HISTORY AND THEORY OF DATUM PLANES OF THE GREAT LAKES

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INTRODUCTION

Like other natural watercourses (1), the Great Lakes (figure 1) have levels which fluctuate in response to natural phenomena. There are seasonal variations: the lakes are generally higher in summer than in winter. Superimposed on the seasonal variations are more random long-period variations. In addition, the level at any given location on a given lake will vary over irregular periods from several minutes to several hours because of forces disturbing the lake surface, principally wind. Therefore, in describing depths in the lakes it is convenient to have fixed planes of reference or datum planes. This plane on each lake is commonly referred to as the Low Water Datum.

The datum planes of the Great Lakes have two main purposes. First, they provide a reference for depiction of depths on navigation charts. Second, they provide a reference for determining depths to which improved navigation channels are dredged. The latter represents an economic matter since the positions of the planes are related to (but do not necessarily determine) the number of cubic yards of material that must be dredged to give the desired depths. Other purposes can be ascribed to datum planes as references descriptive of the behavior of lake levels. Terms such as "Mean High Water" and "Mean Low Water" can be defined and can be significant, for example, to shore property owners. The term "Low Water Datum" is generally used with reference to navigation, and the discussions herein are confined to navigation considerations.

This paper describes the past and present datum planes of the five Great Lakes as used in the United States and describes the bases for selection of planes. Since Lakes Michigan and Huron are considered hydraulically as a single lake, they have a common datum. Lake St. Clair is generally considered a part of the Lake Erie basin and usually not

(1) The natural fluctuations of Lakes Superior and Ontario are modified by artificial control of their outflows.

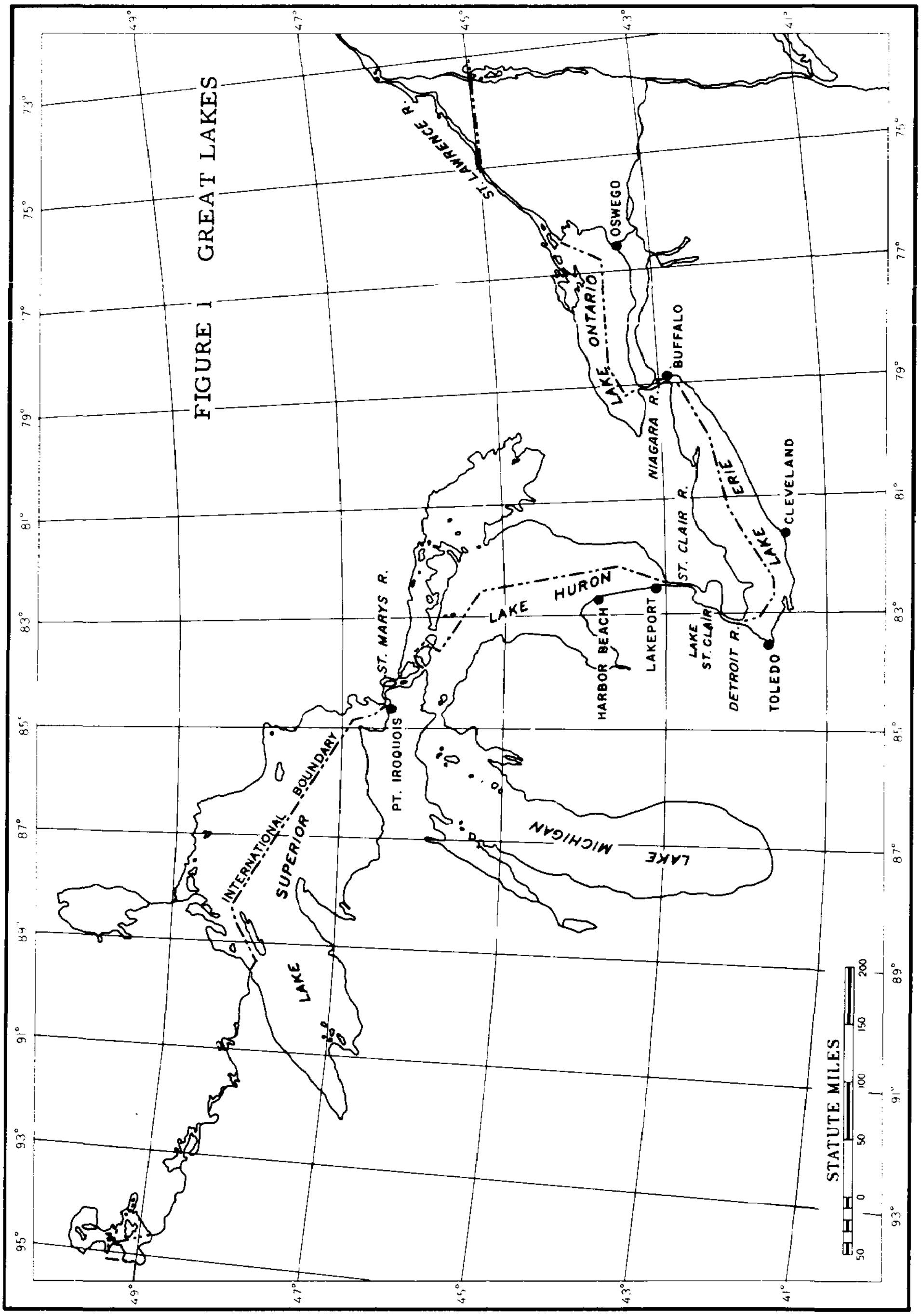
FIGURE 1 GREAT LAKES
LAKE SUPERIOR
INTERNATIONAL BOUNDARY
PT. IROQUOIS
ST. MARYS R.
LAKE HURON
LAKE MICHIGAN
HARBOR BEACH
LAKEPORT
ST. CLAIR R.
LAKE ST. CLAIR
DETROIT R.
TOLEDO
LAKE ERIE
CLEVELAND
NIAGARA R.
BUFFALO
LAKE ONTARIO
OSWEGO
ST. LAWRENCE R.
STATUTE MILES
50 0 50 100 150 200

