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PREDICTING THE DATE OF LAKE ICE BREAKUP

BY

G. P. WILLIAMS

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PREDICTION DE LA DATE DE DEGEL DE LA GLACE SUR LES LACS

SOMMAIRE

Les déviations normales des dates de dégel sont calculées pour tous les lacs du Canada où des dossiers assez complets ont été tenus et pour quatre lacs du Wisconsin couverts par de longs dossiers. La précision avec laquelle il est possible de prédire le dégel a été évaluée pour douze de ces lacs en utilisant les dossiers de dégel et de température de l'air. Deux moyens de prédiction ont été employés: la méthode des degrés-jours de fonte et la méthode de l'équation de régression. Des équations générales sont établies afin de permettre des prédictions pour les lacs où les dossiers sont incomplets.

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Predicting the Date of Lake Ice Breakup

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Abstract. Standard deviations for lake breakup dates were calculated for all lakes in Canada with reasonably long breakup records and for five lakes in Wisconsin with long-term records. Standard deviations were about 13 days for coastal lakes and 7–11 days for continental lakes. The accuracy of the melting degree day method of predicting breakup dates were investigated for 12 of these lakes; standard deviations ranged from 3.3–8.0 days. Regression equations for predicting breakup dates were developed from past breakup and air temperature records for the 12 lakes; standard errors ranged from 1.6–4.3 days. General forecast guidelines were developed for application to lakes with limited breakup records. The equations and forecast guidelines are suitable only for continental lakes where wind and river inflow effects are not dominant.

INTRODUCTION

The date of lake ice breakup, defined as the day on which a lake is completely cleared of ice, marks the beginning of the navigation season for northern lakes used for transportation. For several weeks prior to breakup, ice covers on these lakes are in a weakened condition and cannot be used by either ski equipped or float planes. A prediction of the duration of the period when supplies cannot be flown in would be of value in the planning of construction, logging, and mineral and oil exploration activities. If the date of breakup could be predicted, it would be easier to schedule supplies and logging drives, and full advantage could be taken of a short open water season. To date, there is only limited published information available on the problem [Williams, 1965].

This paper presents the results of an investigation of the accuracy with which the actual date of breakup can be predicted by using past breakup and air temperature records and current weather information from meteorologic stations. Weather records for this analysis were obtained from the records of the Canadian meteorologic stations published monthly by the Canadian Meteorological Branch of the Department of Transport and from Allen [1964]. Information on the effect of wind on breakup was obtained through the courtesy of the Canadian Meteorological Branch, which distributed ques-

tionnaires to observers at numerous lakes across Canada.

VARIABILITY OF BREAKUP DATES OF LAKES

The standard deviation of breakup dates, calculated from past breakup records, is a measure of the variability of the date of lake ice breakup. Since breakup dates are distributed normally [Williams, 1968], the standard deviation can be used to calculate the probability that breakup will occur within any particular period. For example, if the standard deviation of breakup dates for a given lake is 8 days, breakup will occur within ± 8 days of the average breakup date about 68% of the time and within ± 16 days about 95% of the time.

The estimated standard deviation of breakup date was calculated for all lakes in Canada with a reasonably long breakup record. The estimated standard deviation was also calculated from long-term records of five lakes in Wisconsin [Ragotzkie, 1960]. Figure 1 gives their location. Estimated standard deviations, sometimes referred to as estimated standard deviations of the universe [Ezekiel, 1953] because of adjustment for the number of observations, will be referred to as standard deviations. Table 1 shows the average standard deviation for lakes subdivided according to length of record. Lakes subject to mild, coastal weather and consequently having thin ice covers are listed as 'coastal' lakes to distinguish them from in-

Fig. 1. Location of lakes.

land 'continental' lakes subject to more extreme weather conditions.

