SEICHES AND SET-UP ON LAKE WINNIPEG

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ABSTRACT

Recorder charts of water level for the ice-free season are examined for six stations on Lake Winnipeg for the years 1961–1964. Transverse and longitudinal seiches are identified for the north and south basins. An interference pattern is noted for seiches over two different fetches at Victoria Beach. Typical weather situations producing transverse and longitudinal seiches are identified. Moderate to large set-up is examined for 37 cases and geostrophic winds scaled off from weather charts covering an 18-hr period preceding the peak set-up. Using corrections for curvature, motion of the pressure system, deviation from the main axis of the lake, and air stability, an assumed over-water component is computed for each case. The correlation between set-up and over-water wind square is found to be 0.81. Standard deviation of actual set-up from that predicted by the regression equation is 0.076 m.

INTRODUCTION

In October 1962, a combination of inexperience and misadventure forced three duck hunters to spend the night on a small island in the Netley Marshes at the south end of Lake Winnipeg. During the night the water level rose, their boat was set adrift, and they spent most of the following day standing in water 1 m deep. One of them died as a result of the exposure.

Such sudden risings of the water—and correspondingly sudden falls—have long been a source of discussion. Over two centuries ago, when the explorer Pierre Radisson arrived at Hudson Bay, he was told by the Indians of a large body of water whose surface rose and fell. Radisson reasoned that such fluctuations must be a tide and that the body of water must be the Western Ocean. In all likelihood, however, it was Lake Winnipeg.

The risings and fallings are, of course, not tides, but the results of the wind sweeping across the lake's surface.

The authors are indebted to the District Engineer and staff of the Water Resources Branch, Department of Northern Affairs and National Resources, for providing the water level information contained in this study; to G. A. MacKay, Prairie Hydrometeorologist, Regina, Saskatchewan, for suggestions regarding maximum value estimates; and to students M. Hirt, W. Graham, W. Nichiporick, R. Brown, and M. Perry for work in abstracting data and preliminary calculations.

SEICHES ON LAKE WINNIPEG

When the surface of an enclosed body of water such as a lake is disturbed, standing waves are sometimes set up causing the water to rise and fall rhythmically at the shorelines. Such waves are called seiches. An examination of the water-level charts for Lake Winnipeg indicates that seiches occur frequently. In this lake, it was necessary to consider the southern basin of the lake separately from the northern basin. The southern basin extends from the mouth of the Red River to Black Island. The northern basin, much larger, extends from Matheson Island to the north end of the lake. The narrows of the lake, as well as the blocking effect of Hecla and Black Islands, effectively isolate the seiches of one basin from those of the other. Fig. 1 shows the main features of the lake.

Seiches of the southern basin

Water-level records for Winnipeg Beach and Victoria Beach indicate two distinct types of seiches, one having a period of about 1.7 hr and the other about 5.0 hr. The 1.7-hr seiche (Fig. 2) at times exhibits an amplitude as great as 0.45 m in its initial

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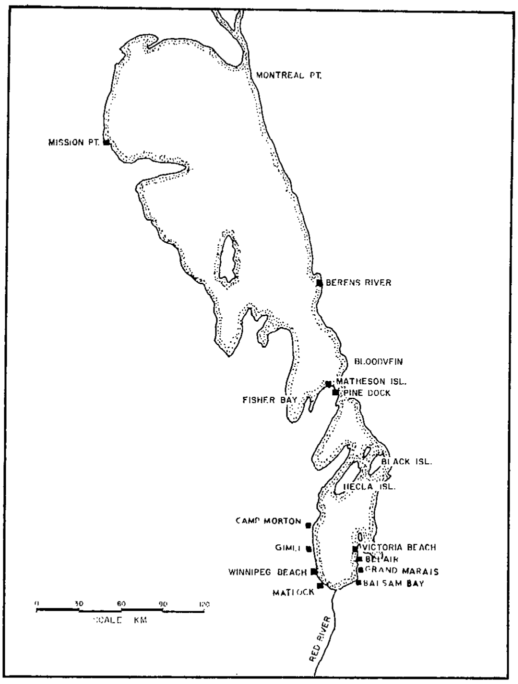

FIG. 1. Index map of Lake Winnipeg.

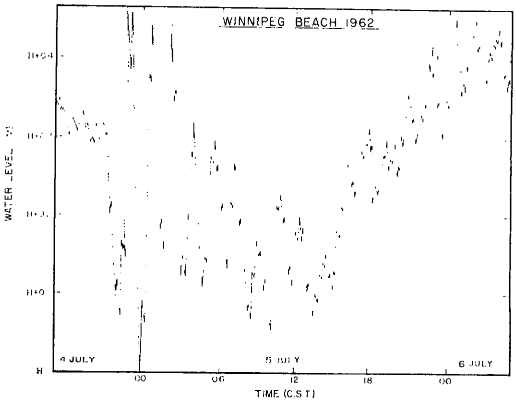

FIG. 2. Stage hydrograph, Winnipeg Beach, 4–6 July 1962.

stages. (Amplitude, as used here, refers to the difference between low and high level.) Damping out is gradual, with 10–12 oscillations sometimes being present before the wave motion disappears. The 5.0-hr seiche generally has a smaller amplitude, although Fig. 3 shows one of 0.4 m.

Shorter period seiches are sometimes observed; these are of small amplitude, superimposed on the main periods, and damp out rather quickly. Of 53 cases of short-period seiches in the southern basin, the mean period was found to be 1.68 hr with a range of 1.50–1.78 hr; of 54 cases of long-period seiches, the mean period was 5.13 hr with a range of 4.0–6.5 hr.

Seiches of the northern basin

Several different seiches are in evidence on the water-level charts of the northern basin. At Mission Point there is a strong tendency for a 4.5-hr seiche (Fig. 4). At Pine Dock an oscillation with a 3.5-hr period is noted. The Matheson Island charts show many oscillations, some of them with high amplitude and short period; one having a period of about 4 hr, however, recurs rather frequently. A long-period seiche of about 13 hr is in evidence from time to time at all recording stations in the northern basin. The amplitude of this seiche is greatest at Matheson Island.

The seiches in the northern basin tend to persist for longer periods than do those in the southern basin. The seiche shown in Fig. 4, for example, remained in evidence for some 60 hr.