FIG. 1

identified separately in a discussion of the Great Lakes. However, it is an important segment of the Great Lakes system and a datum plane has been established for it. No attempt is made to describe the use of datum planes in Canada other than to note the coordination of the present planes by the two countries.

HISTORY OF DATUM PLANES (2)

In the development of the Great Lakes as waterways recognition of the need for datum planes was not immediate, as the earliest lake hydrographers often recorded water depths only in terms of water levels at the times of their surveys. An evolutionary process spanning a period of over 50 years was required to develop the modern concept of datum planes.

Early planes

Unusually high water occurred on all of the lakes in 1838. Planes of reference used by the Lake Survey for lake levels prior to 1876 were intended to be the highest levels observed in 1838. In the Annual Report of the Chief of Engineers, U.S. Army, for 1876, these planes were officially defined as distances below particular benchmarks. How closely the 1876 planes corresponded to the high water of 1838 is problematical since level records of 1838 are incomplete.

The 1876 planes of references were considered too high for charting or harbor improvement. The first datum plane used on published Lake Survey charts was for Lake Erie during the period 1870-1875 and was the mean level of that lake over the period 1860-1870. Beginning in 1876 and until 1901, the datum planes used on nearly all Lake Survey charts were the mean lake levels 1860-1875. These planes were from two and one-third to slightly over three feet lower than the 1876 planes.

Connection to Sea Level

Elevations for the Great Lakes based on sea level were first obtained by (a) spirit levels performed by the U.S. Coast and Geodetic Survey (now National Ocean Survey) from New York City to Greenbush, New York, on the Hudson River (now Rensselaer) and (b) spirit levels and water transfers (3) performed by the Lake Survey from Greenbush to Lake Ontario

(2) Most of the discussion of the former planes to the year 1932 is based on an unpublished Lake Survey report "Datum Planes on the Great Lakes" by Sherman Moore, 1939, File 3-2869. A history of the datum planes is also given by Ropes, 1965.

(3) The setting of water level gages at opposite ends of a lake to give the same average readings, based on the assumption that averaged over the selected period the lake has a level surface.

and through the chain of lakes (U.S. Deep Waterways Commission, 1896). These elevations are said to be based on the levels of 1877 although the field work was accomplished during a number of years.

Probably because of generally low water on the lakes in 1895-1896, the mean lake levels of 1860-1875 were found to be too high for charting. As a result, new planes of reference, called Standard Low Water, were adopted for Lake Survey charts in 1901. But revision of planes for channel and harbor improvements was deferred.

