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BY

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PREFACE

This brief review of the knowledge on the subject of evaporation from natural surfaces has been prepared in report form for use in answering inquiries and to serve as an introduction to the subject. Several extensive review papers are already available in the published literature.

The author is a research officer with the Snow and Ice Section. The members of this Section have a special interest in evaporation because of the way in which it influences such matters as the heat losses from water, ice and snow surfaces, the properties of the snow cover, and the temperature and moisture content of the ground itself.

Ottawa
November 1959

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EVAPORATION FROM NATURAL SURFACES

by

G.P. Williams

Many persons are concerned with the calculation of evaporation from water, snow, ice, and ground surfaces, including the total evaporation loss or "evapotranspiration" from vegetation covered surfaces. There are several extensive reviews available which summarize evaporation theory, measurement, and calculation (1,2,3,4,5), although much of this information is not in a form which can be readily digested and applied. It is the purpose of this report to summarize briefly the main factors which determine the rate of evaporation, to outline the difficulties in evaporation measurement, and to give a comparison of the evaporation rates as calculated by four different formulae.

VAPOUR-PRESSURE DIFFERENCE

The factors which affect evaporation are generally known but the relative contribution of each cannot usually be calculated accurately because of complex interrelationships. Perhaps the most important is the dependence of the rate of evaporation on the difference between the vapour pressure at the evaporating surface (e_w) and the vapour pressure (e_a) above the surface. Vapour pressure is defined as the partial pressure of the water vapour in the atmosphere. (The relative humidity of the air equals $100(e/e_s)$ where e/e_s is the ratio of actual vapour pressure to the saturation vapour pressure at the same temperature.) It has been found that the rate of evaporation does correlate with $e_w - e_a$, where e_a is measured at some standard height.

WIND AND TURBULENCE EFFECTS

Transfer of water vapour from an evaporating surface to the free air stream takes place through two layers: the laminar layer adjacent to the evaporating surface where transfer is essentially a molecular process, and the turbulent layer above the laminar layer where vapour transfer is essentially by turbulent mixing. The resistance to vapour flow is much higher in the laminar layer than in the turbulent. Therefore, the thickness of the laminar layer is an important factor in the over-all resistance to the vapour flow. This thickness is largely determined by the wind speed. It can be several millimeters under stable conditions and practically zero for very high wind speeds. The wind speed also determines the degree of turbulent mixing and therefore the resistance to vapour flow in the turbulent layer.

Often the effect of wind speed and vapour pressure differences are combined in the following form

$$E = (K)\ U\ (e_w - e_a)$$

where U = mean wind speed
K = turbulence factor

Closely related to atmospheric turbulence is the effect of surface roughness. This roughness factor is often introduced into the general evaporation equation as follows:

$$E = \frac{K\ U\ (e_w - e_a)}{f\ (Z)}$$

$f(Z)$ = roughness parameter.

NATURE OF THE EVAPORATING SURFACE

The discussion so far has considered the factors which, except for the roughness parameter, are independent of the surface. Evaporation from surfaces such as soil, vegetation, snow and ice require consideration of the material and the nature of its surface. For instance, the maximum temperature which a snow or ice surface can attain is 32 degrees F, and hence evaporation will not take place unless the vapour pressure of the air is less than the saturated vapour pressure of air at 32 degrees F.

For a porous material such as soil, the rate of evaporation may be determined by the availability of water. If the soil surface is saturated, the evaporation rates will probably be fairly close to those from a water surface. However, if the soil is not saturated the rate will be controlled by the availability of water, which is governed by many factors including degree of saturation and soil properties.

Evaporation from a vegetative surface is further complicated by transpiration. Evapotranspiration is related not only to the factors already considered but also to the nature of the vegetation. Evaporation from surfaces such as concrete requires the consideration of the same general factors such as exposure to wind, vapour pressure differences, surface roughness, and availability of water.

