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Effect and Implications of Differential Isostatic Rebound on Lake Superior's Regulation Limits

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ABSTRACT: *In 1902, U.S. federal authorities established water level limits for Lake Superior as part of the requirements permitting hydropower water diversions from the lake's outlet, the St. Marys River. The vertical datum to which these limits are referenced must be adjusted every 25 to 30 years due to differential isostatic rebound (i.e., crustal movement). Because crustal movement unequally changes the land-to-water relationship along Lake Superior's shoreline, the method by which the limits are established on a new datum could accelerate the natural effects of crustal movement with adverse effects on shoreline flood levels, navigation depths, and lake outflows. With the implementation of the new International Great Lakes Datum of 1985, a study was undertaken 1) to review the methods used to establish the limits on previous datums and 2) to quantify the changed land-to-water relationship between the limits established in 1902 and those referenced to the new datum. Rates of differential crustal uplift, determined from linearly regressing water level differences between gauge pairs with time, were used. The study shows that although the numerical values of the upper and flow reduction threshold limits have changed due to subsequent datum adjustments and different reference gauge locations, the relationship of the limits with respect to the lake's outlet and the lake-wide average has not changed from that established in 1902. The present method of regulating Lake Superior based on a lake-wide average water level is shown to maintain the natural changes in the land-to-water relationship around the lake due to crustal movement. Due to these natural changes, the upper regulation limit is now 0.21 m higher at Duluth, Minnesota, and 0.26 m lower at Michipicoten, Ontario, than in 1902. By 2050, these differences will be as much as 0.34 m higher and 0.43 m lower, respectively. Thus, the implications of crustal movement should be considered in long-term planning, particularly with respect to establishing flood levels along Lake Superior's southwestern shore and navigation depths along the northeastern shore.*

INDEX WORDS: *Regulation limits, isostatic rebound, datums, Lake Superior, water levels.*

INTRODUCTION

Many changes to the St. Marys Rapids have altered Lake Superior's natural outflow regime. The most significant of these changes occurred after 1887 as a result of development for hydropower generation, navigation, and railroad transportation across the rapids. These changes are documented by Edmands (1931), the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (1970), and Hartmann (1988). U.S. federal authorities established maximum, minimum, and flow reduction threshold water level limits for Lake Superior, beginning in 1902, as part of the requirements permitting water diversions from the St. Marys Rapids for hydropower development. These limits were established to prevent the hydropower interests from manipulating lake levels to the detriment of riparian and navigation interests. Full regulation of Lake Superior outflows began in 1921 with the completion of "compensating works" at the head of the St. Marys Rapids. Regulation plans or "rules of operation" were developed which embodied the water level limits.

Since these limits were initially established, they have changed over time due to datum adjustments, use of different reference gauges, and Orders of Approval issued by the International Joint Commission (IJC). The datum (an elevation reference system) must be periodically adjusted due to differential isostatic rebound (hereafter referred to as crustal movement); the gradual rising or rebounding of the earth's crust since the retreat of the glaciers from the Great Lakes region at the end of the last ice age. Because crustal movement unequally changes the land-to-water relationship along Lake Superior's shoreline, the method by which the limits are established on a new datum could accelerate the natural affects of crustal movement with adverse effects on shoreline flood levels, navigation depths, and lake outflows. With the implementation of the new International Great Lakes Datum of 1985, a study was undertaken 1) to review the methods used to establish the limits on previous datums and 2) to quantify the changed land-to-water relationship between the limits established in 1902 and those referenced to the new datum. The effect of crustal movement on the relationship of Lake Superior's water level to its shoreline is presented first, followed by a review of the evolution of the regulation limits to those in use today. The implications of crustal movement for lake regulation are then illustrated, and the change in the land-to-water relationship of the limits quantified for various locations along the lake's shoreline.

