average annual parameters versus time in Figure 5(a–g), respectively. The slopes of the trend lines are highly significant from both the regression modelling and using the Mann–Kendall statistic for all parameters except water levels (Table 5b). These results demonstrate there is sufficient evidence to indicate (on the basis of 1970–2005 period) an increasing trend for evaporation, air overlake temperature and decreasing trends for all other parameters. Interpretation of the statistical coefficients shows that since the P-value for the rate of change with time of flow in St Mary's River, runoff, evaporation, air overlake temperature and water level are very low, there is statistical significance at 5% level. The 95% confidence limits of slope for overlake precipitation (−1.90 ± 3.02), overland precipitation (−1.97 ± 2.54), flow of St Mary's River (−11.7 ± 8.46), runoff (−3.42 ± 2.82), evaporation (2.28 ± 2.05), air overlake temperature (0.051 ± 0.023) and water level (−0.01 ± 0.004) and only for the overlake and overland precipitation does a value of 0 exist for the trend in the 95% confidence intervals.

Assessment of time series with a quadratic regression model

Comparison of some of the results for the time series over 105 years with increasing trends, and that for the second period of time (1970–2005) with decreasing trends, demonstrate different behaviour evident in the hydrologic parameters. These results lead to the conclusion that a

Table 4 | Annual average values of hydrologic parameters in Lake Superior, 1970–2005

Year	Overland precipitation (mm)	Overlake precipitation (mm)	Runoff ($m^3 s^{-1}$)	Outflow St Mary's ($m^3 s^{-1}$)	Water level (m)	Evaporation (mm)	Air overlake temperature (°C)
1970	907.2	830.95	622.17	2,138	183.46	572.21	3.57
1971	880.23	848.42	671.05	2,897	183.60	578.78	3.51
1972	834.99	828.36	600.61	2,799	183.57	620.82	1.93
1973	817.82	809.65	517.72	2,144	183.59	568.55	4.53
1974	839.52	769.23	548.04	2,214	183.61	581.31	3.15
1975	787.1	796.84	499.31	2,314	183.60	630.57	4.06
1976	673.31	651.76	440.71	1,992	183.50	740.1	3.17
1977	980.84	972.79	454.81	1,993	183.36	453.03	3.73
1978	754.83	786.84	454.98	2,409	183.45	596.98	3.02
1979	871.08	901.09	625.74	2,493	183.49	460.45	2.50
1980	773.16	798.07	480.76	2,175	183.44	607.15	3.30
1981	720.88	772.48	455.88	2,074	183.36	549.08	4.22
1982	930.27	964.03	521.05	2,008	183.40	558.38	2.74
1983	848.09	872.57	538.05	2,513	183.57	645.92	4.34
1984	832.16	808.42	529.66	2,447	183.55	567.62	4.01
1985	967.55	1,002.65	609.41	2,426	183.66	600.28	3.03
1986	820.78	751.27	545.84	2,607	183.74	503.07	4.12
1987	702.59	698.13	335.63	1,841	183.48	584.06	5.77
1988	943.78	879.17	468.63	1,829	183.31	680.27	3.94
1989	717.04	699.45	526.46	2,308	183.41	643.55	2.94
1990	819.29	742.42	466.96	1,836	183.25	551.77	4.57
1991	900.59	870.71	498.80	1,980	183.34	598.56	4.47
1992	851.69	786.83	617.55	2,232	183.39	573.99	3.70
1993	808.22	749.51	601.01	2,182	183.46	588.83	3.45
1994	773.14	720.77	509.42	2,183	183.45	510.6	3.89
1995	894.06	884.87	456.39	1,935	183.36	706.49	4.01
1996	962.13	924.79	699.26	2,523	183.54	496.35	2.68
1997	722.55	703.55	514.75	2,417	183.60	498.25	3.90
1998	765.08	719.26	327.66	1,749	183.33	604.08	6.56
1999	909.97	887.92	557.76	1,935	183.26	680.76	5.59
2000	757.41	655.19	437.61	1,807	183.26	678.7	4.80
2001	879.91	878.96	525.45	1,893	183.20	583.25	5.60
2002	762.13	761.88	522.94	2,083	183.29	694.67	4.76
2003	683.31	697.36	463.96	1,903	183.19	708.23	4.04
2004	799.56	803.44	601.23	2,078	183.18	693.77	4.08
2005	797.86	780.84	502.45	2,212	183.10	669.11	5.59