Measurement of Evaporation

The difficulties in measuring direct evaporation from specified surfaces such as water, snow, ice, and vegetation are formidable. Consequently, measurements have generally been restricted to those taken with instruments which measure the evaporative power of the air and not the actual evaporation. The instruments include tanks or pans, porous porcelain bodies, and wet paper surfaces. Suitable correction must be applied to adjust the measured evaporation rate from the saturated instrument surface to correspond to evaporation from a specified surface; to obtain such a reliable coefficient is a difficult part of evaporation analysis (6).

In an attempt to bring some standardization to evaporation measurements some authors have suggested the term "latent evaporation", and have proposed that evaporation for climatological purposes be defined in terms of the maximum amount of water which can be evaporated from liquid to vapour at some standard surface (7). The black Bellani plate, a relatively inexpensive instrument, has been suggested as this standard evaporation instrument.

One of the chief difficulties in obtaining a coefficient which will relate evaporation from a standard surface to evaporation from a natural surface is the difference in heat storage. For example, the stored heat in a large water reservoir provides energy for evaporation during the fall and winter months, whereas the small amount of water in a standard evaporation pan has little capacity for heat storage (8). Height of the rim above the water surface, influence of the pan colour, and dimension of the tank parallel to the wind direction are other properties which affect evaporation rates and result in an element of uncertainty in relating evaporation from pans to evaporation from larger water bodies.

*EVAPORATION MEASUREMENT IN CANADA

The amount of evaporation from tanks of water exposed to the weather has been measured at a few stations in Canada for over thirty years. The total evaporation, known as evapotranspiration, has been measured at a few stations in Canada during the last ten years. Other methods, such as the Piché atmometer and the Bellani plate, have also been used in Canada, but few observations have been published.

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*Much of this portion of the report has been obtained from a note on Evaporation Measurements in Canada by D.W. Boyd, Meteorologist attached to D.B.R.

Middleton (9) gives a short discussion of evaporation measurements and describes the evaporation tank and other instruments. Robertson (10) has collected the monthly totals of the tank evaporation measurements at Experimental Farms in Canada to the end of 1952, and in an appendix he gives specifications for a standard evaporation tank.

Measurements of evapotranspiration have been made at Toronto, Windsor, Guelph, Kapuskasing and Norman Wells. Descriptions of the installations at Canadian stations and tabulations of the measurements are given in a series of papers by Sanderson (11,12,13,14).

At the present time there do not seem to be many other evaporation measurements available in Canada. An evaporation pan with a rain shield has been in operation at Summerland for some time; the Experimental Farm at Regina is using a Piché evaporimeter in addition to a tank. Readings from these instruments are on file at the Meteorological Office, Department of Transport, Toronto.

With one exception it would appear that the only Canadian records published on the black Bellani plate are those used as examples in papers by Robertson and Holmes (15). Observers at the McGill Knob Lake research station reported on measurements of evapotranspiration from a lichen woodland surface and compared these measurements with computed values and with the black Bellani plate measurements (16). It was found that the measured evapotranspiration was only one third of the theoretically estimated amounts. The observations suggest that often the type of surface is more important than climatic conditions in governing evapotranspiration, and that great care must be taken in using computed evaporation rates to estimate evaporation amounts from specified surfaces.

A paper by Berry (17) would be very useful to anyone requiring an estimate of evaporation from lakes and reservoirs in the Canadian prairie region. Not only is the usefulness of evaporation pan measurements in Western Canada analysed but evaporation rates are also calculated for this region.

Evaporation Formulae

The measurement of evaporation requires the careful attention of skilled observers over a period of years before satisfactory results can be obtained. Often these records are not available, or the relationship between evaporation from a control surface and a specified surface is not known. For these reasons it is often necessary to estimate evaporation losses from theoretical or empirical formulae. Unfortunately most of these formulae are subject to the same limitation as are evaporation pan records in that they contain a coefficient which must be evaluated by comparison with measured evaporation losses from a specified type of surface.

There are three main approaches to the problem: formulae based on the theory of turbulent mixing, formulae based on the energy balance at the surface, and empirical formulae.

The formulae based on the theory of turbulent mixing are not generally used because they require observations which are not ordinarily available, i.e., observations of vapour pressure and wind speed at different levels.

