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Generalized Estimates of Free-Water Evaporation

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Abstract. A modified method for deriving free-water evaporation estimates from network observations of air temperature, dew point, wind movement, and incoming minus reflected radiation is presented. Taking into account the difference between air and water temperature in computing emitted radiation from the water surface, the expression is an improvement over the original Penman type equation where observation of net radiation over the actual water surface is lacking. The accuracy of the method depends on the applicable mass transfer wind function. Techniques are derived to adjust for the effects of advected energy and heat storage when applying the free-water evaporation estimate to actual water bodies. Computations of lake evaporation made with the modified method for a number of locations where verification data are available indicate that the relation provides a suitable basis for estimating actual evaporation without the expense of continuous over-water observations. (Key words: Evaporation; evapotranspiration; lakes)

NOMENCLATURE

- E, evaporation (in./day);
- E_a, evaporation computed by aerodynamic equation, assuming $T_0 = T_a$;
- E_L, lake evaporation (adjusted for net advection);
- e_a, e_2, vapor pressure of air at height a or 2 meters (inches of mercury);
- e_s, saturation vapor pressure at air temperature;
- e_0, vapor pressure at water surface;
- Q_b, emitted radiation (same units as evaporation);
- Q_h, sensible heat transfer from water surface;
- Q_i, energy content of inflow to lake (same units as evaporation);
- Q_{ir}, incident minus reflected radiation;
- Q_n, net radiation;
- Q_0, energy content of outflow from lake;
- S_1, S_2, energy storage at beginning and end of period;
- T_a, air temperature;
- T_0, water temperature;
- u_a, u_4, wind movement at height Z_a or 4 meters (mi/day);
- Z_a, height above surface;
- α, ratio of evaporation to total energy exchange;
- Δ, slope of saturation vapor-pressure versus temperature curve;
- ϵ, emissivity of water surface;
- γ, psychrometric constant;
- σ, Stefan–Boltzmann constant.

INTRODUCTION

A need for accurate appraisal of water resources has become more and more urgent. The effectiveness of a proposed conservation reservoir is directly dependent upon the increased evaporation losses that would result. However, most techniques for deriving actual losses of water hinge upon estimates of free-water evaporation.

Energy-budget and mass-transfer techniques can provide satisfactory estimates of evaporation from existing reservoirs, but the inherent costs restrict their application. More important, perhaps, these techniques are not applicable to reservoir design; for such purposes, it becomes necessary to rely on evaporation pan observations or generalized estimates of one form or another.

Continuing evaporation studies have been under way in the U. S. Weather Bureau since 1950, initiated at the time of the interagency experiments at Lake Hefner, Oklahoma [*Kohler,* 1954]. The principal objectives of these investigations have been to develop more reliable methods for estimating lake evaporation from network observations (Class A evaporation pans and/or meteorological factors) and to design a more suitable evaporation instrument for network use [*Nordenson and Baker,* 1962]. The scope of the present paper is limited to the discussion of a revised technique for estimating free-water evaporation from meteorological observations.

Based in part on the work of *Penman* [1948] and *Ferguson* [1952], a method was developed some years ago [*Kohler et al.,* 1955] for computing lake evaporation from observations of global solar radiation, air temperature, dew point, and wind movement. Although the method has been found to yield generally good results and is widely used, several aspects of its derivation may lead to appreciable errors under some circumstances. It was assumed (1) that the evaporation from a thin free-water surface is 70% of that from the Class A pan, so long as air and pan water temperatures are equal; (2) that the effective area of the pan for sensible heat transfer is 2½ times the exposed water surface area; and (3) that net, all-wave radiation could be derived as a function of air temperature and global solar radiation. Inherent in the latter assumption is an error in emitted long-wave radiation dependent on any difference between air and water temperature. Although the approach described herein is not without empiricism and approximations, it is not subject to the criticisms cited above.