Theoretical calculation of seiche period

The first approximation for calculating seiche periods in a not too irregular basin is provided by the well-known Merian Formula (1828), $T = 2L\ (gH)^{-\frac{1}{2}}$, which, in metric units, can be expressed as:

$$T = 0.1774\ LH^{-\frac{1}{2}}$$

where L is the basin length in km, H the average depth (m), and T is the seiche period in hr. For Lake Winnipeg, H can be estimated only roughly and is subject to considerable seasonal and other variations. For instance, during March to December 1936, the difference between the highest and lowest daily means varied from 0.33 m in May to 0.8 m in October. The Lake Winnipeg and Manitoba Board (1958) gives the highest and lowest monthly means of water level (above mean sea level) as 218.32 m in September 1927 and 216.04 m

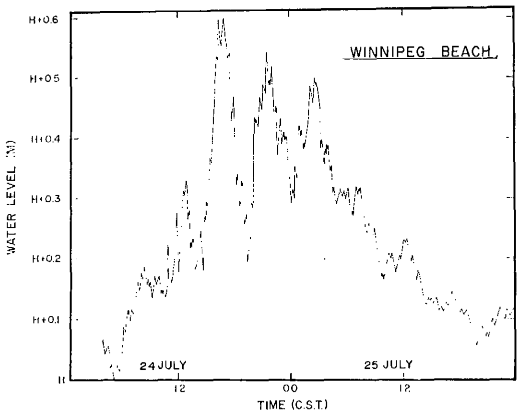

FIG. 3. Stage hydrograph, Winnipeg Beach, 24–25 July 1962.

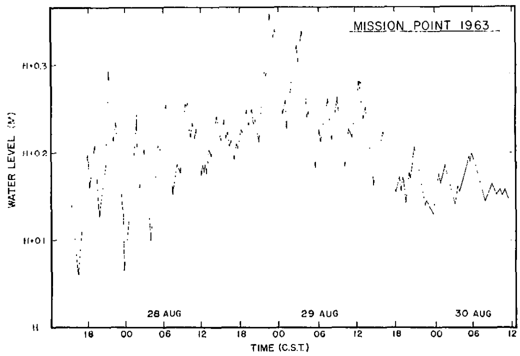

FIG. 4. Stage hydrograph, Mission Point, 27–30 August 1963.

in December 1940—a difference of 2.28 m. Since such fluctuations in depth occur, one would not expect to find the same seiche periods at all times.

The southern basin is approximately rectangular. A seiche oscillating transversely across the lake would be acting over a distance of 24–32 km depending on where the cross section was made. A longitudinal seiche, operating from north to south, would have a length of about 90 km.

Table 1 shows the seiche periods calculated for a number of traverses from west to east across the southern basin and for depths 0.6 m above and 0.6 m below normal. The greater depth in the northern part of the basin is counterbalanced by the slightly longer fetch, resulting in remarkably close agreement in the calculated period at the first four of these traverses. The last, where shallow water is encountered approaching the Red River delta, shows a significantly longer period. When the observed periods are compared with those calculated in Table 1, it becomes obvious that the short-period seiches observed at Winnipeg and Victoria beaches are transverse uninodal seiches. The observed values practically all fall within the values calculated for $H \pm 0.6$ m.

Two seiches may sometimes operate simultaneously, causing interference and reinforcement. Fig. 5 illustrates such a case with reinforcement occurring at intervals of 8.9 hr. An attempt was made in this case to determine theoretically the periods of the individual seiches. There were two traverses of the lake that appeared most likely to be seiche producers. One extended due east from Gimli and was 27.3 km long; the other extended from the bay north of Gimli to the Victoria Beach bay, a distance of 32.2 km. The average lake level on that day was used in determining depths. The seiche periods for the two selected traverses were 1.48 and 1.77 hr. Six of these short waves and five of the longer ones would reinforce every 8.9 hr. Hence, it is likely that these were the seiches operating at the time in question. Mortimer (1965) refers to a similar beat phenomenon at Ludington, Michigan.

In calculating seiches operating longitudinally on the southern basin, the fetch used was from the mouth of the Red River to Black Island and Clement's Point, a distance of 90 km. Using an average depth of 9.15 m over this axis gives a period of 5.28 hr. If the depth is increased, the period is shortened so that for 10.67 m the period is 4.90 hr. When these calculated values are compared with the observed range of long-period seiches at Winnipeg and Victoria beaches, it is seen that they can be classified as longitudinal uninodal seiches.

The bays and islands of the northern basin make a number of different seiches possible. Three of the more prominent are:

1. Mission Point to the east shore south of Montreal Point. The fetch here is 103

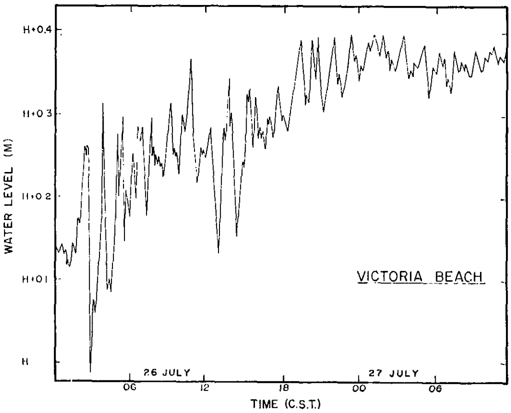

FIG. 5. Stage hydrograph, Victoria Beach, 26–27 July 1963.

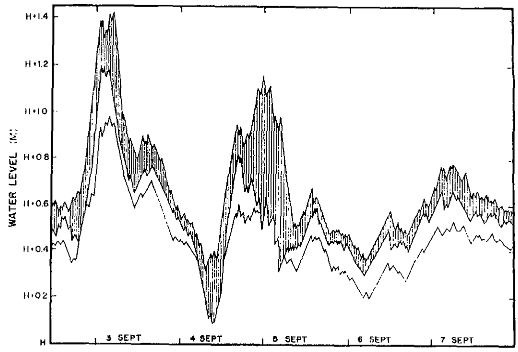

FIG. 6. Stage hydrographs, Matheson Island (upper trace) and Pine Dock (lower trace) 2–7 September 1961.

km and the average depth is 15.25 m. The calculated seiche period is 4.7 hr, which agrees closely with the 4.5-hr seiche observed frequently on Mission Point charts (Fig. 4).

2. Head of Fisher Bay to the mouth of Bloodvein River. The fetch here is 59.5 km, the average depth 6.7 m, and the calculated period 4.1 hr. This traverse apparently explains the 4-hr period shown on the Matheson Island chart.

3. North end of lake to the Narrows. The fetch here is 276.8 km. An average depth of 14.63 m yields a period of 12.9 hr. The 13-hr seiche frequently seen on the Matheson Island trace can best be explained as a uninodal seiche operating along the length of the northern basin.

This longitudinal seiche of approximately 13 hr can also be seen at Mission Point and the Berens River. The amplitudes here are considerably less than at Matheson Island, which is to be expected as these stations are closer to the nodal line of a uninodal seiche. The width of the lake at Mission Point may also have a suppressing effect on a longitudinal seiche while the irregular shoreline and numerous islands near the Berens River probably have a damping effect.

A period of approximately 13 hr is also in evidence, rather surprisingly, at Pine Dock and can perhaps best be explained as a forced oscillation passing through the Narrows from the northern basin. Support for this explanation appears from a comparison of the traces at Matheson Island and Pine Dock, which shows coupling between the two although amplitudes at the latter are smaller (Fig. 6).

