Journal of Sustainable Development; Vol. 18, No. 2; 2025
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

Great Lakes Water Level Trends Using the Moving Statistics Method, with Implications for Climate Change and Cities

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Received: February 5, 2025 Accepted: March 5, 2025 Online Published: March 6, 2025

doi:10.5539/jsd.v18n2p15 URL: https://doi.org/10.5539/jsd.v18n2p15

Abstract

Increasing magnitudes of precipitation and evaporation are predicted for future climate change. Knowing whether these trends are occurring can help water managers plan with respect to future erosion, flooding, and design changes for shoreline infrastructure. Data from all the Laurentian Great Lakes (Erie, Michigan-Huron, Ontario, St. Clair, and Superior) were analyzed here to determine whether these trends are being realized. The Moving-Statistics Method is used here using the moving average and moving standard deviation. It was found that Lakes Erie and St. Clair had the highest moving average trend of 0.5 mm/month, while Lake Ontario had the highest moving standard deviation trend (also 0.2 mm/month). Lake Superior had a decreasing moving average, while Lakes Erie, Michigan-Huron, and St. Clair had decreasing values of moving standard deviation. All lakes had moving average values greater than the measurement margin of error except Lake Superior. It is concluded that Great Lakes water levels have changed in the past and probably continue to change in the future. Property owners land managers can use these results to plan future budgets.

Keywords: flooding, drought, sustainability, infrastructure, climate change

Highlights

- Water levels on the Great Lakes are changing over time
- Climate change is causing some lake levels to increase in magnitude
- The variation of levels is also changing
- Cities will have to adjust shore and infrastructure protection accordingly

1. Introduction

There has been increased industrialization and the prevalence of internal combustion engines for transportation. More recently, there has been expansion of computer storage needs for data centers that need large amount of electricity. A large amount of electricity generated comes from the burning of coal. All of these trends have resulted in the warming of the earth's atmosphere. This is thought to bring about increased precipitation with longer time gaps in between precipitation events (EPA, 2024b). This is being shown to cause rising sea levels due to the melting of the polar ice caps. Whether warming is also causing changes in lake levels remains to be seen.

Changing lake levels affects many things that are important to human behavior, such as flooding (Gronewold and Rood, 2019), erosion (Krueger et al., 2020; Theuerkauf et al., 2019; Volpano et al., 2020), access to docks and ports for water transportation, dredging, the ecosystem, and hydropower (Hartmann, 1990; Schlosberg et al., 2014). This could affect the design of water infrastructure such as drinking water intakes, but also the budgets to pay for the upgrades. Being able to quantify these effects is paramount to the sustainability of water resource management.

In addition, changing water levels are known to have ecological and biogeochemical ramifications. Low lake levels can cause groundwater levels to decrease, thereby causing acidification of freshwater lakes due to a decrease in cation inputs (Webster et al., 1996). Habitat of invertebrates and fish are lost when the shore is exposed (Sass et al., 2006). Littoral sediment exposure and rewetting results in increased mercury contamination in fish (Watras et al., 2020). Lake drawdown can be below the level that reservoirs and water supply schemes can obtain water (Friedrich et al., 2018).

The fundamentals of the hydrologic cycle also come into play regarding the basin supply of water. Of interest in large lakes are precipitation and evaporation. Precipitation will add water to lakes through direct input but also through watershed runoff and inflow via rivers. Of course, water also flows out of lakes. Evaporation is increased by higher temperatures, less cloud cover, atmospheric teleconnections, higher wind speed, and lower humidity. This can be linked to large scale atmospheric circulation patterns in the Pacific or Atlantic oceans (Hanrahan et al., 2010, 2014; Trenberth et al., 1988; Watras et al., 2014). Increased temperatures may cause an increase in the flux between the hydrologic cycle components. It is unclear, however, whether precipitation or evaporation flux will be greater (Sherwood and Fu, 2014; Putnam and Broecker, 2017).

The International Joint Commission (IJC) is an intergovernmental body that deals with the Great Lakes. The IJC has two locations on the Great Lakes in which the water can be regulated (IJC, 2024). These occur at the outflows of Lakes Superior and Ontario. These controls can regulate the flow of water and, therefore, the lake levels, thereby moderating lake levels somewhat. Controls are moderated based on precipitation amounts, supply from upstream lakes, diversions in and out of the system, and basin runoff. Regulation is balanced between the various interests of affected parties.

Trends in lake properties have been observed. These include temperatures, (Zhong et al., 2016), ice cover (Wang et al., 2012), wind speeds (Desai et al., 2009), and water levels (Gronewold et al., 2013, 2016, 2021). Ice cover can affect the albedo feedback and evaporation rates (Austin and Colman, 2007) as well as lake-effect snowfall (Burnett et al., 2003; Kunkel et al., 2009). There have been large fluctuations in great lakes water levels in the past, attributed to net basin supply, defined as the precipitation and runoff minus evaporation (Gronewold et al., 2016). There have been increases and lows, changing by approximately 2m (Assel et al., 2004; Gronewold and Stow, 2014).

Modeling has shown some promise in our understanding of the Great Lakes behavior (Kayastha et al., 2022). Lake-to-lake modeling with regulation rules in the Coordinated Great Lakes Regulating and Routing Model has been performed (Clites and Lee, 1998; Quinn, 1978). General Circulation Models (GCM) have been used to provide fluxes to temperature, precipitation, and wind speed to use as input for Great Lakes Environmental Research Laboratory (GLERL) models, which consisted of Lake Basin Runoff Model and the Large Lake Thermodynamic Model for future evaporation estimates (Quinn, 1978; Clites and Lee, 1998). Early studies (e.g., Croley, 1990; Chao, 1999; Mortsch et al., 2000; Lofgren et al., 2002; Angel and Kunkel, 2010) had a high degree of uncertainty, predicting both increases and decreases in water levels. This was possible due to the non-inclusion of feedback between the land and the lake (MacKay and Seglenieks, 2013). The use of air temperature instead of water temperature also affected results (Lofgren et al., 2011). Dynamic downscaling from GCMs have also been tried but have also resulted in contradictory results (MacKay and Seglenieks, 2013; Notaro et al., 2015). Recently more advanced models for the Great Lakes have been used (Sharma et al., 2018; Xue et al., 2022; Xue et al., 2017; Giorgi et al., 2012; Chen et al., 2006, 2013; Sun et al., 2020; Durnford et al., 2018). Use of a two-way coupled 3D regional climate modeling system (GLARM) is conjunction with LBRM and CGLRRM was tried to resolve the land-lake-atmosphere interactive processes to predict levels on a climate timescale (Kayastha et al., 2022).

