EVAPORATION—ITS MEASUREMENT AND ESTIMATION

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INTRODUCTION

Water is brought as vapour into the air by evaporation. It is a physical process by which water vapour escapes from any free liquid water surface or wet surface at a temperature below the boiling point of water. In addition to loss by evaporation from soil, water is also lost by transpiration from vegetation covering the soil or water surface. This combined loss is known as evapotranspiration.

Measurement of evaporation and evapotranspiration is of importance in many scientific fields. It is one of the main components of water budget which knowledge is indispensable for the solution of numerous water management problems. Reliable evaporation data are required while projecting and exploiting reservoirs, ponds, shipping canals, irrigation and drainage systems. They are especially important in arid zones where water must be used in the most rational way. The solution of the water requirements of crops lies in the accurate determination of the loss of water by evapotranspiration from cropped fields.

FACTORS INFLUENCING EVAPORATION

Factors influencing evaporation from free water surface:

(*a*) Solar and sky radiation.
(*b*) Temperature both of the air and of the evaporating surface.
(*c*) Wind speed.
(*d*) The difference between the saturation vapour pressure of the air at the evaporating surface temperature and the actual vapour pressure of the air.
(*e*) Atmospheric pressure.
(*f*) Depth, size and state of the evaporating surface.
(*g*) State of the surroundings and the configuration of the water body.
(*h*) Impurities and vegetation in the water body.

Factors influencing evaporation from bare soil surface:

In addition to meteorological conditions, evaporation from soil depends on:

(*a*) Moisture content of the soil.
(*b*) Depth of water table.
(*c*) Physical properties of soil.
(*d*) Chemical composition of the soil.

Factors influencing evapotranspiration:

(*a*) Meteorological factors (solar and sky radiation, air temperature, saturation defecit, wind, etc.).

(*b*) Plant factors (number of stomata, depth of active root zone, etc.).

(*c*) Soil factors (physical properties of the soil, its moisture content, etc.).

EVAPORATION INSTRUMENTS

The direct measurement of evaporation or evapotranspiration under field conditions is not feasible at least not in the sense one is able to measure temperature, humidity, wind, etc. As a consequence a variety of devices and techniques have been developed for estimating the loss of water from water and land surfaces by suitable instrumental techniques. There are three main types of evaporation instruments; atmometers, pan or tank evaporimeters and lysimeters. Each instrument has its advantage, defects and limitations of application.

Atmometers

A variety of atmometers are in use in various parts of the world. The most frequently used atmometers are those employing porous surfaces such as filter papers (Piche, Daigo and Hirata types), ceramic spheres (Livingston atmometer) and ceramic discs or plates (Bellani atmometer). The most popular of these are the Piche and the Bellani atmometers. In these evaporation is measured in cubic centimeters and can be converted to depth.

Merits of atmometers

There is no standard method of exposing these atmometers. The different types of atmometers indicate different amount of evaporation under similar meteorological conditions. The theory and substantial physical recommendations concerning the technique of observation and the use of these instruments are not available up to the present time. Atmometer exposures fail to simulate natural conditions and the value of atmometer observation is not a reliable index of evaporation. It is also extremely difficult to keep the evaporating surfaces clean. However, atmometers are likely to remain useful instruments in small scale surveys, although their use is not recommended for water resource surveys. They are simple to use, small in size, cheap and portable. They can be usefully applied after due precaution in practical agriculture for timing irrigation and in bioclimatic and microclimatic studies for getting an idea of comparative evaporation.

Pan or tank evaporimeter

These are the most widely used instruments for evaporation measurement from free water surfaces. The pan also forms the basis of several techniques for estimating evapotranspiration. There are three types of exposure employed for pan installation—surface, sunken and floating.

Surface pans

Evaporation pans of various sizes installed on the ground surface are in use in many countries. These experience greater evaporation than sunken pans, primarily because of the added radiant energy intercepted by the sides. Adverse side-wall effects can be eliminated to a great extent by an insulated pan, but this adds materially to the cost.

Sunken pans

The main advantage claimed for sunken pans is that the aerodynamic and radiation characteristics are more nearly like those of a lake. Sunken pans collect more trash; they are difficult to clean; leaks cannot easily be detected and rectified; and the height of vegetation adjacent to the pan is quite critical. Moreover, appreciable heat exchange does take place between the pan and the soil under circumstances which depend on many factors including soil type, moisture content and vegetation cover. Use of a large sunken pan is likely to reduce these defects and the consequent relative variation.

Floating pans

The floating evaporation installation is used for the study of evaporation from reservoirs and lakes. It is mounted on a special raft with float-cisterns. Observational difficulties are the chief disadvantages of floating pans and splashing frequently renders the data unreliable.

Standard pan

At present there is no universally recognised international standard evaporimeter pan or tank. During the I.G.Y. the World Meterolological Organization recommended the use of Class *A* pan as an interim instrument for recording evaporation as a result of which the Class *A* pan became the most extensively used evaporimeter. But in spite of this many countries, particularly U.S.S.R., had used various other kinds of tanks, either mounted above the ground or sunken into the ground, of varying dimensions and shapes. Unless the evaporation readings collected by the various countries are based on a reliable evaporimeter—the readings of which could be reduced to some internationally accepted standard evaporimeter—the evaporation values obtained by the various countries would not be comparable. Recognizing this fact the W.M.O. has set up a Working Group on the Measurement of Evaporation with the following terms of reference:

(*a*) To draft a chapter on the measurement of evaporation for the Guide to Meteorological Instrument and Ovserving Practices;
(*b*) To make recommendations for the selection of an interim international reference evaporimeter taking into account the results reported by Members on comparison of evaporimeters;
(*c*) To consider the role of evaporation pans in the study of evaporation and evapotranspiration;
(*d*) To consider and advise whether the evaporation pan might be superseded by the measurement of definable meterological elements.

A standard plan together with the specifications for the evaporimeters whose comparison has been recommended by the W.M.O. has already been circulated. In order to find out the present status of evaporation measurement the W.M.O. circulated a questionnaire to all the countries. The results of somes of the pan evaporimeter comparisons revealed from the answers received from the various countries are summarised below with a view to facilitate the inter-comparison of the evaporation values of the various countries after reducing to a suitable standard.

India:

(i) $\dfrac{\text{20 ft. diameter, 10 inches deep, mounted above ground}}{\text{Class } A \text{ pan}} = 0.78$ (2 years at Poona).

(ii) The experiments at Poona have shown that when a G.I. wiremesh (22 s.w.g.; hexagonal mesh 1½ inch between opposite sides) is used, the evaporation measured in this tank has to be multiplied by a factor 1.144 to obtain the evaporation in a Class *A* pan without any cover.

(iii) The evaporation measured by the use of a pan varies with the size of the pan. Evaporation E in inches from a pan of diameter d in feet is given by $E = E_a + A \times B^{-d}$ where E_a = evaporation in inches from class A pan adjusted to lake evaporation, A and B are constants determinable experimentally. In case of Poona they were found to be 0.1393 and 1.148 respectively. Similar studies in U.S.A. have shown that the size effect is negligibly small beyond 12 feet diameter.

Israel:

$$\frac{\text{Sunken pan (12 ft. diameter, 3.3 ft. deep)}}{\text{Class } A \text{ pan}} = 0.74 \text{ (6 years; at Lod Airport)}$$

Kenya:

$$\frac{\text{Kenya pan (4ft. diamter, 14 inches deep, screened}}{\text{Class } A \text{ pan}} = 0.77 \text{ (4 years; at Dagorethi Headquarters)}$$

Netherlands:

$$\frac{\text{Sunken pan (50 cm. diameter \& 25 cm. deep)}}{\text{Class } A \text{ pan}} = 0.64$$

New Zealand:

$$\frac{\text{New Zealand sunken pan (3 ft. diameter, 3ft. deep)}}{\text{Class } A \text{ pan}} = 0.96 \text{ (*) } (2\tfrac{1}{2} \text{ years; at Winchmore)}$$

Norway:

$$\left.\begin{array}{ll} \text{(i)} & \dfrac{\text{'Aslyng' (sunken, surface area of } 1/3\,\text{m}^2 \text{ and one metre deep) with screen}}{\text{Class } A \text{ pan}} = 0.63 \\[2ex] \text{(ii)} & \dfrac{\text{'Aslyng' without screen}}{\text{Class } A \text{ pan}} = 0.77 \\[2ex] \text{(iii)} & \dfrac{\text{Andersson (8 cm. diameter, 5 cm. deep, made of perspex, placed about 10 cm. above the soil surface)}}{\text{Class } A \text{ pan}} = 0.63 \end{array}\right] \begin{array}{c} \text{3 years;} \\ \text{at} \\ \text{Oslo} \end{array}$$

From (i) and (ii) it is seen that the readings on unscreened Aslyng pan are 1.22 times greater than those of a screened one.