The standard deviation for coastal lakes was about 13 days; for continental lakes, 7-11 days. These results compare reasonably well with similar calculations for Swedish lakes with long-term records [Eriksson, 1920]. In the north of Sweden, the standard deviation is 10 days; in mid-Sweden, 15 days; and in the southern coastal regions, 20 days. The period between earliest and latest breakup dates (95% of the time) is 30-40 days for continental lakes and 50 days or more for coastal lakes.

The wide fluctuation in yearly breakup dates is primarily due to variations in weather during the ice melting period. A cold, late spring results in delayed breakup; a warm, early spring results in early breakup. Although the process of melting is complex [Williams, 1967], air temperature is one of the most important variables affecting the degeneration of lake ice.

The importance of air temperature may be illustrated by comparing air temperature and breakup records for years when abnormal conditions prevailed. In 1945, for example, breakup averaged 15-25 days earlier than normal, and March air temperatures were 10°F-16°F above

normal over an extensive area of eastern Canada (Figure 2). In 1947, over generally the same region, breakup averaged 12-16 days late, and April air temperatures were from 6°F-10°F below normal. On occasion, abnormal air temperatures can affect the breakup date of lakes over even more extensive areas. A late breakup was observed in 1956 at almost all lakes across Canada where records were kept.

TABLE 1. Estimated Standard Deviation for Breakup Date for Some Lakes in North America

Number of Lakes	Length of Breakup Record, years	Average Standard Deviation, days
Continental Lakes		
28	5-10	7.1
8	11-20	7.9
8	21-40	8.2
3*	40-70	8.7
2*	100-105	10.9
Coastal Lakes		
6	5-10	12.7
4	19-23	13.0

* Obtained from records of lakes in Wisconsin [Ragotzkie, 1960].

Below normal air temperatures during the spring offset the many local factors, such as depth, size and shape of lake, ice thickness, and wind, that can influence the date ice clears from a lake.

ANALYSIS OF SELECTED LAKES

In the initial stages of the study, an attempt was made to develop techniques for predicting breakup dates. These techniques were based on several parameters that can affect lake ice breakup, such as solar radiation, wind velocity, and ice thickness. Unfortunately, adequate records of these parameters were not available at meteorologic stations near lakes where breakup dates had been recorded. Subsequent analysis was therefore based only on air temperature data, which are usually available from past records and are part of routine meteorologic forecasts.

Twelve continental lakes were chosen for detailed analysis in investigating the accuracy with which breakup dates can be predicted from

available breakup and air temperature records. Several factors determined the choice of lakes, the most important being availability of meteorologic records of solar radiation or hours of sunshine, air temperature, and wind speed. Although the solar radiation records proved unsatisfactory because of missing or incomplete records, the lakes were originally chosen on the assumption that radiation records could be used in the analysis. Lakes were excluded where wind or river runoff would be major factors affecting breakup. Although wind is a factor in clearing ice from some of the lakes chosen, it was assumed that air temperature rather than wind was dominant. Lakes with 20 years or more of record were excluded because either basic meteorologic data were missing or the size of the lake indicated that wind would be the dominant factor determining breakup.

If the lakes with the longest breakup record could have been used in the analysis, allowance would have had to be made in the statistical analysis for changes in breakup date caused by climatic fluctuation. Long term breakup records available in North America show that from about 1870–1940 breakup of lakes occurred at progressively earlier dates [Williams, 1970]. A significant increase in spring air temperature occurred during the same period [Thomas, 1968]. Since about 1940, there has been no apparent trend for breakup to become earlier or later. The gradual change in breakup dates may explain the tendency for the standard deviation to increase with length of record (Table 1).

The lakes and the names and locations of meteorologic stations from which air temperature records were obtained are listed in Table 2. Estimated area, estimated maximum fetch, average date of breakup, and standard deviation are also tabulated. Available breakup records were too limited to warrant arranging the data according to lakes with comparable depth, area, shape, or orientation. The observation sites include long, narrow lakes, such as Setting; small lakes, such as Knob or McLaughlin; and parts of larger lakes, such as Brochet Bay on Reindeer Lake.