Table 5a | AFC and Mann–Kendall coefficients for hydrologic parameters, Lake Superior (1970–2005)

	ACF	Z (Mann–Kendall test)	Significance level
Precipitation overlake	−0.23	−1.60	YES (negative at 10% level))
Precipitation over land	−0.18	−1.70	YES (negative at 10% level))
Flow of river	0.31	−2.20	YES (negative at 5% level)
Runoff	0.10	−2.25	YES (negative at 5% level)
Evaporation	0.03	2.26	YES (positive at 5% level)
Air overlake temperature	0.26	2.90	YES (positive at 5% level)
Water level	0.70	−4.70	YES (negative at 5% level)

Table 5b | Regression statistics for hydrologic parameters for Lake Superior (1970–2005)

	Regression equation	Slope with 95% confidence limits	*P*-value	*R*-square (%)	Normality test (R–J)
Precipitation over lake	$Y = -1.90X + 4{,}588$	-1.90 ± 3.02	0.05	5.1	0.99
Precipitation over land	$Y = -1.97X + 4{,}746$	-1.97 ± 2.54	0.046	15.1	0.996
Flow of river	$Y = -11.71X + 5{,}462$	-11.71 ± 8.46	0.013	18.9	0.98
Runoff	$Y = -3.42X + 7{,}391$	-3.42 ± 2.82	0.013	15.1	0.99
Evaporation	$Y = 2.28X - 3{,}927$	2.28 ± 2.05	0.03	12.3	0.98
Air overlake temperature	$Y = 0.051X - 96.90$	0.051 ± 0.023	0.001	28.0	0.98
Water level	$Y = -0.01X + 204.3$	-0.01 ± 0.004	0.0002	47.8	0.99

non-linear regression model could be fit more appropriately over the long period of time. As a result, the time series were examined with a quadratic regression model defined:

$$Y = aX^2 + bX + C. \tag{7}$$

Figure 6(a–e) show the trends obtained by a quadratic regression model, the Table 6 illustrates the equations of these trends. As illustrated, this model presents a better fit line over the 105-year period. It demonstrates that during the first 70 years of the 20th century, the trends demonstrated positive slopes whereas during the latter portion of the 20th century, the trends demonstrate negative slope.

WATER BALANCE IN LAKE SUPERIOR FOR 1970–2005

Consider now the water balance (or hydrologic budget) for Lake Superior, expressed as the difference between the inflows and outflows:

$$\text{Water Balance (WB)} = \text{Inflow volumes} - \text{Outflow volumes}$$

or

$$\text{WB} = (V_{\text{precip}} + V_{\text{runoff}}) - (V_{\text{outflow}} + V_{\text{evap}}) \tag{8}$$

where V_{precip} is total overlake precipitation volume, V_{runoff} is total runoff volume, V_{outflow} is total outflow volume from the lake and V_{evap} is total overlake evaporation volume (all variables measure in units of per year).

The values of precipitation and evaporation are in mm, and those of runoff and outflows are in $m^3 s^{-1}$. If WB is negative, this means there is loss of water in the Lake. Table 7 demonstrates the average annual hydrologic parameters in the Lake obtained by the data series in the period of 1970–2005. For the surface area of the Lake equal to 82,097 km^2 (Table 2), the values of these parameters as volume of water are:

$$V_{\text{precip}} = 805 \times 10^{-6} \times 82,097 = 66.1\,\text{km}^3$$

$$V_{\text{evap}} = 596 \times 10^{-6} \times 82,097 = 48.2\,\text{km}^3$$

$$V_{\text{outflow}} = 2,182 \times 86,400 \times 365 \times 10^{-9} = 68.8\,\text{km}^3$$

$$V_{\text{runoff}} = 600 \times 86,400 \times 365 \times 10^{-9} = 19.0\,\text{km}^3$$