The energy balance approach is an attempt to obtain evaporation by computing or measuring such factors as radiation, convective heat loss, heat storage - so obtaining values of evaporation indirectly. Because it is difficult to obtain reliable estimates of radiation and convective heat loss, and because there are still some doubts concerning the relationship between convective and evaporative heat losses, this approach is limited to special studies.

Penman (18) combined the two approaches and produced a formula in which evaporation from open water surface can be estimated provided mean air temperature, mean dew-point temperature, mean wind speed, and mean daily duration of sunshine are known. Penman also included in his analysis evaporation rates from wet bare soil and turf expressed as fractions of that from open water.

Evaporation is often expressed as a function of various atmospheric elements in an empirical formula. There are several well known formulae, generally with a wind speed term and vapour-pressure difference term. Dalton (19) in 1802 derived this relationship which has often been known as Dalton's law. It is recognized that the simplified equations of the Dalton type neglect many factors, but the need for a formula using only commonly available climatological factors makes the use of this type of formula widespread.

COMPARISON OF EMPIRICAL EVAPORATION FORMULAE

Several different empirical formulae were examined. An empirical formula by Meyer (20), published in 1915, is examined because it has been the basis of at least two Canadian studies of evaporation from open water surfaces. A recent Russian formula

(21), a Lake Hefner empirical formula (22), and an empirical formula developed by Penman (18) are also examined. These four formulae and the definition of the parameters contained are attached as Appendix A.

Evaporation rates were calculated assuming a constant wind speed at 5 mph, with a vapour pressure difference varying from 0 to 0.25 in. Hg.

Figure 1a shows that although the general form of the equation is the same, there is considerable variation in calculated evaporation. For example, at 0.25 in. of mercury vapour pressure difference the Kuzmin formula gave a monthly evaporation loss of 3 in., whereas Penman's formula gives a value of 5.9 inches.

Figure 1b shows a plot of calculated values for a constant vapour pressure difference of 0.10 in. of mercury with wind speed varying from 0 to 25 mph. With increasing wind speed the difference between various methods of calculation increases rapidly. For example, at 20 mph the lowest value is slightly over 2.25 in. whereas the highest value is over 7.0 inches.

The purpose of comparing these calculations is to show that calculated values of evaporation from open water surfaces are subject to considerable uncertainty. These formulae can be used to provide estimates of evaporation losses, especially when the wind speed and vapour pressure differences are normal, but for anything unusual in the way of site or climatic conditions the results should be used with caution.

For the higher wind speeds the writer would be inclined to favour the formulae of Penman or the Lake Hefner empirical formulae over the formulae of Meyer or Kuzmin.

Kuzmin states that when estimating evaporation from larger water surfaces (length of wind travel over the water surface exceeding 1 km) appropriate coefficients representative of the given reservoir must be included in the evaporation formula. Harbeck stresses that there is no assurance that the constant of proportionality computed for the Lake Hefner data would apply to any other lake.

EVAPOTRANSPIRATION FORMULAE

The problem of calculating total evaporation loss (or evapotranspiration loss) from a soil surface or surface covered with vegetation is even more difficult than calculating evaporation loss from an open water surface. However numerous techniques have been developed for estimating evapotranspiration from meteorological or pan-evaporation data.

Two well known techniques developed by Thornthwaite (23) and Penman (18) use the concept of potential evapotranspiration: the water loss which will occur if there is no deficiency of water in the soil for the use of vegetation.

In developing his method, Thornthwaite limited the study to rainfall and temperature observations in different latitudes, assuming that potential evapotranspiration depends only on temperature, latitude, and time of year. A recent review discusses the general applicability and limitations of this formula (24).

Penman derived some coefficients relating evaporation from wet bare soil and from sod with adequate water supply to evaporation from a free water surface.

These two approaches will give estimates of evapotranspiration losses but should be used with caution for special site conditions, particularly if the availability of soil moisture or type of vegetative cover, and not climate factor, is likely to be the determining factor. Appendix B lists the essential items in these formulae.

Blaney (25) gives a review of evapotranspiration measurements in the United States which would be particularly useful to the irrigation engineer interested in consumptive use of water in irrigated areas.