In spite of all the past studies, predictions contradict each other due to the complicated nature of the physics and thermodynamics of the land, lakes, and atmosphere. A statistical approach is tried here, based on past data, to aid decision-makers to determine if changes in management are required. The method used is the Moving Statistics Method (MSM) and has been used for precipitation and streamflow data (Manzano and Barkdoll, 2022; Barkdoll, 2023; Peter and Barkdoll, 2023). A statistical approach has the advantage that all the atmospheric processes are contained in the data, and, unlike modeling, it is unnecessary to guess how to model them. The long-term trends are studied here and not the cycles and short-term temporal trends. The MSM is simple and straightforward and has not yet been tried on these data.

2. Methods

The largest freshwater lakes in the world, located in the U.S. and Canada are the Laurentian Great Lakes (Fig. 1). They have a surface area of approximately 244,000 km^2. They collectively hold approximately 23,000 km^3 of water. This is 28% of the world's amount (U.S. Environmental Protection Agency and Government of Canada, 1995). The Great Lakes affect the regional climate, such as precipitation and temperature. This is due to low albedo and surface roughness and large thermal inertia (Changnon and Jones, 1972; Notaro et al., 2013; Scott and Huff, 1996). In addition, the lakes affect the atmospheric stability during warm and cold seasons, which affect precipitation, convective cloud, evaporation, and latent and sensible heat fluxes.

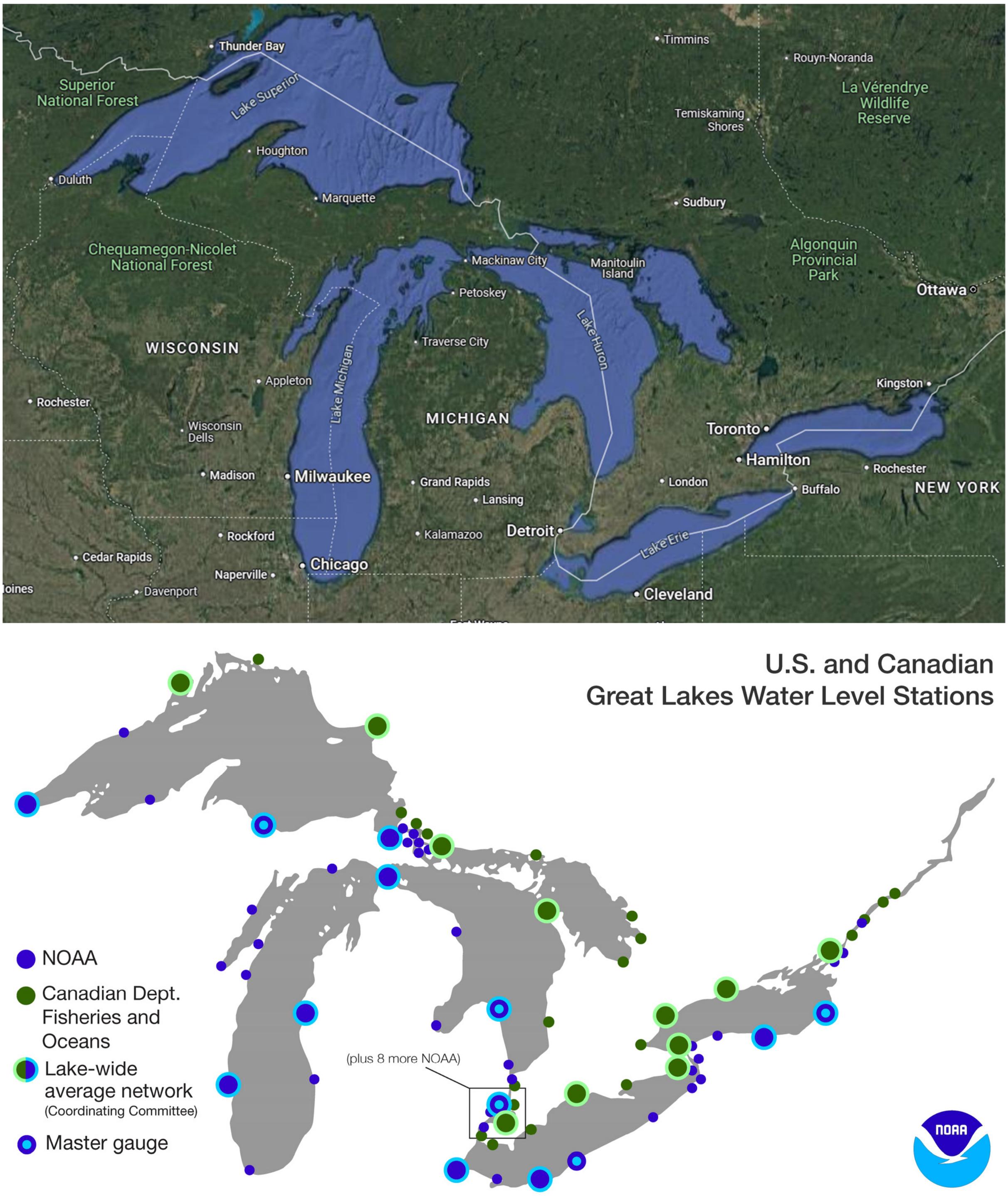


Fig. 1. Map of the Laurentian Great Lakes (top:Google Maps; bottom:NOAA (2025))

A 2D plot is used in the MSM. This plot has the slope of the linear regression line for the moving average for each lake on the horizontal axis and the slope of the linear regression line for the moving standard deviation on the vertical axis. The first tells the trend of the lake level and the second tells the trend of the variability of lake level. This helps determine if the effects of climate change are present in the data. Since climate change will both increase precipitation but also evaporation, it is unclear which will dominate. If precipitation is greater, then the lake levels will increase and vice versa. Periods in between increasingly large precipitation events would lead to an increase in the standard deviation of lake levels as well. The moving average and standard deviation are calculated over a

21-month window to enable enough data to be included to have a meaningful number of data points but not too long to overly smooth out the data. The values of the statistics are reported at their center to minimize time shifting.