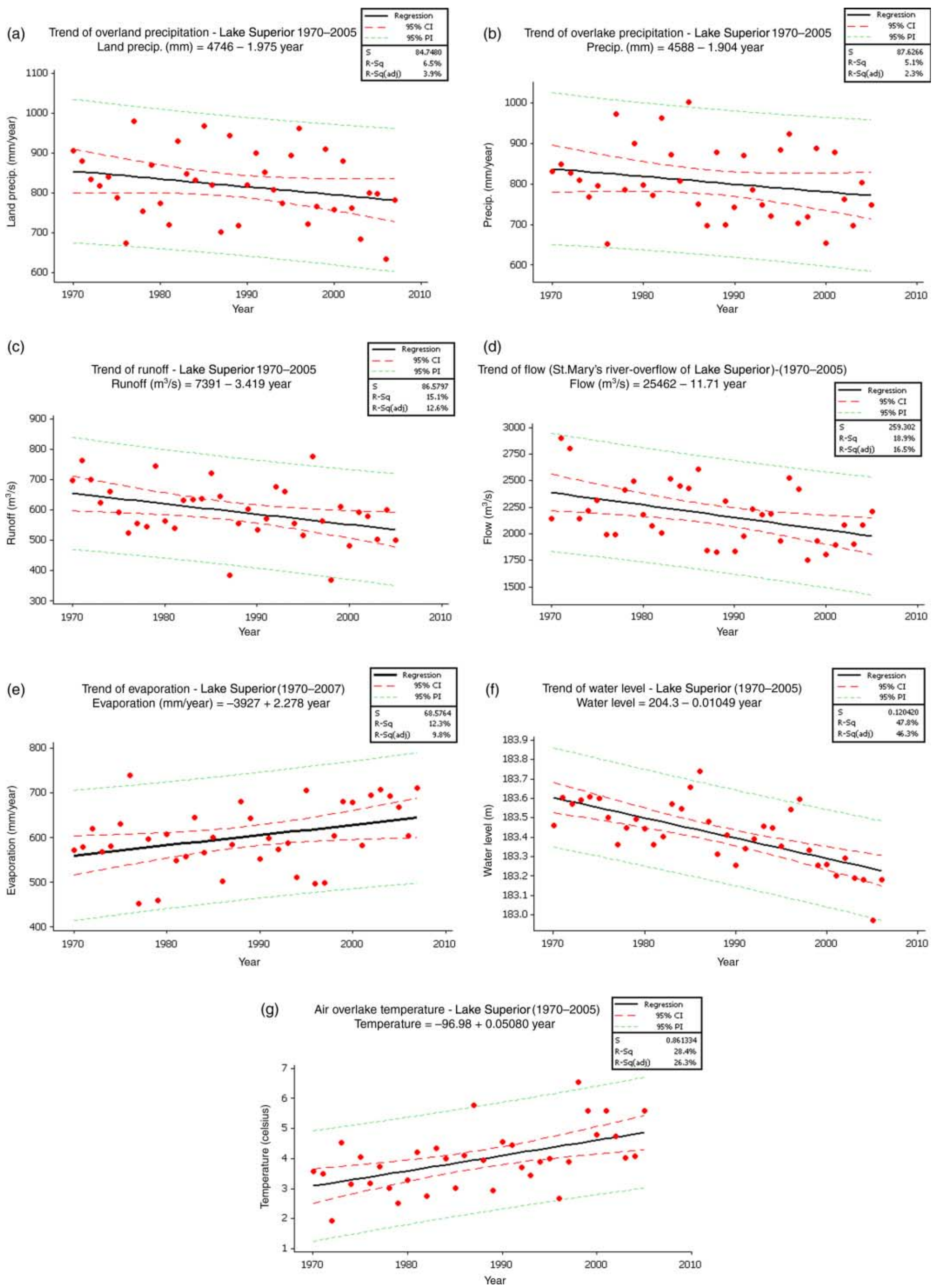

Figure 5 | Trends for (average annual) (a) overlake precipitation, (b) overland precipitation, (c) runoff, (d) outflow, (e) evaporation, (f) water level and (g) air overlake temperature and for Lake Superior (1970–2005).

