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BY

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EVAPORATION FROM WATER, SNOW AND ICE

G. P. Williams[1]

SYNOPSIS

The basic theoretical differences between evaporation from snow, ice and water surfaces are outlined. Some estimated energy budget analyses are made to show the order-of-magnitude of evaporation rates from these surfaces under Canadian conditions. Some measurements of evaporation from snow and water surfaces made in Canada are presented to confirm the theoretical considerations.

INTRODUCTION

The main purpose of this symposium is "to provide an opportunity for Canadian researchers in evaporation to exchange information and views, and to encourage the use of the best methods available by engineers, foresters, agriculturists, meteorologists and others, for dealing with evaporation" (9). With this aim in mind, this paper has been written to provide background material for the discussions, particularly for those dealing with the basic ideas concerning evaporation from saturated surfaces.

In evaporation investigations there are two points of view. The first might be termed the "research" point of view where, with special instrumentation and adequate staff, investigations are undertaken to increase the knowledge of the evaporation process and to develop or check theories of evaporation. The second might be termed the "operational" point of view where, with existing records and existing techniques, attempts are made to estimate evaporation rates for specified surfaces under given conditions. This second point of view is emphasized in this paper by (a) outlining the energy balance approach to the evaporation problem, (b) presenting energy budget calculations for some typical conditions in Canada, (c) outlining briefly the mass transfer approach, and (d) presenting some limited observations of evaporation from snow and water surfaces and comparing them with one of the available empirical formulae.

ENERGY BALANCE APPROACH

One form of the energy balance equation at an evaporating surface

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is as follows:

$$Q_e + Q_{sw} + Q_{lw} + Q_s + Q_c = 0$$

where Q_e = evaporative heat,

Q_{sw} = net short-wave radiation,

Q_{lw} = net long-wave radiation,

Q_s = heat conducted to the surface from below (change in the total heat stored in the ice or water, including the heat associated with the freezing of water or melting of snow or ice), and

Q_c = convective heat (sensible heat).

If the various terms in this equation can be measured or calculated, Q_e can be estimated. As Penman (16) points out, "the fundamental basis of the energy balance approach is unchallenged, the challenge is to our ability to measure or estimate all the quantities needed to exploit the principle of the conservation of energy." Therefore, the problem of measuring or estimating the different parameters of the energy balance equation for snow, ice, and water surfaces will be emphasized. The energy that is available because of precipitation, ground water, or river flow has been ignored in this discussion.

Q_{sw}, the Energy Available from Short-wave Radiation

The amount of short-wave radiation absorbed at an evaporating surface, Q_{sw}, equals R_{sw} (1 - r)

where R_{sw} = short-wave radiation reaching the surface, and

r = albedo, sometimes given as the percentage of short-wave radiation reflected.

The amount of short-wave radiation that is reflected, r, varies with the type of water, snow or ice, and also with the elevation of the sun, especially in the case of water. There is enough agreement among various investigators to give the following approximate values:

	r(albedo)
New snow	0.80 - 0.90
Old snow	0.60 - 0.80
Melting snow	0.40 - 0.60
Ice	0.40 - 0.50
Water	0.05 - 0.15

These values indicate that considerably less short-wave radiation is reflected from an ice surface than from a snow surface and that considerably less short-wave radiation is reflected from a water surface than from an ice surface.

Comparative values showing the seasonal variation of Q_{sw} have been estimated for two latitudes in Canada and are given in Figure 1.

The average insolation for two stations, Ottawa (latitude approximately 45°N), and Aklavik (latitude approximately 68°N) were obtained from estimates of average insolation given by Mateer (13). The average reflection values for snow, ice and water used for these two latitudes are those given by Budyko (6).

Figure 1 illustrates the differences in the energy available from short-wave radiation at the two sites. During the winter period, October to May, the average energy available from short-wave radiation at Aklavik is approximately 32 $cal/cm^2/24$ hr for snow surfaces, compared with 77 $cal/cm^2/24$ hr for the winter period November to April at Ottawa. During the summer period, June to September, the average energy available from short-wave radiation for water surfaces at Aklavik is approximately 333 $cal/cm^2/24$ hr, compared with 415 $cal/cm^2/24$ hr for the period May to October at Ottawa.

Q_{lw}, Long-wave Radiation

In detailed studies where adequate records are available, the long-wave radiation components are broken down into incoming long-wave radiation from the atmosphere, reflected long-wave radiation, and long-wave radiation emitted by the surface.

Where adequate records are not available, empirical formulae have been developed to estimate net long-wave radiation from standard meteorological observations. One type of equation proposed by Brunt (5) is as follows:

$$Q_{lw} = \sigma \, Ta4 \, (a + b \, e) \, f(n/N)$$

where σ = Stefan-Boltzmann constant

Ta = mean air temperature

e = meanvapour pressure of air

a,b, = constants

f(n/N) = cloudiness factor

In regard to this type of formula Brunt states: "These equations are best regarded as empirical formulae, which, within the limits of vapour pressure which occur in the atmosphere, give a reasonable representation of the average amount of radiation in given conditions. No such formulae can give accurate representation of individual observations which frequently show wide variations of R (incoming long-wave radiation) for the same values of T and e."

To show the approximate value that can be expected for the long-wave radiation term Q_{lw}, mean monthly values were calculated for the Ottawa latitude, using the empirical formula proposed by Brunt, with appropriate constants, and mean monthly values for air temperature and air vapour pressure. The calculated values for Q_{lw} varied from 220 to 250 cal/cm^2/24 hr for clear sky conditions. There was no marked seasonal trend, as the increase of vapour pressure in the summer was offset by the decrease of air temperature in the winter. A preliminary analysis of sky conditions in the Ottawa area indicated that the mean value of long-wave radiation, Q_{lw} should be reduced to about 120 cal/cm^2/24 hr for average sky conditions.

Observations made at night by the author at Ottawa for the period October 1 to November 30, 1960, give an average value of 5.75 cal/cm^2/hr (138 cal/cm^2/24 hr) for the net long-wave radiation from a water surface.