The procedure is:

1) Obtain lake level data for the entire period of record,

2) Calculate the average lake level from the first twenty-one months of the period of record, reporting it in the middle month of that time period (11 months),

3) Repeat for each twenty-one month time period, marching forward in time, month by month,

4) Do this also for the standard deviation for each twenty-one month time period,

5) For the moving average data obtained in Step 3, calculate the linear-regression best-fit line slope, mMA

6) For the moving standard deviation data obtained in Step 4, calculate the linear-regression best-fit line, mMSD

7) Plot these on the MSM Plot, which comprises mMV vs. mMSD

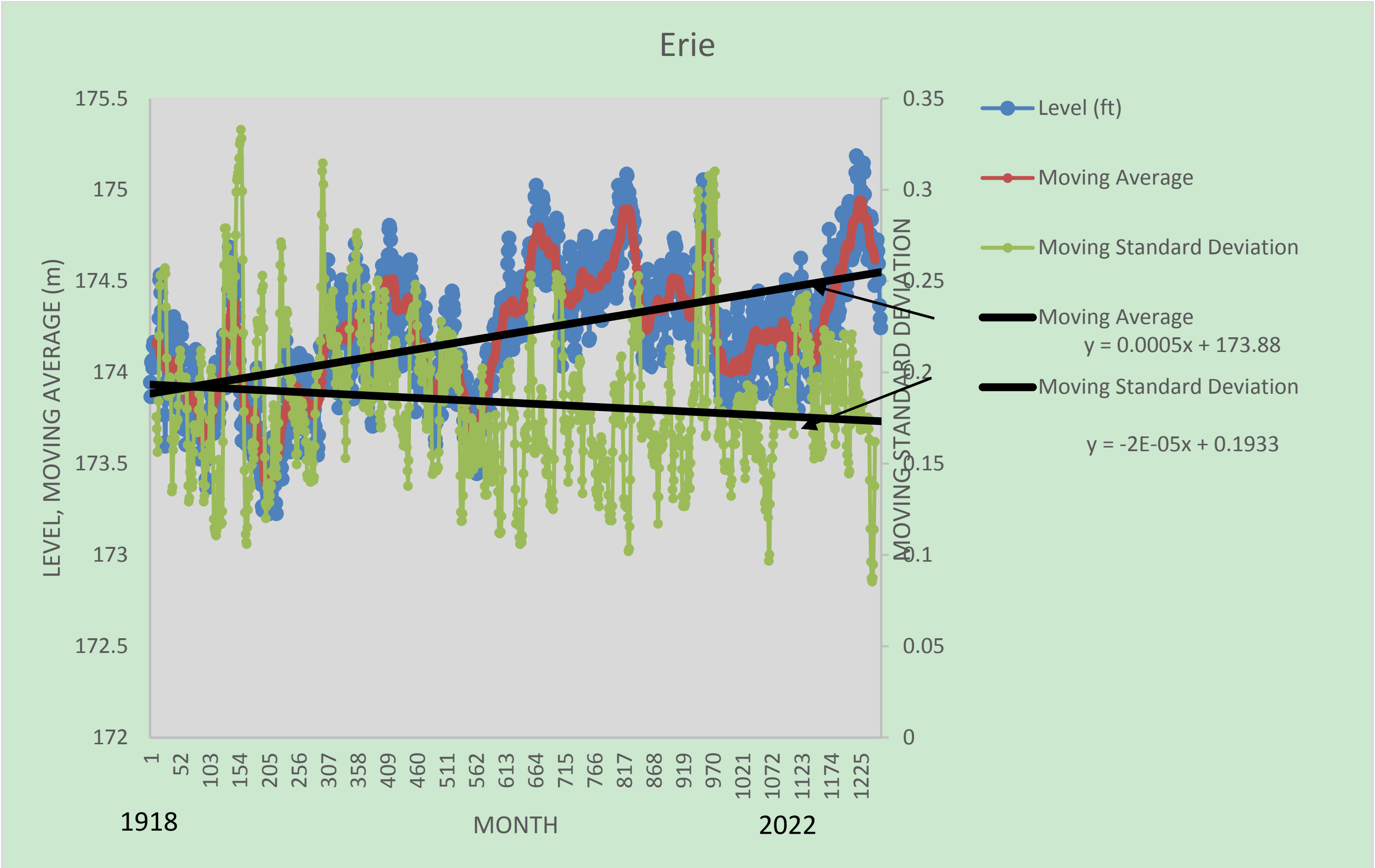
8) Repeat Steps 1-8 for each lake to be analyzed.