DISCUSSION

This report outlines briefly the principles of evaporation from any surface, and indicates some of the problems of measurement and calculation of evaporation amounts. The limitations of both measurement and calculation are such that a high degree of certainty cannot be attached to either the measurement or calculation of evaporation amounts from natural surfaces under field conditions.

It is unlikely that the means of obtaining estimates of mean wind speeds over large water surfaces, vapour pressure differences over open water surfaces, soil water availability, rainfall and snowfall amounts (which need to be known in some cases to make evaporation estimates meaningful) will improve enough to result in more reliable calculation of evaporation losses than can be made now. For some studies where special instrumentation can be used, as has been done in the Lake Hefner studies, it may be possible to obtain evaporation formulae for special cases which will be highly reliable. Except in cases where such special studies are warranted, the prediction of evaporation rates will have to be based on the available methods, approximate though these may be.

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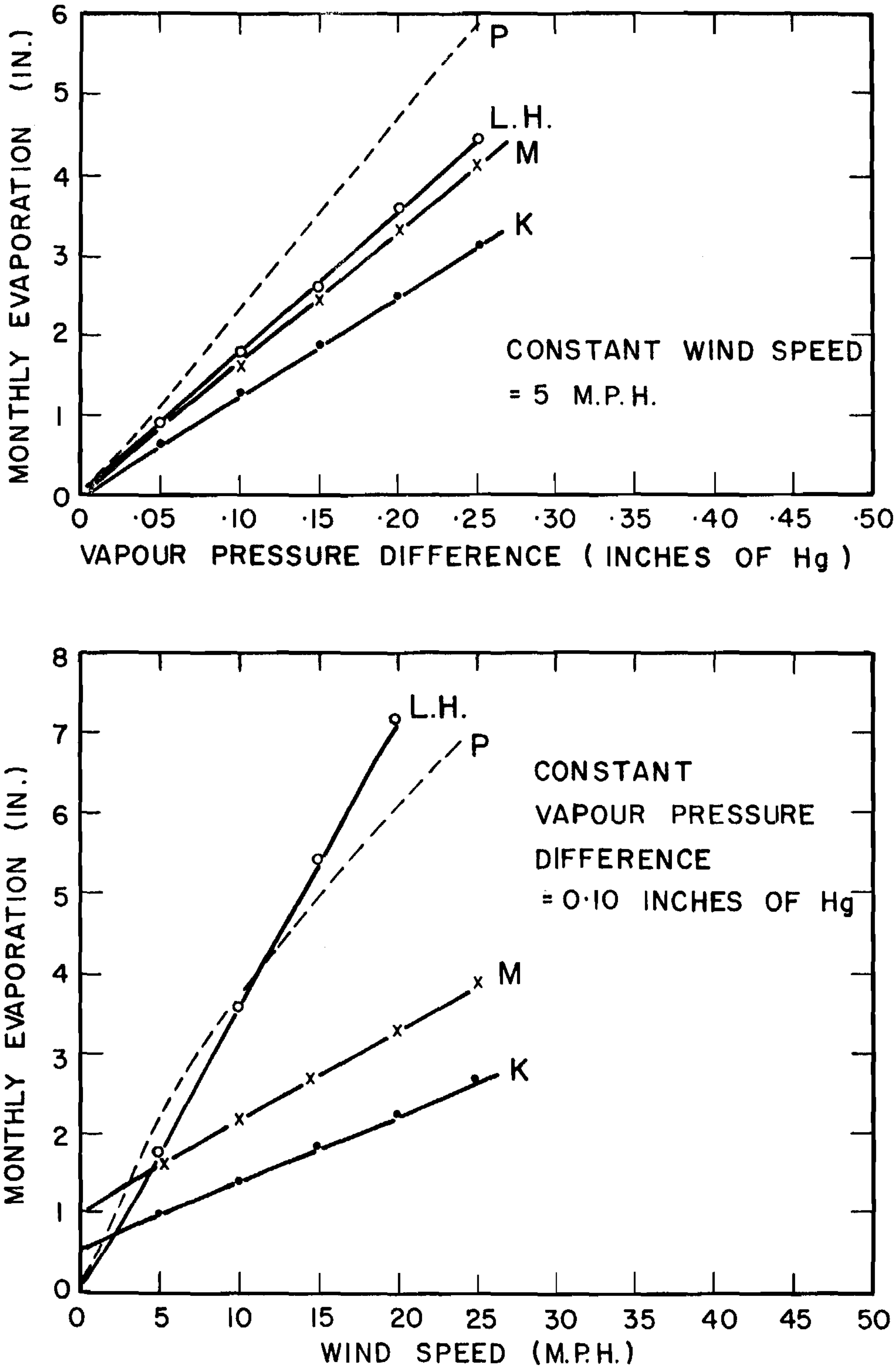