Some average values taken from various sources that can be used for comparison are as follows:

	Q_{lw} cal/cm^2/24 hr	Source
Open snow fields	155	D.H. Millar (14)
Snow in pine stands, Sierra Nevada	40	D.H. Millar (14)
Average value, Lake Klämmingen, Sweden	123	Johnsson (10)
Average calculated value Lake Ontario	96	Bruce and Rodgers (4)
Average values Lake Mead and Lake Hefner	150-162	Lake Mead Studies (19)

Radiometers have been developed to measure the combined net short-wave and long-wave radiation. Because these instruments are still at the state of development where they require practically constant supervision in order to yield reliable results, however, they are not suitable for routine observation programs. It is only in special studies that such instruments have found useful application to date. For more general application of the energy balance equation to evaporation, long-wave radiation will at present have to be calculated using formulae such as that developed by Brunt.

Q_s, Heat Storage Term

The amount of heat transferred from the underlying material to or away from the evaporating surface in a given time is called in this paper the rate of change of heat storage (Q_s). To understand the conditions under which this heat storage energy can be important to the evaporation process, some thermal properties of snow, ice and water are briefly considered.

As the thermal conductivity of ice is approximately ten times that of average snow, the heat available for evaporation by conduction through ice is about ten times that available by conduction through snow subject to a similar temperature gradient. The thermal conductivity of ice is about five times that of still water. In the case of water, however, heat can be brought to the surface by convective or turbulent transfer as well as by conduction. The convective heat transfer can be large in comparison with the heat brought to the surface by pure conduction.

Priestley (17) has considered that the total change in heat content of various media subject to a temperature change at their surface is proportional to $pc\sqrt{k}$, where k is the thermal diffusivity of the medium, p is the density and c is the specific heat. He considers that the "rate of heat flux consequent on an imposed temperature regime at the boundary will be directly proportional to $pc\sqrt{k}$" and for this reason defines this quantity as the "conductive capacity" of the medium. He has given the following values of $pc\sqrt{k}$ for various media:

	$pc\sqrt{k}$
New snow.	0.002
Old snow	0.012
Ice	0.05
Still water	0.039
Stirred water	
(a) great stability	0.32
(b) moderately stable	7.0
(c) homogeneous, strong currents . .	17.0

To illustrate further the influence of the conductive capacity of different media, some values obtained by the writer for the rate of change of heat storage for different media in the Ottawa area are as follows:

	Average Q_s cal/cm^2/24 hr	Average Temperature Gradient °C/cm
12 in. of snow	7	0.2
12 in. of ice (no snow)	46	0.1
open water (average depth 20 ft)	165	0.01 or less

The value of the heat storage term depends not only on the conductive capacity but also on the temperature gradient in the media. At certain times when the snow layer is thin or when ice is first forming, the temperature gradient may be quite large and the resulting heat flow to the surface correspondingly significant.

Q_c, Energy Lost or Gained by Convection From the Air

The direct measurement of Q_c, the convective component, is most difficult. Such measurements have been undertaken for special studies only and are not available in Canada for the more general application of the energy balance equation. For practical applications, a relation between evaporation and convection is assumed which enables the convective component Q_c to be related directly to the evaporative component Q_e. Bowen (3) derived such a relationship which has become known as Bowen's ratio.

By assuming that the convective heat transfer and vapour transfer processes are identical, the expression derived is:

$$R = \frac{Q_c}{Q_e} = \frac{K\,(T_o - T_a)}{(e_s - e_a)}$$

where R = Bowen's ratio,

K = constant,

T_o = surface temperature,

T_a = air temperature,

e_s = vapour pressure of air at the surface, and

e_a = vapour pressure of air above the surface.

The general validity of this expression has been the subject of much discussion. The Lake Hefner investigators have stated (18): "The Bowen ratio appears to be sufficiently accurate for computing energy utilized by evaporation for most conditions. In exceptional conditions, for example, when evaporation rates are small and the difference in vapour pressure of the atmosphere and that of air saturated at the surface - water temperature approaches instrumental accuracy, the Bowen ratio is inadequate".

Usually the vapour pressure differences over snow and ice are small, so that caution should be exercised in applying the Bowen ratio to relate convective and evaporative heat losses under such conditions. One of the difficult factors to measure in Bowen's ratio is surface temperature, particularly of snow and ice surfaces where the temperature-measuring device normally must be exposed to the incoming short-wave radiation. Available evidence does indicate that when a reliable value for Bowen's ratio can be calculated, it can be used to evaluate the comparative magnitude of evaporation and convection heat losses, if values are averaged over a period of a month or several days.

It should be stressed that unless Q_c or Q_e can be measured independently, the errors in measuring or estimating all the components in the energy balance equation are accumulated in the remainder $Q_c + Q_e$. Thus, if Q_c and Q_e are evaluated by assuming that Bowen's ratio is valid, it becomes very difficult to assess the accuracy of the estimate for Q_e which is obtained.

Estimated Energy Budget for a Small Lake at Ottawa

To illustrate further the relation between evaporation and the other components of the energy exchange, the energy budget of a small lake in the Ottawa area is presented. It was assumed in this analysis that no energy was brought into the lake by precipitation or groundwater flow, and that the lake had no snow on the ice during the winter.

Figure 2 shows the estimated monthly values of the components of the energy balance. In calculating the various components many assumptions had to be made. Therefore the values obtained must be considered as approximate, but they do show on an annual basis the relative importance of the different components of the energy exchange.

The approximate short-wave term was obtained from the average values used in Figure 1. For the purposes of illustration the long-wave radiation was considered constant at 120 cal/cm^2/24 hr.

The rate of change of the heat storage was estimated during the ice-free period from average values given by Johnsson for Lake Klämmingen (10), and from some measurements made by the author on the rate of heat loss from a small lake in the Ottawa area. The heat used to melt the ice and the heat loss during the period of ice formation were estimated from typical rates of ice growth and melting measured in the Ottawa area.

The sum of $Q_c + Q_e$ was obtained by adding or subtracting the rate of change of heat storage from the calculated net radiation. An average value was obtained for Bowen's ratio by direct calculation during those periods when records were available and by estimation during the periods when records were incomplete. The average value of Bowen's ratio obtained was then used to separate the Q_c and Q_e components. The values obtained for the term Q_c compare reasonably well with those given by Johnsson for Lake Klämmingen during the ice-free period.