In 1903, the U.S. Coast and Geodetic Survey made an adjustment (without an orthometric correction) of the levels of 1877 which changed the values of sea level elevations established on the Great Lakes and became known as 1903 Datum [4]. Corresponding changes were made in the elevations of the 1901 datum planes except that the new elevations (as directed by the Chief of Engineers, U.S. Army, in 1909) were rounded to the nearest half foot. This resulted in a maximum change in the physical position of any plane of 0.09 foot. It is worthwhile to note here that the 1901 planes, like the earlier planes, were defined as specified vertical distances from particular benchmarks (Annual Report of the Chief of Engineers, U.S. Army, 1909, p. 2484). The physical position of a plane was, and is, considered changed only when the distance from its controlling benchmark was changed.

TABLE 1

Comparison of datum planes

Elevations in feet above mean tide at New York, 1903 Datum

Lake	Mean Lake Levels 1860-1875	Planes of 1901	Planes of 1909		Planes of 1933	Planes of 1955	
			Nominal values	Adopted values		Nominal values	Adopted values
Superior	603.22	600.56	600.56	600.50	601.6	601.63	601.60
Michigan-Huron	581.64	578.51	578.51	578.50	578.5	578.54	578.50
Erie	572.77	569.91	569.91	570.00	570.5	570.55	570.50
Ontario	246.55	242.96	242.96	243.00	244.0	244.03	244.00

Table 1 shows a comparison of elevations above mean tide at New York City of the mean lake levels 1860-1875 and Standard Low Water for 1901 and 1909. Since all values shown on the table are referred to the same datum (1903), the differences between values represent differences between the physical positions of the planes, as described above.

(4) 1903 Datum and the later 1935 Datum and International Great Lakes Datum (1955) should not be confused with Low Water Datum; these datums, which are identified by the year of their establishment, represent coordinated revisions of benchmark elevations throughout the region.

1933 Planes

The 1909 planes were used for charting rather than channel and harbor improvements, and it was found desirable to adopt a single datum plane for each lake to be used both for charting and for improvement work. In 1933 the Chief of Engineers approved such single planes for each lake, also as shown in table 1. Each of these planes became known as Low Water Datum on its lake and represented what might be described as the lake's average low water level.

The physical positions of the 1933 planes were fixed, have remained essentially fixed and are expected to remain fixed by defining them at a single point on each lake as a vertical distance from a particular benchmark. Water level gages located at the defining points became known as the "master" gages since water levels transferred from each to any other location on the same lake served to establish the position of Low Water Datum at such other location.

Differential Gage Site Movement

At the time of the establishment of the 1933 planes, it was recognized that progressive differences between water levels at different locations on the same lake were occurring, i.e., over a period of years water levels at these locations were becoming higher or lower than water levels at the master gage site. Since water levels at any site depend on elevations assigned to benchmarks at that site, these progressive difference probably were due to rise or subsidence of benchmarks at the various sites with respect to benchmarks at the master site. The differences amounted generally to a fraction of a foot per hundred years. The result was that water in most United States harbors was becoming deeper (MOORE, 1949). The phenomenon became known as "crustal movement" based on the conclusion that it was caused by differential movement of the earth's crust, although the interpretation of the data remains open to some doubt. A better term at present is "differential gage site movement". Whatever the cause, the changes were sufficient to require benchmark elevations in the harbors on a given lake to be adjusted to provide, at a selected time, water surface elevations that were the same in these harbors as at the master gage site. Such an adjustment was made for each lake based on the year 1935. This adjustment is known as the 1935 Datum.

Present Planes

In the early 1950's, a joint decision was made by the Lake Survey, the Canadian Hydrographic Service and the Geodetic Survey of Canada to adjust again benchmark elevations for differential gage site movement and, further, to redetermine sea-level elevations through the Great Lakes region. The Canadian Departments of Transport and Resources and Development also participated in this decision. As a result, a new datum called International Great Lakes Datum (1955) [IGLD (1955)], was established which was referred to mean water level at Father Point, Quebec, on the Gulf of St. Lawrence (The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (5), 1961). Elevations based on the new datum are dynamic elevations (i.e., they are measures of the work done in lifting a pound mass) and represent the elevations which existed in the year 1955. Dynamic elevations avoid the difficulties of orthometric elevations, which do not portray equipotential surfaces, and instrumental elevations, which depend on the route of levelling followed. The dynamic elevations were computed from data obtained by instrumental levels along the connecting rivers and water transfers across the lakes. Elevations of benchmarks were changed, and physical positions of the 1933 United States planes were changed only to the slight extent necessary to provide rounded values (as was done in establishing the 1909 planes).