PENMAN COMBINATION EQUATION

Both aerodynamic and energy balance types of evaporation equations require observations of water surface temperature. *Penman* [1948] eliminated this requirement by simultaneous solution of equations of the two types. His equation is

$$E = (Q_n\Delta + E_a\gamma)/(\Delta + \gamma) \qquad (1)$$

where

- Δ = slope of the saturation vapor-pressure versus temperature curve (de_s/dT) at the air temperature T_a;
- E_a = evaporation given by the aerodynamic equation, assuming water temperature $T_0 = T_a$ (see equation 7);
- Q_n = net radiation energy expressed in the same units as evaporation E;
- γ = psychrometric constant appearing in Bowen's ratio equation

$$Q_h/E = \gamma(T_0 - T_a)/(e_0 - e_a) \qquad (2)$$

in which

- Q_h = the sensible heat transfer;
- e_a = atmospheric water vapor pressure;
- e_0 = water vapor pressure at T_0.

Equation 1 assumes: (1) that Q_n is representative of exchange at the water surface; (2) that E_a is based on an equation that yields the correct value of E when T_0 is known; (3) that any net advection to the water body (by inflow and outflow) is balanced by a change in heat storage; and (4) that Δ at T_a is a good approximation of the mean value between T_a and T_0. These assumptions and inherent restrictions are formidable with respect to the applications considered in this paper and, therefore, each is discussed in some detail.

NET RADIATION

If observations of net radiation are made directly over the water surface of interest, the Q_n term in equation 1 presents no problem. This is seldom the case, however, and the purpose in deriving equation 1 was for application in the absence of over-water observations. It is possible that network observations of 'incident minus reflected all-wave' radiation might be available in the future through use of an insulated pan or Cummings radiation integrator [*Harbeck,* 1954], but there would still remain the requirement for emitted long-wave radiation by the water body.

Since emitted long-wave radiation is dependent upon water temperature, it should be treated as a separate radiation term in the derivation of equation 1. Thus, while Penman's derivation takes into account the effect of any difference between air and water temperature on evaporation and convective heat transfer, his method of computing net radiation [*Penman,* 1948, p. 123] assumes that the emitted radiation from the water body is a function of the air temperature. With a temperature difference of 10°F, which is not particularly extreme, the resulting error in emitted radiation is on the order of 70 langleys per day ($T_0 = 80$°F). Were there no other errors involved, the use of Penman's equation for net radiation would result in an overestimate of evaporation under calm, humid conditions and an underestimate when conditions were dry and windy.

In order to modify equation 1 to reflect the effect of a difference in air and water temperatures on emitted radiation, Q_n can be expressed as

$$Q_n = Q_{ir} - Q_b \tag{3}$$

$$Q_n = Q_{ir} - \epsilon\sigma T_0^4 \tag{4}$$

where

Q_{ir} = difference between incident and reflected radiation (all-wave);
Q_b = emitted radiation;
ϵ = emissivity of the water surface;
σ = Stefan–Boltzmann constant (7.81×10^{-11} equiv. in. evap. per cm²/°K⁴/day);
T_0 = water temperature in degrees Kelvin (°K).

To a first approximation (first two terms of binomial expansion), equation 3 may be rewritten

$$Q_n = Q_{ir} - \epsilon\sigma[T_a^4 + 4T_a^3(T_0 - T_a)] \tag{5}$$

where T_a is in °K.

Substituting for Q_n in equation 1 and letting $T_0 - T_a = (e_0 - e_s)/\Delta$, we find

$$E = \frac{(Q_{ir} - \epsilon\sigma T_a^4)\Delta + E_a[\gamma + 4\epsilon\sigma T_a^3/f(u)]}{\Delta + [\gamma + 4\epsilon\sigma T_a^3/f(u)]} \tag{6}$$

where $f(u)$ = wind function appearing in the aerodynamic equation, i.e.

$$E = f(u)[e_0 - e_a] \qquad E_a = f(u)[e_s - e_a] \tag{7}$$

The derivation of equation 6 hinges upon the elimination of the vapor-pressure difference $(e_0 - e_s)$ by simultaneous solution of the equations for E and E_a. The similarity between equation 6 and the original Penman equation is evident; the term appearing parenthetically with γ corrects for the emitted long-wave radiation at temperature T_0 rather than T_a.

