

# Water Levels of the Great Lakes of North America

William A. Gough

(Department of Physical and Environmental Sciences, University of Toronto at  
Scarborough, 1265 Military Trail, Scarborough, Ontario, Canada M1C 1A4)

[Abstract] The low Great Lakes water levels of recent years are reviewed and placed in the context of variations over many decades of recorded water levels. The recent recovery of the lower lakes is contrasted with the continued lower levels in the upper lakes. The potential impact of climate change on Great Lakes water levels is explored.

[Key words] water levels; Great Lakes; Canada; climate change

[CLC number] P343.3; P341 [Document code] A [Article ID] 1672-6561(2005)04-0008-06

[Biography] William A. Gough, Ph. D., Associate Professor of University of Toronto. Main research field is global environment and climate change.

## 0 Introduction

The Laurentian Great Lakes are a dominant feature in the central eastern portion of the North American continent. 18% of the world's freshwater supply resides in the Great Lakes totaling 22 684 km<sup>3</sup> of water in a drainage basin of 244 000 km<sup>2</sup> (Fig. 1). Lake Superior is the deepest of the five lakes with a maximum depth of 407 m. Lake Superior is connected to the other lakes via the St. Mary's river which was dammed in the early 1920s to allow control of the Lake Superior water levels. Immediately downstream of Lake Superior are Lakes Michigan and Huron. These lakes are hydraulically equal being linked by the Strait of Mackinaw and therefore have the same water level. Michigan has a maximum depth of 252 m and Lake Huron has a maximum depth of 220 m. Lake Huron is linked to Lake Erie through the Detroit

and St. Clair Rivers and Lake St. Clair. Lake Erie is by far the shallowest of the five major Great Lakes having a mean depth of only 19 m and a maximum depth of 64 m and as a result behaves much differently than the other lakes. For example it is the first to freeze over in the winter. Lake Erie is connected to the lowest of the lakes, Lake Ontario, through the Niagara River. This river hosts a dramatic gorge, Niagara Falls, which is the largest drop in elevation in the Great Lakes system. It is a popular tourist destination as well as a major source of hydro electric power for the

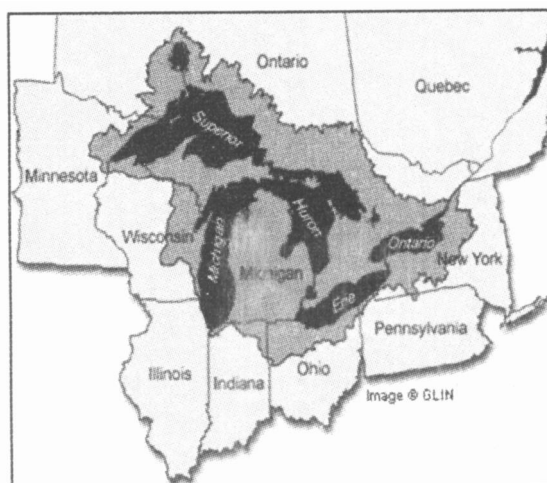


Fig. 1 Map of the Great Lakes Region of North America

[Received date] 2004-12-20

[Foundation item] State Administration Of Foreign Experts  
Affairs, New development in water re  
sources and environment

Canadian province of Ontario and New York State of the USA. Lake Ontario is the smallest lake in surface area. It has a maximum depth of 245 m. The water levels of Lake Ontario are controlled by a dam in the St. Lawrence Seaway built in the 1950 s.

The present lakes were formed 14 000 to 10 000 years ago due to scouring of a retreating glacier. Lake Superior, the head waters of the Great Lakes and most northerly and westerly of the five major lakes, is underlain by ancient Precambrian rock (the Canadian Shield), one of the oldest features on the planet. The other lakes (Michigan, Huron, Erie, and Ontario) were etched out of Paleozoic deposits. These were formed 600 to 300 millions years ago when the region was part of a vast sea. In addition to the scouring of the Paleozoic and Precambrian Eras, the retreating glacier left behind substantial glacial deposits which form much of the current surface geomorphology.

The relative easy access from Europe has led to the colonization of the region over the last three hundred years. At present approximately 1/4 of the Canadian population and 1/10 of the American population live in the Great Lakes drainage basin (over 30 000 000) including such cities as Toronto, Hamilton, and Windsor in Canada, Detroit, Cleveland, Chicago, and Milwaukee in the United States. Most of the Great Lakes communities depend on the lakes for municipal water supply, transportation, and recreation.

The Lakes have a profound effect on the local climate<sup>[1]</sup> dramatically influencing precipitation patterns (eg. snowbelts) especially downstream of the Lakes and in general mitigating temperature extremes. Precipitation ranges from 600 to 1 300 mm per year in the Great Lakes basin. The peak amounts result from lake effect precipitation<sup>[1]</sup>. Locally a well defined lake breeze provides summertime cooling<sup>[2, ①]</sup>. The lakes have also been

shown to affect the trajectory and genesis of mid latitude cyclones<sup>[3]</sup>. Surrounding the Great Lakes are widespread wetlands. These wetlands thrive under conditions of varying water levels<sup>[4]</sup>.