Sudan:

$$\frac{\text{Sunken pan (12 ft. diameter, 4 ft. deep)}}{\text{Class } A \text{ pan}} = 0.65 \text{ (2 years; at Khartoum).}$$

In these comparisons evaporation from a 12 ft. in diameter and 3 ft. deep pan has been assumed to be quivalent to lake evaporation.

(*) This coefficient is too high in comparison with those found between a sunken pan and Class *A* pan in other countries.

U.S.A.:

Average lake-to-pan ratios (Annual)

Location	Class *A* Pan	BPI sunken 6 ft, diameter, 2 ft. deep.	Colorado sunken 3 ft. square 2 ft. deep.	Screened sunken (young) 2 ft. diameter, 3 ft. deep.
Denver, Colorado (12 ft. pan 3 ft. deep)	0.67			
Fullerton, California (» »)	0.77	0.94	0.89	0.98
Ft. Mc Intosh, Texas (» »)	0.73			0.88
Falcon Dam, Texas (» »)	0.68			0.91
Dryden, Texas (» »)	0.73			0.96
Lake Elsinor, California	0.77			0.98
Red Bluff Reservoir, Texas	0.68			
Lake Okeechobee, Florida	0.81		0.98	
Lake Hefner, Oklahoma	0.69	0.91	0.83	0.91
Felt Lake, California	0.77	0.90	0.84	0.98
Lake Colorado City, Texas	0.72			

U.S.S.R.:

(i) Ratios of evaporation based on 11 years' data at Valday.

	May	June	July	August	September
20 m²/GGI-3 000	0.99	0.97	0.97	0.95	0.91
20 m²/Class *A* pan	0.71	0.71	0.73	0.79	0.89

(ii) Mean evaporation values (mm) of 3 000 cm² area pan having different depths at Valday (1952-1961).

Depth of pan (m)	Month						Total
	May	June	July	Aug.	Sept.	Oct.	
0.25	65	91	90	72	36	13	367
0.50	66	92	92	74	39	15	378
1.0	70	93	92	77	45	20	397
2.0	70	94	92	76	49	25	406

(iii) Evaporation values (mm) of GGI-3 000 pans installed into different types of soil.

Type of soil	Month						Total
	May	June	July	Aug.	Sept.	Oct.	
(a) *At Valday (1951-1955) — Humid Zone:*							
Sand	71	84	84	74	44	16	373
Loam	74	85	88	77	46	16	386
Peat	71	87	87	75	46	14	380
(b) *At Dubovka (1958) — Arid Zone:*							
Sand	198	207	183	202	129	—	919
Loam	146	186	161	167	114	—	792

The data of the above comparisons appear to indicate that sunken pans give more representative values than the pans exposed above ground and that their readings in humid areas are not influenced by the type of soil in which they are embedded while in arid areas the type of soil introduces a considerable variation. However, this would require to be confirmed by comparisons carried out under a variety of climatic regimes.

General precautions

The site must be even and horizontal and must, if possible, be open on all sides so that free circulation of air is not hindered. When selecting the site the availability of fresh water for filling and replenishing the evaporation tanks should be borne in mind. If a large amount of fresh water cannot be obtained, the evaporimeters can be filled initially with mineral water, but topped up only with fresh water. Temperature of the replenishing water should be about the same as that of the water in the evaporimeter. The evaporimeters should be tested for leakage whenever a sudden rise in evaporation is noticed. Routine test for leaks should preferably be made once in six months, particularly for sunken pans. Care should be taken to maintain water at the correct level in the evaporimeters and that no shadows are cast on the evaporimeter.

Although evaporation from large water storage depends on local meteorological conditions and exposure, it is not as sensitive to variations as is the equipment set up to measure evaporation losses. The measured loss by an evaporimeter depends, in addition to the above factors, on the type and dimensions of the pan or tank, the material from which it is constructed, and its colour and some of these factors may be varied to bring about, in extreme cases, a change as high as 50% in the measured loss.

When the depth of tank used is large and the temperature change between the successive measurements is also large, the magnitude of error arising out of differential thermal expansion of both the container and the water in it may be significant. Under such conditions it will be desirable to apply suitable corrections. Appendix I shows a sample of such corrections applicable to a Class *A* pan made of copper, zinc or iron. In order to eliminate the uncertainties arising out of different colours it will be desirable to use water resistant white paint as a standard one for painting both the inner and outer surfaces of the evaporimeter except the bottom which should be painted black.

Foreign materials such as leaves, dust and algae, get into the evaporation tank and affect the rate of evaporation. It is important, therefore, that the pans should be cleaned at intervals. In some localities the problem of birds, animals, etc., drinking from the pan makes it necessary to screen it. The use of screen reduces the sunshine and wind at the water surface with a resultant decrease in evaporation. Rains, particularly the heavy type, are a problem and a source of confusion in evaporation measurements from open tanks. Heavy rains may overflow the tank and invalidate measurements. The records are also not reliable under very high wind conditions due to splash out.

Soil evaporimeters

The estimation of the loss of moisture from the soil surface by evaporation is of great importance in agricultural meteorology, hydrology etc. Evaporation from soil surface is comparable to that from a free water surface provided the soil surface remains saturated with water. For measurement of evaporation from bare soil the following types of soil evaporimeters filled with natural soil samples are in general use: (*a*) ordinary weighing soil evaporimeters and (*b*) hydraulic soil evaporimeters. Soil evaporimeters GGI-500-50 with an area of 500 cm^2 and 50 cm deep and GGI-500-100 with an area of 500 cm^2 and 100 cm deep are in general use in U.S.S.R. Hydrometeorological stations. In general, the soil evapotransporimeters should be sufficiently big in size, be embedded in soil in an open site representative of the field condition prevailing in the area.

Snow evaporimeters

Very little information is available on measurement of evaporation from snow. Some attempts have been made to measure evaporation from snow by snow evaporimeters and determining the loss by gravimetric method.

Lysimeters

Lysimeters are multipurpose instruments, they are used to study several problems of the hydrological cycle, e.g. infiltration, run-off, evaporation and evapotranspiration. The determination of evapotranspiration is based on the water balance equation.

Precipitation = evapotranspiration (or evaporation from soil) + surface run-off + underground drainage + change in water storage of the block of soil concerned.

Lysimeters of various designs are used for the study of evapotranspiration (or evaporation from soil).

Volumetric lysimeter

In the volumetric method the lysimeter consists of a field tank in which plants can be grown under essentially field conditions, a water supply and percolation apparatus and a mechanism to control the water in the field tank. The water regulating mechanism is a simple float valve device connected to the supply tank. Measurements are made of the amount of water added, the rainfall (if any), and the percolating water at the bottom of the tank. By bringing the moisture in the soil upto field capacity at the beginning and at the end of the experiment the evapotranspiration loss in the interval is worked out.

Evapotranspiration (or evaporation from soil) = Inflow + rain + amount of water added at end of period— the amount percolated.

Gravimetric lysimeter

Recording by using a balance

Weighing makes a lysimetric installation complex. The lysimeters are installed on balances or lifted on and off for weighing by a crane. Dead weight below the expected range in weight variance may be eliminated by a counter weight. The weight or changes in weight of the lysimeter is measured. The weighing of lysimeters ought to be made in underground weighing chambers or in shelters protected from wind.

Recording by the Archimedean principle

In this type of lysimeter use is made of Archimedes principle and balance is replaced by a hydraulic system. The soil container is floated in a suitable liquid (water, aqueous zinc chloride, etc.) held in an outer container. A loss or gain of weight in the floating tank results in a change of level of the liquid in the annular space. This method also permits continuous recording. The recording system consists of a float actuated liquid level recorder giving a continuous record of weight changes of the floating tank on a clock-driven chart.

Merits of various types of lysimeters

For fairly reliable measurements of evapotranspiration or evaporation from soil the tanks size should not be less than 1 square metre in area and 1 m. in depth, the dimensions should be more for deep rooted crops.

Volumetric lysimeters are simpler, enabling the use of large tanks-necessary to contain a sufficient number of spaced plants and deep enough to permit deep root systems to develop freely—which are difficult to weigh.

Floating lysimeters have the advantage of being more economic and needing less maintenance. Floating lysimeters are also easily adopted to continuous recording.

Lake evaporation

The hydrologists, irrigation engineers, meteorologists, etc. all want to have an estimate of evaporation from the natural free water surface. The physical conditions for the various types of pans mentioned above are largely different from what exist in the case of evaporation from natural surfaces. Many experiments have been made to find out coefficients by comparison of pan evaporation with observed evaporation from large tanks and/or natural lakes. The coefficient does not only differ with type of the pan but also with the climatic regimes. It has been found that the coefficient varies from 0.75 to 1.00 in the case of U.S.S.R. GGI-3,000 pan while a floating GGI-3,000 pan given approximately coefficient of 0.90. In Class *A* pan when pan water and ambient air temperatures are equal the coefficient is found to be 0.70. In bare arid areas the coefficient approaches 0.60 and in humid areas it tends to be 0.80.