As stated at the beginning of this section, an insulated evaporation pan can be used to compute the difference between incoming and reflected radiation Q_{ir} for a free-water surface, and the U. S. Weather Bureau now is testing such pans for possible network application. There are in existence net, all-wave radiometers that can be used to obtain observations of Q_{ir}, provided that they are exposed over a water surface and provided that the temperature of the surface is also observed. Reasonably good estimates of Q_{ir} can also be obtained using an incident all-wave radiometer and assuming an average coefficient of reflection. However, there is at present no network of all-wave radiometers in the U.S.A. In the absence of such measurements, the application of equation 6 must be based on observations of global solar radiation (approximately 100 stations in the U.S.A.) and empirical relations for estimating other components of Q_{ir}.

Numerous empirical relations have been developed for estimating atmospheric radiation (global, long-wave). In most such relations, air temperature and vapor pressure near the surface and some index of extent and/or height of cloud cover constitute the independent variables [*Angstrom,* 1919; *Anderson,* 1954; *Koberg,* 1964]. More recently and in some ways related to the studies reported here, *Anderson and Baker* [1967] have developed a similar relation.

When atmospheric radiation must be estimated, it will normally be necessary to estimate reflected radiation as well. The reflectivity of a water surface for atmospheric radiation has been shown to be 0.030 [*Anderson,* 1954]. The reflectivity for short-wave radiation depends upon the sun altitude and the amount and type of clouds, but for practical purposes it can be assumed to be constant (0.06) when dealing with periods a day or more in length.

There are, of course, many meteorolgical stations for which even incident solar radiation observations are lacking. In this event, this term must also be estimated to apply to equation 6. Numerous empirical relations have been derived for basing such estimates on per cent sunshine [*Hamon et al.,* 1954] or cloud cover [*Brunt,* 1939].

AERODYNAMIC EQUATION

Penman [1948] originally proposed that the wind function in the aerodynamic equation take the form

$$f(u) = a + bu = 0.35 + 0.0035u_2 \qquad (8)$$

where u_2 = 2-meter wind movement in miles per day (for evaporation in inches per day and vapor pressures in inches of mercury). The constants in equation 8 were based on observations of evaporation from a sunken pan 2.5 feet in diameter. As a result of the Lake Hefner studies, *Penman* [1956] proposed that the constant a be reduced to 0.175.

The selection of an appropriate wind function is not a simple matter, even though the effects on E are much less than on E_a. *Tanner and Pelton* [1960] emphasize the importance of using a wind function applicable to the surface under consideration. They and other investigators [*Businger,* 1956; *Van Bavel,* 1966] suggest the use of a function that is based on wind profile theory and that includes a roughness parameter. This approach is undoubtedly sound when all required observations can be taken at the site and particularly when dealing with evapotranspiration from a particular vegetated surface. If it is assumed that the roughness parameter is constant with time and the same for all free-water surfaces, the equation used by *Van Bavel* [1966, equation 4] takes the form of equation 8, where $\alpha = 0.0$.

An analysis of Lake Hefner data [*Kohler,* 1954, Table 27] yields $b = 0.00304$ when a is assumed to be zero—4-meter wind and 2-meter vapor pressure at the barge (mpd and cm Hg, respectively) and evaporation in inches per day. If a is not forced to zero, the Lake Hefner data yield $a = 0.051$ and $b = 0.00287$. The same equation ($a = 0.0$) seems to apply for Lake Mead [*Kohler,* 1958, Table 23], and it is believed to be generally applicable so long as the water body is sufficiently large that the vapor pressure measurement (2 meters) is well within the vapor blanket. There is a definite 'size effect' [*Harbeck,* 1962] when the wind observation is made over the water and the vapor pressure used is indicative of up-wind conditions. Since the wind measured over the water is dependent on the over-water distance, Harbeck's results do not necessarily indicate the true effect of lake size on actual evaporation. In other words, Harbeck's analysis would show a variation in $f(u)$ with lake size even though evaporation were independent of this factor.