EFFECTS OF CRUSTAL MOVEMENT ON LAKE SUPERIOR WATER LEVELS

Lake Superior, as well as the other Great Lakes, is subject to crustal movement. As stated earlier, this is the gradual rising of the earth's surface that began at the end of the last ice age. The surface was depressed by continental ice sheets which advanced into the region, and has been rebounding since their retreat (Hough 1958). The phenomenon of crustal movement in the Great Lakes regions was recognized as early as the mid-1800s [Stuntz 1869 (as cited in Clark and Persoage 1970)]. Recent estimates of the rates of uplift have been made from water level records (Clark and Persoage 1970, Coordinating Committee 1977, Tait and Bolduc 1985, Tushingham 1992), post-glacial beach ridges (Larsen 1987), and most recently, numerical models of glacial isostatic adjustment theory (Tushingham 1992). The rate of uplift is not uniform throughout the Great Lakes region and results in differential rates of change between specific sites. The rate of uplift increases across the region of the Great Lakes from the southwest to the northeast, following the direction of the glacial retreat.

Because of crustal movement, the datum used to define Great Lakes water levels has been periodically adjusted. The datum currently in use is the International Great Lakes Datum of 1985 (IGLD 1985), adopted in January, 1992. This datum was preceded by the International Great Lakes Datum of 1955 (IGLD 1955), established in 1962. Both datums were established under the auspices of the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Coordinating Committee). This binational (Canada - U.S.) committee was formed in 1953 to develop and coordinate hydraulic and hydrologic data of the Great Lakes-St. Lawrence River System. Datums used prior to IGLD 1955 include the Datums of 1935, 1903, and 1877.

Crustal movement changes the relationship of the lake's gravitational equipotential surface to the shoreline and this effect is reflected in the water level records from gauging sites around the lake. To establish the apparent vertical movement rates between any two gauging sites, the difference between their averaged June to September monthly mean levels is linearly regressed with respect to time (Moore 1948, Coordinating Committee 1977, Tait and Bolduc 1985). The rate of movement is given by the slope of the linear equation through the plot of differences. Figure 1 demonstrates this technique for the rate of apparent vertical movement of Duluth, Minnesota, relative to Pt. Iroquois, Michigan. Figure 2 shows the locations of these sites. The negative slope shown in Figure 1 indicates the land surface at Duluth is subsiding with respect to that of Pt. Iroquois. Table 1 provides calculated vertical movement rates for locations around Lake Superior, relative to Pt. Iroquois, as calculated by the Coordinating Committee (1977) based on data recorded from 1931 to 1974. The slope shown in Figure 1 is slightly different from that given in Table 1 because it is based on data from 1931 to 1992.

The rate of change between other gauge pairs can be estimated from Table 1. For example, based on

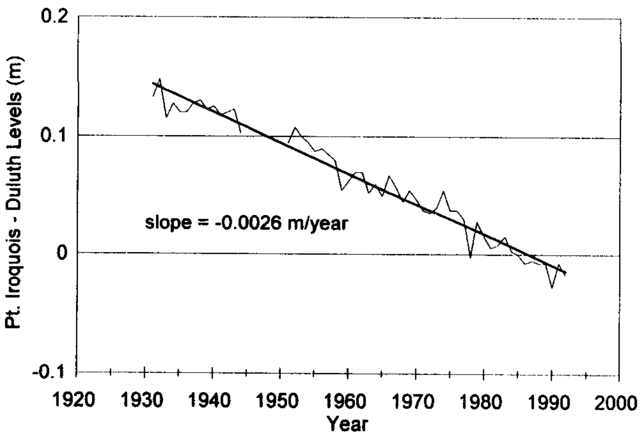

FIG. 1. Rate of change of water level differences between Duluth, Minnesota, and Pt. Iroquois, Michigan, using differences in mean water levels for 4-month means (June to September), referenced to IGLD 1985.

the vertical movement rates in Table 1, land at Duluth is subsiding at a rate of about 0.525 m per century with respect to Michipicoten, Ontario [+0.290 m – (–0.235 m)].

The effects of differential crustal movement on Lake Superior water levels may be better understood if the lake is visualized as a basin being rotated about an axis running across the lake from Pt. Iroquois to a point south of Thunder Bay, Ontario. The northeastern rim is gradually rising, and as time progresses, the shores to the southwest of the axis will fall. At Duluth, for example, water levels would be expected to rise at about 0.235 m per century (Table 1) relative to the shoreline. Conversely, water levels at Michipicoten would be expected to fall about 0.290 m per century (Table 1).