TABLE 2

Definition of 1955 low water datum

Lake	Master Gage Location	Controlling Benchmark and Elevation Feet IGLD (1955)		Distance of Low Water Datum Below Benchmark, Feet
Superior	Point Iroquois, Mich.	BM Lighthouse	620.62	20.62
Michigan-Huron	Harbor Beach, Mich.	BM Huron	581.90	5.10
Erie	Cleveland, Ohio	BM Doorstep	580.49	11.89
Ontario	Oswego, N.Y.	BM A	250.67	7.87

Table 1 shows the elevations of the 1955 planes (Low Water Datum) based on the levels of 1903 in order to provide a comparison of the positions of the planes with the positions of the earlier planes. Table 2 shows the master gage locations, identification and elevations (levels of 1955) of controlling benchmarks, and locations of the 1955 planes with respect to the benchmarks. Low Water Datum elevations for the Great Lakes now in use by the United States and Canada (although the two countries use different master gage sites) are, in feet IGLD (1955), Lake Superior 600.0, Lake Michigan-Huron 576.8, Lake Erie 568.6, and Lake Ontario 242.8. The Low Water Datum elevation for Lake St. Clair is 571.7 feet, IGLD (1955).

(5) This committee was formed in 1953 by U.S. Army Corps of Engineers and the Canadian Departments of Transport, Mines and Technical Surveys, and Resources and Development to provide a basis for acceptance of identical basic data, principally lake levels and connecting river flows, by both countries. The committee is advisory to the appropriate operating agencies of the two countries.

Levelling along the connecting rivers and collection of water level data on the lakes are now underway to provide a basis for determining dynamic elevations of benchmarks existing in the year 1970.

Responsibility for Datum Planes

Because the Corps of Engineers has had United States responsibility for charting of the Great Lakes and navigation improvements of the lakes, the Corps has assumed the concomitant responsibility of establishing the United States datum planes. Under a reorganization plan effective 3 October 1970, responsibility for charting of the Great Lakes was transferred to the National Oceanic and Atmospheric Administration, Department of Commerce, which now shares responsibility for datum planes. However, whatever agencies are involved, recommendations for datum plane changes would appropriately come from the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data as a result of an internationally coordinated study.

THEORY AND SELECTION OF DATUM PLANES

General Considerations

Ideally, the datum planes should be selected from knowledge of lake levels over an extensive future period, say 50 years, but the only certain knowledge is of levels of the past. Any estimate of the future levels which the datum planes must accommodate can be little more than an assumption that past levels will recur with possible modifications to account for artificial changes such as diversion changes, etc. (see below). The expectation of recurrence, of course, can contain no hope of sequential repetition and can only be a prediction that statistical characteristics, principally duration (exceedance frequencies), of past levels will be duplicated in the future.

In the period 1933-1968 the frequencies with which recorded monthly average lake levels exceeded the 1933 Low Water Datum planes during the navigation season April-November were Lake Superior (at Marquette, Michigan) 93 per cent, Lake Michigan-Huron (at Harbor Beach, Michigan) 83 per cent, Lake Erie (at Cleveland, Ohio) 95 per cent, and Lake Ontario (at Oswego, New York) 94 per cent. Figure 2 shows the relation to Low Water Datum of the average recorded lake levels for the navigation season 1933-1968.

If occurrences of monthly average levels above Low Water Datum were independent events, the frequencies (probabilities) of two or more lakes being simultaneously above datum would be the product of the individual frequencies. This product for all four lakes is 69 per cent.