In all these experimental determination of coefficients, the variations occur due to the varying amounts of heat flow across the bottom and sides of the evaporimeters. Kohler and his co-workers have suggested a method to adjust the Class *A* pan evaporation data to obtain shallow lake evaporation by the use of figures 1 and 2. Average pan water and air temperatures and total wind run at pan level are required in using these diagrams for making the suitable adjustments of evaporation values. Shallow lake evaporation thus obtained will again be different from the evaporation of a deep lake. In the case of a deep lake one has to take into account the heat energy that is stored and net energy that is advected into the lake due to inflow and outflow. Only a part of the energy that is advected into the lake is utilized for evaporation. Considering all these factors, Kohler and his co-workers have worked out the following equation for obtaining deep lake evaporation from shallow lake evaporation.

$$E_1 = E_0 + M\,(Q_v' - Q_v)$$

where E_1 = lake evaporation (inches).

E_0 = evaporation from shallow lake (inches).

Q_v' = net energy advected into the lake (to be obtained from measurements of volumes and temperatures of in and out flows) converted into equivalent evaporation in inches.

Q_v = change in energy storage (to be computed from periodically determined temperature profiles from the lakes) converted into equivalent evaporation in inches.

M = proportion of advected energy (into a lake) utilized for evaporation. This can be obtained by the use of figure 3.

The following expression may be used for a reduction of the floating GGI-3,000 pan readings to reservoir evaporation

$$E_0 = 0.9\,E\,\frac{e_0 - e_2}{e'_0 - e_2}$$

where E_0 = evaporation from lake or other water body at raft location (mm).
E_1 = floating GGI-3,000 pan evaporation (mm).
e_0 = saturation vapour pressure at water body surface temperature (mb).
e'_0 = saturation vapour pressure at pan water temperature (mb).
e_2 = vapour pressure at a height of 200 cm above water surface (mb).

ESTIMATION OF EVAPORATION AND EVAPOTRANSPIRATION

Apart from pan and lysimeter approaches, there are five main approaches to estimate evaporation from water and soil surfaces and evapotranspiration. These are water budget, energy budget, aerodynamic including both mass transfer (sometimes called bulk aerodynamic method) and aerodynamic profile, eddy correlation methods and combination approach which is a combination of a energy budget and aerodynamic approches. Brief descriptions of these methods are given below.

Meanings of symbols used in this section are given in Appendix II.

Estimation of evaporation from water surface

Numerous attempts have been made to compute evaporation from water surface from standard meteorological data by empirical approach and by physical approach based on fundamental principles.

Formulae based on physical principles

Water-budget method

In this method evaporation is determined as a residual component of water-budget equation :

$$E_L = P + I_r - O_r - \Delta S$$

It is usually not possible to measure with sufficient accuracy the items comprising the water budget equation. Precipitation on the reservoir surface can seldom be measured accurately. The volumes of inflow and outflow include both surface flow and ground water flow. The volume of ground water inflow and outflow including seepage are usually unknown. Another item in the water-budget that is difficult to measure is the ground-water (bank) storage in the reservoir. Although the water budget approach is extremely simple in theory, its application is limited to those sites where errors in measuring seepage, inflow and outflow are small compared to evaporation.

Energy-budget method

This method is based on the principle of conservation of heat energy. A precise determination of evaporation from any type of surface may be made if accurate knowledge is available of all the factors contributing to the heat balance at the evaporating surface. The energy budget per unit surface of a reservoir per unit time may be expressed as:

$$Q_s - Q_{rs} + Q_{la} - Q_{rl} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_k$$

$$= \frac{\left[(e_o^* - e_a)^{0.88} - (e_o - e_a)^{0.88}\right](0.37 + 0.0041\,u_p)}{\left[(e_o^* - e_a)^{0.88} - (e_o - e_a)^{0.88}\right](0.37 + 0.0041\,u_p) + (7.6 \times 10^{-11})\left[(K_o^*)^4 - K_o^4\right] + 0.000367\,P\left[(T_o^* - T_a)^{0.88} - (T_o - T_a)^{0.88}\right](0.37 + 0.0041\,u_p)}$$

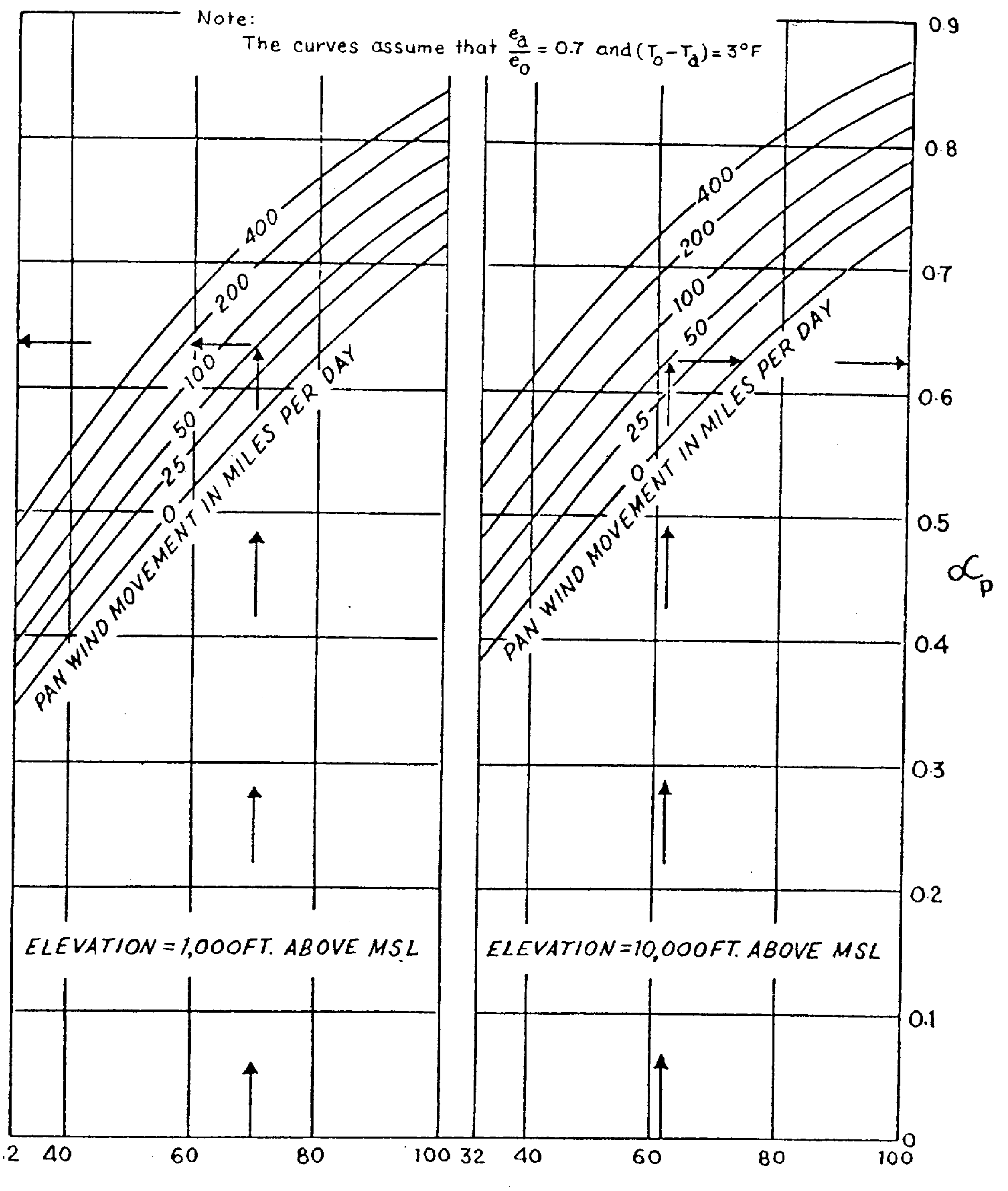

Fig. 1 — Proportion of advected energy (into a class 'a' pan) utilized for evaporation.