Of importance is the fact that the axis of crustal movement rotation passes very near Lake Superior's outlet. Because of this unique orientation, the rela-

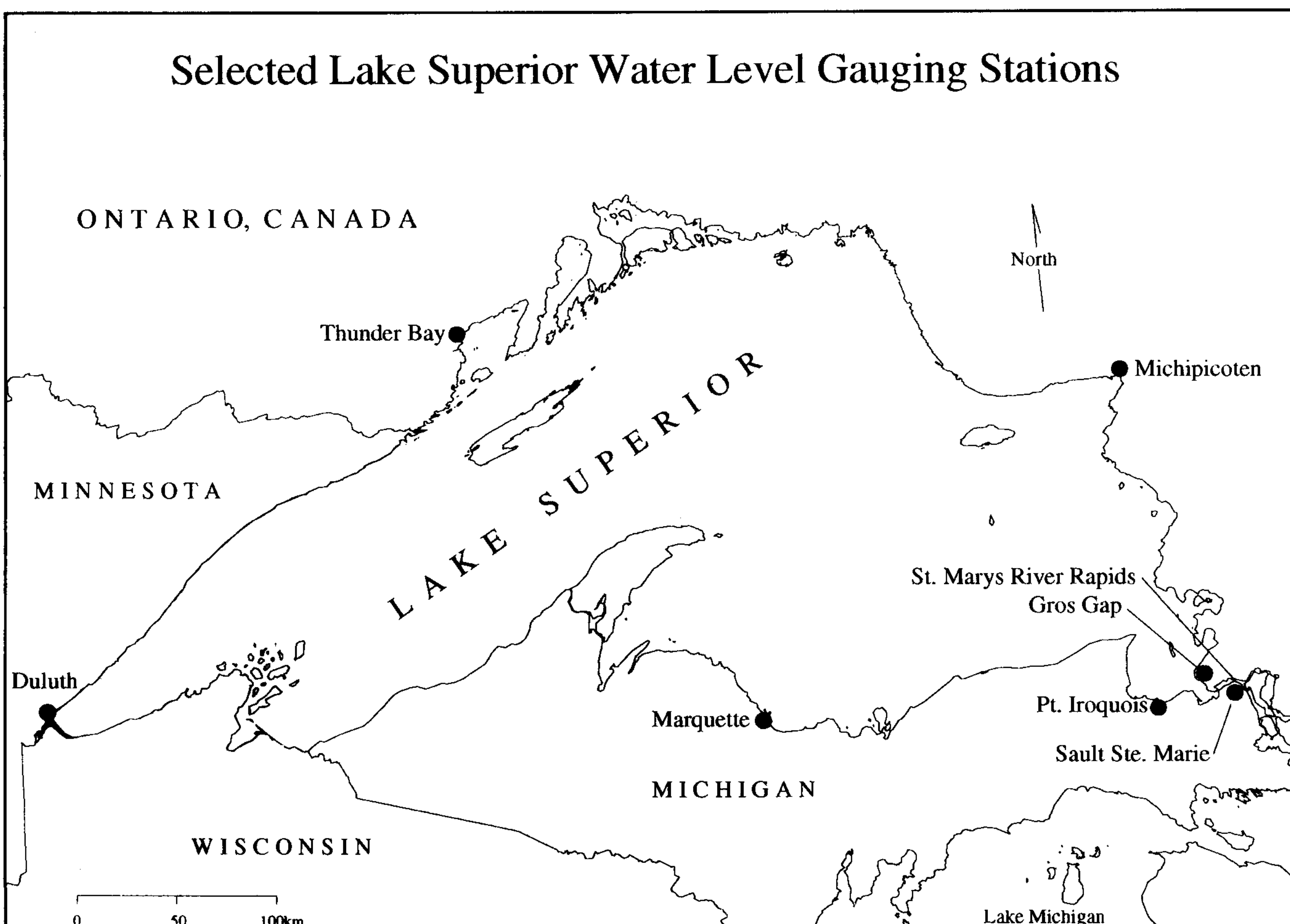

FIG. 2. Locations of Lake Superior water level gauges referenced in the text.