The results of this approximate analysis are shown in Figure 2.

The estimate of the radiation components, though satisfactory to show seasonal trends, could be greatly in error, particularly for a single month. If the calculated net radiation was in error by 10 per cent, the error would be of the same magnitude as the convective term. Therefore unless the radiation terms can be measured accurately, not much confidence can be placed in the convective term Q_c. But even if the convective term is out by as much as 100 per cent, the trend in the evaporation term will still be representative of true evaporation, particularly during the summer months when the evaporation component Q_e is large compared to Q_c.

The heat storage term is significant for a small lake. If ice thickness and water temperature records are available, the rate of change of the heat storage can be estimated with reasonable accuracy.

Although, on the basis of this preliminary analysis, the convective component is likely to be much smaller than the evaporative component, during the spring melt period when warm air is passing over the melting ice or cold water, the convective component may become more significant.

Figure 2 indicates that during the spring, about the same amount of energy is used in evaporating ice as in melting it. Other studies (7, 1) have shown that the amount of energy used in melting is usually much greater than the energy used in evaporation. It should be pointed out that as it requires approximately 80 cal/gram to melt ice compared with 675 cal to sublimate it, the mass of ice melted is large compared to the mass evaporated. It also should be pointed out that an ice cover rarely remains clear of snow throughout a winter season. If an ice cover becomes snow covered the amount of radiation absorbed is reduced, the heat flow through the cover is also reduced, and the evaporation component will be lessened.

<u>Comparison of Energy Balance of Pond, Small Lake and Large Lake</u>

To show the effect of depth of water on the energy balance, the energy budget for a small lake is compared with the energy budget of a shallow tank and a large deep lake. Figure 3 shows this comparison of the approximate energy budgets for these three sizes of water bodies.

The energy budget for the small lake is the same as in the preceding analysis. The calculated energy budget for Lake Ontario presented by Bruce and Rodgers (4) was used as an example of a large deep lake. The monthly energy budget of the small tank was estimated by means of the same general approximations used to obtain the energy budget of a small lake. The net radiation energy terms were assumed to be the same as for the small lake. Whenever possible, measured values of the heat storage term and values of Bowen's ratio were obtained from observations made at Ottawa and used in the calculations.

Figure 3 shows that the rate of change of heat storage and convection terms are relatively small for the tank and that net radiation is approximately equal to, and in phase with, evaporation. It is for this reason that various authors (15) working with saturated soil are able to estimate evapotranspiration from measured net radiation.

In the case of the small lake the heat storage term becomes more significant. During the period September to November the energy from heat storage is available for evaporation resulting in higher evaporation than from the small tank. In the case of the very large and deep lake, the heat storage term becomes very important and causes the evaporation to be out of phase with the net radiation.

If it is desired to relate evaporation from a small pond or Class A pan with the evaporation from a larger, deeper body by means of a coefficient, it can only be done with qualifications. For example, from Figure 3, the relation between the small tank and small lake follows a regular pattern from April to August which might be predictable. During the fall months, however, evaporation from the small lake is likely to exceed evaporation from the small pond and the coefficient would have to be adjusted. If evaporation from a small tank is used to estimate evaporation from a very large lake, the coefficient would vary from month to month and it is unlikely that the relationship would be predictable except perhaps on a yearly basis.

With the records available it was not possible to present more complete observations on the effect of the heat storage term on evaporation, but it is considered that what has been presented is a fair description of what occurs. Mansfield (12), in Australia, has made a more detailed analysis of the influence of depth, and hence of heat storage, on the annual cycle of evaporation. In his analysis the calculated monthly evaporation for a water body 10^4 cm deep was approximately 2 months out of phase with the maximum evaporation for a water body 10^3cm deep, and approximately $2\frac{1}{2}$ months out of phase with a water body 10^2cm deep.

MASS TRANSFER APPROACH

Numerous mass transfer equations have been derived for estimating evaporation. A review (2) of these equations was undertaken prior to the Lake Hefner study (18) and the most promising were tested in that investigation. Only a few aspects of mass transport formulae, related directly to their use, will be briefly considered in this paper.

Several mass transfer formulae require measurement of the vapour pressure and wind velocity profiles; observations which are usually not available. Often, the difference in wind speed and vapour pressure between two heights is very small and this fact imposes stringent requirements on the instrumentation and the experience of the observer.

Simpler forms of mass transfer formulae have been developed where evaporation is assumed proportional to a function of average wind speed and the difference between the vapour pressure of the air at the evaporating surface and the vapour pressure of the air at some level above the surface. One simplified example of such a formula is given below as a basis for discussion:

$$E = K \frac{f(u)\,(e_s - e_a)}{f(Z_o)}$$

E = evaporation rate,

$f(u)$ = function of wind velocity,

$f(Z_o)$ = roughness parameter,

e_s = vapour pressure at surface,

e_a = vapour pressure of air at same level above the surface, and

K = constant (which includes air density and air pressure terms)

The difference between e_s and e_a is usually fairly large so that the requirement on the accuracy of the measuring instruments is not so severe as it is when trying to determine the vapour pressure profile in the free air stream. But the determination of e_s does present problems due in part to the large gradient in vapour pressure which can exist at the surface and the difficulty sometimes encountered in defining the position of the surface. Often the vapour pressure at the surface is determined by assuming it equal to the saturated vapour pressure corresponding to the surface temperature. This, of course, then creates the problem of accurately measuring the surface temperature.

In comparing evaporation from snow or ice surfaces with water surfaces the vapour pressure difference $e_s - e_a$ has special significance. Because the maximum temperature that a snow or ice surface can attain is 32°F the maximum vapour pressure at the snow or ice surface cannot be greater than the saturated vapour pressure of air at 32°F which is 6.1 mbs. Hence evaporation from snow or ice cannot take place unless the dew point is below 32°F (e_a is less than 6.1 mb).

Roughness Parameter

The difficulty of evaluating the roughness parameter $f(Z_o)$ and its importance in mass transfer formulae is stressed in the Lake Hefner studies (18) where it is stated that "the roughness parameter of a natural water surface is a critical factor because the computed evaporation depends so much upon it. Values of Z_o for open water, generally the open ocean, have been variously quoted between 0.02 to 0.6 cm. Even if there were agreement as to value, it would not follow that the same value would apply to a small lake." Further in their report they state: "Although the values of Z_o quoted above are based only on measurements near the centre of the lake, they have been considered applicable to the entire surface and used accordingly. There is certainly a possibility that Z_o varies downwind, since all the conventional surface characteristics (wave height, etc.) do so."