We are forced to rely on 'up-wind' observations in computing E_a for generalized evaporation estimates, and the equation used should provide unbiased values of evaporation when solved with observed vapor pressure of the water surface. It follows that lake size should appear as a parameter in the equation for E_a were there any appreciable difference in the actual evaporation from large and small lakes. It appears, however, that any such differences are small [*Kohler et al.,* 1958, page 60], and all tests subsequently discussed were accordingly based on the equation

$$E_a = (0.181 + 0.00236u_4)(e_s - e_2) \qquad (9)$$

where all observations are taken over land. This upwind equation was derived by least-squares analysis of Lake Hefner wind, dew point, and water temperature data. It will be noted that the constants in equation 9 are in good agreement with those proposed by *Penman* [1956] if we take into account the difference between u_4 and u_2.

ENERGY STORAGE AND ADVECTION

Since equation 6 is based on the assumption that net radiation is dissipated through evaporation and sensible heat exchange with the overlying air, it is necessary to consider the effects of heat exchange within the water body as they are related to energy storage and advection.

It can be shown that the effects of advected energy (water) are unimportant except when flows are large relative to the rate of evaporation. Even then, the inflow and outflow temperatures must be appreciably different. The effects of changes in energy storage, on the other hand, may be relatively large, depending on the period of computation and the depth of the lake. Energy storage can be safely neglected in the computation of mean annual evaporation in all cases and in the computation of annual evaporation from shallow lakes.

It can be reasoned that the effects of advection and changes in storage are brought about through a change in the water surface temperature, and we can assume for practical purposes that an incremental change in the water surface temperature has no significant effect on incoming or reflected radiation or on the vapor pressure of the air above the lake. In other words, the effects of advection (and/or changes in energy storage) are distributed between evaporation, sensible transfer, and emitted radiation. The portion of such energy affecting evaporation is

$$\alpha = (\partial E/\partial T_0)/(\partial E/\partial T_0 + \partial Q_h/\partial T_0 + \partial Q_b/\partial T_0) \qquad (10)$$

where Q_h = sensible heat transfer and Q_b = emitted radiation, both expressed in the same units as the evaporation E. From equations 2, 3, 4, 7, and 10, it is found that

$$\alpha = \Delta/[\Delta + \gamma + 4\epsilon\sigma T_0^3/f(u)] \qquad (11)$$

The ratio α is in some ways analogous to Bowen's ratio. Strictly speaking, it should be applied with wind observations immediately above the water surface [*Kohler et al.*, 1955], but $f(u)$ as defined in equation 9 can be used without appreciable error. Figure 1 provides a convenient solution for α in terms of T_0 and u_4. Two charts are presented (1000 feet and 10,000 feet, msl) to accommodate the variation of γ with atmospheric pressure.

It should be noted that equation 11 applies for 'net advection'—the energy content of inflow Q_i, less that of outflow Q_o, less any increase in energy storage during the period $(S_2 - S_1)$. In other words

$$E_L = E + \alpha[Q_i - Q_o - (S_2 - S_1)] \qquad (12)$$

where E = computed free-water evaporation assuming net advection to be zero, E_L = estimated lake evaporation, and the storage and advection terms are in the same units as E. Thus, whereas equation 6 provides generalized estimates of evaporation from a thin free-water surface, equation 12 should be used in comparing the results with evaporation from specific lakes.

TESTS OF MODIFIED EQUATION

It is believed that the reliability of equation 1 has been demonstrated to be adequate for practical application, provided that observations of net radiation are available and an appropriate aerodynamic function is used [*Van Bavel*, 1966]. Equation 6 is essentially the same as equation 1, except that provision has