Causes of Lake Winnipeg seiches

Most early investigators of seiches (e.g., Chrystal and Wedderburn 1905) suggested that they were caused by changes in atmospheric pressure acting on the water surface. However, Darbyshire and Darbyshire

TABLE 1. *Calculated transverse seiche periods for the southern basin*

Traverse	L length (km)	H avg depth (m)	Period for depth H	Period for depth $H - 0.6$ m	Period for depth $H + 0.6$ m
Drunken Point to Elk Island	29.0	10.35	1.60	1.65	1.55
Camp Morton to Victoria Beach	29.8	10.35	1.64	1.69	1.60
Gimli to Belair	27.7	9.75	1.57	1.62	1.53
Winnipeg Beach to Grand Marais	24.9	7.62	1.61	1.67	1.54
Matlock to Balsam Bay	24.9	6.10	1.79	1.89	1.71

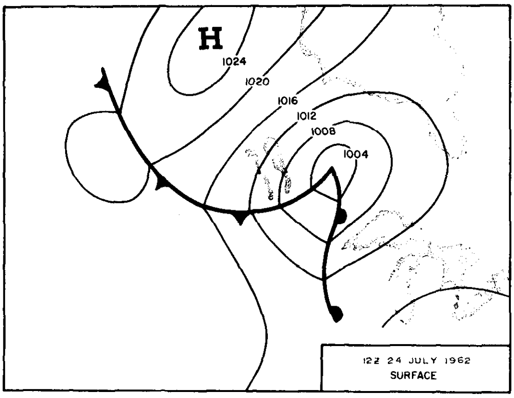

FIG. 7. Surface chart 1200 GMT, 24 July 1962.

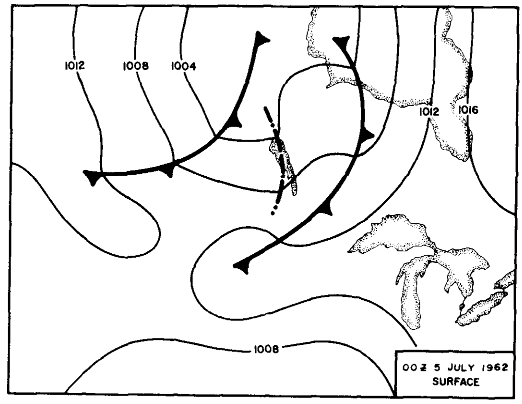

FIG. 8. Surface chart 0000 GMT, 5 July 1962.

(1957) investigated seiches on a small lake; they considered changes in wind stress to be the cause and attempted to relate the sharpness of the windshift to the amplitude of the seiche. In an investigation of a major storm surge on Lake Michigan, Platzman (1958) found that computations using pressure difference alone accounted for about half the observed amplitude and suggested that wind stress would account for the remainder. Klinker and Karbaum (1961) claimed that the amplitude of a seiche is approximately proportional to the square of the windspeed maximum. Of course, it is difficult to separate the influence of wind from the influence of pressure differential, since one seldom occurs without the other.

Longitudinal seiches on the southern basin of Lake Winnipeg occurred following the passage of a deep low eastward across the lake. The pressure gradient was stronger to the rear of the low than in its van. The tight gradient behind the low swept a cold front southward over the lake, and the seiche commenced after the passage of this front. Fig. 7 shows the synoptic weather situation responsible for the seiche shown in Fig. 3.

The transverse seiches of the southern basin were not associated with well-developed lows; indeed, quite flat pressure was normally indicated by synoptic charts. The seiches were produced by north–south oriented instability lines moving eastward across the lake. Thunderstorms accompanying these instability lines produced strong surface winds; they also produced sudden pressure changes so that again it is difficult to say whether wind change or pressure caused the seiche. Fig. 8 shows the synoptic weather situation responsible for the seiche illustrated in Fig. 2.

A cold front, or trough, oriented at an angle to the longitudinal and transverse axes frequently showed evidence of both periods although with reduced amplitudes.

The transverse seiches of the northern basin were also found to be associated with north–south oriented troughs moving eastward across the lake, usually accompanied by thunderstorms.

The longitudinal seiches of the northern basin were not so readily correlated with the weather pattern, although in most instances they appear to follow the passage of an east–west oriented cold front.

In examining the transverse seiches of the southern basin, we found that at Winnipeg Beach (west side of lake) the seiche typically began with a fall in water level; at Victoria Beach (east side of lake) there was an initial rise. This was true in 90% of the cases studied; since the seiches are caused by squall lines moving eastward across the lake, such results are to be expected. The strong downdraft winds from the squall line thunderstorms have a marked west to east component tending to lower

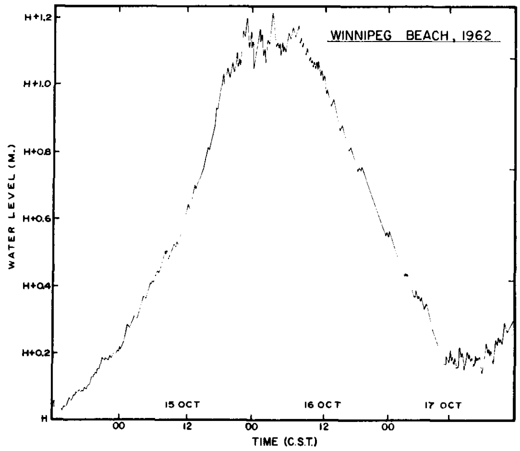

FIG. 9. Stage hydrograph, Winnipeg Beach, 15–17 October 1962.

the water level on the west side and raise it on the east side. The sudden rise of pressure accompanying the downdraft also tends to depress the water first on the west side.

A somewhat different case occurred on 28 October 1962, when a marked pressure pulsation moved from northwest to southeast across the southern basin. Pressures at both Gimli and Winnipeg fell 9 mb and then returned to their former values within an hour. Surface winds increased briefly to south-southeast 11 m/sec. If pressure fluctuations are mainly responsible for seiches, this might be expected to induce a significant one. However, while a transverse seiche in the southern basin was produced by this pressure pulsation, its amplitude was quite small (13 cm compared with 46 cm often noted with thunderstorm-induced seiches). Although an isolated case, this might be taken as an indication that pressure changes have less influence than wind changes in inducing seiches.

Of the southern basin seiches, those with greatest amplitude occurred when the instability line or cold front causing them moved across the lake at speeds of 9–11 m/sec. The speed of a free wave on the southern basin is about 10 m/sec. This suggests that the higher amplitude seiches may be the result of resonant coupling. Platzman (1958) stated that such coupling does occur; in the case of a 2-m surge on Lake Michigan in 1954, the 28.8-m/sec speed of the disturbance causing it agreed closely with the speed of a free wave on the lake.

Energy supplied to water by the air varies as the square of the windspeed; therefore a strong wind is considerably more effective in producing a surge than a lighter wind. In shallow Lake Winnipeg, the speed of a free wave varies from about 11.3 m/sec on the southern basin to 13.9 m/sec on the northern basin. Hence, a fast-moving disturbance on Lake Winnipeg would leave behind the free wave, making unusually high surges such as the one observed on Lake Michigan (Ewing, Press, and Donn 1954; Harris 1957) unlikely on Lake Winnipeg.