Because roughness parameters depend on such features as wave heights, height of snow drifts, and type of vegetation growing above a snow cover, values of roughness parameters are likely to be quite variable. For example, the values of the roughness parameter Z_o found for water for one observational period during the Lake Hefner study varied from 0.55 to 1.15 cm. The roughness parameters presented by Priestley (17) for snow covers varied from 0.005 cm for smooth snow on short grass to 0.10 cm for snow surfaces on natural prairie. Because of this variability, evaporation formulae which require a value of roughness parameter for solution must be treated with caution, particularly if the period of observation is of short duration.

Mid-ocean and Mid-desert Conditions

In using mass transfer formulae a distinction should be made between the two extremes under which evaporation takes place under field conditions. Penman (16) has called these two extremes "mid-ocean" and "mid-desert". He states "The first is almost self-explanatory: it is the state in which evaporation takes place from a limited area in the midst of an infinite sheet of the same kind of surface. A square kilometre in mid-ocean satisfies this condition, but it may be equally well satisfied by a field in the midst of an extended area of vegetation. At the other extreme, "mid-desert" conditions are those in which a reservoir or other evaporating surface is surrounded by an infinite plane from which no evaporation takes place."

When evaporation is measured from snow covers using evaporation pans filled with snow and flush with the surface, the "mid-ocean" condition is closely approximated. If evaporation is measured from a Class "A" evaporation pan surrounded by arid land, however, the condition approaches the "mid-desert" condition.

In the first case, the air passing over the evaporation pan will not undergo appreciable modification even if the pan were of very large size. In the second case, the size of the evaporation pan or body becomes a consideration as the temperature and vapour pressure of the air are modified as it passes from the arid area over the wet evaporating surface. Halstead and Covey (8) have demonstrated that under extreme conditions the rate of evaporation will vary appreciably with the size of the body because of this effect.

Other authors (11) suggest that the increase in vapour pressure of the air downwind across an open-water surface is offset by an increase in wind speed downwind from the leading edge of a lake and thus the rate of evaporation does not decrease appreciably downwind across an open-water surface.

General Considerations

Numerous empirical formulae have been developed which are similar in form to formulae based on mass transfer theory. Usually only the mean wind speed and vapour pressure terms are considered. Other variables such as surface roughness are incorporated into an evaporation constant. These empirical formulae neglect many factors but the need for formulae, using commonly available records, makes their use widespread.

One condition not considered in using either empirical or mass transfer formulae is the effect on evaporation when the wind is strong enough to disturb the surface. In exposed areas where the wind can move large quantities of snow or cause spray to blow off wave tops, evaporation rates at least for short time intervals, might be considerably higher than a general evaporation equation would indicate.

One problem, common to all these formulae, is to obtain values of wind speed, air vapour pressure, and surface temperature, which are representative of average values over the entire evaporating surface. If estimates of evaporation on a short-term basis are required, then the need of obtaining adequate values for these variables is critical. If long-term estimates are required the problem is not so critical as the variability of these factors tend to average out.

COMPARISON OF MEASURED EVAPORATION RATES FROM PANS AND SMALL TANKS

During the past few years the author has measured the evaporation from snow covers and small bodies of water in the Ottawa area. Although this paper is not concerned with measurement, the records obtained are presented and compared with a pan evaporation formula to indicate the magnitude of evaporation rates that can be expected from snow and water, two of the surfaces that have been under discussion.

Evaporation Measurements

Snow evaporation was measured by placing circular pans (4 cm deep with 355 sq cm area) filled with snow, flush with the snow surface and weighing the pans at different time intervals. The weight loss or gain during the time period was assumed to be due to evaporation or condensation at the surface during the period of observation. The aluminum pans were painted white to reduce the absorption of radiation from the sun.

Snow measurements were taken at Ottawa during the years 1956-57, 1957-58 and 1958-59. In addition measurements were taken at Ft. Frances, Ontario, in 1957-58, 1958-59, and at Glacier, B.C., in 1957-58, 1958-59. The work of Mr. O. R. Carlson at Ft. Frances (Department of Northern Affairs and National Resources) and Mr. P. Schaerer at Glacier (National Research Council) is gratefully acknowledged. The sites at Glacier and Ft. Frances are considered to be semi-sheltered because the measurements were made in a cleared section of a general forest area. The site at Ottawa is considered semi-exposed as the observation area was exposed to drifting snow.

There were many days when it was impossible to obtain reliable measurements because of weather conditions and so the records are rather sporadic. The opportunity for measurement at Ft. Frances was greater than at Ottawa or Glacier and consequently there are more observations from this site than from the other two, particularly during the colder months when the rate of evaporation is small. Figure 4 shows histograms of the evaporation rates observed at the three stations.

At Ottawa evaporation losses were observed from other surfaces as well. These included the water surface of a Class "A" evaporation pan which was set up as part of the evaporation measurement program of the Meteorological Branch, Department of Transport, water saturated peat moss placed in a 4-ft diameter pan (12 in. deep) flush with the ground near the Class "A" pan site, and a water surface in a 10-ft diameter tank, 12 in. deep, placed flush with the ground at the same location. The pans were located in a grassed field which was frequently wet and therefore the evaporation condition can be considered as approaching "mid-ocean" rather than "mid-desert". The analysis of the records obtained is not yet complete but some results are presented and compared with the observed losses from the snow cover.

Analysis of Results

The average values of all measurements are shown in Figure 5, where measured evaporation rates are plotted against the average vapour pressure difference. Average values for the vapour pressure of air over the periods of observation were calculated by using the relative humidity and air temperature recorded at nearby standard meteorological stations. In calculating air vapour pressures for Ft. Frances, the dew-points recorded at Kenora were used.