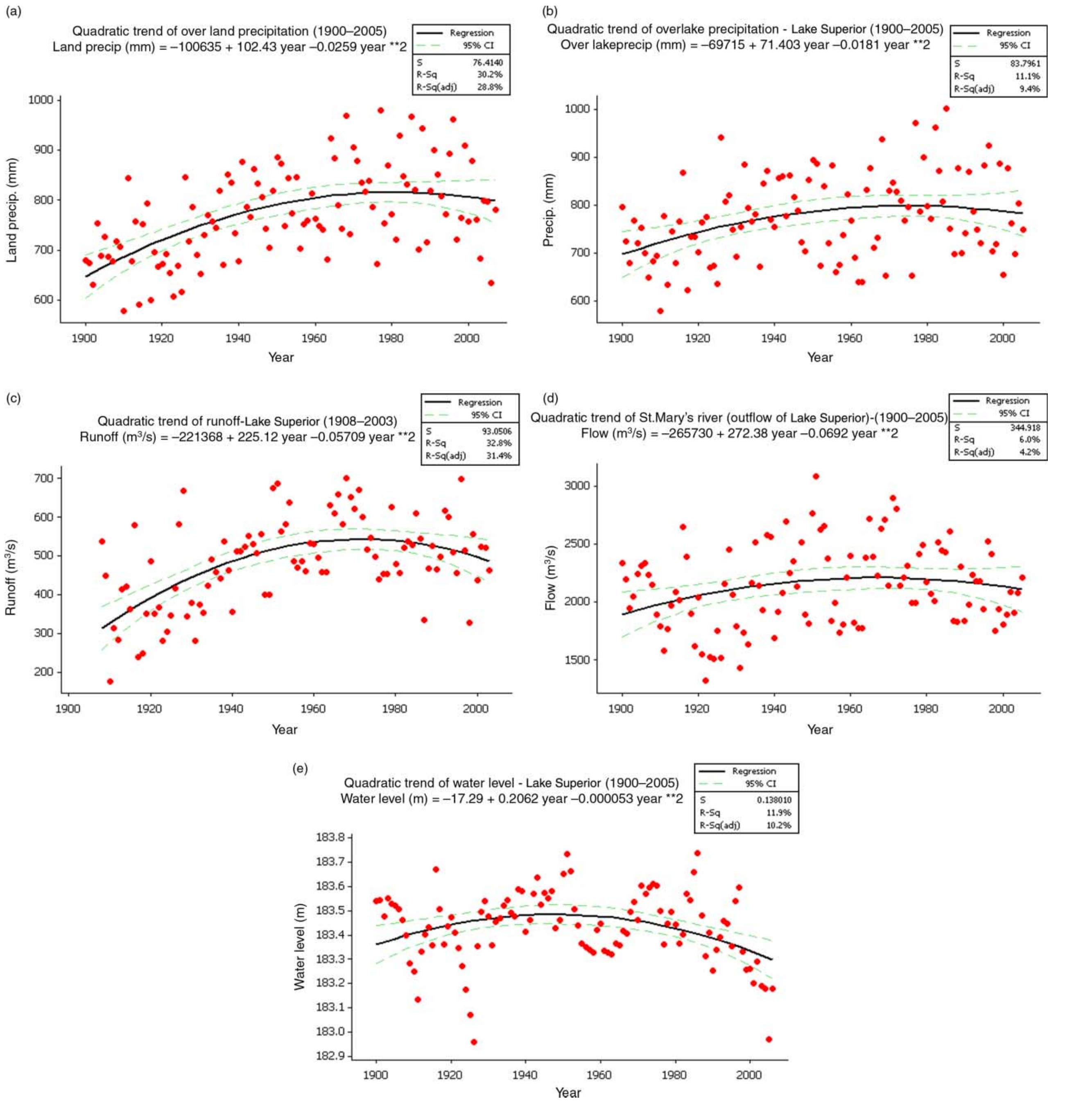

Figure 6 | Quadratic trends for average annual (a) land precipitation, (b) overlake precipitation, (c) runoff, (d) outflow and (e) water level for Lake Superior (1900–2005).