TABLE 1. Lake Superior Vertical Movement Rates.[1]

Gauge Location (1)	Gauge Location (2)	Rate (m/century) (3)	Rate (ft/century) (4)
Pt. Iroquois, Michigan	Thunder Bay, Ontario	+0.058	+0.19
Pt. Iroquois, Michigan	Michipicoten, Ontario	+0.290	+0.95
Pt. Iroquois, Michigan	Marquette, Michigan	–0.122	–0.40
Pt. Iroquois, Michigan	Duluth, Minnesota	–0.235	–0.77

[1]Rates between gauge locations are the apparent movement per century. Positive values signify that the second gauge location is rising with respect to the first station. (Source: Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1977)

tionship of the lake's mean level to the lake's outlet remains unaffected by crustal movement. This is not true for the other Great Lakes (Clark and Persoage 1970). This relationship is illustrated in Figure 3 which shows the differences between the averaged June to September Lake Superior water level determined using a five-gauge average (representative of the true equipotential lake surface) and the averaged June to September levels recorded at each of the five gauges. The five gauges (refer to Fig. 2) are located at Pt. Iroquois, Marquette, Duluth, Michipicoten, and Thunder Bay and are used because of their distribution around the lake's shoreline. These differences were computed from levels referenced to IGLD 1955. As Figure 3 shows, the differences between the five-gauge average levels and levels recorded at Pt. Iroquois (representing levels at the lake's outlet) are small (generally less than 1 cm) and change little over time. Thus, water levels (averaged over a long enough time period to remove short term fluctuations due to storms and barometric pressure changes) recorded only at Pt. Iroquois can be considered representative of the lake-wide (five-gauge) average.

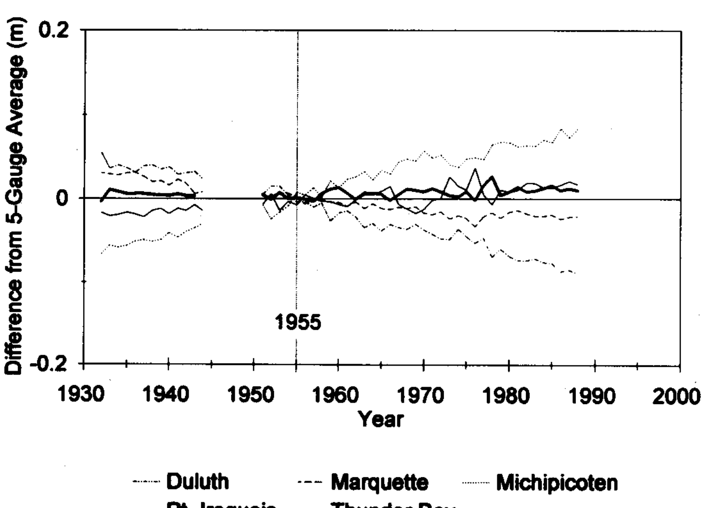

FIG. 3. Rate of change of water level differences between the five-gauge average and each gauge using differences in mean water levels for 4-month means (June to September), referenced to IGLD 1955.

The negative slopes of the plotted differences (Fig. 3) for Marquette and Duluth indicate that these sites are subsiding with respect to the lake's equipotential surface. The positive slopes of the plotted differences for Thunder Bay and Michipicoten indicate that these two sites are rising with respect to the equipotential surface. Also note that the minimum difference between the five-gauge average and the levels recorded at each gauge occurs in 1955. The date, 1955, is the episodic year in which the water level gauges were adjusted to establish the IGLD 1955 reference plane. Prior to and following that year, the differences between the recorded water levels and the five-gauge average diverge, reflecting the effect of crustal movement. Thus, levels recorded at a single gauge site, with the exception of the Pt. Iroquois site, do not represent the true equipotential surface and are either numerically too high or too low, prior to and after 1955.