WIND SET-UP ON LAKE WINNIPEG

Set-up, as used here, is the departure from mean level of the water surface at any point on the lake. This study is confined to the positive departures from mean level at the south end of the lake, which are found by subtracting from the peak level shown on the Winnipeg Beach hydrograph the level extracted from a smooth curve drawn through the plot of monthly means at Berens River (chosen because it was the station closest to the center of the lake). We did not have observations from the north end of the lake, so we could not define set-up as the difference in level between readings at the two ends of the lake. Fig. 9 is an example of set-up at Winnipeg Beach, and Fig. 10 illustrates the weather situation prevailing at the time.

Previous investigations

Perhaps the most common approach to the study of set-up is statistical. A large number of cases of set-up are recorded, and appropriate assumptions are made as to probable maximum set-up and probable frequency of set-up of a certain magnitude. This has already been done for Lakes Winnipeg and Manitoba and the information is included in the Report of the Lake Winnipeg and Manitoba Board (1958).

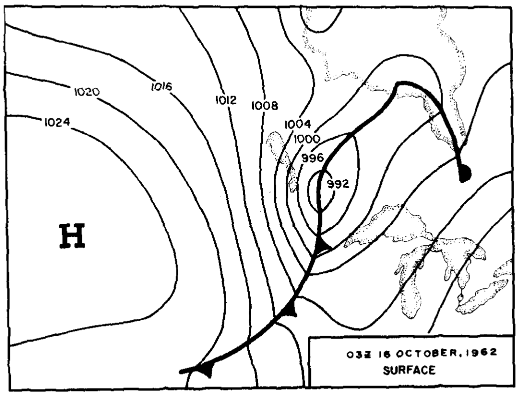

FIG. 10. Surface chart 0300 GMT, 16 October 1962.

At the other end of the scale is the dynamic approach, as exemplified in particular by the Lake Erie Study of Platzman (1963). The basic Ekman equations of mass transport are manipulated for programming on a computer (IBM 704), taking into account the bottom and shoreline configurations of the lake. Two conjugate Richardson lattices are used; input consists of hourly wind vectors from each of six first order stations on the perimeter of the lake. Computations cover a 7.5-nm grid with iteration period of 6 min, and the output is the level attained at all points on the lake. This is perhaps the ideal approach, provided one has access to a suitable computer, and provided the input data are known with sufficient accuracy. It makes use of actual winds, and hence is not a method of prediction. Platzman stated (1963, p. 5), "Satisfactory prediction of winds at an individual station for a period of, say 36 hours, probably can be made only as a by-product of prediction of the weather map itself. Moreover, only geostrophic (or gradient) winds are predicted at present with adequate reliability. For this reason, geostrophically computed drag may be the only practical recourse for operational wind tide prediction."

To approach the problem from the operational standpoint, one must consider each case in relation to its wind field. Relationships between wind and set-up have been studied for many large lakes. Studies of Lake Erie are of particular interest since it is comparable in size and depth to Lake Winnipeg (Keulegan 1953; Harris 1953; Hunt 1959; Gillies 1959; Irish and Platzman 1962; Richards 1965).

Relationship between set-up and wind

The relationship between wind and the slope or tilt of lake surfaces has been investigated (Haurwitz 1951; Munk 1955; Francis 1954). The usual assumption is that the wind stress, and therefore the set-up, is proportional to the square of the over-water wind. This is logical if we assume that the percentage transfer of energy from the wind to the water remains constant through the range of windspeeds. Then, ignoring variations in density, we may equate the kinetic energy lost by the air (whose variable is the square of the windspeed) to the potential energy gained by the water (whose variable is the height deviation or set-up). The square law is applicable over a land surface where the roughness parameter is independent of windspeed. However, over a water surface, various investigations suggest that a higher power than the square is involved. Francis (1954) suggested that the cube of the windspeed should be used. Darbyshire and Darbyshire (1955) calculated the relationship for Lough Neagh on the basis of both the square and the cube, obtaining correlations of 0.84 and 0.85. Munk (1955) agreed that a higher power than two is applicable, and his hypothesis favors a cubic law, but observations show an exponent somewhat lower than 3. Newbury (1964) in relating a number of formulas to observational results, favored one developed by Sibul (1954): $T_s = 5.65 \times 10^{-6} U^{2.15}$. Platzman (1963) stated that the index should be between 1.5 and 2.5.

Keulegan's curve drops off to the right at higher values, indicating that a power less than 2 would be required to obtain a linear relationship (Fig. 11). For the steady state, where the net velocity of water along

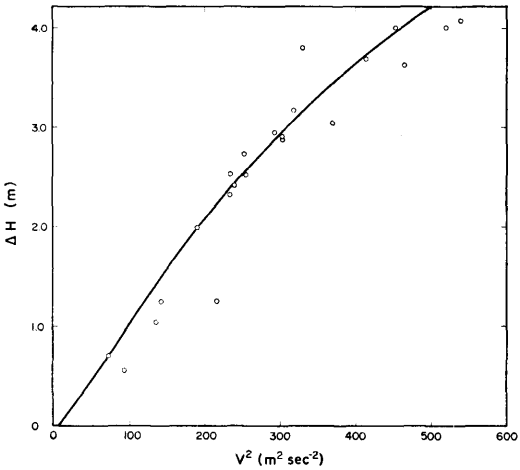

FIG. 11. Relationship between effective wind square and set-up (from Keulegan 1953).

the main axis is zero, the slope at a point on the water surface is given by

$$\frac{\partial h}{\partial x} = \frac{\tau_s\,(+\,\tau_b)}{g\rho_w H}, \qquad (3)$$

where τ_s is the surface tangential stress, τ_b is bottom stress, and ρ_w is water density.

If variations in water density are ignored, depth is considered constant, bottom stress is considered only a small fraction of surface wind stress, and the surface wind stress τ_s is considered proportional to the square of the over-water wind component, we obtain the Zuidersee Formula:

$$\Delta H = V_w^2 L / CH, \qquad (4)$$

where ΔH is total set-up, V_w is the over-water wind component in the direction of the main axis, L is the fetch, and H is depth. C is a constant, whose value lies between 360 and 445 when V_w is in m/sec, H in m, and L in km.

Effect of constrictions on Lake Winnipeg

A point of difference between Lake Winnipeg, and, for example, Lake Erie, is the constrictions on the former (*see* Fig. 1). The 2-km-wide channel at the narrows and the even narrower constriction at Hecla and Black islands inhibit the free flow of water from one end of the lake to the other and impose a time lag on the production of a full set-up (Fig. 12). In an open lake, the time required to produce a full set-up from a state of equilibrium would probably be equal to the time required for a free wave to travel the length of the lake. In the case of a lake the length and depth of Lake Winnipeg, this would be about 10 hr. The effect of the constrictions is that set-ups are produced initially in each of the three basins, with strong currents across the constrictions. Considerable additional time is required to transfer from the northern to the southern basin a volume of water sufficient to achieve a set-up over the whole lake. On the other hand, the persistence of a strong wind situation is not unlimited, and some compromise must be found. It was decided to use the computed over-water wind for the 18-hr period preceding the time of maximum set-up, although more than that is required to reach equilibrium in cases of extreme set-up, or when a substantial negative set-up precedes the onset of the northerly winds.