The vapour pressure of the air at the snow surface was calculated by assuming that the average snow-surface temperature is equal to the mean air temperature. Studies at Ottawa indicate that over a period of time average snow-surface temperature equals average air temperature. Whenever the snow was melting the vapour pressure at the surface was assumed to be equal to 6.1 mb. The vapour pressure at the other surfaces was obtained by assuming that it was equal to the saturation vapour pressure of air at a temperature equal to the average, measured temperature of the surface.

Because of the difficulty of obtaining satisfactory evaporation measurements and of estimating average vapour pressure differences, it was realized that accurate correlations could not be expected. The snow evaporation measurements in particular showed considerable scatter when plotted on a daily basis. The results are presented, however, and compared with a recent Penman formula for evaporation pans to show that if observations are averaged over a long enough period, reasonable estimates of evaporation can be obtained when suitable records are available.

Wind speed records were not available for the snow observations at Ft. Frances or Glacier. Records at the Ottawa site indicated that the average wind speed at 2 metres was approximately 100 miles per day for the observation periods. This value for the wind speed was used in the Penman formula given below:

$$E_o = 0.35\,(e_o - e_d)\,(0.5 + \frac{U_2}{100})$$

which for a wind speed of 100 miles per day at two metres simplifies to:

$$E_o = .039\ \Delta e$$

where Δe = vapour pressure difference, (mb of Hg), and

E_o = evaporation rate, cm/24 hr.

Observations obtained at Norman Wells, N.W.T. by Mr. R. Brown of the Division of Building Research for the Meteorological Branch evaporation measurement program are also plotted on Figure 5. Although this site could be considered as an exposed site, the observations are comparable to the observations made at Ottawa. If wind speed records had been available at all stations and used in the analysis, better correlations might have been achieved.

Other authors (11) have confirmed that pan evaporation can be reliably estimated from empirical functions involving wind speed, dew-point, and water temperature. They have also pointed out that usually when pan water temperature is observed, pan evaporation is measured so that the empirical functions are, in this case, of limited usefulness. If the surface vapour pressure can be estimated from mean air temperature as was done in the case of the snow observations, then the empirical functions derived can be used to estimate pan evaporation using only commonly available records of wind, dew point and air temperature. Penman (16) has attempted to eliminate the need for water-temperature observations through simultaneous solution of an empirical mass-transfer equation and an energy balance equation. Of course, even if pan evaporation formulae or records are available, there still remains the problem of obtaining a suitable pan coefficient if they are to be used to estimate evaporation from lakes. Detailed discussions of this and other aspects of pan evaporation are given in the Lake Mead Studies (19) and will, undoubtedly, be the subject of considerable discussion in other papers at this symposium.

CONCLUSIONS

It was pointed out that evaporation investigations fall into two classes: those associated with the fundamental evaporation process, and those associated with the estimation of evaporation for practical application. For the first case, stringent requirements will be placed on the quality and accuracy of the instruments and the experience of the observer. To quote Penman (16) once again, "There is the purely scientific problem of the physics of the evaporation process, the solution of which involves complex ideas, complex experimental techniques, and may at times appear completely irrelevant to field problems." Frequently in evaporation studies investigators attack the evaporation problem from a research point of view when the instrumentation and facilities available do not justify such an approach.

Common to almost every evaporation problem, be it an operational or a research problem, is the difficulty of obtaining a direct measure of evaporation to compare with any calculated value. Consequently, it is most difficult to put limits on the accuracy of evaporation estimates. If estimates are obtained by different methods there will be a choice of estimate. The best estimate will usually have to be decided on the basis of the records that were available for analysis. For whatever formula or method is used, the accuracy of the estimate will depend on the quality of the basic records available. Thus, from the operational point of view at the present time in Canada, the need is to measure and record, under field conditions, all the quantities needed to check and use the methods that are now available for estimating evaporation losses.

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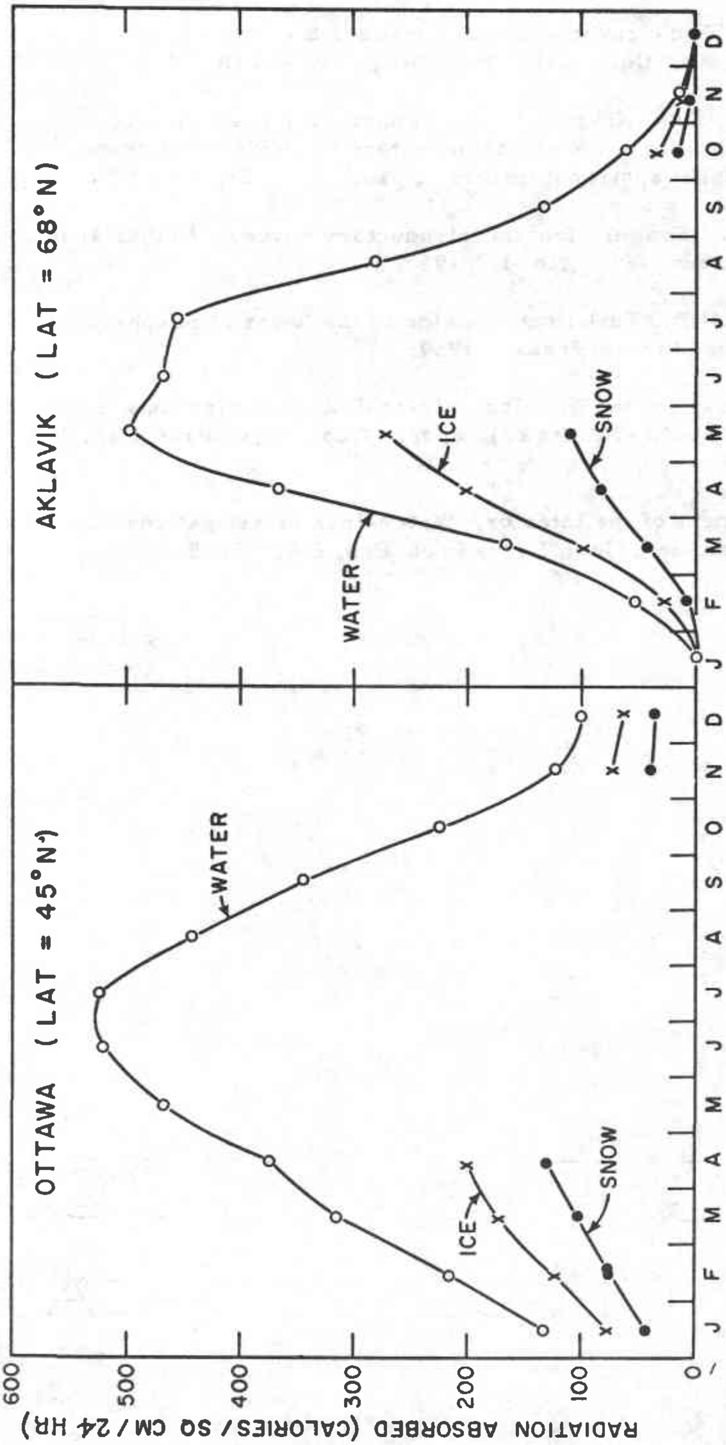

Figure 1 - Comparison of radiation absorbed by snow, ice and water surfaces.