Once the levels recorded at the gauges diverge significantly (such as in the mid-1980s—Fig. 3), it is necessary to update the datum. This occurs every 25 to 30 years on the Great Lakes. In January 1992, when IGLD 1985 was introduced, all recorded water levels were adjusted to this new datum. The impact of the datum adjustment on recorded data can be seen by comparing Figure 4, generated using water levels referenced to IGLD 1985, to Figure 3. The slopes of the plotted lines do not change. However, the position of the minimal difference year moves from 1955 to 1985—the episodic year of the new datum. Accordingly, the year-by-year differences shown in Figure 3 change to those in Figure 4. At sites such as Duluth, where levels relative to the lake-wide average are increasing with time (recall the shoreline there is subsiding relative to the lake-wide average), recorded levels prior to the episodic year (1985) are numerically lower than the corresponding lake-wide average. For example, the 1940 averaged June to September level at Duluth is 183.40 m, and for the five-gauge average it is 183.52 m, a difference of –12 cm. After 1985, the recorded levels are numerically higher than the corresponding lake-wide average. For example, the 1990 averaged June to September level at Duluth is 183.36 m and for the five-gauge average it is 183.33 m, a difference of +3 cm. The difference of the second example is not as dramatic as the first example because it's date is closer in time to 1985. The converse is true at sites where levels are falling (the shoreline is rising) over time. This can be illustrated in the same manner as the two previous examples knowing that the 1940 level at Micipicoten is 183.63 m, and the 1990 level is 183.32 m. This phenomenon should be understood and noted by all water level data users.

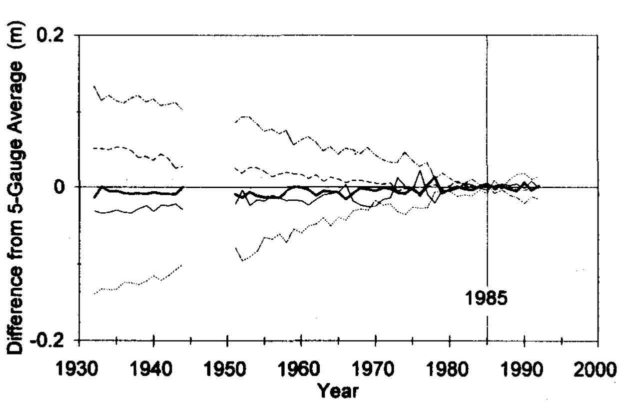

FIG. 4. Rate of change of water level differences between the five-gauge average and each gauge using differences in mean water levels for 4-month means (June to September), referenced to IGLD 1985.

EARLY LAKE SUPERIOR WATER LEVEL REGULATION LIMITS

Hartmann (1988) researched the origin of the Lake Superior level regulation limits. The first limits were established by the U.S. Secretary of War under the Rivers and Harbors Act of 1902 in approval of early U.S. power canal diversions from the St. Marys Rapids. Referenced to the Datum of 1877, the maximum and minimum levels were 183.79 m (603.0 ft) and 183.18 m (601.0 ft), respectively. A threshold level of 183.34 m (601.5 ft), at which diversions had to be reduced, was also specified. [Here and in the following section, values in English units are given following their metric values because conversions between datums (excluding IGLD 1985) depend on benchmark elevations published in Engish units, and continuity with historical references and water level records is preserved. Metric values were obtained by multiplying the English values by 0.3048 m per ft.] These limits were set for levels measured above navigation locks (for traversing the St. Marys Rapids) at Sault Ste. Marie, Michigan (Fig. 2). In 1914, U.S. and Canadian power companies applied to the International Joint Commission (established by the Boundary Waters Treaty of 1909) for increased diversions from the St. Marys Rapids. They proposed "compensating works" which would allow increased diversions while still meeting the requirements of the 1902 permit. In testimony given before the International Joint Commission (IJC 1914a), the limits referenced to the Datum of 1877 were converted to the Datum of 1903 by applying a difference of 0.06 m (0.2 ft) between the datums at Sault Ste. Marie. These limits were then referenced to levels measured at Marquette on the Datum of 1903 by applying an adjustment of 0.12 m (0.4 ft), a correction to compensate for the fall in the river's water level from Lake Superior to Sault Ste. Marie. This conversion resulted in a maximum level of 183.98 m (603.6 ft), a minimum level of 183.37 m (601.6 ft), and a flow reduction threshold of 183.52 m (602.1 ft) on the Datum of 1903 at Marquette. In Orders of Approval, issued by the International Joint Commission (IJC 1914b), the upper and lower regulation limits were specified as 183.98 m and 183.52 m, respectively, with the understanding that lake outflows would not exceed those that would have occurred prior to 1887 if the level should fall below 183.52 m. Although the limits were referenced to levels at Marquette, the Orders of Approval also specified that the mean lake level was to be determined by taking the average of levels recorded by no less than four gauges, half maintained by the U.S. and half by Canada. From the testimony, it appears that the four-gauge average was specified because of concerns voiced over the short-term effects of storms on recorded levels.