Two methods of predicting breakup dates were investigated. The melting degree day method attempts to estimate the date of breakup from the number of melting degree days that

Fig. 2. Dependence of breakup date on air temperature.

TABLE 2. General Information Available for Lakes Chosen for Detailed Study

Meteorologic Station	Elevation, feet	Lake	Estimated Area, mi ²	Maximum Fetch, miles	Year of Record	Average Breakup Date	
							Standard Deviation, days
Killaloe 45°34'N, 77°25'W	571	Golden	15	4-6	8	April 25	4.6
Megantic 45°35'N, 70°52'W	1362	Megantic	10	8-10	16	April 30	9.6
Moncton 46°07'N, 64°41'W	248	McLaughlin	0.5	1	16	April 25	7.8
Sudbury 46°29'N, 80°59'W	850	Ramsey	2-3	1-2	17	April 27	9.4
Arvida 48°26'N, 71°11'W	335	Kenogami	30	16-20	10	May 9	8.3
Nitchequon 53°12'N, 70°54'W	1759	Nitchequon	North End of Large Lake	4-6	11	June 13	8.3
The Pas 53°49'N, 101°05'W	890	Grace	5	1-2	13	May 12	7.8
Knob Lake 54°48'N, 66°49'W	1681	Knob	1	1-2	11	June 11	7.9
Wabowden 54°55'N, 98°38'W	764	Setting	60	25-30	7	May 26	5.3
Brochet 57°53'N, 101°41'W	1150	Brochet Bay	Bay on Reindeer Lake	4-6	15	June 5	6.5
Watson 60°07'N, 128°49'W	2248	Watson	5	4-6	18	May 25	4.4
Ennadai 61°08'N, 100°55'W	1065	Ennadai	North End of Large Lake	8-10	9	July 8	7.7

Elevation is given in feet above sea level.

accumulate before breakup occurs [Stankiewicz, 1947]. The regression equation method correlates the duration of the ice melt period with the date of the start of significant melting and deviations from average air temperature during the melt period. The melt period is defined as the period from the date on which significant melting starts to the date when ice clears the lake. The start of significant melting was defined as the date when accumulated degree days reached 50.

Regression equations were developed for each of the 12 lakes by multiple correlation analysis of available breakup and air temperature records. The equations were further analyzed for presentation in a general form that could be of value for forecasting breakup for lakes with limited breakup records.

MELTING DEGREE DAY METHOD

Melting degree days were accumulated by using a base temperature of 32°F from the

time the daily mean air temperature first rises above 32°F until the date of breakup for each year for each of the 12 lakes. The average number of degree days required to clear ice

TABLE 3. Standard Deviation and Accumulated Melting Degree Days to Breakup Date

Lake	Average Accumulated Melting, degree days	Standard Deviation, degree days	Standard Deviation, days
Golden	210	46	6.6
Megantic	236	67	8.0
McLaughlin	203	41	5.5
Ramsey	194	54	5.7
Kenogami	352	32	3.3
Nitchequon	347	46	4.1
Grace	269	67	5.7
Knob	249	59	6.3
Setting	367	52	4.7
Brochet Bay	334	65	6.4
Watson	372	56	4.7
Ennadai	537	76	4.8

from the lakes and the standard deviations are shown in Table 3.

Standard deviations in melting degree days were converted to days by dividing by average values of melting degrees for a single day during the melt period. For example, the average daily air temperature during the melt period at Ennadai Lake is 48°F. Therefore, on the average, there are 16 melting degree days during a single day. The standard deviation is thus calculated to be 76/16, or 4.8 days. This conversion is not completely satisfactory, because melting degree days late in the melt period can differ from the average. It was necessary, however, in order to compare the results obtained by the melting degree day method with those of other methods of forecasting.