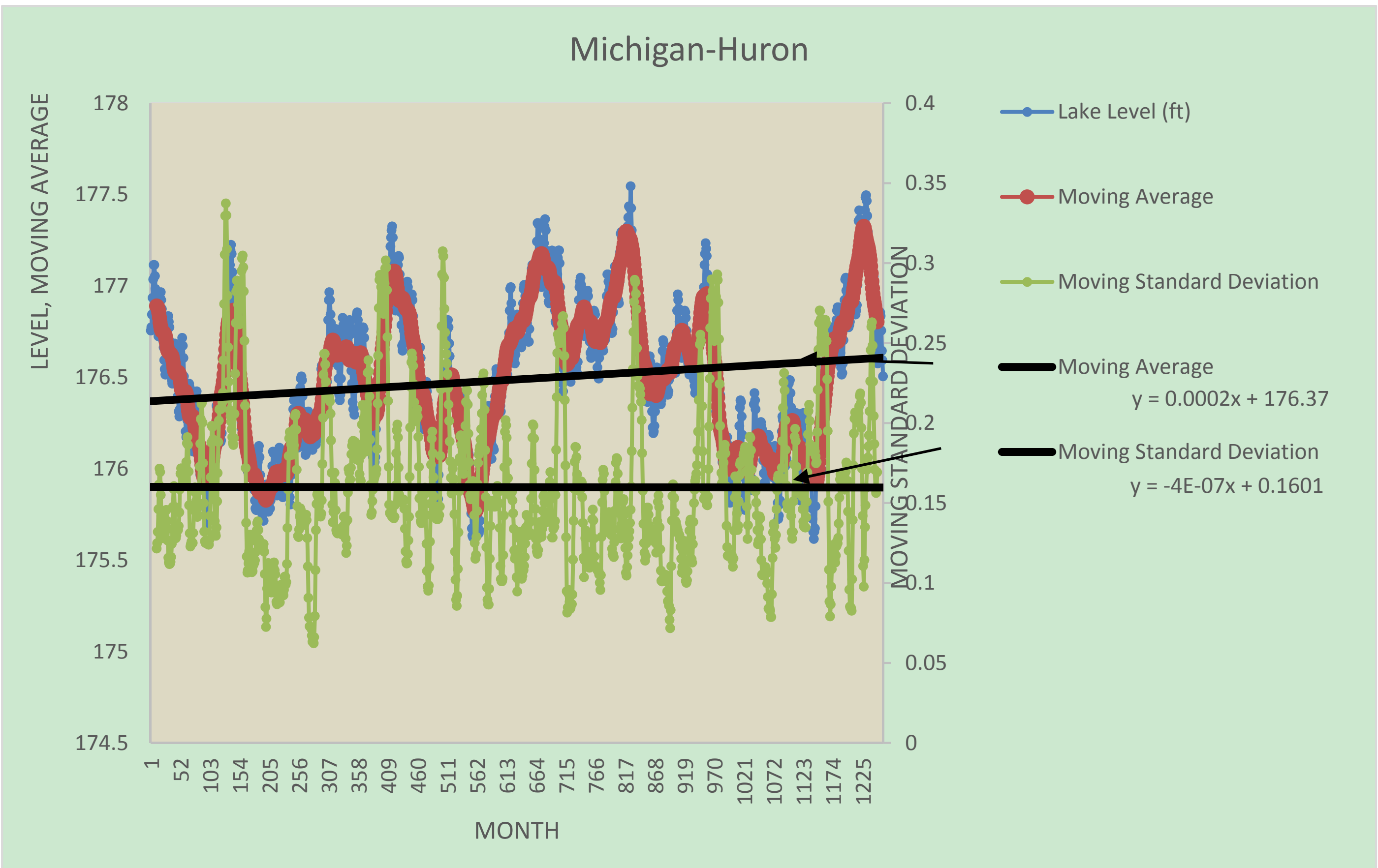
Data Source

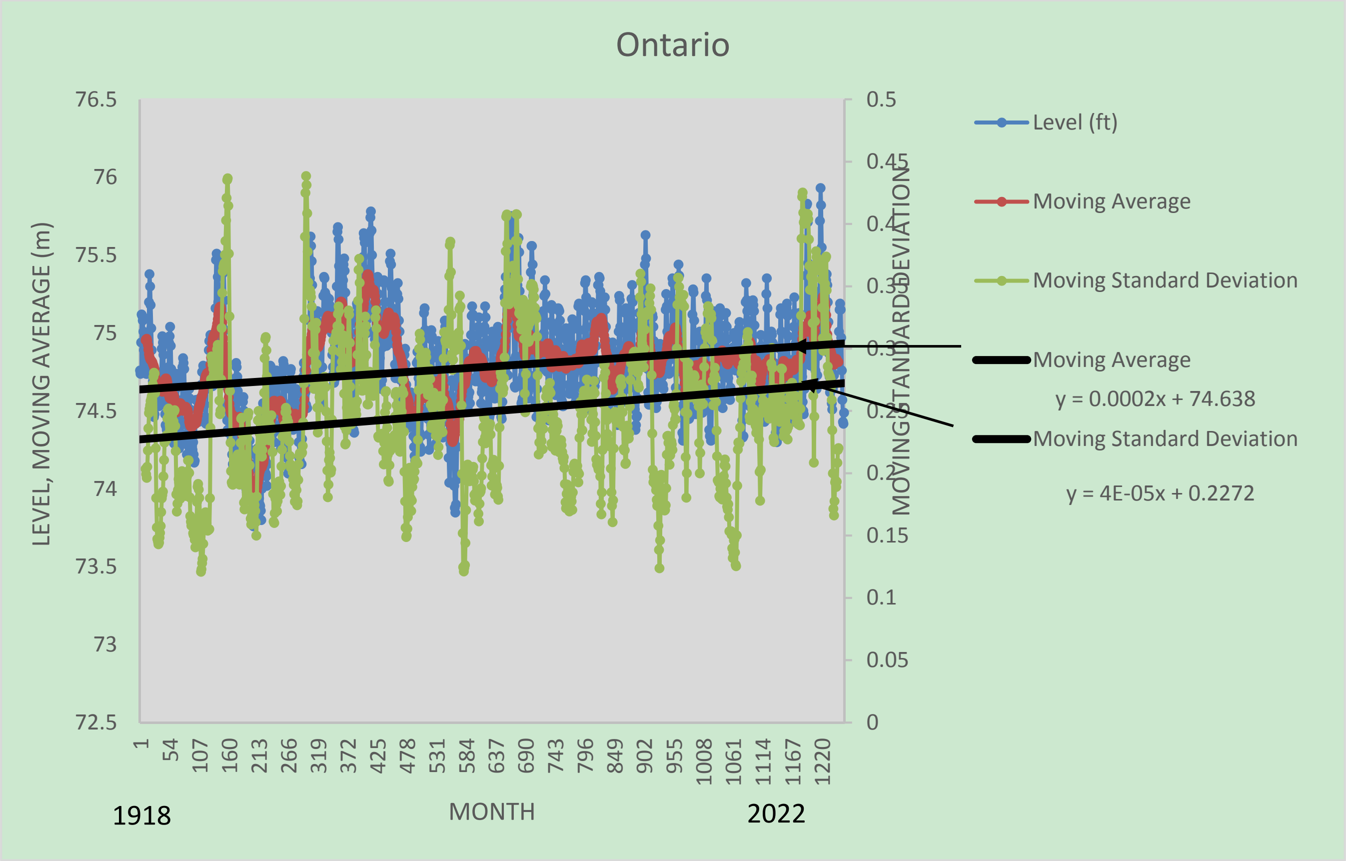
Great Lakes water level data were obtained from the Great Lakes Water Level Data maintained by the U.S. Army Corps of Engineers (USACE, 2024). The data are mean monthly values from 1918 to 2022. Water levels are measured by a set of gages along the lake shore (EPA, 2024). Lake levels are recorded by the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Center for Operational Oceanographic Products and Services (CO-OPS). The U.S. operates 53 level gages in the Gret Lakes and the St. Lawrence Seaway. The gages are sumps located into the ground in six feet diameter shafts made of brick and blocks. The intake pipe extending out into the lake can vary from 3.3 to 579 m (US Army, 2024). This enables measurement in high and low water level situations. The intakes are controlled by valves that remove wave action. These wells also negate the effects of ice on the water level. Dual shaft encoders are used, that contain both a primary and redundant sensor. They are optical sensors that can work even when the power goes out. The water gage is a Baldwin MT40 series encoder with an accuracy of ±0.003 meters. The meters have heat lamps to allow functioning in cold environments. The accuracy of the measuring equipment is reported as 0.06m (Xiang et al., 2021). Measurements are taken at several locations shown in Fig. 1.