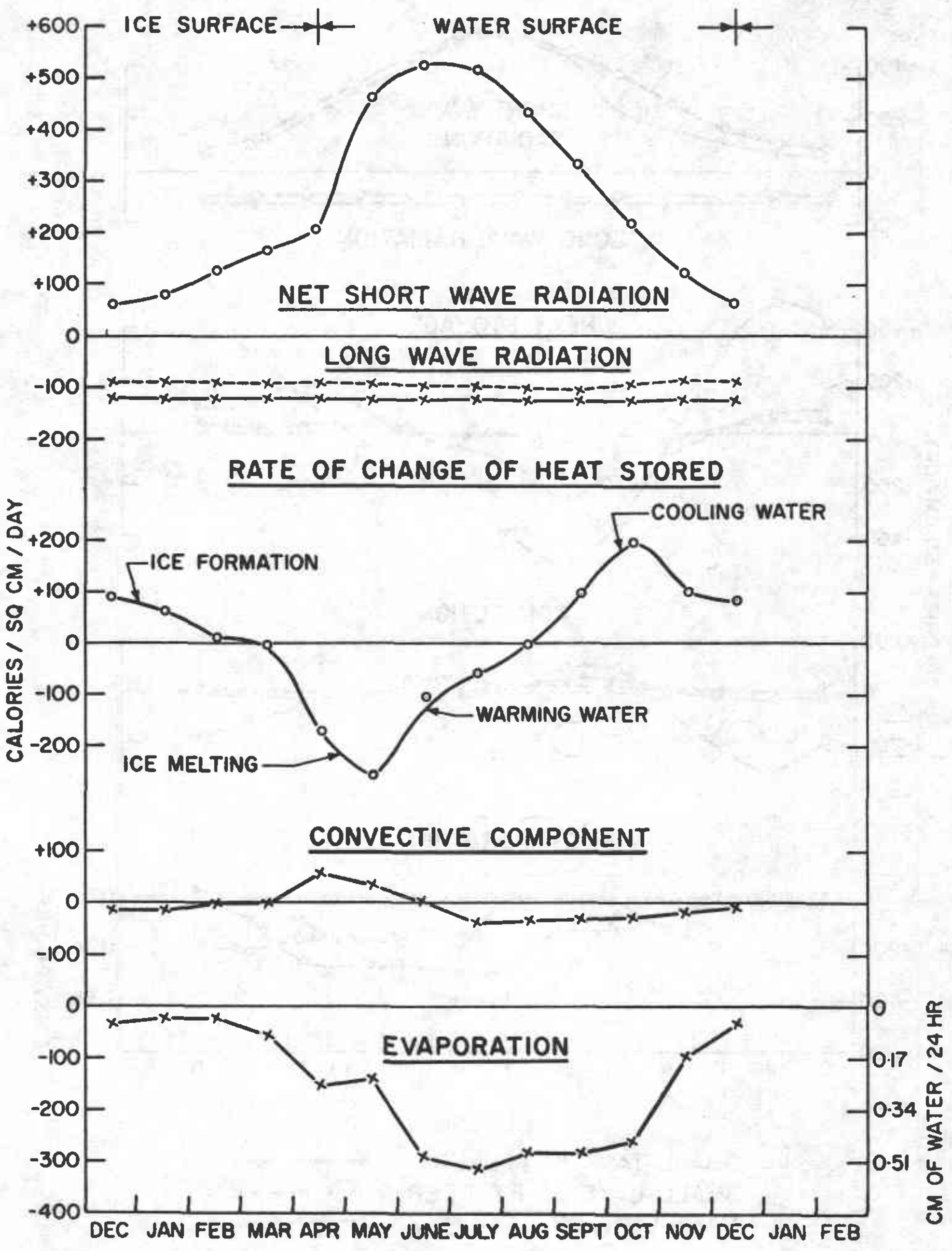

Figure 2 - Estimated monthly energy balance, small lake, Ottawa.