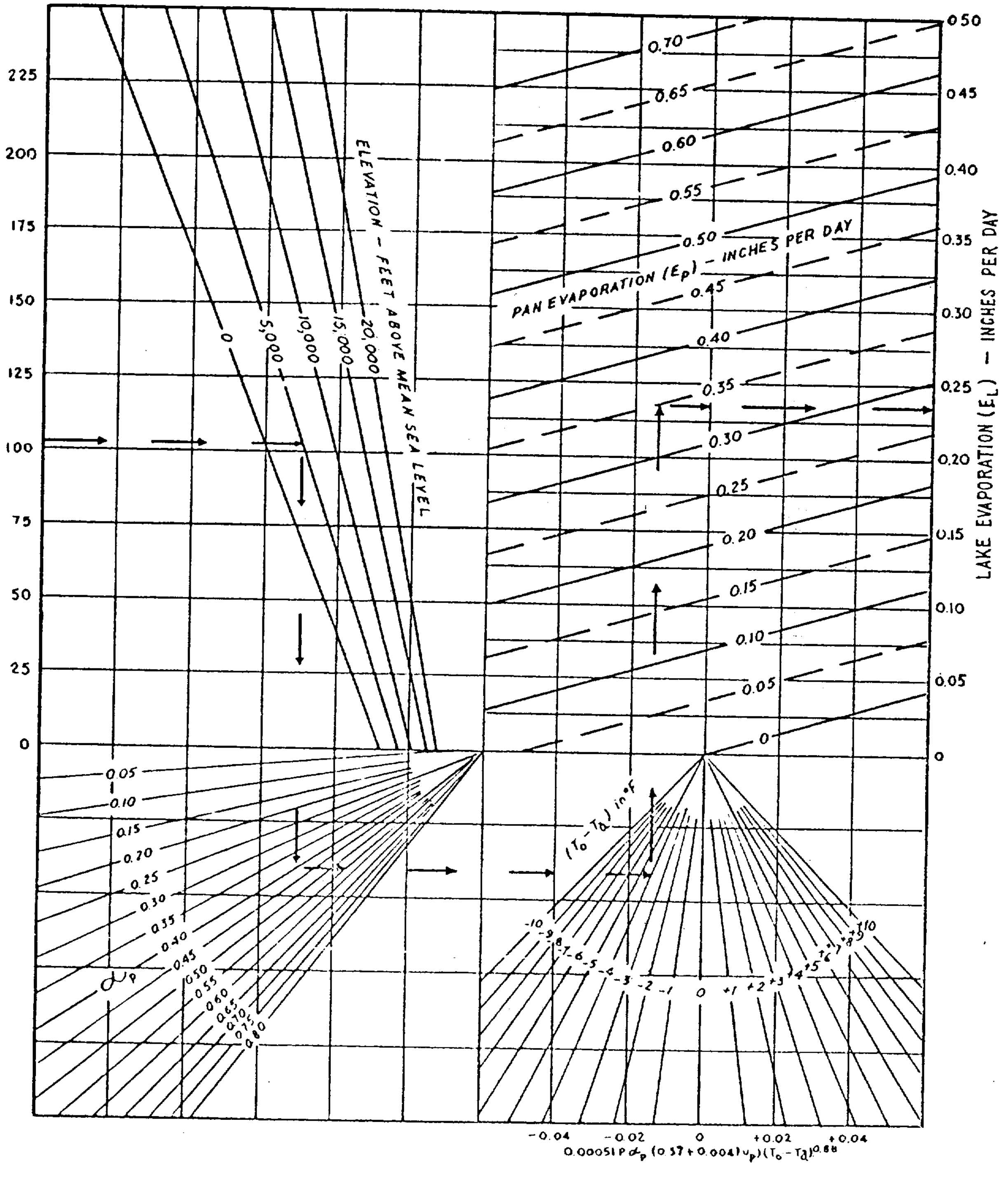

Fig. 2 — Conversion of class a pan evaporation to lake evaporation.

$$\alpha = \frac{(e_0^* - e_0)(0.00304 U_4)}{(e_0^* - e_0)(0.00304 U_4) + (7.6 \times 10^{-11})\left[(K_0^*)^4 - K_0^4\right] + 0.000367 P (T_0^* - T_0)(0.00304 U_4)}$$

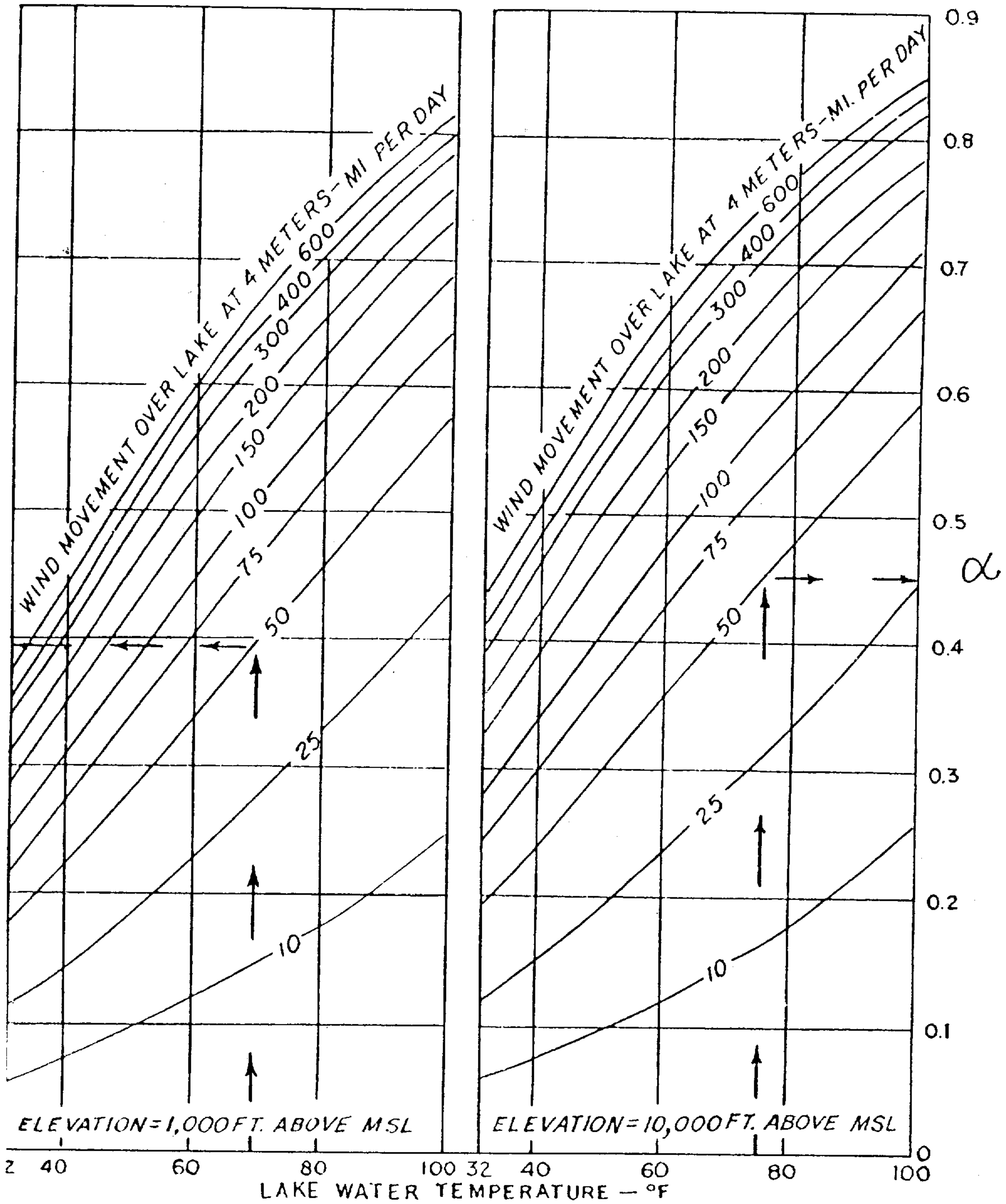

Fig. 3 — Proportion of advected energy (into a lake) utilized for evaporation.

The instrumentation required in this method is rather complex. However, if a reliable net radiation meter is available, this is one of the best methods.

For obtaining evaporation directly the above equation can also be written as:

$$E_L = \frac{Q_s - Q_{rs} + Q_{la} - Q_{rl} - Q_w - Q_k}{\varrho_w L\,(1 + \beta)}$$

Mass transfer method

This method is also known as 'bulk aerodynamic method4' There are a multitude of mass transfer equations. The basic theory of these equations is that the transfer of water vapour from the evaporating surface to the air occurs along the gradient of moisture concentration. The evaporation is proportional to the product of wind and the humidity gradient. This method has the chief advantage that all the factors can be easily measured by standard instruments. The equation is of the form

$$E = f(u)\,(e_w - e_z)$$

Aerodynamic (profile) method

The aerodynmaic profile technique for the determination of evaporation is concerned with the transfer of water vapour between two levels in the air at a small distance above the evaporating surface. The aerodynamic profile formula is valid only for neutral conditions of stability of air.

$$E = \frac{-k^2\,\varrho\,(q_2 - q_1)\,(u_2 - u_1)\,10.0}{(\log z_2/z_1)^2}$$

Eddy — correlation method

This method is also knwon as 'eddy-flux' or 'eddy-transfer' method. It consists of measuring short period fluctuations in vertical wind velocity and water vapour about some arbitrary level.

The mass of water vapour passing up or down through unit area in an element of time will be equal to $\varrho\, wqdt$. The average quantity of moisture transferred vertically through the horizontal plans in unit time will be equal to ϱwq (i.e. mean value of ϱwq).