The difference volume is therefore:

$$WB = (66.1 + 19) - (68.8 + 48.2) = 85.1 - 117 = -31.9\,\text{km}^3$$

and hence the fall in water level is approximately:

$$H_{(\text{depth of water})} = (31.9/82,097) \times 10^5 = 39\,\text{cm}$$

This demonstrates the water level of Lake Superior has dropped 39 cm during the period 1970–2005, or at a rate of approximately 1 cm per year. If these trends continue, the only action for water managers to avoid additional reduction in water level is to reduce the discharge within St Mary's River. To maintain the water level in the lake,

Table 6 | Quadratic regression model for hydrologic parameters of Lake Superior (1900–2005)

	Regression equation	*P*-value	*R*-square (%)
Precipitation overlake	$Y = -0.0181X^2 + 71.403X - 69{,}715$	0.002	9.4
Precipitation over land	$Y = -0.0259X^2 + 102.43X - 100{,}635$	0.0002	28.8
Flow of St Mary's River	$Y = -0.0692X^2 + 272.38X - 265{,}730$	0.042	4.2
Runoff	$Y = -0.05709X^2 + 225.12X - 221{,}368$	0.0001	31.4
Water level	$Y = -0.000053X^2 + 0.2062X - 17.29$	0.0001	13.8

Table 7 | Average annual hydrological parameters (1970–2005) obtained from NOAA data series (2005)

Into the lake	Overlake precipitation (per year)	805 (mm)
	Runoff	600 ($m^3 s^{-1}$) equal 231 (mm)
Out to the lake	Evaporation (per year)	596 (mm)
	Outflow (discharge of St Mary's River)	2,182 ($m^3 s^{-1}$) equal 838 (mm)

it would be necessary to reduce the release from Lake Superior to approximately one-half the amount of discharge, to an average value of 1,100 $m^3 s^{-1}$. This management action is not easy as it creates other problems such as a reduction in ships' cargo handling and a fall in hydroelectricity generation levels.

DISCUSSION AND CONCLUSION

The aim of this research is to identify, using statistical analyses of available data and analyzing the hydrologic parameters, the reason for the reduction in the water level in Lake Superior. The results demonstrate that drought and/or climate change are causing disequilibrium in the water budget in Lake Superior. To demonstrate this, initially a 105-year historical data series of overlake and overland precipitation, flow of St Mary's River, runoff and water level in the Lake Superior were analyzed with linear regression analysis and non-parametric Mann–Kendall trend tests. The results and trends show that in the 20th century there have been increasing trends in all hydrologic parameters except water level of the lake; however, the last 35 years show very different trends. For the last 35 years, there are statistically significant decreasing trends in all hydrologic parameters (except for air overlake temperature and evaporation), particularly in water level. Water budget calculations illustrate that declining water levels of Lake Superior are occurring at a rate of approximately 1 cm yr^{-1} (39.0 cm in 35 years), the ramifications of which translate to challenges in the future for the operation of power plants at reduced generation levels, and requirements to decrease the loads of cargo ships.

This conclusion indicates that in the first half of the 20th century there were increasing trends in the water cycle of inflows and outflows in Lake Superior. However, in the last decades of the 20th century and first portion of the 21st century, this balance has changed and may be the result of an increase of greenhouse gas concentrations and global warming with a decrease in precipitation rates, runoff and inflows to Lake Superior.

One of the ways to preserve the volume and water level of Lake Superior is to reduce outflows. For example, reducing evaporation in Lake Superior is impossible, but management control of outflow in St Mary's River is an appropriate solution to stabilize the water volume in the lake. However, another problem arises: lower water levels means increased dredging and less cargo for the shipping industries that rely on the Great Lakes waterway.

It should be noted that the concept of uncertainty is a basic issue in all hydrologic modelling and climate change research. Uncertainty is a term to describe errors and biases associated with calculations and estimates, and all measurements and calculations have uncertainty. In this regard, the uncertainty of the results was estimated using 95% confidence intervals. Consequently, the results of hydrologic data series such as overlake and overland precipitation, air overlake temperature and evaporation from Lake Superior with a low autocorrelation may be due to the impact of global warming and climate change.

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First received 28 July 2008; accepted in revised form 25 May 2009. Available online November 2009