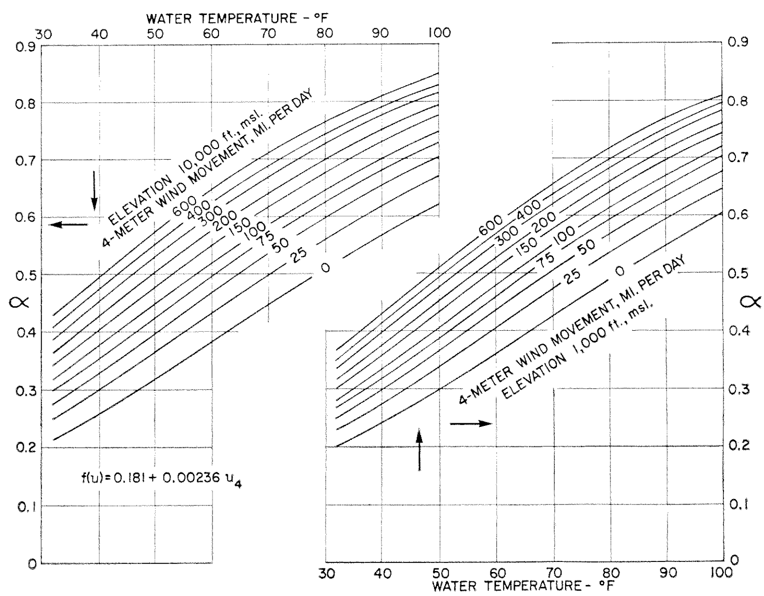

Fig. 1. Variation of α with water temperature, wind movement, and elevation.

been made for using observations of 'incident minus reflected' radiation and eliminating water temperature from the emitted radiation term. It appears, therefore, that the results of tests of equations 6 and 12 would depend in large measure on the adequacy of: (1) the aerodynamic equation; (2) the technique for estimating the advection correction; and (3) the accuracy of the data used in the test. The importance of item (3) should not be minimized, since all required data are seldom available, and the values of lake evaporation derived by water budget or other independent techniques are usually not sufficiently reliable to serve as a true test.

Equations 6, 9, and 12 were tested using data collected at Lake Hefner, Oklahoma; Lake Mead, Arizona-Nevada; Felt Lake, California; Silver Hill, Maryland; and Sterling, Virginia. Water budget measurements of evaporation were available for comparison for Lake Hefner [*Harbeck and Kennon,* 1954] and Felt Lake [*Baker and Linsley,* 1960]. In the case of Lake Mead, only energy-budget and mass transfer estimates were available for comparison. Measured evaporation from large sunken evaporation pans was used for verification at the Silver Hill and Sterling sites (15 and 16 feet in diameter, respectively).

In making the tests, daily evaporation was derived from equation 6 using an electronic computer and taking advantage of the work of *Lamoreux* [1962]. The daily changes in energy storage cannot be determined with sufficient accuracy when they are small relative to the measured energy content of a lake; therefore, comparisons were based on periods a week to a month in length (equation 12). Some of the data required for the tests were not observed in all cases and therefore had to be estimated or obtained by adjustment (see Table 1). The results of the tests are shown in Figures 2 through 6.

The results for Lake Hefner, Felt Lake, Silver Hill, and Sterling are promising; there is only slight bias in each case, and the relatively large scatter for Felt Lake can be partially attributed to the questionable accuracy of the water

TABLE 1. Explanation of Data Used in Tests in Those Cases Where Observations Were not Available

Location	4-Meter Wind Movement	Atmospheric Radiation	Reflected Atmospheric Radiation	Reflected Solar Radiation
Lake Hefner (2386 acres)		Measured nighttime values extrapolated to 24-hour period	3% of atmospheric radiation	
Lake Mead* (108,000–146,000 acres)	Boulder City 1/2-meter wind, assuming $n = 0.3$	Measured nighttime values extrapolated to 24-hour period	3% of atmospheric radiation	6% of observed solar radiation
Felt Lake (46 acres)	On-site, 1/2-meter wind, assuming $n = 0.3$	Equation of Anderson and Baker	3% of atmospheric radiation	6% of observed solar radiation
Sterling (20 sq. m)	On-site, 2-meter wind, assuming $n = 0.3$	Equation of Anderson and Baker	3% of atmospheric radiation	6% of observed solar radiation
Silver Hill (15 ft. diam)	On-site, 1/2-meter wind, assuming $n = 0.3$	Equation of Anderson and Baker	3% of atmospheric radiation	6% of observed solar radiation

* Las Vegas air temperature plus 4°F and dew point plus 1°F to adjust for differences in elevation.