Denoting mean values of these components by a bar and the instantaneous deviations from these mean values by a prime, the equation can be written as:

$$\begin{aligned}\overline{\varrho wq} &= \overline{(\varrho w)q}\\ &= \overline{[\varrho\bar{w} + (\varrho w)'][\bar{q} + q']}\\ &= \overline{\varrho\bar{w}\bar{q}} + \overline{\varrho\bar{w}q'} + \overline{(\varrho w)'\bar{q}} + \overline{(\varrho w)'q'}\end{aligned}$$

By the above reasoning second and third terms vanish giving

$$\overline{\varrho qw} = \overline{\varrho w}\,\bar{q} + \overline{(\varrho w)'q'}$$

The term $\overline{\varrho w}\,\bar{q}$ represents the mean transfer through the reference level and the second term $\overline{\varrho w'}\,q'$ is the eddy flux. This gives evaporation directly.

Formulae based on combination method

Penman's formula

Penman's method is based on a combination of the aerodynamic and heat balance approaches and requires a knowledge of mean air temperature, relative humidity, solar radiation and wind speed:

$$E_\infty = \frac{\Delta_a H + E_a\,\gamma}{\Delta_a + \gamma}$$

A similar approach has been used by Kohler and his co-workers for computation of evaporation from extensive shallow lake. Their technique is represented in the form of a handy nomogram shown in figure 4. Observations on solar radiation, air temperature, dew point, wind velocity at Class A pan anemometer height are required in the use of this method. In the absence of solar radiation data the same may be estimated from the sunshine data or cloud cover data by the use of one of the suitable standard formulae available for that purpose.

McIlroy's formula:

$$E \,.\, L = \frac{s}{s+\gamma_1}(Q_n - Q_k) + h \,.\, D$$

Some empirical formulae:

$$E_L = 0.13\,(e_W - e_2')\,(1 + 0.72\,U_2)$$
$$E_L = 0.131\,U_2\,(e_W - e_2')$$
$$E_L = 0.291\,A^{-0.05}\,U_2\,(e_W - e')$$

Estimation of evaporation from soil surface

Studies on estimation of evaporation from bare soil alone are very limited. An empirical formula developed by Turc given below is reported to be useful for estimation of evaporation from bare soil.

$$E_g = \frac{P + m}{\sqrt{1 + \left[\frac{P + m}{l}\right]^2}}$$

Estimation of evaporation from snow surface

The evaporation from snow may be determined from meteorological data. Two equations are given below:

$$E_s = (0.18 + 0.098\,U^{10})\,(e_s - e_2') \qquad (1)$$
$$E_s = 0.239\,(Z_a Z_b)^{-1/6}\,(e_s - e'z_a)\,Uz_b \qquad (2)$$

Estimation of evapotranspiration

Techniques for determining evaporation and evapotranspiration are essentially identical. The actual evapotranspiration falls below the potential evapotranspiration when it is checked by lack of water as the soil dries. The rate of evapotranspiration is also influenced by the type of vegetation, its stage of development and its root intensity.

A number of formulae have been derived for the estimation of potential evapotranspiration from meteorological data.

Formulae based on physical principles

Method of water-budget:

This method is based on the use of the water budget equation of the soil layer with the active moisture exchange which can be expressed as

$$E_T = W_1 - W_2 + P - S_r - P_s$$

By means of the method of water budget it is possible to determine the evaporation from soil in the zone of insufficient moisture supply for long time intervals of the warmer period of the year (month, season) when values P_s and S_r can be neglected.

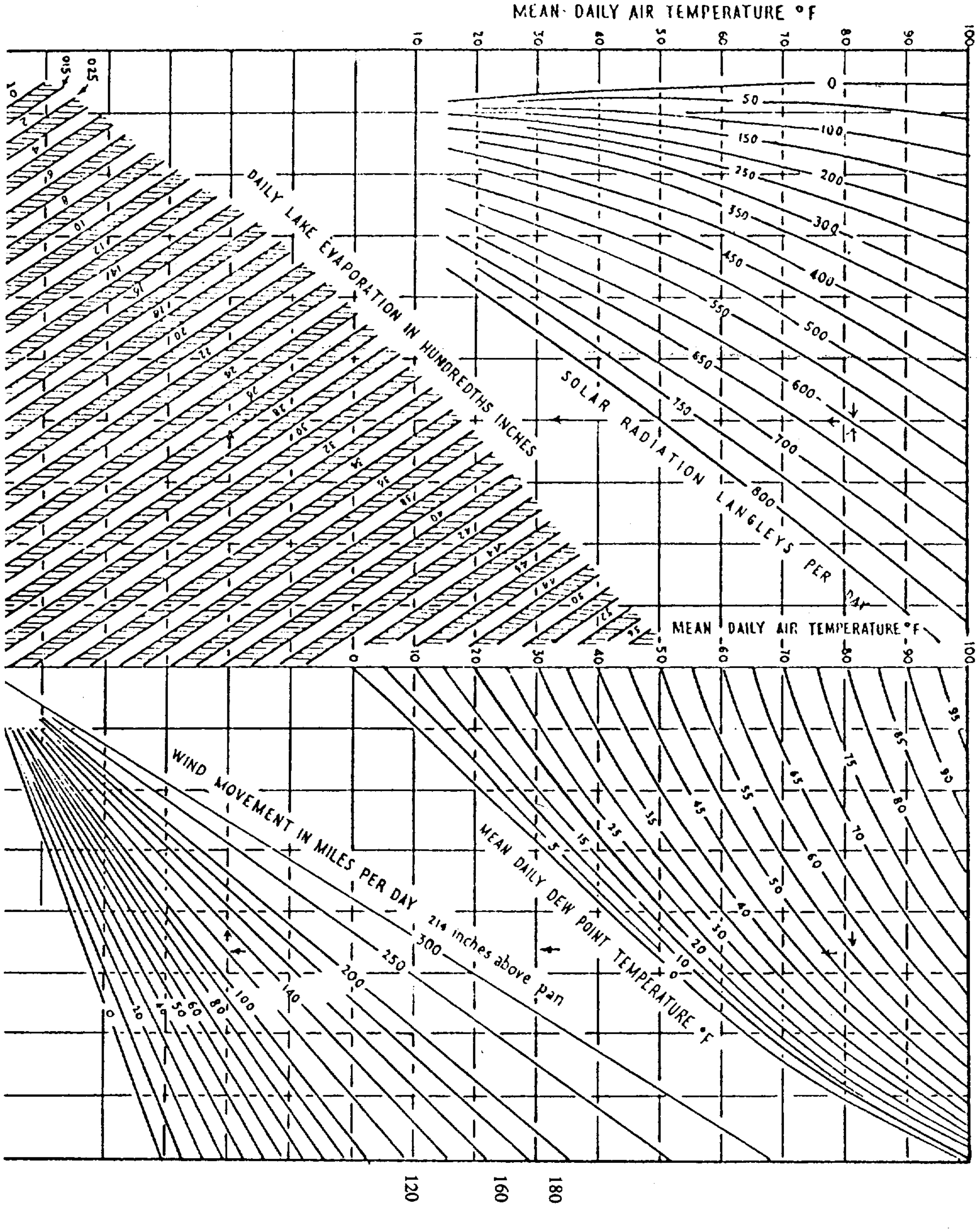

Fig. 4 — Lake evaporation relation. Note — The international pyrheliometric scale which became effective in united states on July 1, 1957. Provides values which are 2.0 percent less than those previously obtained. This evaporation relation is based on radiation values obtained prior to that date. For compurations based on data subsequent to July 1, 1957 increase radiation values by 2 percent.

The thickness of the soil layer of the active moisture exchange is defined by the diurnal and seasonal variations of the soil temperature and by the length of roots of the plants.

When a significant moisture exchange exists between the upper soil layers and the lower ones, the method of water budget for determination of evaporation is not acceptable.

Energy-budget method

In the case of crops the evaporating surface is three dimensional. The energy budget equation for the estimation of evapotranspiration from cropped surface is given by:

$$LE_T = \underset{1}{Q_n} + \underset{2}{\int_0^z C_p \nabla_H (\varrho u T)\, \delta z} + \underset{3}{\int_0^z \frac{0.622L}{R} \nabla_H \frac{(ue)}{(T)}\, \delta z} - [\underset{4}{S} + \underset{6}{Q_n} + \underset{5}{N}] -$$

$$- \underset{7}{\int_0^z C \varrho_c \frac{\delta T}{\delta t} . \delta z} - \underset{8}{\int_0^z C_p \varrho \frac{\delta T}{\delta t} . \delta z} - \underset{9}{\int_0^z \frac{0.622\, L}{RT} . \frac{\delta e}{\delta t} . \delta z}$$

Term 2 represents the horizontal divergence of sensible heat.
Term 3 represents the horizontal divergence of latent heat.
Term 7 represents changes in heat storage due to changes in crop temperature.
Term 8 represents changes in heat storage due to changes in sensible heat of air.
Term 9 represents changes in heat storage due to changes in latent heat of air.