The over-water wind

Keulegan (1953) and Hunt (1959) have tried to obtain an effective over-water wind for use in developing the wind vs. set-up relationships. Hunt analyzed data from anemometer readings on commercial lake vessels in Lake Erie to determine relationships between wind over water and wind over land; he included the effect of stability determined by comparison of air and water temperatures. For Lake Winnipeg, there are no observations available for over-water winds and there is only one land station (Gimli) within the prescribed 32-km limit and, therefore, no possibility of independent determination of the wind-over-water/wind-over-land relationship. Any attempt to apply the Lake Erie findings of Hunt to this area is hampered by lack of sufficient suitable land wind observations; an attempt to relate the Gimli and Winnipeg winds to the set-up at Winnipeg Beach was not encouraging. The only realistic

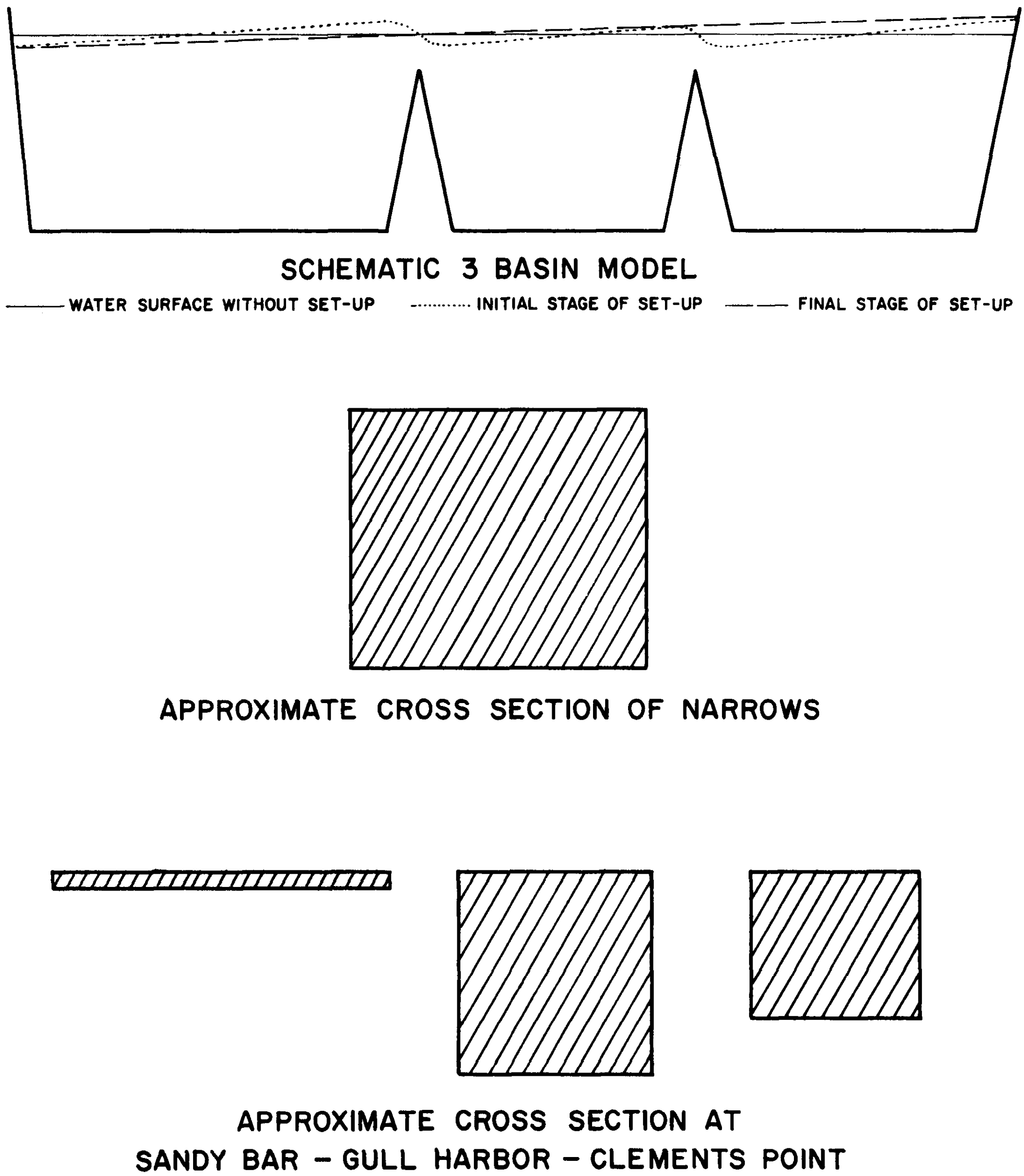

FIG. 12. Schematic representation of constrictions on Lake Winnipeg.

approach to an operational method was to obtain an effective over-water wind from gradient wind computations. Although this method has limitations, it seems unlikely that actual wind observations will be available soon. In any case, an attempt to forecast the set-up would be based on wind data derived from gradient computations on prognostic charts.

Reduction from geostrophic to effective over-water wind

The effect of air stability was considered in a manner similar to that used by Hunt