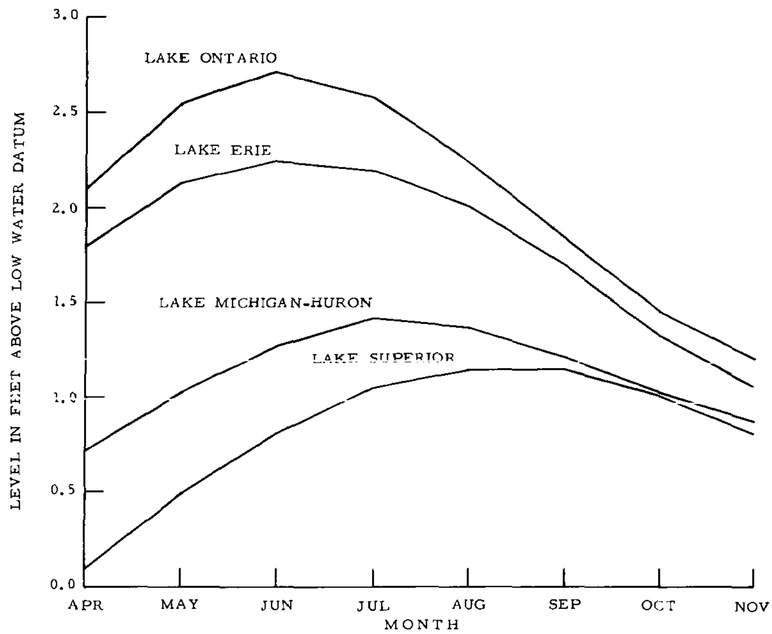

FIG. 2. — Average levels of the Great Lakes, April-November, 1933-1968, referred to Low Water Datums.

The recorded frequency for the four lakes, which is 77 per cent, is higher as would be expected.

In using past levels to indicate future levels, a difficulty results because changes of water level regime often occur. Even if nature cooperated by providing an identical future sequence of meteorological events to that of the 1933-1968 period, the levels resulting therefrom would not be statistically the same as the comparison period because of systematic changes. These changes include dredging of the connecting channels for the 25-foot project completed in 1937 and the 27-foot project completed in 1962 (particularly the St. Clair and Detroit Rivers), initiation of diversion from the Albany River basin into Lake Superior in 1939, modification of the Lake Superior regulation plan in 1955, and initiation of the regulation of Lake Ontario in 1960.

It is possible to adjust recorded levels to a fixed set of conditions, expected to apply in the future, in order to obtain a better estimate of future levels. Such adjustments of recorded levels have been made for various hydraulic studies.

Recorded water levels for the period 1900-1967 adjusted to selected fixed conditions (as developed by the Regulation Subcommittee of the International Great Lakes Levels Board) show that the frequencies of exceedance of the monthly average levels of the present Low Water Datums are 84 per cent for Lake Superior, 96 per cent for Lake Michigan-Huron, 99 per cent for Lake Erie and 99 per cent for Lake Ontario. Figure 3 shows the relation of the average of the recorded adjusted monthly average levels during the navigation seasons to the Low Water Datums.

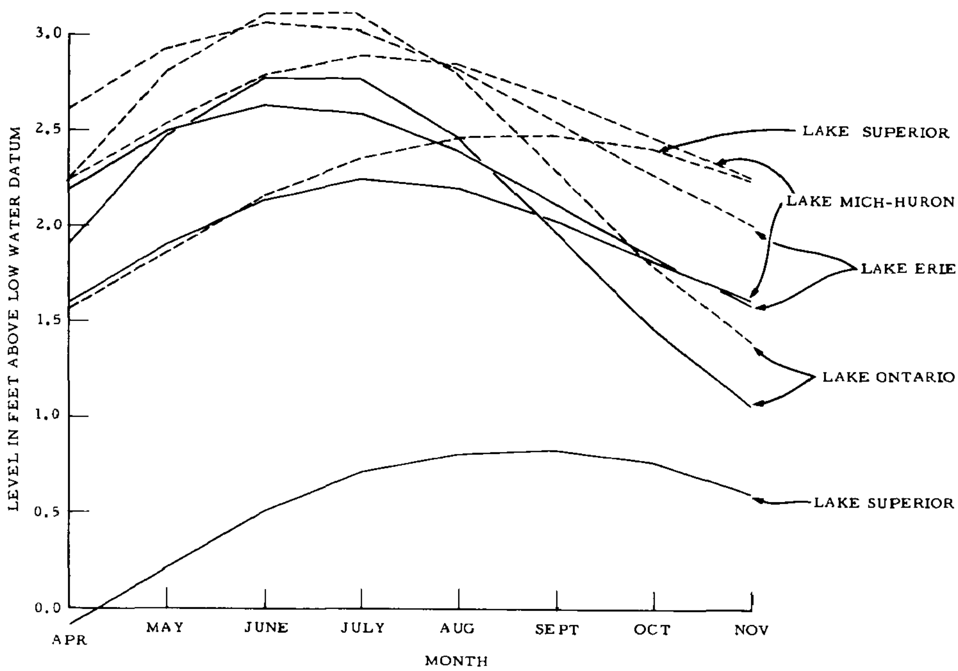

FIG. 3. — Adjusted average levels of the Great Lakes, April-November, 1900-1967, referred to Low Water Datums.
——— Present datums.
— — — Datums equal to the lowest monthly level of the total period.