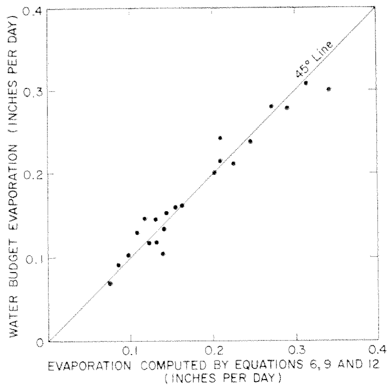

Fig. 2. Verification of equations 6, 9, and 12 for Lake Hefner (periods of 7 to 19 days, 1951-1952).

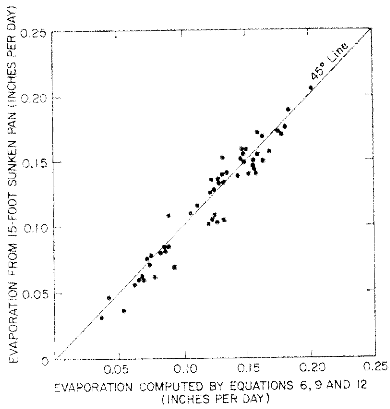

Fig. 4. Verification of equations 6, 9, and 12 at Silver Hill (periods of 7 to 31 days, 1954-1960).

budget. The results for Lake Mead, showing a bias of 18%, are cause for concern. This is particularly true since a similar technique [*Kohler et al.*, 1955] yielded excellent results. Further examination seemed to indicate that the bias resulted either from the use of nonrepresentative wind data (estimated from ½-meter Boulder City observations) or from the use of a wind function that was not applicable to lakes of this size. This conclusion stems from the fact that evaporation computed from equation 9 using the observed water temperature (and the same wind and dew point data) exceeds the accepted total evaporation by more than 30%.

The requirement for a representative 'overland' wind near a large lake where mountain-valley and land-sea winds are appreciable [*U. S. Weather Bureau*, 1953] naturally presents difficulties. Since we realized that the adjusted Boulder City wind data might not be representative for the purpose, we decided to study the possible use of over-water wind data collected at the Boulder Basin barge.

The 4-meter over-land wind at Lake Hefner was 0.82 of that observed near the center of the lake (approximately 1 mile fetch). Since this ratio is dependent upon the fetch, it should be appreciably smaller for the Boulder Basin of Lake Mead, where the fetch to the barge was about 4 miles. If it is assumed that the vertical distribution of wind is of the form

$$u_4/u_a = (4/Z_a)^n \tag{13}$$

where u_a = windspeed at height Z_a, observations yield the following values of n: 0.30 over-land at Lake Hefner; 0.15 over-water at Lake Hefner; 0.10 over-water at Lake Mead.

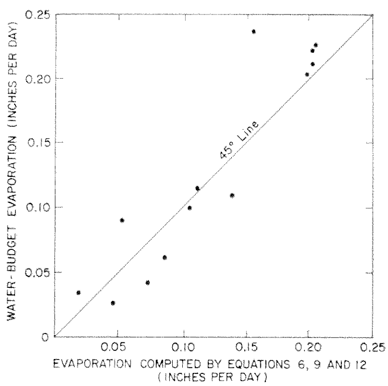

Fig. 3. Verification of equations 6, 9, and 12 for Felt Lake (approximately monthly periods, 1954-1955).

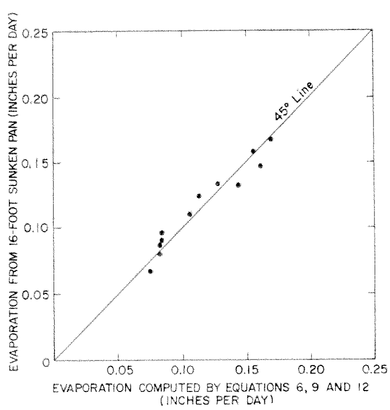

Fig. 5. Verification of equations 6, 9, and 12 at Sterling (periods of 15 to 25 days, 1964-1966).