The photosynthesis storage may be in certain cases significant being as high as5 to 10% of net radiation. The other storage terms are negligibly small except near about sunrise and sunset. The divergence terms are minimum close to the crop surface at a sufficient distance downwind. The divergence, photosynthesis and other storage terms may be neglected under certain circumstances.

Aerodynamic profile method

Rider's formula

The method given under evaporation is applicable for computation of evapotranspiration. Since in the case of a crop the boundary from which turbulence transport is effective is at some distance above the soil surface, the aerodynamic profile formula for the estimation of evapotranspiration is given by:

$$E_T = \frac{34.6 \times 10^{-5} (u_2 - u_1)(e_1 - e_2)}{T_a \left(\log \dfrac{Z_2 - d}{Z_1 - d}\right)^2}$$

where d is given by

$$\frac{u_3 - u_1}{u_2 - u_1} = \frac{\log (Z_3 - d) - \log (Z_2 - d)}{\log (Z_2 - d) - \log (Z_1 - d)}$$

The formula is valid only for neutral conditions of stability of air.

Deacon and Swinbank formula

$$E_T = \frac{C_s U_s^2 (q_1 - q_2)}{(u_2 - u_1)}$$

under conditions of neutral stability C_s is given by

$$C_s = \frac{K^2 \left(\frac{u_2}{u_1} - 1 \right)^2}{[\log (z_2/z_1)]^2}$$

In the use of this formula z_s should be taken as close to the surface as possible to be independent of stability effect so that the drag co-efficient can be used in non-neutral conditions without serious error. Once C_s is determined it is not necessary to measure heights for estimating E_T and the upper level may be chosen at a sufficient elevation to ensure confident measurement of wind and humidity differences.

Formulae based on combination method

Penman's formula

The formula given under evaporation when used with the proper value for '*r*' the reflection coefficient, appropriate to the vegetative cover and replacing E_α by E_{aT} gives *potential* evapotranspiration.

McIlroy's formula

$$E_T L = \frac{s}{s + \gamma_1} (Q_n - S) + h (D - D_0)$$

h and D_0 are determined empirically for each crop and site by comparison with any other reliable method.

Tanner's formula

$$E_T.L = Q_n - S - C_v \gamma_2 U_M \Delta T$$

where

$$C_v = \frac{Q_n - S}{u (e_1 - e_2 + \gamma_2 \Delta T)}$$

In the use of the above formula Q_n, S, u and vapour pressure difference between the two levels can be measured during a period of one hour even at mid-day.

Some empirical formulae

Blaney and Criddle formula

$$E_T = 25.4 \,.\, K.F$$

Values of K for different irrigated crops under arid and semi-arid areas are:

Alfalfa	0.85
Corn	0.80
Cotton	0.65
Grass hay and pasture	0.75
Citrus trees	0.60
Deciduous trees	0.70
Potatoes	0.75
Rice	1.20
Vegetables	0.60

This is a purely empirical formula and does not yield uniformly consistent results and can be used only as a rough guide. (Halkias, Veihmeyer and Hendrickson, 1955.)

Thornthwaite's formula

Thornthwaite's formula given below is based on correlation between mean air temperature and transpiration rates.

$$E_{PT} = 16\, L_a \left(\frac{10\, \bar{T}}{\mathrm{I}}\right)^a$$

Temperature records and the latitude are sufficient to compute potential evapotranspiration at any place. Arithmetic solution of the equation is laborious but graphical solution of the equation is available.

Leichtmann's formula

$$E'_T = \frac{0.41\, \overset{2}{\varepsilon}\, Z_0^{2\varepsilon}}{(1-\varepsilon)^2\, (Z_1^{\varepsilon} - Z_0^{\varepsilon})^2\, (Z_2^{\varepsilon} - Z_{0.5}^{\varepsilon})}\, U_1\, (e'_{0\cdot 5} - e'_2)$$

The formula can be used when $U_1 \geqslant 0.8$ m/sec, and $e'_{0.5} - e'_2 \geqslant 0.1$ mb.

Application of heat budget

$$E_T = \frac{(Q_n - S)\,(e'_{0\cdot 5} - e'_2)}{60\,(e'_{0\cdot 5} - e_2 + 0.64\,\Delta T')}$$

Turc's formula

Based on lysimetric data Turc derived an expression which gives evaporation from cultivated field as a function of available moisture and "evaporating power of the air".

$$E_T = \frac{P + m + V}{\sqrt{1 + \left[\dfrac{P + m}{l} + \dfrac{V}{2l}\right]^2}}$$

Instrumental Requirements and Precautions

Reservoir Evaporation

Energy-budget method

Net radiation can be measured by exposing any commercially available net radiometer over the water surface at a sufficient distance from the shore. Where raft mounting is not possible, shore based installations having a total hemispherical radiometer and a shortwave radiometer can be used for obtaining incoming long wave and short wave radiation while the reflected and back components of the radiation are estimated.

For determination of advected energy it is necessary to have measurements of volumes and temperatures of inflow, outflow, precipitation on lake surface and seepage. For determination of energy storage, temperature profiles of the lake at selected time intervals are required to be made at a number of places well distributed over the lake with observations at close intervals of height in the top layers. For this thermistor thermometers or any conventional resistance thermometers will suffice. A Bathythermograph though less accurate may be used in deep lakes if continuous recording is required.

A good commercial hygrothermograph (for calculating Bowen's ratio) exposed at a height of 2 to 3 metres above water surface, commercial thermometers and current meters (for measurement of temperature and volume of the inflow and outflow) will do.

Mass transfer or bulk aerodynamic method

The main advantage of this method is that it permits the use of commercially available instruments.

For wind speed any commercial cyclometric pattern cup anemometer will suffice. The anemometer must be raft mounted and exposed near the centre of the lake at a specified height preferably two metres. A shore based installation is not recommended for anemometers. Relative humidity measurements should be made at a site close to the lake but outside its vapour blanket. Commercially available ventilated psychrometers or hydrothermographs would be sufficient for the purpose. A number of stations round the lake would be required in case the wind direction is very variable.

For water surface temperatures raft mounted commercially available instruments would suffice. Proper care will have to be taken to ensure that the sensing element is so placed in water that it bobs in and out of the water when there are ripples and waves and is just under water surface under calm condition.

Aerodynamic profile method

Here specially designed sensors have to be used to accurately measure the small gradients of wind speed and vapour pressure at small height intervals over the water surface. The ~~temperature sensors must read correct to 0.05°C and the~~ humidity sensors must yield an accuracy of 0.01 mb of vapour pressure.

For accurately measuring the total wind run the anemometer must have a minimum internal friction and a minimum lag in responding to the instantaneous wind. They should have starting speeds of less than 10 cm/sec and a distance constant of less than one metre [the distance constant being the amount of air travel past the anemometers before it registers $66\frac{2}{3}\%$ response to an instantaneous change in wind speed. For given anemometer this is a constant over the natural range of wind speeds and is determinable in a wind tunnel by the locked rotor technique (Thornthwaite *et al*, 1961)]. They should also be selected from a matched lot so that their calibration curves are similar.

All the formulae derived for use of this technique assume that the eddy transfer co-efficients for water vapour and momentum respectively are equal but this is debatable thing (Priestley, 1952). However, from measurement of wind profile and evaporation from small pots it has been inferred (Pasquill, 1949) that the two are equal under neutral conditions of stability. They are also equal under unstable conditions provided that Deacon wind profile is used (Swinback, 1955).

Eddy correlation method

The instrumentation for this method is very complex and is still in a developmental stage. Essentially this requires the use of (i) an anemometer for vertical wind having a linear response for the various angles of attack of the wind, (ii) a high speed recorder-cumcomputor for separately registering the up and down drafts and making necessary computations and (iii) a fast response dew point hygrometer.

Generally, the instruments used for measuring vertical wind consists of a single hot wire anemometer to measure total wind speed together with a sensitive bivane to record fluctuations in elevation and azimuth. The vertical component of the wind w is obtained from the equation $w = u \tan i$, where $u =$ the horizontal component of the wind and $i =$ the elevation angle.

Some efforts have also been made to develop a sonic anemometer for absolute direct measurement of the vertical wind. However, the sonic anemometer is not yet suitable for field use.