In 1936, the Datum of 1935 was established within the United States (International Lake Superior Board of Control 1936). Research of available literature (primarily U.S. Lake Survey reports and International Lake Superior Board of Control reports) showed no reference to converting the regulation limits from the 1903 datum to the 1935 datum. The limits continued to be referred to as 183.98 m and 183.52 m in the Board of Control reports, although recorded levels were reported referenced to the Datum of 1935. Other U.S. Lake Survey reports also continued to refer to these limits in terms of the Datum of 1903.

With the implementation of IGLD 1955 in 1962, the regulation limits were given as 183.49 m (602.0 ft) and 183.03 m (600.5 ft) in subsequent Board of Control and International Joint Commission reports. Hartmann (1988) surmised that the regulation limits were converted to the new datum by applying the mean of the differences between the Datums of 1903 and 1955 at five gauge locations: Marquette, Pt. Iroquois, Southwest Pier (located at Sault Ste. Marie), Thunder Bay, and Gros Gap, Ontario (Fig. 2). However, the use of this five-gauge average seems unsatisfactory in that the Southwest Pier gauge is located on the St. Marys River and does not represent lake levels. In addition, this combination of five gauges is not that used in lake regulation, nor is it well balanced with respect to crustal movement.

Another way exists in which the regulation limits may have been converted. The regulation limits originally determined relative to Marquette on the Datum of 1903 could have been converted to IGLD 1955 at Marquette, then adjusted for crustal movement to Pt. Iroquois, preserving the 1902 relationship of the limits with respect to the lake's outlet and the lake-wide average level. This would have been done by adding the Marquette gauge benchmark elevation difference of –0.57 m (–1.86 ft) (Coordinating Committee 1978) between the above two datums to the Datum of 1903 limits, yielding 183.41 m (601.74 ft) for the upper limit and 182.95 m (600.24 ft) for the lower limit, referenced to IGLD 1955.

These limits could then have been adjusted for the crustal movement of Marquette relative to Pt. Iroquois as shown in (1), assuming all lake gauges were in harmony in the episodic years of the datums:

$$Z_{Pt.I} = Z_M + 0.004\ (1955–1903) \qquad (1)$$

where $Z_{Pt.I}$ are Pt. Iroquois levels (ft, IGLD 1955), and Z_M are Marquette levels (ft, IGLD 1955). The differential movement rate of 0.004 ft per year was determined by linear regression of the differences between the June to September averages of levels recorded at Pt. Iroquois and Marquette for 1931 to 1961. These are the data that would have been available, and the units in use, at the time IGLD 1955 was implemented in 1962. This rate agrees with that published by the Coordinating Committee (Table 1) using data from 1931 to 1974.

Applying this conversion, +0.21 ft, to the level limits at Marquette on IGLD 1955, and rounding to the nearest tenth of a foot, yields 602.0 ft for the upper limit and 600.5 ft for the lower limit. Their metric equivalents are 183.49 m and 183.03 m, respectively. An adjustment based on this approach seems consistent with the understanding of crustal movement impacts and the practice of adjusting data common at the time of the limits' update.