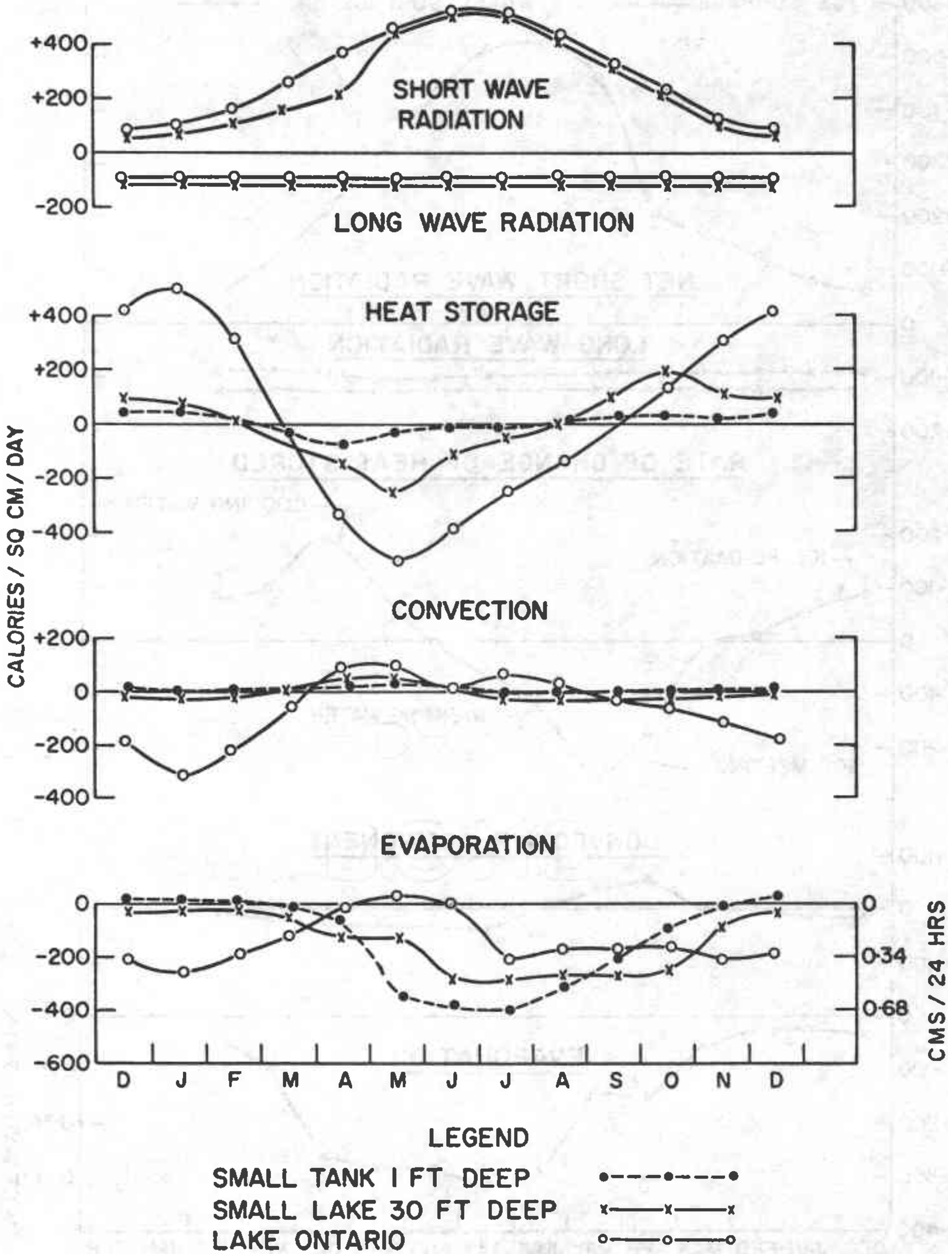

Figure 3 - Comparison of energy balance of small tank, shallow lake, large lake.

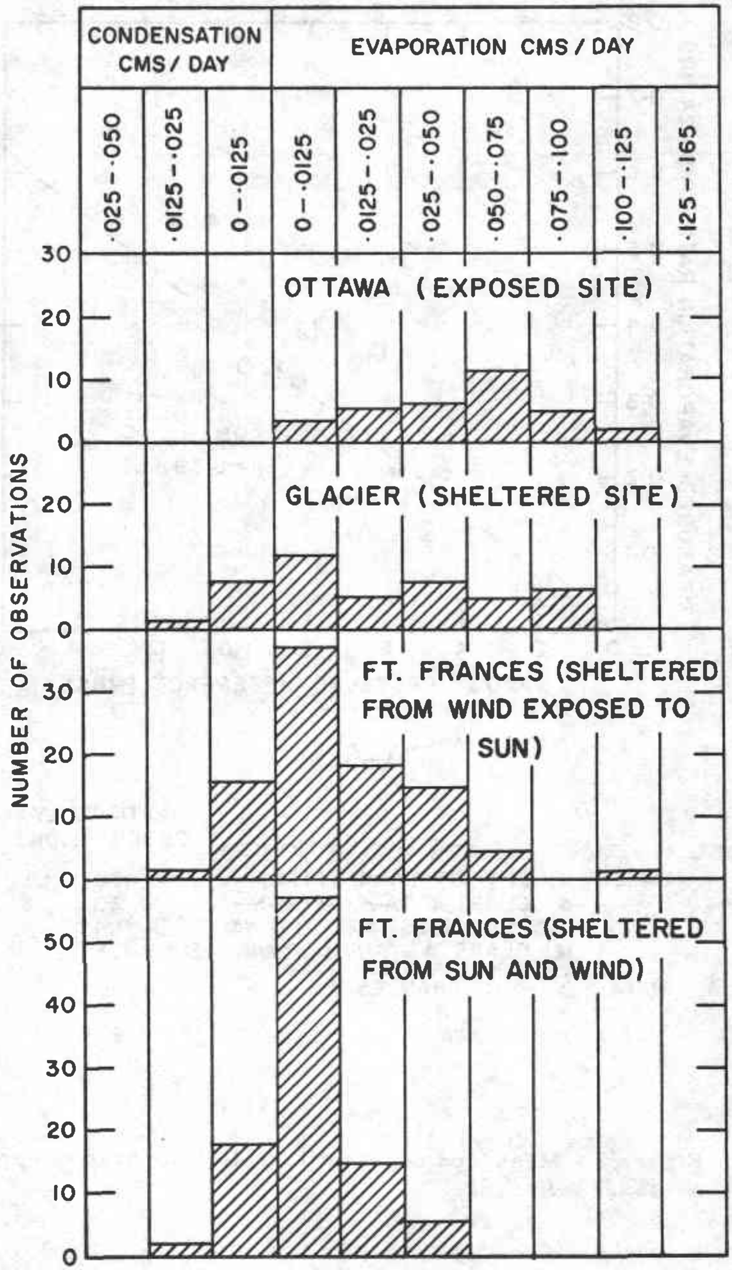

Figure 4 - Histograms of evaporation observations at Ottawa, Glacier, Fort Frances.