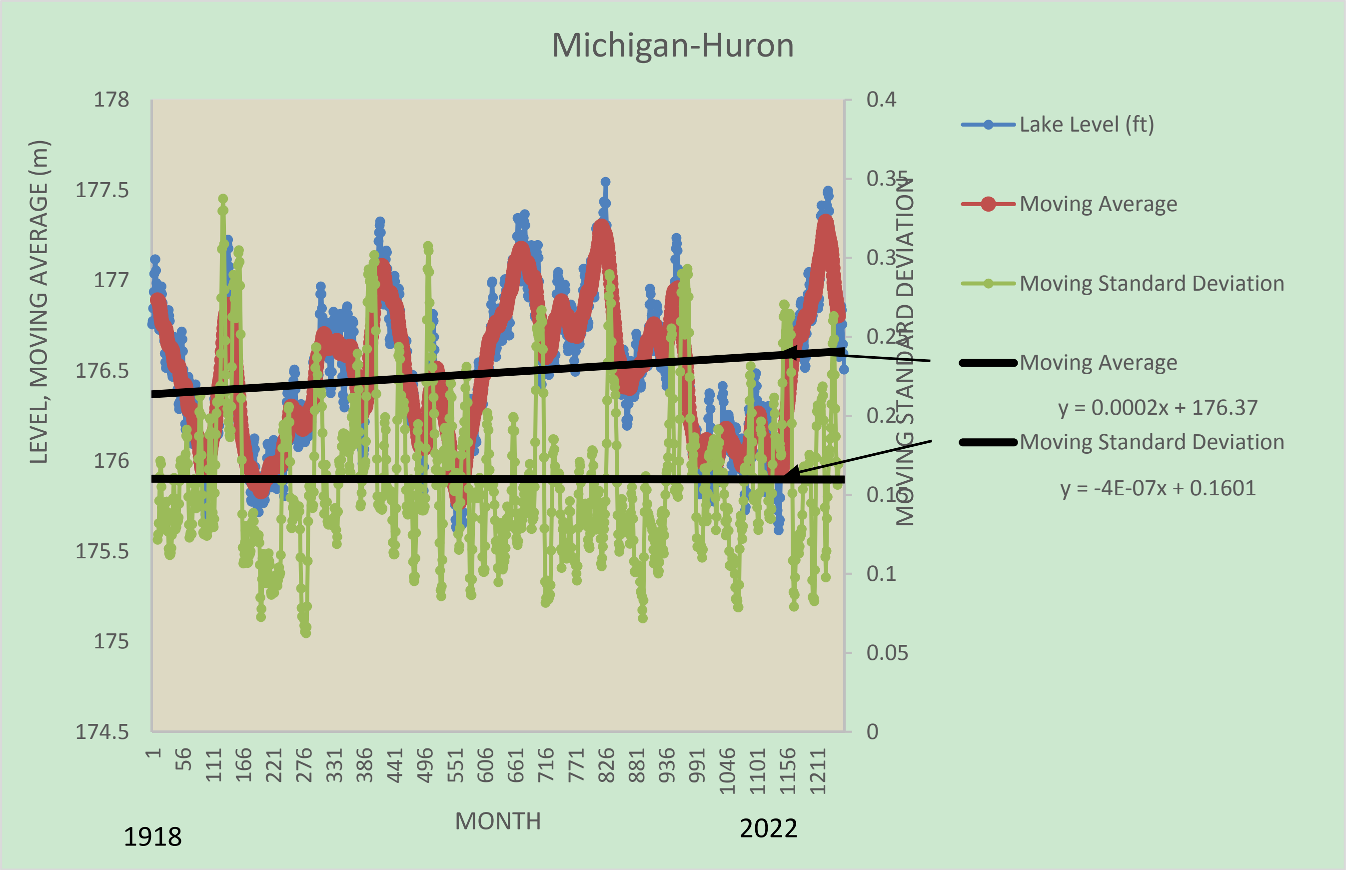
3. Results

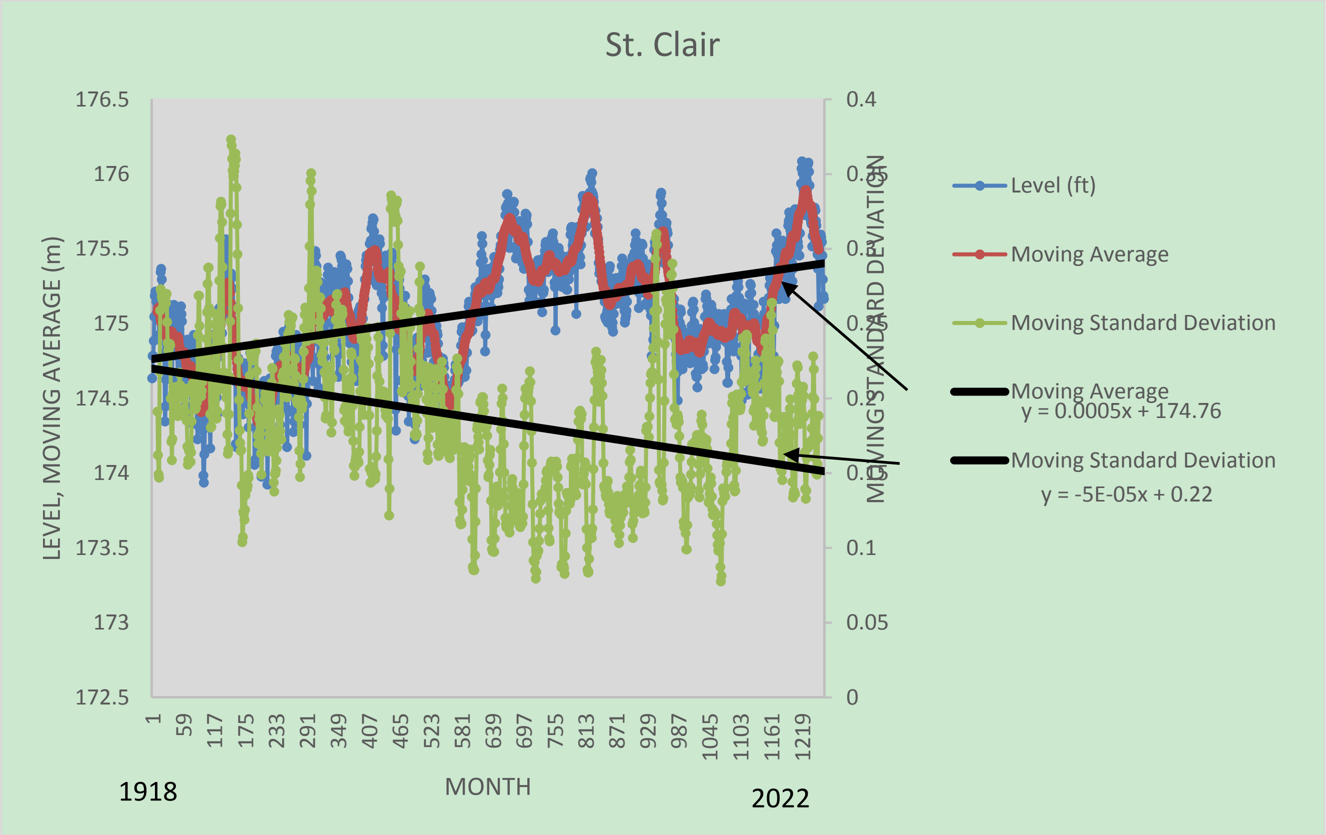
The slopes of both the moving average and moving standard deviation for all the Great Lakes were obtained for all the Great Lakes from the raw data and calculations (Fig. 2). It can be seen that Lake Erie has an increasing trend for lake level with a decreasing variation. Lake Michigan-Huron has an increasing lake level trend but an decreasing variation. Lake Ontario has both an increasing lake level and variation. Lake St. Clair has an increasing level and decreasing variation. Lake Superior has a decreasing level and increasing deviation trend. The values were then tabulated (Table 1). The highest positive level increase was for Lakes Erie and St. Clair at 0.5 mm/month, while the largest decreasing level was for Lake Superior at -0.007 mm/month. Regarding the moving standard deviation, the largest positive slope was for Lake Ontario of 0.52 mm/month, while the largest negative slope was for Lake St. Clair at -0.05 mm/month. Subsequently, the MSM Plot was formed (Fig. 3). Normalizing by the maximum value of mMA and mMSD allows an inter-lake comparison. The highest values for both mMA and mMSD were for Lake Ontaria (upper right quadrant). The highest mMSD value was Lake Erie, although it had an insignificant mMSD slope. Lake St. Clair had the highest mMSD but a negligible amount of mMA.