PRESENT REGULATION LIMITS

In 1964, in response to extreme low levels on the Great Lakes, the Governments of Canada and the United States issued a Reference to the International Joint Commission to study further regulation of the Great Lakes. The Commission concluded, as a result of the study completed in 1976 (IJC 1976), that Lake Superior could not be regulated within the 0.46 m (1.5 ft) range specified in the 1914 Orders of Approval. In a Supplementary Order of Approval, dated 3 October 1979 (IJC 1979), they amended the 1914 Orders of Approval, keeping the upper limit of 183.49 m (602.0 ft), but specifying a revised lower limit of 182.39 m (598.4 ft). In addition, the Supplementary Order specified that lake outflows should be reduced to those that would have occurred under condtions which existed prior to 1887 if the mean lake level were to fall below 183.03 m (600.5 ft).

The upper limit of 183.49 m and the flow reduction threshold limit of 183.03 m followed directly from the original 1914 Orders of Approval and the earlier permit issued by the U.S. War Department. The lower limit of 182.39 m appears to be the minimum level that resulted when recorded water supplies (1900–1967), adjusted for Great Lakes basin diversions, were applied to the 1955 Modified Rule of 1949 (International Great Lakes Levels Board 1973). This regulation plan was in use from 1955 to 1973 (International Lake Superior Board of Control 1981).

These regulation limits were recently converted to the new International Great Lakes Datum of 1985. The conversion also included changing from English units to metric units, consistent with data collection in Canada and in accordance with a U.S. Government mandate for federal agencies to convert to the metric system. The limits were converted to IGLD 1985 in the following manner (Noorbakhsh, U.S. Army Corps of Engineers, personal communication, 1993).

The regulation limits referenced to IGLD 1955 were first converted to metric by multiplication of 0.3048 m per ft and rounded to three decimal places. The conversion factors from IGLD 1955 to IGLD 1985 of the five gauges used in Lake Superior regulation [Pt. Iroquois (0.377 m), Marquette (0.345 m), Duluth (0.285 m), Thunder Bay (0.383 m), and Michipicoten (0.439 m)—refer to Fig. 2] were averaged and added to the IGLD 1955 regulation limits. The limits, referenced to IGLD 1985, were then rounded to two decimal places, yielding limits of 183.86 m and 182.76 m.

A similar exercise, converting the regulation limits to IGLD 1985 with respect to Pt. Iroquois only, yielded regulation limits of 183.87 m and 182.77 m (Lee 1992). Because the difference was small (1 cm) and the method used to convert from the Datum of 1903 to IGLD 1955 was not known, the decision was made by the International Lake Superior Board of Control's Regulation Representatives to convert the regulation limits using the five-gauge average, consistent with the Orders of Approval call for use of multiple gauges in determining the lake level.

IMPLICATIONS OF CRUSTAL MOVEMENT WITH RESPECT TO LAKE REGULATION

As shown previously, the relationship of the upper regulation limit and the flow reduction threshold limit has not changed with respect to the outlet (as represented by the Pt. Iroquois gauge) or the lake-wide average over time. However, the relationship of the limits with respect to other locations around the shoreline has changed over time due to the natural effects of crustal movement. To illustrate this, consider the city of Duluth, located on the U.S. southwestern shoreline of Lake Superior (Fig. 2). Since the establishment of the upper regulation limit of Lake Superior by the U.S. War Department in 1902, the Duluth shoreline has fallen about 0.21 m [-0.00235 m/year × (1993–1902)] relative to the outlet of the lake (or alternatively, and perhaps more significantly, the water level at Duluth is now 0.21 m higher for the same average lake level recorded in 1902 as in 1993). Since the regulation limits have been maintained as a fixed land-to-water relationship at the outlet of the lake, the upper regulation limit is now 0.21 m higher with respect to the Duluth shoreline. Conversely, over the same time period, the upper regulation limit is now 0.26 m [0.00290 m/year × (1993–1902)] lower with respect to Michipicoten's shoreline (located in Canada on the lake's northeastern shoreline). In the year 2050, the upper regulation limit will be about 0.34 m higher relative to the Duluth shoreline, and 0.43 m lower relative to the Michipicoten shoreline, than in 1902, assuming the current movement rates.