The recorded adjusted levels described above contain no adjustment for differential gage site movement. The selection of datum planes could be affected if the defining benchmarks at the master gage sites are rising or subsiding with respect to the lake outlets. However, the regulation of Lakes Superior and Ontario tends to eliminate such effect of site movement on those lakes. The rates of movement of the defining benchmarks at Harbor Beach, Michigan (about 60 miles from the outlet of Lake Michigan-Huron), and Cleveland, Ohio (about 170 miles from the outlet of Lake Erie), with respect to the lake outlets are both less than 0.5 foot per hundred years (both outlets rising). These changes are of no practical significance in the selection of datum planes.

Selection of Planes for Charting

A mariner using a navigation chart is confronted with a series of numbers representing water depths that will be present when the water surface is at a specified elevation. On Lake Survey charts of the Great Lakes, the specified elevation on each lake is the 1955 Low Water Datum described above. The Great Lakes are essentially nontidal, but their water surface elevations change continuously and sometimes rapidly. Trends of several years' duration may cause the water to rise or fall a foot or two, seasonal variations within a given year of the same magnitude are superposed on the long-term trends, and short-period fluctuations lasting a few hours and having a magnitude of several feet may occur locally on a given lake. It is therefore impossible to select Low Water Datums which coincide with the water surface other than as rare occurrences. The selection must be made on the basis of statistical criteria, such as exceedance frequencies and level averages, obtained most practically from monthly average levels.

There is no practical way to provide for localized short period level fluctuations in the selection of datum planes. Monthly average levels generally reflect a negligible effect of short-period fluctuations at any location. But it is possible for wind tide to affect the monthly average level at a given location by a few inches.

If every mariner were fully aware of the nature of fluctuations of lake level in affecting water depths and had full knowledge of the existing lake level, there would be little basis for preferring one datum over another within reasonable limits (a very low datum plane would tend to show some land areas where usually there is water, and a very high datum plane would show large depths in areas where usually the depths are small). Under such conditions the best choice might be a datum equal to the average, or perhaps median level, in order to minimize deviations of existing level from datum. However, many and possibly most mariners do not have this knowledge, and the chartmaker must protect all mariners by recording nearly the least depths ever expected to occur. Such a policy assures that a mariner, even with complete lack of knowledge of the current lake level and how it affects the charted depths, will rarely incur a disaster as a result of actual depths being less than charted depths during the normal navigation season.

A Low Water Datum for charting must therefore be selected to be equal to a level exceeded most of the time. To select a datum equal to the lowest level expected to occur has been generally considered impractical. The recorded adjusted levels of Lakes Erie and Ontario, April-November 1900-1967, as described above, provide an indication of the differences between datums and minimum levels. In this set of levels the amounts by which the Low Water Datums exceed the minimum monthly average levels are Lake Superior 1.64 foot, Lake Michigan-Huron 0.86 foot, Lake Erie 0.43 foot, and Lake Ontario 0.95 foot.

In terms of marine safety it is difficult to draw a dividing line between safe and unsafe datums. There is little or no basis, for example, to decide that a datum which the level exceeds 90 per cent of the time is safe while a datum with only an 80 per cent exceedance frequency is not safe. While the use of datums equal to the lowest recorded adjusted level might be feasible, such a change, or any lowering, of the present datums is not warranted in order to improve marine safety because there is no evidence that the present datums are unsafe.

Another consideration in the selection of datum planes as references for charted depths is compatibility, i.e., the state of having the planes of each lake bear the same relation to the water levels. A mariner on Lake Erie one day and Lake Huron the next, or perhaps dividing his sailing time between these two lakes over the course of a month or longer, would certainly find some convenience in having the actual depths exceed the charted depths by the same amount on each lake. But the levels of the lakes do not vary with the same periods or amplitudes, and it is therefore impossible to assure compatibility at a given time by selection of datum planes. Further, the quantitative definition of compatibility is uncertain. Having the levels of both lakes within the same 0.2 foot range with respect to Low Water Datum would be satisfactory to almost every mariner, within the same 0.5 foot range would probably be satisfactory to many, and within the same 1.0 foot range would perhaps be satisfactory to relatively few.