The standard deviation for the melting degree day method for the 12 lakes ranged from 3.3–8.0 days. For some lakes, such as Kenogami or Nitchequon, these deviations are considerably less than standard deviations of breakup dates. For other lakes, such as Megantic and Golden, standard deviations are about equal to or greater than those calculated from the distribution of breakup dates.

The melting degree day method is particularly unsuitable for forecasting the breakup of large lakes. Accumulated melting degree days and standard deviations were calculated for Cold Lake with an estimated area of 140 square miles and Big Trout Lake with an area of 340 square miles. Accumulated melting degree days were 512 and 537, respectively, with standard deviations of about 12 days. Air temperatures measured at shore stations of large lakes are probably higher than air temperatures over the extensive expanses of melting ice, and the resulting values for accumulated melting degree days are relatively high. The variable influence of wind and currents in clearing ice from these large lakes probably contributes to the relatively large standard deviations. Similar results would probably be obtained for the main body of Reindeer Lake, where according to the local observer, breakup occurs about 2 weeks later than it does at Brochet Bay.

One shortcoming of the melting degree day method is that degree days accumulated in the early stages of melt are given the same weight as degree days accumulated during advance stages of melt. In the later stages, not only is

TABLE 4. Duration of Melt Periods, Standard Deviations, and Average Dates of Start of Significant Melt

Lake	Average Date of Start of Melt Period	Average Duration of Melt Period, days to clear	Standard Deviation, days
Golden	March 31	24.7	5.5
Megantic	April 8	22.0	8.3
McLaughlin	April 3	22.0	6.9
Ramsey	April 8	19.4	5.4
Kenogami	April 7	32.0	7.3
Nitchequon	May 16	27.6	5.9
Grace	April 22	20.1	6.2
Knob	May 17	25.4	5.1
Setting	April 25	31.4	5.3
Brochet Bay	May 8	28.4	5.4
Watson	April 26	28.6	4.6
Ennadai	June 8	30.3	2.9

the available solar radiation usually greater, but the percentage of incoming radiation absorbed because of reduced surface albedo is greater as well. Several attempts were made to improve the melting degree day method by using base temperatures higher than 32°F and by putting more weight on degree days accumulated late in the melt season. These attempts, although unsuccessful, provided the basis for the regression equation method of forecasting breakup dates.

REGRESSION EQUATION METHOD

The first step in the regression equation analysis was to calculate for each year and each lake the date on which significant melting was assumed to start. A study of past records indicated that after 50 degree days, daily minimum air temperatures tended to remain above 32°F. This arbitrary definition of start of the melt period agrees reasonably well with a previous definition that assumed that the melt period began when the average air temperature for 5 days was above 32°F [Williams, 1965].

Once the start of significant melting had been calculated, the duration of the melt period (the difference in days between date of start of melting and actual breakup) was calculated for each lake. The average date of start of melt, the average duration of the melt period, and standard deviations are shown on Table 4. The average number of days for ice to clear

from a lake varied from 19.4–32.0 days and averaged from 19.4–24.7 days for the four most southerly lakes and from 25.4–32.0 days for the more northerly lakes (with the exception of Grace Lake, which averaged 20.1 days). Standard deviations averaged 5.8 days and ranged from a low of 2.9 days for Ennadai to a high of 8.3 days for Megantic.

The standard deviations for the duration of the melt period are comparable to standard deviations for the melting degree day method, which averaged 5.5 days and ranged from 3.3–8.0 days. Thus breakup dates can be forecast for the 12 lakes almost as accurately by calculations based on the date of start of melting and expected duration of the melt period as by the melting degree day method. This estimate of breakup date can be made as soon as the start of melting is known by assuming an average value for the duration of the melt period for a particular lake.

The duration of the ice melt period at Ennadai is especially consistent, the standard deviation being equal to 2.9 days. Relatively high air temperatures during the melt period (48°F) combined with high solar radiation in June at this latitude may cause the rate of ice deterioration at this lake to be about the same each year.