In this method it is necessary to have instrument capable ofmeasuring simultaneous fluctuations of the deviations from the mean of the vertical wind and of q so that the term $\overline{(\varrho w)q'}$ can be obtained. So long it was not possible to measure these. Instruments actually measure $\overline{\varrho wq}$ (total flux) and $\overline{\varrho w}\ \bar{q}$ (eddy flux combined with the flux due to the mean motion). Thus as a first approximation it is necessary to assume that the term will be zero over extensive flat surfaces free from obstructions so that

$\overline{\varrho w v}$ can be substituted for $\overline{(\varrho w)'q'}$. The error involved in such an assumption has been recognized. Swinbank (1955) has pointed out the problem as follows:

An assessment of the magnitude of this term is difficult, if not impossible, because no means of measuring $\overline{\varrho w}$ with sufficient accuracy exists. The difficulty is evident when we recall that the direction $\overline{\varrho w}$ is normal to the ground and that an error of one degree in assessing this direction will, with a wind quasi-parallel to the ground of say 5 m per sec, yield a spurious value of $\bar{w}$ of nearly 10 cm per sec.

McIlroy (1961) has recently indicated that the problems of determinig the mean vertical motion of the air has not yet been solved and that it is still necessary to assume this term to be zero.

"Accurate determination of $\overline{\tan i}$ virtually impossible. Since it should be small at least on the average, over a virtually horizontal surface such as that at Edithvale the best course (also adopted by Panofsky 1956) is to assume that it is always zero."

To use this technique effectively, vigorous attempts are being made by the various research organizations to devise very ~~sensitive~~ instruments having very small time constant and at the same time the desired sturdiness for regular field use. Although the technique is direct but application is hindered by the rigid requirements of the instrumentation.

Penman's formula

Standard screen meteorological measurements are needed for air temperature and dew point though ventilated thermometers are preferable. Standard cup anemometers are sufficient for wind speed.

McIlroy's formula

Besides measurements of net radiation by commercially available net radiometers, standard screen meteorological measurements are needed for wet bulb depression and standard cup anemometers are needed for wind speed. Temperature profile instruments as per energy budget method are needed.

Evaporation from crop surfaces

Energy-budget method

Commercially available net-radiometer for measurements of net radiation and a soil heat flux recording system to measure the heat flux in the soil at a few positions are adequate.

The requirements of instruments and accuracy of measurements with regard to temperature and vapour pressure gradient are similar to the aerodynamic profile method. For cancellation of any systematic errors it is desirable to effect regular and frequent interchange of temperature and humidity sensing elements between the levels, either manually or automatically. To minimise advection storage and buoyancy effects measurement of temperature and humidity gradients should be made as close to the surface as possible — in cases of strong heating or advection it may be 0.25 metre but height up to one metre can be used under more normal conditions.

Aerodynamic profile and Eddy correlation method

The instrumental requirements for the aerodynamic profile and eddy-correlation technique are the same as given for these techniques under reservoir evaporation. For these studies however it is advisable to mount the temperature and dew point sensors on suitable movable booms to ensure a slow horizontal scanning for avoiding any possible error that may be due to the presence of relatively cold or hot pockets.

McIlroy's formula

Same as in the case of water surface as regards net radiation, wet bulb depression and wind speed. An estimation or measurement of soil heat flux by heat flux plates will be sufficient.

Tanner's formula

A standard cup anemometer will be sufficient for wind speed. Requirements for other elements are the same as for energy budget and aerodynamic methods.

Location of instruments

In all these methods, to ensure that the measurements made are truly representative of the evaporating surface, it is necessary to have an upwind fetch of not less than 100 times the height to which the instruments are exposed (de Vries, D. A., 1959).

CONCLUDING REMARKS

From the above discussions it will be seen that although precise equations have been developed by using unique physical parameters, the estimation of evaporation by the use of those equations is handicapped by one of the two following reasons: (1) Measurement of parameters involved is very difficult (as in the case of water budget and energy budget methods) or (2) Suitable instruments required for measuring the related parameters are not available (as in the case of eddy correlation method). A few other equations are available which are semi-empirical in nature. It is, therefore, necessary to take the aid of certain measuring device by which the physical loss by evaporation is measured either under conditions which simulate precisely the conditions that exist in case of natural evaporation or under such known conditions so that the evaporation thus measured can be adjusted to obtain evaporation under natural conditions. It is not only difficult to precisely simulate the physical conditions under which natural evaporation occurs but the physical conditions for natural evaporation are also numerous and varying from place to place and occasion to occasion. As already discussed the natural water surface may be shallow or deep, may be a free surface or be partly covered with the vegetation, may be disturbed by varying degrees of ripples, waves and even foams, arising out of high winds. There is, therefore, no other alternative than to adopt such technique for measurement of evaporation by which the measurement made at different places by different countries could be reduced to a certain standard physical condition say the physical conditions that prevail over an extensive and fairly smooth water surface uncovered by any vegetation. Unless such a procedure is adopted the routine evaporation records of the various countries meant for general use for meteorological and hydrometeorological purposes will not be comparable.

The evaporation from sea surface is affected not only by the waves but by the foams and spray caused by high winds in the field of a storm and breakers near about the coastal regions. Several attempts have been made to theoretically estimate the effect of roughness caused on sea surface due to wind. The estimates made by different authors vary considerably. For instance, Sverdrup (1937-8) concludes that evaporation from a hydro-dynamically rough surface is twice that from a smooth surface while Montgomery (1940) infers it to be the same in both cases. According to Norris (1948) the evaporation from a hydro-dynamically rough surface would be four times the evaporation from smooth surface.

In the case of sea spray small water particles are atomized in the air and hence the evaporation (which has been called as Mechanical Evaporation — Volklov — 1959) will undoubtedly be very high. It is very difficult to either estimate with reasonable accuracy or measure experimentally the evaporation loss under these conditions.

Attempts have however been made (Okuda and Hayami 1959 and Volkov 1959) to measure evaporation from sea spray and foam. It is recognized that the area producing sea spray due to high winds is very much less compared to the total oceanic area of the globe as a whole. Yet the value of evaporation from sea spray is likely to be of so high a magnitude that it is of considerable importance, particularly in certain regions. Coastal region of the West Coast of Indian Peninsula during the summer monsoon months is an example of this kind of evaporation, evaluation of which is of considerable importance to synoptic meteorologist.

In the literature potential evapotranspiration has been defined as the evapotranspiration loss occurring from a fully covered thin leaved grass field kept always at saturated conditions. Some experiments have been conducted on a samll scale in India to measure potential evapotranspiration using in Napier grass and evapotranspiration of wheat and sugarcane by placing the lysimeters (sunken) inside the cropped fields. Table 1 shows the comparative figures of potential evapotranspiration loss for Napier grass of different heights. Table 2 shows the evapotranspiration loss in case of wheat with the progress of the growth of the plant, Table 3 shows evapotranspiration loss in case of sugarcane where the physical conditions were exactly the same but the lysimeters contained plants of the same age but of varying vigour in growth. From these tables it is clear that the rate of transpiration loss depends considerably on the stage of growth of the plants although all other physical parameters are kept constant. It is, therefore, a matter of serious consideration whether a physical parameter which is used for climatological purposes should derive its definition involving a biological entity.

TABLE 1

	Potential evapotranspiration — mm (average daily).
Saturated bare soil	12.0
Napier grass (6″ height)	18.3
Napier grass (12″ height)	27.1
Napier grass (24″ height)	35.7

TABLE 2

Period	Evaporation from extensive water surface	Actual evapotranspiration (Volumetric method) – Wheat
	(Pan × 0.7)	
II to IV week	72.8 mm	55.6 mm
V to VII week	70.4 mm	74.8 mm
VIII to X week	80.9 mm	82.0 mm

It will be perhaps not out of place to mention the optimum network of evaporation

TABLE 3

Evapotranspiration Experiment — *Sugarcane* 1964-65

Period	Plant stage	Tank 1		Tank 2		Tank 3	
		Average volume of representative mothercane in ccs	Average daily evapo-transpiration mm	Average volume of representative mothercane in ccs	Average daily evapo-transpiration mm	Average volume of representative mothercane in ccs	Average daily evapo-transpiration mm
26.7.64 to 10.8.64	Plants 5 months old.	779	4.4	594	3.7	499	3.0
5.9.64 to 19.9.64	Commencement of elongation	1 411	6.3	1 291	4.5	866	4.3
3.10.64 to 17.10.64	Rapid elongation	1 571	7.4	1 666	6.8	1 061	5.3
10.11.64 to 24.11.64	Canes maturing	1 965	3.2	2 125	4.6	1 446	3.7

measuring stations. The optimum number of stations needed for obtaining a fairly reliable areal average can be obtained by the following equation:

$$N = \left(\frac{C_v}{P}\right)^2$$

where N = the number of stations.
C_v = coefficient of variation of evaporation values obtained from the existing stations and
P = is the desired degree of percentage of accuracy in estimated evaporation for the area.