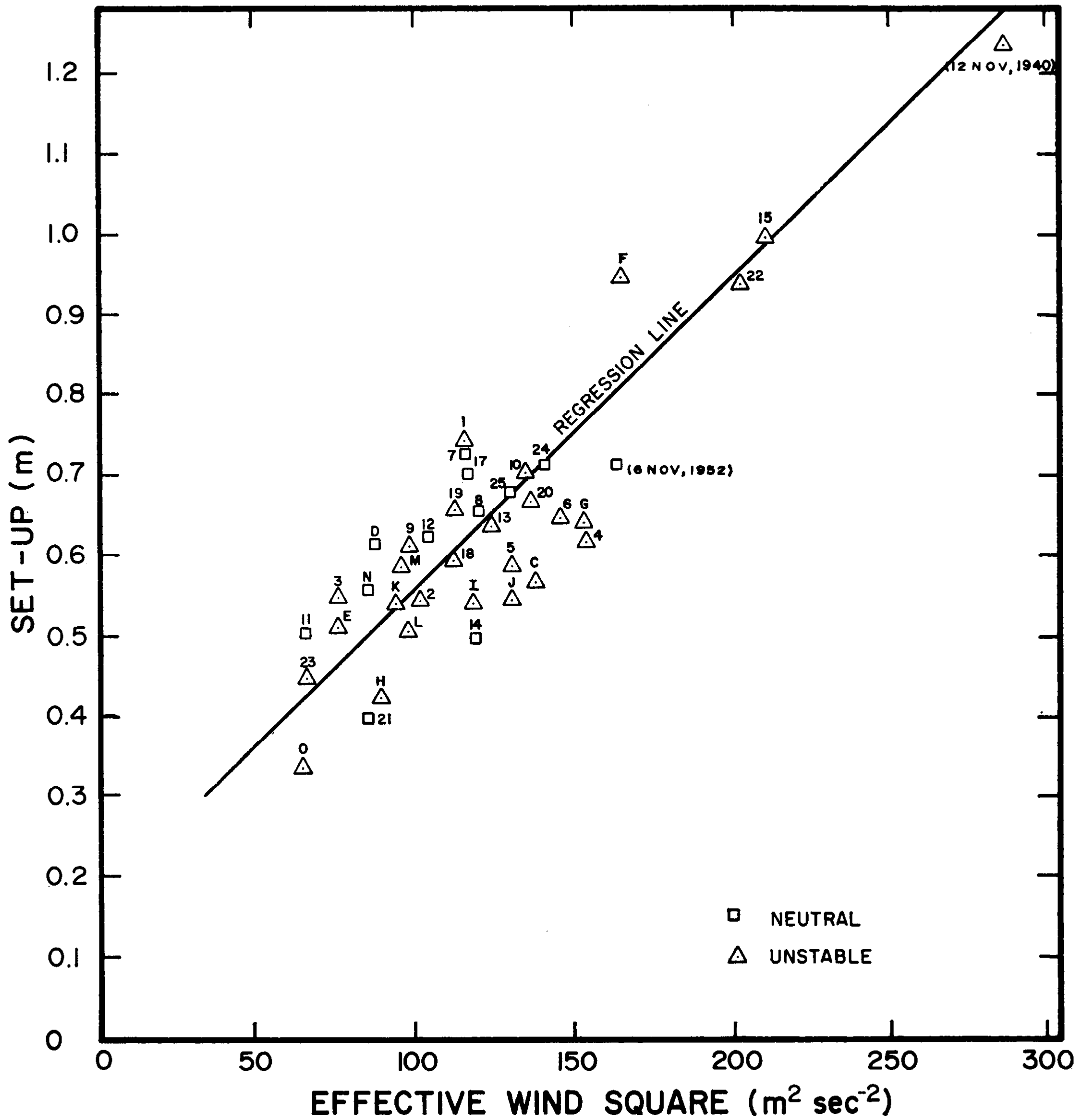

FIG. 13. Relationship between effective wind square and set-up at Winnipeg Beach.

(1959). He divided the cases into three categories:

Stable– $T_A - T_W \geqslant 4.5C$,

Neutral– $T_A - T_W$ between –4.0C and +4.0C,

Unstable– $T_W - T_A \geqslant 4.5C$,

where T_A is air temperature (C) and T_W is water temperature (C).

Again, the difficulty was in the lack of adequate land stations near the lake, and the fact that the Gimli air temperature was too often affected by the over-water circulation. All cases studied were in a northerly flow so the 950 mb temperature at The Pas on the observation nearest to 18 hr before the peak set-up was used for air temperature. For consistency with the Lake Erie study, the borderline between neutral and unstable was taken to be 5.8C. Thus, if $T_W - T_{950} \geqslant 6.1C$ the case was considered unstable, if $\leqslant 5.5C$ the case was considered to be neutral, and 5.5 to 6.1C were considered borderline cases. No stable cases were encountered because all these situations were in a cold-sector circulation.

Reduction of the geostrophic wind to an appropriate over-water wind component was carried out as follows. First, gradient wind was calculated by applying corrections for curvature and for motion of the pressure centers to the scaled-off geostrophic wind by means of the Godson gradient wind nomogram (1948). The assumption was then made that an average cross-isobar angle (α_0) of 15° was reasonable for these cases. The cases are divided into neutral and unstable, so 13° was used for the unstable cases and 17° for the neutral ones. These cross-isobar angles do not, of course, include the effect of motion of the systems. The factor for reducing the speed of the gradient wind to the appropriate over-water value was calculated from these cross-isobar angles in accordance with the formula

$$V_0 = Vg\ (\cos \alpha_0 - \sin \alpha_0)\ , \qquad (5)$$

which for 13° yields 0.75 and for 17° yields 0.66. These values are consistent with those suggested by Haltiner and Martin (1957).

A component correction was applied to gradients giving winds at an angle to the long axis of the lake. On the average, a further 15° deflection was found necessary to account for the effect on motion of the pressure centers; assuming the optimum direction for wind over the water to be 345°, a gradient of 015° would give optimum values. This was found satisfactory for systems having an eastward component of 7.5 to 10 m/sec. If the eastward component differed significantly from these values, a further correction was applied. In practice, a component factor of 1.00 was used for over-water wind from 325° to 005°. For further deviations, a component correction of the cosine of the deviation angle was applied.

Case studies

Twenty-four cases of moderate to large set-up at Winnipeg Beach were selected from the water-level recorder charts for 1961, 1962, and 1963. Geostrophic winds were abstracted and over-water winds computed for six charts at 3-hr intervals (SM and SI) covering the 18 hr preceding the peak set-up. A scatter diagram of the square of the windspeed in m/sec and the set-up in m was prepared and a preliminary curve of best fit drawn. Fifteen cases from June to October 1964 were selected on the basis of wind situation, and the wind square computed as before. The set-up was then predicted using the preliminary best fit curve, and the results were compared with the actual set-up when this became available. Two of the 15 cases could not be verified. The remaining 13 showed a standard deviation of 0.092 m compared with 0.085 m for the 24 initial cases.

When all 37 cases were used, a correlation coefficient of 0.81 was calculated. The regression equation,

$$\Delta H = 0.1707 + 0.00349\ V_w^2,$$

gave slightly better results, the standard deviation of observed values from those predicted by the equation being 0.076 m (Fig. 13).

One difficulty is an inadequate number of cases of extreme set-up in the four years considered. Only four of the 37 cases had a set-up in excess of 0.762 m. The records of the Stevens water-level recorders date back only to 1961 and these are the only records that were considered sufficiently reliable. Records of the Foxboro pressure gauge, however, are available for Winnipeg Beach back to 1913. The response of this instrument is sluggish, but should indicate water level to within about 5 cm.