LEGEND: -----P PENMAN (WIND SPEED FROM STANDARD CLIMATOLOGICAL RECORD)

o———o LAKE HEFNER (WIND SPEED AT 8 METER LEVEL)

x———x MEYER (WIND SPEED AT 25 FOOT LEVEL)

•———• KUZMIN (WIND SPEED AT 2 METER LEVEL)

FIGURE 1 A COMPARISON OF EVAPORATION FORMULAE

APPENDIX A

COMPARISON OF EVAPORATION FORMULAE

1. **Kuzmin P.P.**

$$E = 0.13\ n\ (1+0.72W_2)(e_w-e_a)$$

E = evaporation mm/month
W_2 = wind velocity in m/sec at elevation 2 m ab. w. surface
e_a = vapour pressure of air (mb)
e_w = vapour pressure at water surface (mb)
n = given number of days in month

2. **Meyer A.F.**

$$E = C\ (V_w-V_a)\ \left(1+\frac{W}{10}\right)$$

E = evaporation (monthly measured in in. depth)
V_w = vapour pressure of air at water surface (in. Hg)
V_a = saturated vapour pressure of air (in. Hg) 25 ft above water surface
W = wind velocity in mph approx 25 ft above surface
C = 15 fully exposed pan, small puddles etc.
C = 11 for monthly evaporation from small lakes and reservoirs

3. **Lake Hefner Water Loss Investigations** (Empirical Formula)

$$E = 6.25 \times 10^{-4}\ U(e_w-e_a)$$

E = point evaporation in cm/3 hr
U = wind speed at the 8-meter level in knots
e_w = vapour pressure of saturated air in millibars at temperature of the water surface
e_a = vapour pressure of the air (mb)

4. **Penman H.L.**

$$E_o = 0.35\ (1 + 9.8 \times 10^{-3}\ U_2)\ (e_w - e_a)$$

E = mm/day
U_2 = wind velocity miles per day
$(e_w - e_a)$ = vapour pressure difference in mm of Hg.

APPENDIX B

COMPARISON OF EVAPORATION TRANSPIRATION FORMULAE

1. Penman

$$E = \frac{(H + 0.27Ea)}{+ 0.27} \text{ mm/day}$$ combined estimate for evaporation from a free water surface

where $Ea = 0.35\ (1+9.8\text{x}10^{-3}U_2)(e_w-e_a)$

(with same symbols as in App. A)

H = net radiant energy available at surface

$= \frac{dea}{dTa}$ or $\frac{e_w-e_a}{Ts-Ta}$

Evaporation from wet bare soil = $0.9E_o$

Evaporation from turf with plentiful water supply varies with season:

Nov. - Feb. = $0.6E_o$
March - Apr. = $0.7E_o$
Sept. - Oct. = $0.7E_o$
Midsummer = $0.8E_o$
Whole year = $0.75E_o$

(See original reference for more details)

2. Thornthwaite

$$e = ct^a \qquad (1)$$

where e = monthly evapotranspiration in centimeters
t = mean monthly temperature (°C)

As coefficients 'c' and 'a' vary from place to place - a general equation was developed:

$$e = 1.6\ (10^t/I)^a \qquad (2)$$

where 'a' is the same coefficient as in equation (1)
I = heat index calculated from monogram and tables where mean monthly temperature, latitude of station are known.

(See original paper for more details)