One could argue then, that perhaps the relationship of the regulation limits to the shoreline should be preserved at Duluth, instead of Pt. Iroquois, to prevent an increase in shoreline flood levels. If so, from 1902 to 1993, the limit with respect to Pt. Iroquois would have fallen by 0.21 m and by 0.48 m [(0.00525 m/year) × (1993–1902)] at Michipicoten. Clearly, the effect of crustal movement at Michipicoten would be nearly double with this scenario (and navigation depths reduced correspondingly). To actually regulate the lake so that the relationship of the limits to Duluth's shoreline (or most other locations on the U.S. shoreline) would be preserved, the mean level of the lake would have to be lowered (by increasing lake outflows for a given water level) on a continuing basis to offset increasing water levels resulting from crustal movement. A similar exercise can be conducted to illustrate the effects of regulating with respect to levels at a Canadian site such as Michipicoten. This would require a continual raising of the mean level of the lake (a reduction in lake outflows for a given water level). Under this scenario, the U.S. shoreline would experience increased flooding problems resulting from high water levels during periods of high water supplies to the lake. In either of these scenarios, modification of the lake's outflow also has implications on the water levels of the lower Great Lakes. The above exercise has been repeated for other gauge locations around Lake Superior as shown in Table 2. These results, i.e., the close agreement between Pt. Iroquois levels and the five-gauge average, show that the present method of

TABLE 2. Change in Relationship of the Upper Regulation Limit to Various Shoreline Locations between 1902 and 1993

	Change in Relationship (m)[1]				
Fixed Land-to-Water Relationship Site (1)	Pt. Iroquois (2)	Thunder Bay (3)	Michipicoten (4)	Marquette (5)	Duluth (6)
Pt. Iroquois[2]	0.00	–0.05	–0.26	0.11	0.21
Thunder Bay	0.05	0.00	–0.21	0.16	0.27
Michipicoten	0.26	0.21	0.00	0.38	0.48
Marquette	–0.11	–0.16	–0.38	0.00	0.10
Duluth	–0.21	–0.27	–0.48	–0.10	0.00

[1]Positive values signify that the upper lake regulation limit would be higher now (1993) with respect to the given gauge locations (columns 2-6) than in 1902, if a fixed land-to-water relationship were maintained at the gauge location listed in column 1. Conversely, negative values signify that the upper lake regulation limit would be lower in 1993 than in 1902. For example, if a fixed land-to-water relationship were maintained at Duluth (column 1), the upper regulation limit would be 0.48 m lower now than in 1902, relative to the Michipicoten shoreline (column 4).
[2]Present relationship (considered equivalent to a lake-wide average).

regulating the lake with respect to the lake-wide average maintains the natural changes in the land-to-water relationship around the lake due to crustal movement, and represents the natural process that would occur if the lake were unregulated.

SUMMARY

The present upper regulation limit and the flow reduction threshold of Lake Superior are shown to have their origin in approvals issued by the U.S. War Department of early U.S. power canal diversions from the St. Marys Rapids. Although the numerical values of the limits have changed over time due to datum adjustments and different reference gauges, the relationship of the limits with respect to the lake's outlet and the lake-wide average has been preserved. Regulation of the lake based upon its lake-wide average water level maintains the natural changes due to crustal movement that would occur if the lake were unregulated. However, because of the phenomenon of crustal movement, the relationship of the regulation limits (and water levels) with respect to the U.S. southwestern shoreline and Canadian northeastern shoreline has changed significantly over this century. The relationship will continue to change in the future due to ongoing crustal movement. Modifying the regulation limits to preserve their relationship with respect to any site other than the lake's outlet would accelerate the effects of crustal movement at other locations on the shoreline and affect the water levels of the lower Great Lakes. Because the effects of crustal movement become significant over time, it should be considered in long-term planning, particularly with respect to establishing flood levels along Lake Superior's southwestern shore and navigation depths along the northeastern shore.

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