To check for consistency, two cases of moderate and one of extreme set-up were selected from this period. Wind-square calculations were made, with results as follows:

11–12 November 1940

Effective wind square	298 m^2 sec^{-2}
Set-up predicted by regression equation	1.21 m
Observed set-up	1.17 m

5–6 November 1952

Effective wind square	169 m^2 sec^{-2}

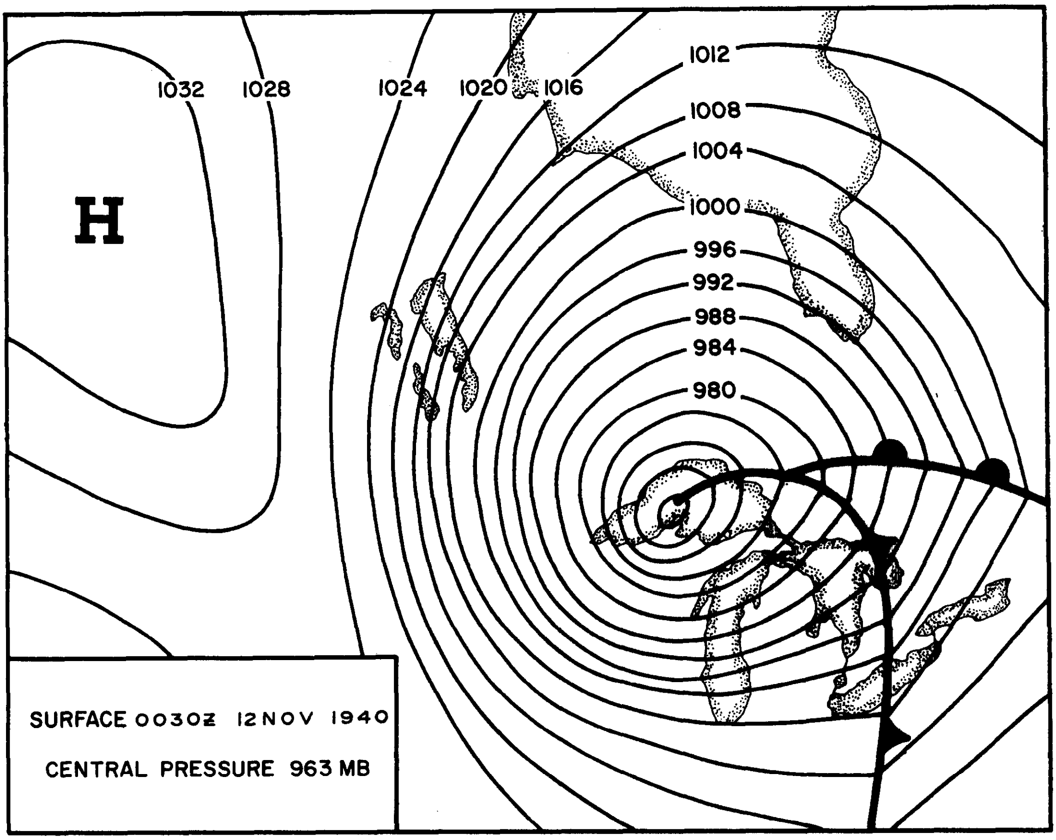

FIG. 14. Surface chart 0030 GMT, 12 November 1940.

Set-up predicted by regression equation	0.765 m
Observed set-up	0.674 m

11 October 1949

Effective wind square	146 m^2 sec^{-2} (neutral case)
Calculated set-up	0.686 m
Actual set-up	0.674 m

On the basis of these three cases, it appears that the results based on the Foxboro gauge are comparable to those based on the Stevens gauge.

Fig. 14 shows the weather situation responsible for the set-up of 1.17 m observed on 12 November 1940.

Effect of seiches on the peak set-up

The set-up was taken as the departure from mean level of the highest point reached on the hydrograph, regardless of whether it was affected by coincidence with a seiche crest, so that cases where seiches of considerable amplitude were present would tend to have higher values in relation to the steady-state wind stress than cases without seiches. To assess the importance of this element, the 24 cases (1961–1963) were examined. The average increase in elevation of the peak seiche over a smoothed curve is 0.046 m. Twenty-one of the cases show a deviation of 0.03 m or less from this value. Three cases show larger deviations of 0.061, 0.091, and 0.152 m. There is no indication that the prediction would be improved by elimination of the effect of seiches.

Mattick (personal communication) pointed out that a considerable time lag (up to 6–7 hr) occurs between the crest at Winnipeg Beach and Victoria Beach (the latter being later) and that a level difference as much as 0.46 m can occur at the time of the Winnipeg Beach crest. Our examination of the charts for Winnipeg and Victoria beaches for 1961–1963 shows that a time lag occurs, though its magnitude was generally 1 to 3 hr (max 4 hr). A possible explanation lies in the fact that the one-dimensional steady-state equation (3):

$$\frac{\partial h}{\partial x} = \frac{\tau_s}{g\rho H}$$

is only valid for the relatively brief period of maximum longitudinal set-up when the axial velocity (u) of the water is zero. While the water is rising, there is an appreciable southward velocity ($-u$) giving rise to an acceleration westward due to the term $-2\omega \sin \psi u$ in the dynamic equations.

$$\frac{\partial v}{\partial t} = -g\frac{\partial h}{\partial y} - fu + \frac{\partial}{\partial z}\left(v\frac{\partial v}{\partial z}\right),$$

where $f = 2\omega \sin \psi$.

This force must be balanced by hydrostatic head, resulting in a pile-up of water along the west shore. Similarly, the receding water has a northward velocity resulting in a tilt of the water surface towards the east shore. Considering this balance of forces by itself, we have

$$\frac{\partial h}{\partial y} = \frac{2\omega \sin \psi\, u}{g}, \tag{6}$$

or approximately $\Delta H = (2\omega \sin \psi u Y)/g$, where Y is the width of the lake and ΔH is the transverse height difference. If the observed difference of 0.46 m were to represent the transverse tilt at Victoria Beach, a calculation of the southward velocity required to maintain this difference yields 1.36 m/sec. This is too high for the open lake, so probably dynamic effects are predominant here and the phenomenon should be explained in terms of a reflected Kelvin wave as described by Mortimer (1963).

To make some estimates of the probable return period of set-ups of a certain magnitude, it was necessary to use wind records covering a longer period of time than the computed winds used for this study. Although it was unsatisfactory to use Winnipeg winds for the study of set-up itself, it is likely that there is a fair degree of correspondence between cases causing maximum winds for the year at Winnipeg and those causing maximum winds for the year over the lake. Wind records for Winnipeg are available for 44 years, and a maximum value study of the Winnipeg record should be fairly reliable.

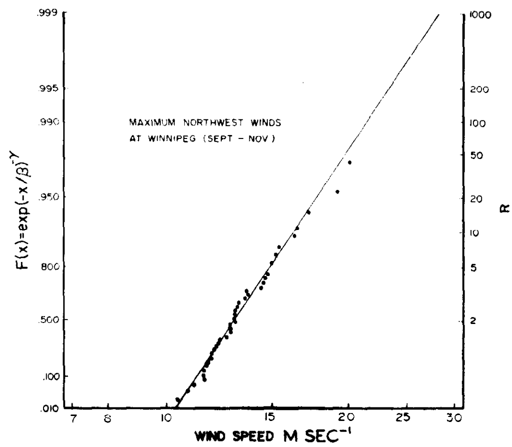

FIG. 15. Maximum northwest winds at Winnipeg, September–November, plotted on Fisher-Tippett probability paper, type 2 distribution.