Erie
175.5
175
174.5
174
173.5
173
172.5
172
LEVEL, MOVING AVERAGE (m)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
MOVING STANDARD DEVIATION
1
52
103
154
205
256
307
358
409
460
511
562
613
664
715
766
817
868
919
970
1021
1072
1123
1174
1225
1918
MONTH
2022
Level (ft)
Moving Average
Moving Standard Deviation
Moving Average
y = 0.0005x + 173.88
Moving Standard Deviation
y = -2E-05x + 0.1933


Michigan-Huron
178
177.5
177
176.5
176
175.5
175
174.5
LEVEL, MOVING AVERAGE
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
MOVING STANDARD DEVIATION
1
52
103
154
205
256
307
358
409
460
511
562
613
664
715
766
817
868
919
970
1021
1072
1123
1174
1225
MONTH
Lake Level (ft)
Moving Average
Moving Standard Deviation
Moving Average
y = 0.0002x + 176.37
Moving Standard Deviation
y = -4E-07x + 0.1601


Ontario
LEVEL, MOVING AVERAGE (m)
MOVING STANDARD DEVIATION
MONTH
1918
2022
Level (ft)
Moving Average
Moving Standard Deviation
Moving Average
y = 0.0002x + 74.638
Moving Standard Deviation
y = 4E-05x + 0.2272


Michigan-Huron
LEVEL, MOVING AVERAGE (m)
MOVING STANDARD DEVIATION
MONTH
1918
2022
Lake Level (ft)
Moving Average
Moving Standard Deviation
Moving Average
y = 0.0002x + 176.37
Moving Standard Deviation
y = -4E-07x + 0.1601