## 1 Great Lakes water levels

Variation of the Great Lakes water levels occur on three time scales. First there are short term fluctuations varying on the scale of minutes, hours or days, often associated with changes in wind patterns or intense rainfall events. The next scale consists of variations on a seasonal scale associated with the seasonal hydrological cycle, winter snow melt, precipitation cycles, and intense evaporation during the summer<sup>[5]</sup>. Finally we are coming to grips with longer term variations, interannual, inter decadal and perhaps even longer variations, possibly the result of long term climate change such as El Nino Southern Oscillation, the North Atlantic Oscillation, and global warming. In addition direct anthropogenic intervention by the creation of diversions or hydroelectrical damming influence lake levels on a seasonal and perhaps longer term time scale<sup>[6-7]</sup>.

Varying water levels have a profound influence on wetlands as mentioned above, availability and quality of water for municipalities, erosion of coastlines, transportation accessibility, hydroelectric generation and recreational uses of Great Lake waters. Due to the higher than average levels since the mid - 1970' s, management plans and scientific research have focussed on responses to high water levels rather than low levels<sup>[8-11]</sup>. However this appears to be changing with recent persistent low levels.

## 2 Hydrological Balance in the Great Lakes

Water levels in the Great Lakes are the net result of a number of competing components (Fig. 2). Water levels rise due to precipitation, groundwater, surface runoff, and river inflow.

① Gough W A, Lelasseux S. Surface observation of Toronto Ontario's urban heat island. The Great Lakes Geographer (submitted), 2004.

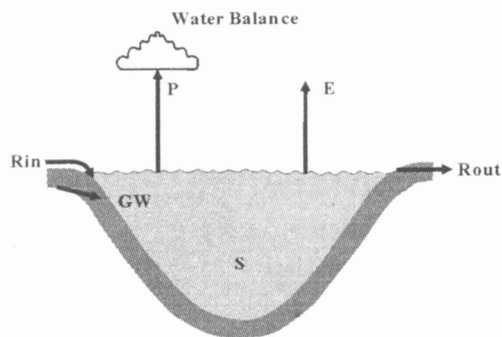


Fig. 2 The Hydrological Balance

**Levels fall from evaporation and river outflow. If these are unbalanced water levels tend to fall or rise accordingly. On a seasonal basis there is a spring increase following a large input from surface runoff of snow melt and spring rainfall. However, late summer evaporation and lower precipitation lead to diminishing levels in the fall. Symbolically the balance can be represented by the following equation:**

$$S = In - Out \quad (1)$$

$S$  is the storage of water in a basin. If  $S$  is increasing, water levels rise, if  $S$  is decreasing water levels fall.

$$In = P + GW + SR + I \quad (2)$$

$P$  is the precipitation intercepted directly by the lake,  $SR$  is the local river inflow from the local drainage basin and consists of part of the rainfall intercepted by the lake drainage basin (some is lost to evapotranspiration, some becomes groundwater),  $GW$  is the groundwater inflow to the lake,  $I$  is the river inflow from other drainage basins. In the case of Lake Ontario, for example,  $I$  represents the inflow from the Niagara River which drains Lake Erie.

$$Out = E + O + D$$

$E$  is evaporation from the lake surface and is a function of temperature and wind,  $O$  is the outflow out of the drainage basin into another drainage basin or into an ocean,  $D$  is water that is diverted out of the Great Lakes drainage basin but not to the ocean directly. For example, water is diverted from Lake Michigan for irrigation and other purposes<sup>[6]</sup>. The diverted water is either evaporated or contributes to the Mississippi River

basin. Water is also diverted from the Hudson Bay drainage basin into Lake Superior. The Welland Canal joins Lake Erie with Lake Ontario enabling the bypassing of the Niagara River (for ship navigation). The Trent Canal links Lake Ontario with Lake Huron. None of these diversions move a substantial amount of water compared to the other terms in the equation.

### 3 Historical Great Lakes levels

Because the volume of the Great Lakes ( $22\,684\text{ km}^3$ ) is large relative to the rates of change of volume due to the processes outlined above, the Lakes effectively have memory or hydro inertia. Once the Lakes experience low levels it takes a number of surplus water years for the lakes to rebound and vice versa. Thus the Lakes have experienced extended periods of high or low water levels. The interannual amplitude is just under  $2\text{ m}$ <sup>[12]</sup>. The seasonal amplitude cycle is  $0.2$  to  $0.4\text{ m}$  with a minimum in January and February and a maximum in June for the lower Great Lakes (Erie, Ontario) and as late as September for the upper Great Lakes (eg. Superior).