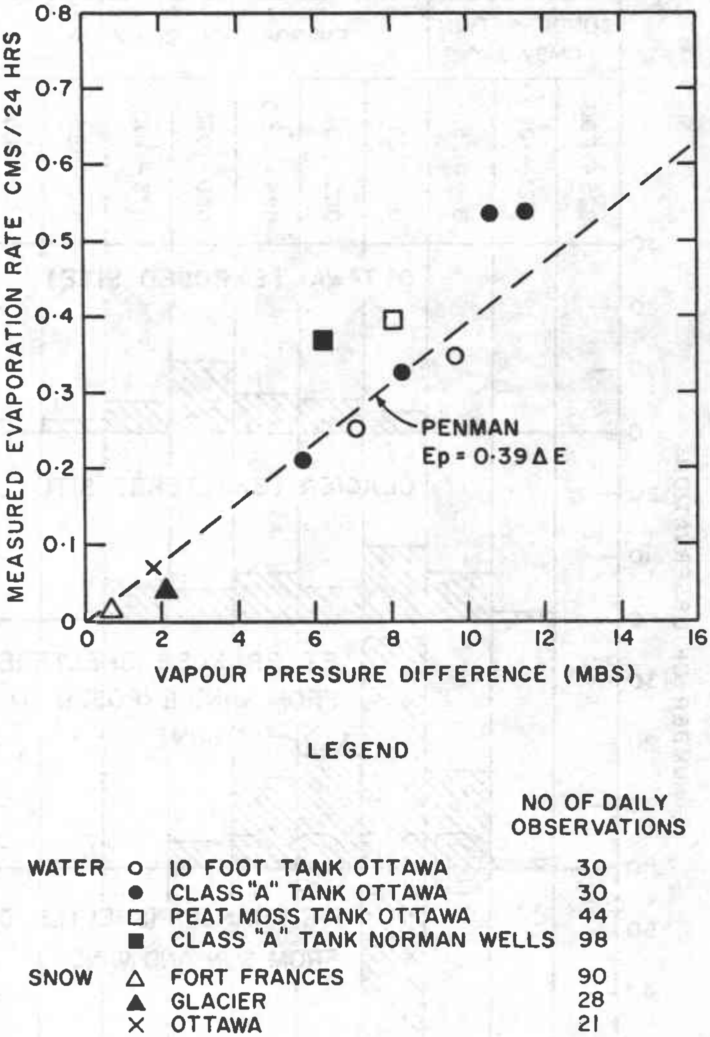

Figure 5 - Measured evaporation rate compared to vapour pressure difference.

Dr. ORVIG pointed out that Mr. Williams, in discussing the energy balance method of measuring and calculating evaporation, wrote the Bowen ratio as the ratio of the temperature difference at two levels to the vapour pressure difference at the same two levels. This assumes the same value for the exchange coefficients in heat and water vapour exchange. Measurements of these coefficients, however, seem to give as many different values as the number of sites investigated. Therefore, in order to obtain general results, it would seem preferable to use the energy balance method.

Penman has found a high correlation between net radiation and water use (evapotranspiration) over a grass surface. In Canada there are large areas of peculiar vegetation types which do not behave as "normal" vegetation. For example, surfaces in the central part of the Labrador-Ungava peninsula have very low rates of evapotranspiration, and low correlation between water use and net radiation. Such conditions, of lower-than-expected evapotranspiration and hence high runoff, are also found in similar areas in Finland. The low evaporation is caused by the insulating effect of the lichen cover, which does not act as a transporting agent for water from the ground to the atmosphere.

Mr. WILLIAMS in reply stated that over snow covers there are periods when it is most difficult to obtain meaningful values for Bowen's ratio. For example, if warm air is passing over a melting snow cover the difference in temperature between the surface and the air is great, whereas, depending on the vapour pressure of the air, the difference between the vapour pressure of the air and the vapour pressure of the surface can be small, and it can even fluctuate between plus and minus values. In this case, calculated values of Bowen's ratio can fluctuate between large positive and large negative values, and it is very difficult to use Bowen's ratio to solve for snow evaporation in the energy balance equation.

Mr. GOLD added that in determining the energy balance, it is assumed that:

$$Q_e = K_e u\,(e_o - e_a)$$

$$Q_c = K_c u\,(e_o - e_a)$$

At some stage in the calculation, an assumption equivalent to Bowen's ratio must be made. In this case, it is assumted that K_e/K_c is constant. Also, it is not only the change in the character of the energy exchange from one area to another which must be considered, but also the change with time at one area.

Dr. ORVIG replied that in investigating the importance of radiation, in the energy balance equation, it is found that it changes markedly from one time to another and also with location. Radiation is overwhelming in the ablation of glaciers in temperate latitudes, such as Switzerland, and in the early part of the melting season in high latitudes. In locations near open water and, in general, late in the ablation season, the importance of eddy flux increases as more warm air is advected over the snow and ice surfaces. The relative importance of convection and radiation in the heat transport to the surface depends therefore on both time and location.

Dr. PORTMAN was interested in Mr. Williams' statement that radiometers "... are still at the state of development where they require practically constant supervision ..." for reliable results. His own experience in working with ventilated radiometers for nearly a dozen years has led to an opposite view. In fact, the ability to measure net radiation is the one bright spot in an otherwise discouraging overall measurement problem.

Mr. WILLIAMS replied that he could only speak about his own experience in the measurement of net radiation. Two commercially available net radiometers were compared, and it was found that there were large differences on a short term basis, but that over a period of several days the agreement was reasonable but by no means perfect. It is pointed out that it is much more difficult to get a reasonable measurement of net radiation over snow covers, where the net radiation term can be small and of the same order of magnitude as the convective and heat storage terms.

Mr. MUKAMMAL said that the eddy transfer coefficients of heat and moisture are different, as has been proved by Priestley, but this difference diminishes as the surface is approached since the stability effect is at a minimum. It is therefore recommended that the potential difference of temperature and humidity should be measured as near the surface as possible for computing Bowen's ratio.

Mr. CAVADIAS said that in the paper there is the remark "Penman has attempted to eliminate the need for water temperature observations through simultaneous solution of an empirical mass-transfer equation and an energy balance equation." In "Hydrology for Engineers" by Linsley, Paulhus and Kohler, there is a similar remark that "Penman has shown that the need for water temperature observations can be eliminated." Is it not true that Penman has not shown, but simply assumed, that the need for water temperatures can be eliminated?

Mr. WILLIAMS replied that he had not checked with field data to see whether or not Penman's method of eliminating the need for water temperature observations is satisfactory, and he would rather not comment on this question without actual calculations to back up any comments.

A list of all publications of the Division of Building Research is available and may be obtained from the Publications Section, Division of Building Research, National Research Council, Ottawa, Canada.