The next step in the analysis was to calculate for each year of record and each lake the deviations of air temperature from the long-

term averages for the individual melt periods. The average air temperature for the melt period was obtained by totaling daily mean air temperatures and dividing this figure by the number of days in the melt period. Air temperature deviations were used in preference to melting degree day deviations because they are more readily available from air temperature records and forecasts. Also, the analysis revealed that better correlations were achieved by using air temperature deviations.

The information compiled on start and duration of melt was combined with air temperature deviations to calculate regression equations for each lake. Multiple correlation techniques were used to correlate deviations from average of duration of melt period (y) with deviations in days from average date of start of melt (x), and deviations of air temperature from the long-term average during the melt period (t).

Regression equations calculated for each lake, standard errors, and correlation coefficients adjusted for length of record [Ezekiel, 1953] are shown in Table 5. All correlations are significant at the 0.05 level [Wishart, 1928] with the exception of those for Ennadai. The duration of the melt period of this lake appears to be independent of both the date on which melt starts and the air temperature.

Standard errors for the regression equation method are compared in Figure 3 with standard deviations for the melting degree day method

TABLE 5. Regression Equations, Standard Error, and Correlation Coefficients

Lake	Regression Equations	Adjusted Standard Error, days	Adjusted Multiple Correlation Coefficient
Golden	$y = -0.78x - 0.97t + 0.93$	2.2	0.92
Megantic	$y = -0.72x - 1.38t + 1.44$	3.5	0.90
McLaughlin	$y = -0.53x - 1.12t + 0.57$	4.0	0.86
Ramsey	$y = -0.40x - 0.80t + 1.68$	2.8	0.85
Kenogami	$y = -0.83x - 1.89t + 4.18$	2.7	0.93
Nitchequon	$y = -0.49x - 0.94t + 0.87$	2.2	0.92
Grace	$y = -0.54x - 0.72t + 1.59$	2.5	0.91
Knob	$y = -0.33x - 0.85t + 2.71$	1.6	0.95
Setting	$y = -0.73x - 0.93t + 0.29$	4.3	0.91
Brochet Bay	$y = -0.47x - 0.89t + 2.57$	3.2	0.80
Watson	$y = -0.93x - 1.20t - 0.40$	3.4	0.86
Ennadai	$y = +0.19x + 0.46t - 0.76$	3.3	0.16

y , deviation from average duration of melt period, days;
 x , deviation from average date of start of melt period, days;
 t , deviation of average air temperature during active melt, °F.

Fig. 3. Comparison of forecast methods for selected lakes.

and standard deviations of breakup dates. For some lakes, the results are excellent; for others, standard errors are not much less than the standard deviations of breakup dates. For example, the standard deviations for breakup dates for Nitchequon and Knob Lakes are 8.3 and 7.9 days; these are much greater than the standard errors of 2.2 and 1.6 days of the regression equations. The standard deviation of breakup dates for Watson and Setting Lakes are, however, 4.4 and 5.3 days, just slightly more than standard errors of 3.4 and 4.3 indi-

cated by the regression equations. Standard errors for many of the lakes could probably be reduced if other variables affecting breakup (wind, ice thickness, and snow cover) could be introduced into the regression equations. There were not enough data available on these variables, however, to justify further calculations. All that can be attempted is a qualitative discussion of their relative importance.

The information that was available demonstrated the effect of wind on breakup. An analysis of available wind records showed that in 15 of 19 cases for which breakup was at least 3 days later than forecast, the 24-hour wind speed on the day of breakup was below the monthly average. In 15 of 23 cases for which breakup was at least 3 days earlier than forecast, wind speed was above the monthly average on the day of breakup. At Knob Lake, where wind effects are minimal, the standard error of estimate was 1.6 days; at Watson Lake, where according to the local observer wind always affects the clearing of ice from the lake, it was 3.4 days. Lakes with potentially long fetches, such as Setting and Megantic, had relatively large standard errors of 4.3 and 3.5 days, respectively.