Fig. 3 to 6 display times series of the Great Lakes water levels from 1918 to 2002. Due to the direct connection between the Lakes and their similar climate, it is not surprising that similar trends emerge among the Lakes. All values are biased by the chart datum. This is a value above which 95% of the water levels have been found historically. The 1930s were a period of low water levels, the 1960s were as well with a period of higher values in between. Since the 1960s the Lakes have experienced a persistent high water period that has only ended in the last few years. Peak lake levels occurred in 1986 and declined sharply due to the 1987 ~ 1990 drought. Due to large interannual variability and this approximate 30 year oscillation, it is difficult to determine if there is a net trend in water levels. The influences of such events as El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are also

difficult to detect due to the “memory” or hydro inertia of a large reservoir system and the influence of upstream input. In addition lake levels are controlled by dams at the ends of Lakes Ontario and Superior which enables the retention of excess water from one year to the next. The influence of the dams can be seen in these figures. In Figure 3, there is a sharp decrease in water levels in the mid 1920s as damming practices on the newly created St. Marys River dam were stabilized. Corresponding maps for Lakes Huron/Michigan and Erie (Fig. 4 and Fig. 5) show greater interannual variability as the outflow from these lakes are not controlled. Finally the dramatic effect of the damming of the St. Lawrence Seaway is shown for Lake Ontario (Fig. 6) with very little interannual variability occurring after 1958 when the St. Lawrence

Seaway project was completed.

# 4 Current Great Lakes levels

Figures 7 to 9 depict the water levels in the Great Lakes for the year 2003 and the early months of 2004. These are placed in the context of mean and extreme values for the lakes. Lake Ontario has higher levels for 2004 than 2003 completing a recovery to mean values (Fig. 7). Lake Erie has 2004 values that are roughly the same as 2003, both near the climatological mean (Fig. 8). Although, Lake Huron/Michigan levels have increased in 2004, they are still well below the climatological mean by 0.5 m (Fig. 8). Lake Superior or lake levels in 2004 are essentially the same as 2003, 10 to 20 cm below the climatological mean.