For this purpose, only wind components from the northwest were needed. Moreover, all cases of large set-up occurred in the months of September, October, and November, so the statistical study was limited to these months.

For each of the 44 years, the case of maximum 18-hr wind travel from the northwest (north and west readings were given a component correction) was selected. The results were plotted on maximum value probability paper (Fisher-Tippett type 2 distribution). The plot (Fig. 15) is very close to the ideal straight line relationship.

According to this graph, a storm of the magnitude of that of 11–12 November 1940 would have a return period of about 60 years. The calculated gradient for that date over Lake Winnipeg results in a set-up (computed from the regression equation) of 1.22 m (observed 1.17 m).

A relationship between the observed winds at Winnipeg and the equivalent com-

TABLE 2. *Estimates of maximum set-up at Winnipeg Beach*

Return period (yr)	Avg* 18-hr wind at Winnipeg (m/sec)	Avg† 18-hr wind Lake Winnipeg (m/sec)	Wind square Lake Winnipeg (m^2/sec^2)	Set-up computed from regression eqn (m)
2	13.0	11.0	121	0.603
10	16.3	14.1	199	0.860
20	17.6	15.2	231	0.969
50	19.7	16.8	282	1.158
100	21.5	18.3	335	1.347
200	23.4	20.1	404	1.573
1,000	28.2	24.1	581	2.188

* For most of this period (1938–1964) the anemometer height at Winnipeg was 23.5 m. For the earlier period, windspeeds were adjusted to conform to this height.
† The computed over-water wind is a reduction of the geostrophic wind as measured by the pressure gradient and represents a wind at some unspecified height above the water surface. This height is obviously much lower than the 23.5-m height of the Winnipeg anemometer, hence the anomaly that the over-water windspeeds are lower than the measured land windspeeds.

puted winds over Lake Winnipeg for these maximum storms was calculated for five years and found to be 1.16. The probable set-up for various return periods was calculated (Table 2) using this relationship.

SUMMARY

Longitudinal seiches on Lake Winnipeg are generally associated with cold fronts passing southward over the lake, while transverse seiches most frequently occur with the passage eastward across the lake of a north–south oriented trough or squall line.

There is some evidence to indicate that seiches with the greatest amplitude occur when the disturbance causing them crosses the lake at free-wave speed.

Northerly winds cause a marked set-up on the south end of the lake. To find the correlation between wind and set-up the over-water winds were computed by determining the geostrophic wind and applying corrections for curvature, motion of systems, inclination to main axis, reduction from gradient level to surface, and air stability. A correlation coefficient of 0.81 was found between the square of the windspeed so obtained and the observed set-up.

The total set-up was found to be considerably less than that computed by the Zuidersee Formula using the generally accepted constant. This is attributed to the effect of constrictions inhibiting the flow of water from one basin of Lake Winnipeg to the other. For this reason, it was necessary to consider a longer period of persistent wind than in the case of an open lake. A period of 18 hr was most suitable.

REFERENCES

CHRYSTAL, G., AND E. M. WEDDERBURN. 1905. Investigations of seiches on Loch Earn by Scottish Lake Survey. Trans. Roy. Soc. Edinburgh, **41**: 823.

DARBYSHIRE, J., AND M. DARBYSHIRE. 1955. Determination of wind stress on the surface of Lough Neagh by the measurement of tilt. Quart. J. Roy. Meteorol. Soc., **81**: 333–339.

———, AND ———. 1957. Seiches in Lough Neagh. Quart. J. Roy. Meteorol. Soc., **83**: 93–102.

EWING, M., F. PRESS, AND W. L. DONN. 1954. An explanation of the Lake Michigan wave of 26 June 1954. Science, **120**: 684–686.

FRANCIS, R. D. 1954. Wind stress on a water surface. Quart. J. Roy. Meteorol. Soc., **80**: 438–443.

GILLIES, D. K. A. 1959. Winds and water levels on Lake Erie. Roy. Meteorol. Soc. Can. Branch Publ., **9**(1): 12–24.

GODSON, W. L. 1948. A new gradient wind nomogram. Bull. Am. Meteorol. Soc., **29**(3): 95–100.

HALTINER, G. J., AND F. L. MARTIN. 1957. Dynamical and physical meteorology. McGraw-Hill, New York. 470 p.

HARRIS, D. L. 1953. Wind tide and seiches in the Great Lakes, p. 25–51. *In* Proc. 4th Coastal Conf., Chicago.

———. 1957. The effect of a moving pressure disturbance on the water level of a lake. Meteorol. Monographs, **2**(10): 46–57.

HAURWITZ, B. 1951. The slope of lake surfaces under variable wind stress. U.S. Beach Erosion Board, Tech. Memorandum No. 25. 23 p.

HUNT, I. A., JR. 1959. Winds, wind set-ups and seiches on Lake Erie. U.S. Lake Survey, Corps of Engineers, Detroit. 36 p.

IRISH, S. M., AND G. W. PLATZMAN. 1962. An investigation of the meteorological conditions associated with extreme wind tides on Lake Erie. Monthly Weather Rev., **90**(2): 39–47.

KEULEGAN, G. H. 1953. Hydrodynamical effects of gales on Lake Erie. J. Res. Natl. Bur. Std., **50**: 99–109.

KLINKER, L., AND H. KARBAUM. 1961. The dependence of seiches in a shallow lake on wind. Z. Meteorol., **15**: 271–277.

LAKE WINNIPEG AND MANITOBA BOARD, PROVINCE OF MANITOBA. 1958. Report on measures for the control of the waters of Lakes Winnipeg and Manitoba, p. 1–58.

MERIAN, J. R. 1828. Über die Bewegung tropfbarer Flussigkeiten in Gefässen. Basel.

MORTIMER, C. H. 1963. Frontiers in physical limnology with particular reference to waves in rotating basins. Great Lakes Res. Div., Univ. Michigan. Publ. 10, p. 1–42.

———. 1965. Spectra of long surface waves and tides in Lake Michigan and Green Bay, Wisconsin. Great Lakes Res. Div., Univ. Mich. Publ. 13, p. 304–325.

MUNK, W. H. 1955. Wind stress on water, an hypothesis. Quart. J. Roy. Meteorol. Soc., **81**: 320–332.

NEWBURY, R. 1964. Wind set-up parameters. M.S. thesis, Univ. Manitoba, Winnipeg. 72 p.

PLATZMAN, G. W. 1958. A numerical computation of the surge of June 26, 1954 on Lake Michigan. Geophysica, **6**: 407–438.

———. 1963. The dynamic prediction of wind tides on Lake Erie. Meteorol. Monographs, **4**(26): 44 p.

RICHARDS, T. L. 1965. Meteorological factors affecting Great Lakes water levels. Canada, Dept. Transport, Tech. Circ. Ser. CIR 4182 TEC 553. 15 p.

SIBUL, O. 1954. Measurement of water surface roughness and wind shear stress. Univ. Calif. Inst. Engr. Res., **71**(4): 23 p.