The thickness of ice to be melted is another variable not considered in the regression equations. The maximum ranged from 21–33 inches for Kenogami, 27–44 inches for Nitchequon, 35–51 inches for Knob Lake, and 38–54 inches for Brochet Bay. The variation in the maximum from year to year is so large that appreciable errors in estimates of the date of breakup would be expected, if allowance were not made for it in regression equations. The results of the regression equation analysis indicate, however,

TABLE 6. Regression Equations Correlating x and y for Different Air Temperature Classifications during Melt Period

Air Temperature Classification	Regression Equation	Standard Error	Correlation Coefficient	Number of Observations
Below average temperature, -2.0°F or $>$	$y = -0.42x + 4.4$	3.1	0.68	35
Average temperature, $-1.9 + 0 + 1.9^{\circ}\text{F}$	$y = -0.53x + 0.9$	3.8	0.75	58
Above average temperature, $+2.0^{\circ}\text{F}$ or $>$	$y = -0.62x - 4.2$	4.0	0.85	58

y , deviation from average duration of melt period;

x , deviation in days from average date of start of melt period.

that ice thickness is not always so important a factor as one might assume. For example, the maximum ice thickness for Lake Ennadai varied from 48–90 inches; under comparable melting conditions, the number of days for ice to clear should show similar variation. The fact that the duration of the melt period of this lake is not highly variable suggests that deterioration of ice depends more on solar radiation and resultant 'candling' of ice than on ice thickness. The importance of ice thickness as a factor affecting breakup date may vary from lake to lake, being especially important where ice covers are relatively thin.

Several other factors could contribute to regression equation errors, for example, variations in the amount of heat stored in the water under the ice, depth of snow cover, snowmelt runoff, and warm springs. Observation error would affect the reliability of the regression equations developed. In addition, the shoreline-area ratio is different for each lake, and this ratio affects the amount of heat that can be advected from land surfaces [Scott, 1964].

GUIDELINES FOR FORECASTING BREAKUP

Records from the 12 stations were combined and used to calculate three regression equations correlating y (as defined previously) with x

Fig. 4. Guideline for forecasting breakup date of continental lakes.

(also defined previously) for air temperature deviations classified as (1) below average air temperature (negative deviations -2°F or greater), (2) average air temperature (deviations -1.9°F to $+1.9^{\circ}\text{F}$), and (3) above average air temperature (positive deviations $+2.0^{\circ}\text{F}$ or greater). It was considered that these generalized equations would be useful for forecasting breakup dates when it is not possible to develop separate regression equations for individual lakes.

Table 6 shows regression equations developed for the three air temperature classifications. The correlations are significant at the 0.05 level [Wishart, 1928]. The standard error of estimate was 3.1 days for below average air temperature, 3.8 days for average air temperature, and 4.0 days for above average air temperature. These equations were used to develop the forecast guidelines plotted in convenient form on Figure 4. The only information needed for their use is average date of breakup, deviation from average date of start of breakup for the year in question, and a forecast air temperature. For example, if the start of breakup is 10 days late and the forecast air temperature is above average, the date of breakup should be about average. The forecast would be adjusted during the melt period if the actual air temperature were different from that forecast.

The regression equations on which the forecast guidelines are based are significantly different; consequently breakup forecasts based on above average and below average air temperature become increasingly different with changes in the start of significant melt. For example, if the date of start is 15 days early, there is only a difference of 7 days between forecasts based on above average or below average air temperature. If the start is 20 days late, there is about a difference of 14 days between above and below average air temperature forecasts. It is difficult to give a sound physical interpretation of this result because the rate of ice decay depends on other parameters such as solar radiation, which may be indirectly related to air temperature. Normally the amount of solar radiation available increases as breakup is delayed. The greater amounts of solar radiation would tend to be more effective in decaying ice at above average than at below average air temperatures.

Fig. 5. Comparison of forecast date of breakup with actual date.