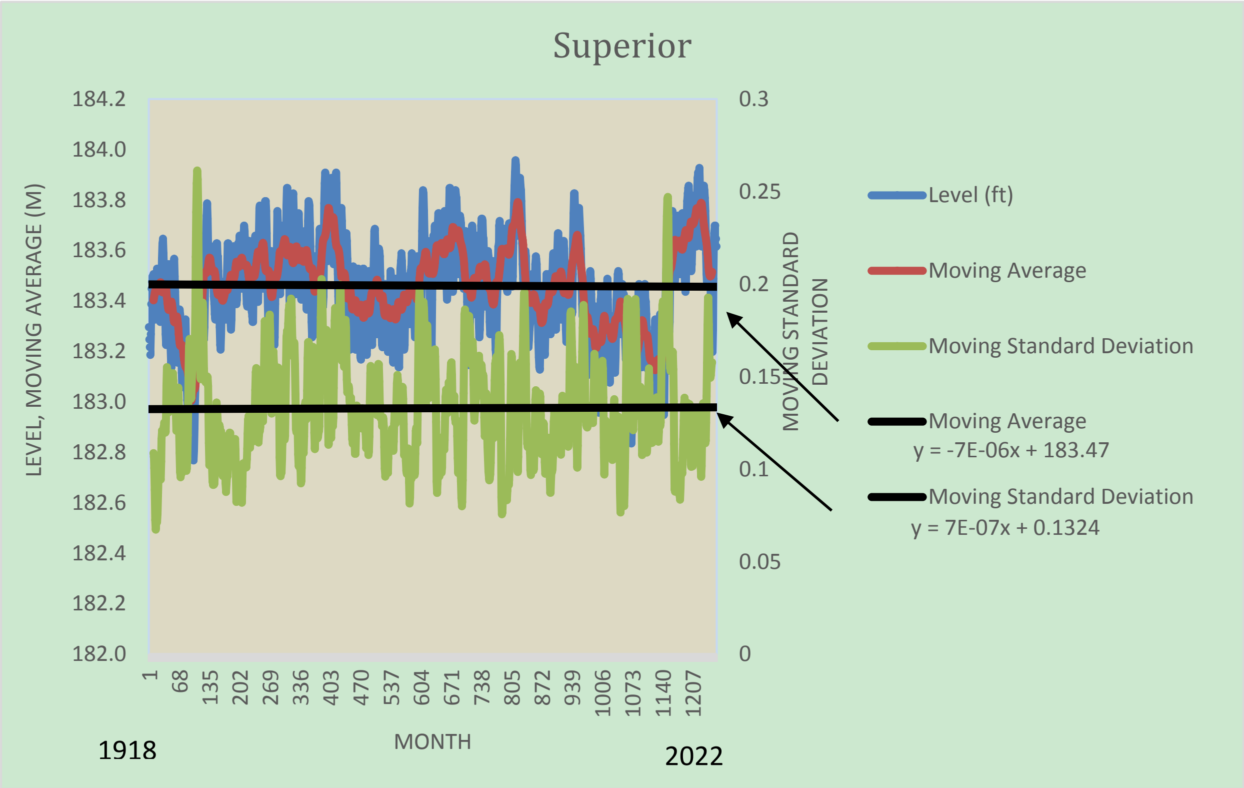


Fig 2. Water level, moving average data and trends, moving standard deviation data and trends for the Great Lakes