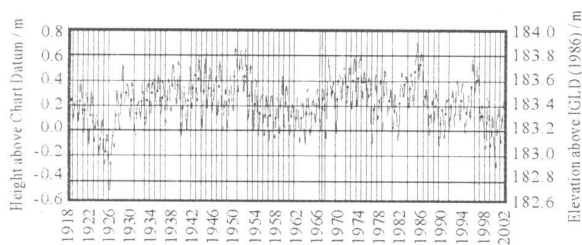


Fig. 3 Lake Superior Water Levels, 1918~2002

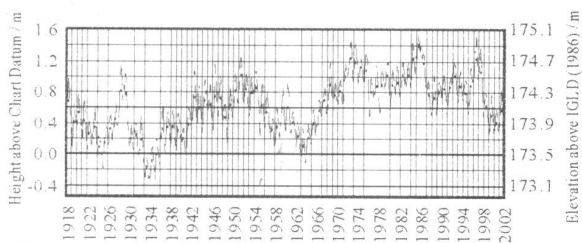


Fig. 5 Lake Erie Water Levels, 1918~2002

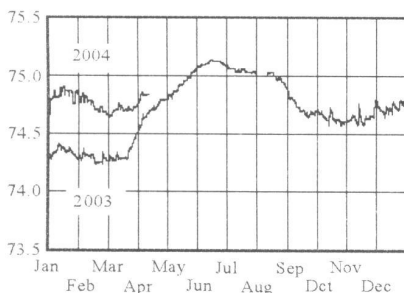


Fig. 7 Lake Ontario Water Levels for 2003 and 2004

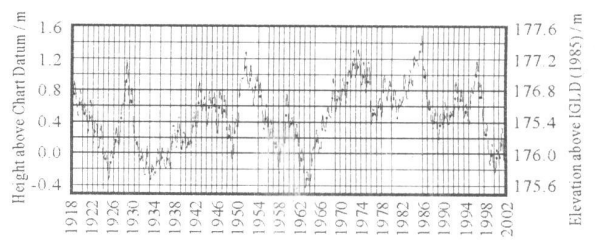


Fig. 4 Lake Huron and Lake Michigan Water Levels, 1918~2002

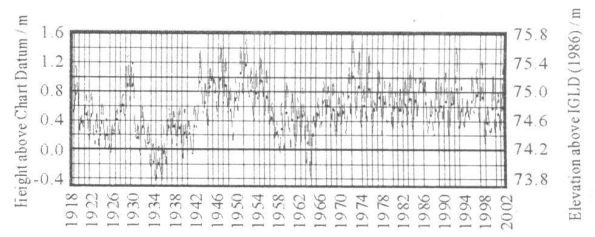


Fig. 6 Lake Ontario Water Levels, 1918~2002

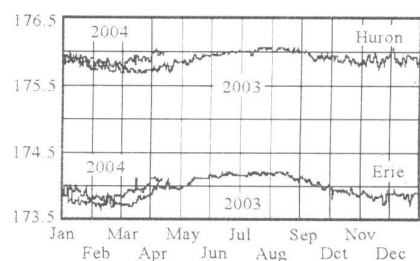


Fig. 8 Lake Huron and Lake Erie Water Levels for 2003 and 2004

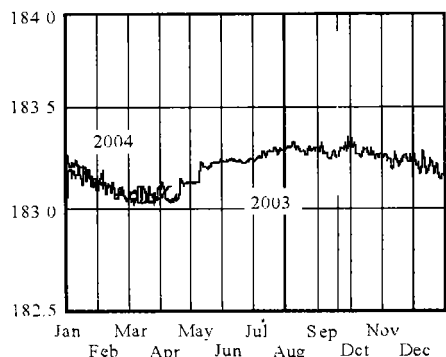


Fig. 9 Lake Superior Water Levels for 2003 and 2004

These results illustrate two points. The first is the mitigating effect of the damming of Lakes Superior and Ontario. These two lakes experienced less of the lower levels since 1996 (especially Ontario) than the other unregulated lakes (Erie, Huron and Michigan). The second is the ability of the lower lakes (Ontario and Erie) to recover more rapidly from low level years than the upper lakes (Superior, Huron and Michigan). The upper lakes level variations are more directly related to variations in over lake precipitation than surface runoff and the lower lakes respond more to surface runoff<sup>[5]</sup>. The reason for this can be seen by calculating the ratio of the lake area to drainage basin area for each of the lakes. Superior has the largest ratio, 0.64, indicating that the lake itself occupies a substantial part of the drainage basin. This ratio decreases downstream reaching a value of 0.30 for Lake Ontario. Thus rainfall over the Lake Ontario basin (both over lake and ground surface) has a greater impact on the lake levels due its relative smaller surface than the other lakes. Thus Lakes Ontario and Erie respond more rapidly to change and recover from an abnormal low or high period more rapidly as is shown for recent years.

## 5 Future Great Lakes levels

Shorter term predictions of Great Lakes water levels (six month) are regularly produced<sup>[14]</sup>. These are predicated on an understanding of the reservoir nature of the basin as a whole, the interaction between lakes and general forecasts of climate conditions (forecasted precipitation and tem-

perature affecting estimates of direct precipitation, indirect precipitation through runoff and temperature based evaporation). As mentioned in the previous section Brinkmann<sup>[5]</sup> showed that the upper Great Lakes are most heavily influenced by over lake precipitation whereas the lower Great Lakes are more influenced by runoff. In addition the lower lakes are influenced by conditions upstream in previous years.

Longer term projections of water levels are part of a broad category of research referred to as climate change impact assessment. Scenarios for the future can be generated artificially (1 °C, 2 °C, 3 °C temperature increases, for example), climate transposition which uses climate data from other locations as a proxy for future climate or scenarios generated from climate modelling, typically general circulation models (GCM's)<sup>[14]</sup>.

Climate transposition studies show the potential for more variable conditions in the Great Lakes regions with more water level variability<sup>[10, 15-17]</sup>. Studies using GCM-based water level projections are not unambiguous, some results indicating future lower levels, others the status quo<sup>[12, 15, 18-19]</sup>. Although there is general agreement that the hydrological cycle will intensify<sup>[20]</sup> which leads to greater precipitation, warmer temperatures will lead to greater evaporation. These results suggest, although not universally, that we are headed for a period of low Great Lake water levels. However, the representation of the Great Lakes in GCM's is not done particularly well due to coarse resolution. Modelling studies also vary considerably on what will occur in specific regions.

The influences of such events as El Nino Southern Oscillation and the North Atlantic Oscillation are also difficult to detect due to the "memory" of a large reservoir system and the influence of upstream input and the level regulations in Lake Superior and Lake Ontario. Other influences such as anthropogenic adjustments to surrounding land use, such as irrigation<sup>[7]</sup> and water diversion<sup>[6, 21]</sup> are beginning to be assessed.

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# 北美地区大湖水位的变化研究

William A. Gough

( 多伦多大学士嘉堡校区 自然科学与环境科学系, 多伦多 1265, 安大略, 加拿大)

[ 摘要] 在数十年来大湖水位变化历史记录背景下, 考察了近年来大湖处于低水位的问题, 并且比较了下游湖区水位最近的回升与上游湖区持续的低水位状况, 探讨了气候变化对大湖水位的潜在影响。

[ 关键词] 水位; 大湖; 加拿大; 气候变化

[ 摘要翻译: 钱会]