The use and probable accuracy of these forecast guidelines are illustrated by estimating breakup dates for four lakes within a 50- to 100-mile radius of a central meteorologic station in Arvida, Quebec. Deviations from average date of start of breakup and air temperature deviations during the active melt period were calculated for each year for which breakup records were available for analysis. The general equations in Figure 4 were used to obtain an estimated breakup date, which was compared with the actual breakup date (Figure 5). The standard errors, ranging from 3.4–6.2 days, are quite reasonable when we consider that no information was available on local factors that might affect the date of breakup. In practice, the accuracy of forecasts could be improved by a knowledge of local site conditions and by adjusting the forecast during the melt period for the air temperature, solar radiation, and wind conditions that actually prevail. These

forecast guidelines will necessarily be of limited accuracy, but they can be used particularly under abnormal conditions to give more objective guidance for estimating breakup dates than is now available.

DISCUSSION OF RESULTS

One of the major factors limiting the usefulness of any method based on air temperature records is the uncertainty in the forecast of air temperature during the melt period. The real problem of forecasting breakup dates is thus a part of the general problem of improving short-term and long-term (30-day) forecasts of air temperature. Studies have been under way in the USSR for some time to improve long-range forecasting of breakup dates by relating air mass circulation to ice formation and breakup [Shulyakovskii, 1963].

Forecasts of weather conditions during the few days prior to breakup are especially im-

portant in determining the date ice will clear from a lake. Ice deterioration can be extremely slow during cool, cloudy weather, and a delay of several days in final breakup may result, even though all antecedent conditions favored early breakup. Above average solar radiation during the last few days of melt can result in rapid deterioration of ice covers, which when combined with strong winds can result in extremely rapid clearing of ice from lakes.

The role of wind was assessed by analysis of the questionnaires circulated to observers who regularly record breakup for the Canadian Meteorological Branch at 54 lakes across Canada. On large lakes, wind almost invariably broke up ice and drove it on the shore. The thickness of such sheet ice ranged from 1-4 feet, and the ice often piled up to heights of 20 feet. For relatively small lakes with a fetch of 2-5 miles, ice from 1-2 feet thick was driven on shore but seldom piled up. In only one case was ice driven on shore where the fetch was 1 mile or less.

The effect of wind depends not only on fetch but also on wind speed, direction, and duration and on the degree of ice deterioration when breakup occurs. These effects are difficult to predict because there is usually no information available on the degree of deterioration of ice covers immediately prior to final breakup, and often only limited information on wind speed, direction, and duration.

The nature of the problem of predicting breakup dates for lake ice is such that quite detailed information on the variables that affect breakup would have to be available for each lake before an accurate method of forecasting could be developed. A comprehensive manual on forecasting lake and river ice formation has been prepared in the USSR [Shulyakovskii, 1963]; it is admitted, however, that reliable methods for taking into account all the factors that determine the destruction and thawing of ice have not yet been developed.

CONCLUSIONS

The date of lake ice breakup fluctuates within a rather wide range. The period between earliest and latest breakup dates is about 30-40 days for continental lakes and 50 days or more for coastal lakes (95% of the time).

The accuracy of the melting degree day

method of forecasting breakup date varies from lake to lake, being especially unsuitable for lakes where wind and river inflow have a dominant influence on breakup. Standard deviations calculated for several continental lakes ranged from 3.3-8.0 days.

Regression equations developed from past breakup and air temperature records make it possible to estimate breakup dates with a standard error of 1.6-4.3 days, if the date of start of breakup and air temperature during the ice melting period are known. General guidelines for forecasting breakup, developed from these equations, can be used when it is not possible to calculate regression equations for an individual lake. The equations and guidelines are suitable only for continental lakes where wind and river inflow effects are not dominant.

The accuracy of methods of forecasting breakup dates for lake ice, based only on air temperature records, is limited by many variables difficult to allow for in regression equations. The effect of wind is especially important, particularly for lakes with a fetch greater than 1 mile.

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