Although compatibility cannot be assured at a given time, statistical compatibility can be improved by selecting datum planes so as to provide the maximum probability that during a given time the planes will be compatible. Lake level exceedance frequencies (of Low Water Datum) in a high range, say 80 per cent to 100 per cent, do not provide as good a criterion of compatibility as do average levels (referred to Low Water Datum). But the two statistics tend to vary in the same way, and both are changed, of course, by a change of the datum planes. Figure 3 shows the relative positions with respect to lake levels of the present Low Water Datums and of Low Water Datums equal to minimum monthly average levels, also based on the recorded adjusted monthly average levels, April-November, 1900-1967.

Selection of Planes for Harbor and River Deepening

Despite the considerable complexity involved in the use of datum planes as references for dredging projects, the selection of planes for this purpose involves only one simple criterion. The criterion is that the selected planes should result in project depths (defined as the dredged depths below Low Water Datum and equal to the safe draft plus allowances) that are slightly greater than the draft of the deepest draft vessel that will use the improved channels. Differences between project depths and safe vessel drafts represent allowances for clearance, squat, exposure, and nature of the channel bottom. Datum planes which do not satisfy this criterion would be unacceptably confusing and possibly not acceptable as charting planes. A detailed discussion of project depths is beyond the scope of this paper.

Priority of Criteria

In the above discussion, separate criteria are indicated for charting planes and for dredging planes except that the unsuitability for charting of certain dredging planes must be noted. However, there is no basis for questioning the wisdom of having the same planes for both charting and dredging, and the selected planes must therefore satisfy criteria for both. The positions of the charting planes have a tangible, though poorly definable, effect on the usefulness and safety of lake charts. The positions of the dredging planes have no equivalent tangible effect. Therefore charting considerations should have priority in the selection of planes.

Although a priority of criteria can be assigned, planes selected on the basis of charting alone are very likely to be suitable for dredging and conversely. This Elysian situation results because the percentages of time the actual depths are intended to exceed charted depths and actual existing drafts are intended to exceed design drafts are similar.

SUITABILITY OF PRESENT LAKE PLANES

Present datum planes (1933 planes) were the first datum planes of the Great Lakes selected to satisfy the requirements of both charting and dredging. In the selection of these planes there is no record of specific lake level statistics being used. But the 1933 criteria were in effect based on the past levels of Lakes Ontario, Erie, and Michigan-Huron and on the expected regulation of Lake Superior, and produced planes that are today consistent with the criteria given herein.

Because the criteria for the selection of planes are not precise, a considerable range of datums, individually and collectively is acceptable. With the possible exception of Lake Superior as described below, the present Low Water Datums satisfy the criteria and are suitable [6]. This is true whether the basis for evaluation is the 1933-1968 water level regime of record, the 1900-1967 recorded adjusted water level regime described herein, or the present water level regime.

With respect to the selection of planes for charting and based on recorded adjusted levels, April-November 1900-1967, both the frequencies with which the levels exceed the datums and the average levels referred to the datums show the Low Water Datum of Lake Superior to be discordant with the datums of the other three lakes. If the conditions on which the recorded adjusted levels used for Figure 3 are based occur and are expected to continue for some time, the Low Water Datum of Lake Superior should be lowered as much as one foot (and the project depths reduced accordingly). But a change of datum now would be premature because a study of regulating all the Great Lakes being made at the direction of the International Joint Commission may result in further regulation of the lakes and consequent change of water level regimes and because continuance of the present datum cannot be expected to have any very serious effects.

The study of regulating the Great Lakes noted above could result in a need for changed datums on any of the lakes.

(6) In contrast, the depth of dredging required to provide a specified benefit to navigation has little flexibility. Because water level regime changes can occur and because dredging will become much more expensive if spoil is to be disposed onshore instead of offshore (Corps of Engineers, 1969), periodic reanalysis, say every 10 years, of project depths may be warranted.

CONCLUSIONS

The primary requirements for datum planes of the Great Lakes — as reference planes for charted depths and dredging projects — have been satisfied by conceptual and practical developments occurring over a period of many years. Present planes, adopted in 1933, are a culmination of these developments. The planes of 1933 satisfy stated criteria for the selection of datum planes and are therefore satisfactory. The Low Water Datum of Lake Superior, which is comparatively higher than the datums of Lakes Michigan-Huron, Erie and Ontario, may need to be lowered in the future.

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