The coefficient of variation in evaporation can be calculated using any kind of pan evaporimeter data where there is a fairly good number of stations taking care to see that the type of pan used and their manner of installation remains unchanged. In many countries there may not be even a skeleton network from which coefficient of variation can be worked out with reasonable degree of confidence. In such cases the optimum number may be worked out using C_v computed from evaporation values from Penman's formula (or the corresponding nomogram given by Kohler and his co-workers) with the help of the usual data recorded at meteorological stations. After deciding the optimum number in an area the locations of the stations can be decided in the following simple objective way. The isolines of evaporation may be drawn for the area under question using the computed evaporation values mentioned above. The number N may then be distributed in the different areas bounded by the consecutive isolines of evaporation in proportion to the areas bounded by them. In each strip lying between the ponsecutive isolines the number of stations can be distributed uniformly.

APPENDIX I

Temp. (°C)	Coeff. of cubical expansion of water as calculated from density variation.	Rise in level of water in inches/degree rise of temperature due to expansion of water and Class *A* pan		
		Copper	Zinc	Iron
	$\times 10^{-5}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$
0	− 6.6	− 1.045	− 1.304	− .880
2	− 3.3	− .748	− 1.007	− .603
4	− 0.1	− .460	− .719	− .295
7	+ 4.5	− .046	− .305	+ .119
10	+ 8.7	+ .332	+ .073	+ .497
15	+ 15.1	+ .908	+ .649	+ 1.073
20	+ 20.6	+ 1.403	+ 1.144	+ 1.568
25	+ 25.6	+ 1.853	+ 1.594	+ 2.018
30	+ 30.3	+ 2.276	+ 2.017	+ 2.441
35	+ 34.2	+ 2.627	+ 2.368	+ 2.801
40	+ 38.0	+ 2.969	+ 2.710	+ 3.134

Linear Expansion of Copper .167 $\times 10^{-4}$,
Linear Expansion of Zinc .263 $\times 10^{-4}$,
Linear Expansion of Iron .106 $\times 10^{-4}$.

Appendix II

MEANINGS OF SYMBOLS

a = $6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49$

A = surface ara of lake (square metres).

c = crop constant. Values of c given by Turc are: Maize and beet = 0.67, Potatoes = 0.83, Cereals, flax, carrots = 1.00, Peas, clover. legume except lucerne = 1.17, Lucerne, medow grasses and mustard = 1.33.

C = heat capacity of crop (cal/gm/°C).

C_p = heat capacity of air at constant pressure (cal/gm/deg).

C_s = drag co-efficient at a certain height Z_s.

d = the displacement of the nominal evaporating surface (cm).

D = wet bulb depression (°C) at some height Z above the surface.

D_0 = the wet bulb depression at zero level (°C).

e = vapour pressure of air (mb).

e' = vapour pressure of air outside lake's vapour blanket (mb).

e_a = saturation vapour pressure corresponding to air temperature (mb).

e_4 = saturation vapour pressure corresponding to snow surface temperature (mb).

e_w = saturation vapour pressure corresponding to water surface temperature (mb).

e_z = vapour pressure of air (mb) at a certain height z.

e'_Z = vapour pressure of air (mb) at a height Z metres.

e'_{Za} = vapour pressure of air (mb) at height 'Z_a' metres.

E = evaporation from water surface (mm).

E_a = $0.263\,(e_a - e)\,(0.5 + 0.01\,U'_2)$ mm.

E_{aT} = $0.35\,(e_a - e)\,(1.0 + 0.01\,U'_2) \ldots$ mm.

E_g = evaporation from bare soil surface (mm).

E_L = lake evaporation (mm).

E_{PT} = monthly *potential* evapotranspiration (mm).

E_s = evaporation from snow surface (mm).

E_T = evapotranspiration (mm).

E'_T = evapotranspiration (mm/hour).

$E_{\propto}$ = evaporation from an extended sheet of open water (mm).

$f(u)$ = empirically derived function of wind speed, commonly expressed in one of the following forms:

$$f(u) = K_1 + K_2\,u$$
$$f(u) = K_3 u$$
$$f(u) = K_3 u^j$$

in which K_1, K_2, K_3 and j are constants.

F = the sum of the monthly consumptive use factors for the period which is 1/100 th of the products of mean monthly temperature (°F) and monthly percentage of daytime hours of the year.

h = wind speed overall transfer co-efficient between surface and height z analogous to the Dalton co-efficient of Penman's equation and can be determined experimentally.

H = heat budget = $R_A (1-r)\,(0.18 + 0.55\,\mathrm{n/N}) - \sigma\, T_a^4\,(0.56 - 0.092\sqrt{e})\,(0.10 + 0.90\, n/N)$.

I = a summation of 12 monthly values of the heat index i and $i = (\overline{T}/5)^{1.514}$

I_r = volume of inflow to the reservoir (mm).

k = the Karman constant ($\simeq 0.40$).

K = empirical co-efficient depending on the type of crop.

l = evaporating power of the air = $1/16\,(\overline{T}, + 2)\sqrt{Q'_s}$.

L = latent heat of vapourization (cal/gm).

L_a = an adjustment for the number of hours of daylight and days in the month and is related to latitude.
m = soil moisture available for evaporation (mm).
M = final yield of dry matter in tens of grammes per hectare.
n/N = ratio of actual to possible hours of bright sunshine.
N = net photosynthesis storage (cal/cm^2).
O_r = volume of outflow from the reservoir (mm).
p = atmospheric pressure (mb).
P = precipitation (mm).
P_s = percolation of water into lower layers of soil (mm).
q_z = specific humidity at a certain height z.
Q_{bs} = long wave radiation emitted by the body of water (cal/cm^2).
Q_e = energy utilized by evaporation (cal/cm^2).
Q_h = energy conducted from the evaporating body as sensible heat (cal/cm^2).
Q_k = change in energy storage of water (cal/cm^2).
Q_{la} = incoming long wave radiation from the atmosphere (cal/cm^2).
Q_n = net radiation flux (cal/cm^2).
Q_{rl} = reflected longwave radiation (cal/cm^2).
Q_{rs} = reflected short wave radiation (cal/cm^2).
Q_s = incident short wave radiation (cal/cm^2).
Q_s' = mean short wave radiation for a period of 10 days (cal/cm^2).
Q_v = net energy brought into the body of water in inflow including precipitation (cal/cm^2).
Q_w = energy carried away by the evaporated water (cal/cm^2).
r = reflection co-efficient of the evaporating surface.
R = specific gas constant of air (mb/c.c/gm/deg).
R_A = extra-terrestrial radiation in evaporation unit (mm).
$s = \dfrac{0.63}{p} \Delta w$
S = soil heat flux (cal/cm^2).
S_r = surface run off (mm).
t = time.
T = air temperature (°C).
$\bar{T}$ = monthly mean air temperature (°C).
$\bar{T}'$ = mean air temperature (°C) for ten day period.
T_o = water surface temperature (°C).
T_a = temperature of the air (°A).
T_M = temperature (°C) at mid-point between z_1 and z_2.
u = horizontal wind speed (cm/unit time).
u_z = wind speed (cm/sec) at a certain height z.
U_M = wind speed (cm/min) at one level in the range z_2 to z_1.
U_s = wind speed (cm/sec) at a certain height z_s.
U_Z = wind speed (m/sec) at height Z (m).
U_2' = wind velocity in miles per day at a height of two metres.
V = additional moisture available for transpiration (mm). This is usually determined by $V = 25\,(Mc/\lambda)\tfrac{1}{2}$.
w = vertical velocity of wind (cm/sec).
W_1 = initial moisture storage of the given soil layer (mm).
W_2 = final moisture storage of the given soil layer (mm).
z = height of exposure of sensors.
Z = height in metres. The subscript indicates the number of metres.
Z_0 = surface roughness parameter (cm).

β = Bowen ratio $= \dfrac{0.61\,p}{1\,000}\left(\dfrac{T_0 - T}{e_w - e}\right)$

γ = psychrometric constant = 0.27.
γ_1 = psychrometric constant = 0.42 mg/gm/°C.

γ_2 $= \dfrac{\text{specific heat of air at constant pressure} \times \text{atmospheric pressure (mb)}}{0.622\,L}$ (mb/day)

ε = parameter of the atmospheric stability taking into account the effect of the thermal stratification on evaporation.
λ = length of the growing season in tens of days.
ϱ = density of air (gm/c.c).
ϱ_c = density of crop (gm/c.c).
ϱ_W = density of water (gm/c.c).
σ = Stefan's constant = 0.827×10^{-10} cal/cm^2/min.
Δ_a = slope of the vapour pressure curve for water at mean air temperature (mm of Hg/°F).
Δe = difference of vapour pressure at heights of 0.5 and 2.0 m (mb).
ΔS = change in the volume of water contained in the reservoir (mm).
ΔT = difference of temperature between levels z_2 and z_1 (°C).
$\Delta T'$ = difference of air temperature at heights of 0.5 and 2.0 m (°C).
Δw = slope of the saturation vapour pressure curve at the mean wet bulb temperature (mb/°C).

∇_H $= \dfrac{\delta}{\delta x} + \dfrac{\delta}{\delta y}$ (per cm.).

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