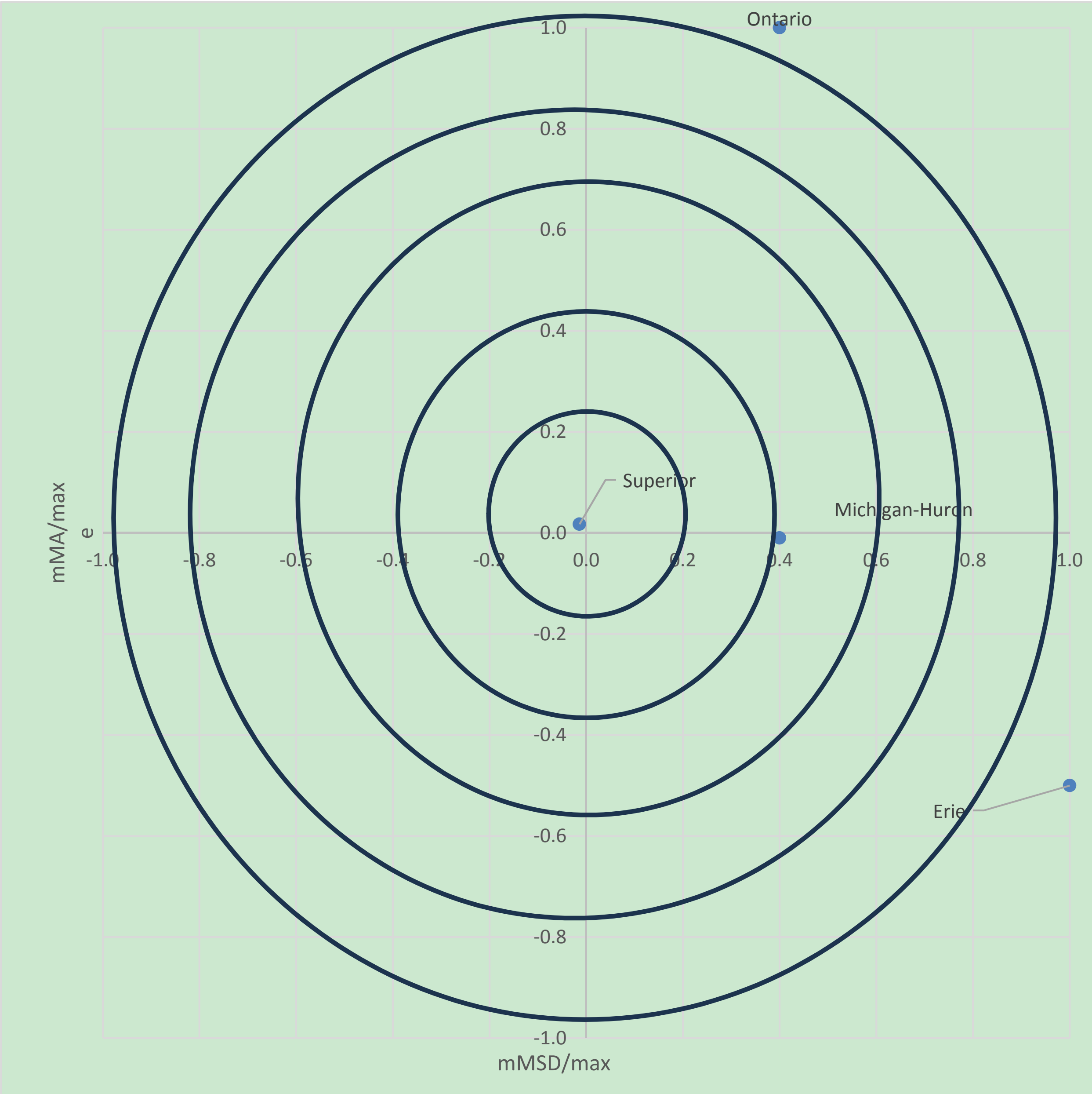


Fig. 3. MSM plot

Table 1. Values for the slope of the moving average and mobbing standard deviation for the Great Lakes

	m_{rd} (m)	SD_{rd} (m)	m_{MA} (mm/month)	m_{MSD} (mm/month)
Erie	174.22	0.37	0.5	-0.02
Michigan-Huron	176.49	0.41	0.2	-0.0004
Ontario	74.79	0.34	0.2	0.2
St. Clair	175.09	0.40	0.5	-0.05
Superior	183.45	0.20	-0.007	0.0007

4. Discussion

The implications for climate change and cities are that some lakes have an increasing water level trend that will cause additional flooding for over 34 million people (Sea Grant Michigan, 2025) The main cities are listed in Table 2. The lake levels will affect shipping in major ports, dick access, flooding, and shore erosion. It is estimated that the infrastructure investments around the Great Lakes and the St. Lawrene Seaway are approximately $8.4 billion. Climate change is predicted to cause precipitation events of higher magnitude but also longer period in between events. This is reflected in the above analysis through the slope of the moving average and moving standard deviation values.

An effort is made here to compare the results of previous studies with that of this study. All studies were of the Great Lakes and, therefore, have similar climatological similarities. The study method is mentioned as well. Of the many lake level prediction models attempted (Table 2) it can be seen that there is a wide variation of results. There is not even agreement on the trend, increasing or decreasing. This points out the complexity of the hydrology and meteorology of the Great Lakes region. For all the Great Lakes, the greatest increase predicted comes from the Mackay and Seglenieks (2013) GLRCM Method, while the lowest is the Hayhoe et al. (2010) GLERL suite. The fastest decrease in level is predicted by the Chao (1999) Method. The minimum percent difference between the maximum and minimum levels is for Lake Ontario at 118% and the maximum is for Lake Erie at 173%. In addition, since the measurement error could be ±0.06m, the difference in slope could be as much as $2*0.06*1000/1273 = 0.09$ mm/month. MSM levels for Lake Superior are within the measurement error, but the other lakes have mMA values higher than this value.

Limitations of this study are (1) that a single trend analysis method was used (linear regression) and (2) that an analysis of past data may not be reflective of future trends since hydrology is changing due to climate change. These can be remedied in future work by (1) comparing other methods of trend analysis and (2) by investigating the change in lake levels statistics over time, respectively.

Table 2. Population of Great Lakes coastal cities (World Atlas 2025)

City	State/Province	Population
Toronto	Ontario	2,791,140
Chicago	Illinois	2,707,120
Missassauga	Ontario	721,599
Milwaukee	Wisconsin	592,025
Hamilton	Ontario	536,917
Cleveland	Ohio	396,698
Toledo	Ohio	287,208
Buffalo	New York	261,452
Rochester	New York	210,565
Oakville	Ontario	193,832
Burlington	Ontario	183,314
Oshawa	Ontario	166,000
St. Catherines	Ontario	133,113
Whitby	Ontario	128,377
Kingston	Ontario	123,798
Ajax	Ontario	119,577
Thunder Bay	Ontario	107,909
Green Bay	Wisconsin	104,057
Erie	Pennsylvania	101,786
Pickering	Ontario	91,771
Total		**4,459,998**

Table 3. Comparison of lake level change predictions (mm/yr)

	Erie	Michigan-Huron	Ontario	Superior
Angel and Klunkel (2010) **GCM/GLERL**	-6.40	-7.50	-6.40	-2.44
Chao (1999)		-22.56		-12.50
Gronewold et al. (2013) **GCM**	-10.06	-14.94	-13.41	-4.88
Kayastha et al. (2022) **FVCOM framework**	9.45	14.63		6.40
Lofgren et al. (2002) **GCM1** **HadCM2**				
Mackay and Seglenieks (2013) **GLRCM**	-12.80	-15.55	-11.28	-4.88
Mortsch et al. (2000) GLERL suite	3.05	3.96	0.00	1.22
Hayhoe et al. (2010) GLERL suite	-0.91	-0.91		-0.91
Notoro et al. (2015) **RCM-MIROCS** **RCM-CNRM**		-9.76		-3.35
MSM (This Study)	6.00	2.40	2.4	-0.08
% difference between min and max values	173	165	118	151

5. Conclusions

Analysis of the moving average and moving standard deviation of the Great Lakes water levels using the Moving Statistics Method reveals the long-term trends in water levels and their variation. This information should be useful to decision makers affected by Great Lakes levels. This study's impact is to guide decision makers in future budget allocations for flood and erosion control and lake levels change.

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Acknowledgments

Not applicable.

Authors contributions

B. Barkdoll performed the study conception, design, material preparation, and writing of the first draft of the manuscript. O. Alamutu performed the data collection and analysis and commented on previous versions of the manuscript.

Funding

This research received no external funding.

Competing interests

The authors declare no conflicts of interest.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.