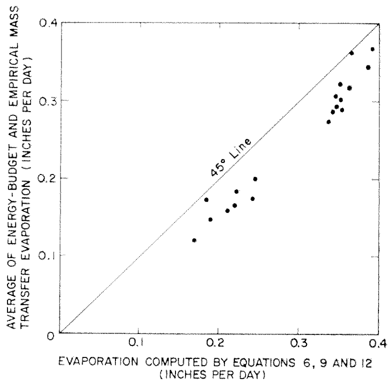

Fig. 6. Verification of equations 6, 9, and 12 for Lake Mead using adjusted Boulder City wind (approximately monthly periods, 1952-1953).

Setting Z_a equivalent to the thickness of the boundary layer, i.e., u_a is the same over land and water, equation 13 gives

$$u_4'/u_4 = (4/Z_a)^{n'-n} \tag{14}$$

where u_4' and n' are applicable to over-land conditions. Based on the above values of n and n' for Lake Hefner, equation 14 gives $Z_a = 15$ meters. Since the observed wind ratio at 16 meters (u_{16}'/u_{16}) was only 0.92, the boundary layer must be somewhat greater than 15 meters, and there are indications [*Marciano and Harbeck,* 1954, page 51] that it may be several times this value.

If equation 9 is to yield the accepted values of evaporation at Lake Mead, it is found that u_4' be taken as $0.42u_4$. Figure 7 shows the results when wind data are obtained in this manner. The surface roughness adjacent to Lake Mead is such that the value of n' undoubtedly exceeds that at Lake Hefner. If we take $n' = 0.40$, equation 14 yields $Z_a = 71$ meters.

It is not possible to reach firm conclusions, but it is considered unlikely that all of the bias in Figure 6 is the result of nonrepresentative wind data. On the other hand, it seems equally unlikely that size effect can be entirely responsible for the bias. In support of the latter view, the application of equation 9 to Lake Ontario yields 26.5 inches of evaporation per year in close agreement with previous studies [*Richards and Rodgers,* 1964].

There is, of course, the possibility that equation 9 is subject to a size effect that becomes appreciable only in the case of an arid climate. With this in mind, computations were made for the Salton Sea, which is more than 8 times the size of Boulder Basin. Equation 9 was found to compute about 10% more evaporation than that determined by *Hely et al.* [1966] using a water budget approach. This bias is small relative to that for Boulder Basin (30%) and is considered to be within the range of experimental error.

CONCLUSIONS

There is reason to believe that the method of computing evaporation presented here will yield better results than the one now in use [*Kohler et al.,* 1955], particularly when observations of atmospheric radiation are available. Whether this is the case must await further verification. Based on the limited verification presented and discussed previously, the authors believe that equation 6 provides a suitable basis for deriving generalized estimates of mean annual free-water evaporation when appropriate data are available. When used in conjunction with equation 12, it should provide reliable estimates of monthly evaporation from existing reservoirs without the expense of continuous over-water observations. It is further suggested that equation 6 might serve to estimate daily potential evapotranspiration for application to hydrologic models [*Kohler and Richards,* 1962].

There remains a question regarding a possible bias due to 'size-effect,' particularly in arid regions, and the requirement for representative wind data in rugged terrain presents

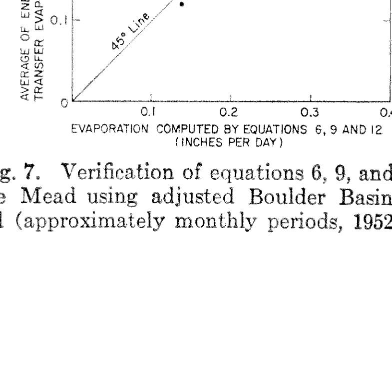

Fig. 7. Verification of equations 6, 9, and 12 for Lake Mead using adjusted Boulder Basin barge wind (approximately monthly periods, 1952-1953).

difficulties. Although there appears to be no size-effect for an aerodynamic equation using wind and vapor pressure measured at low levels near the center of a lake [*Kohler et al.*, 1958], shifting to up-wind vapor-pressure measurements introduces a pronounced size-effect [*Harbeck*, 1962]. When both wind and vapor pressure are representative of up-wind conditions, it is likely that any effect of lake size is dependent upon topography and climate.

The requirement for incoming long-wave radiation is a severe restriction to application and will usually entail that this term be estimated from other meteorological observations. It appears that a network of insulated evaporation pans constitutes the best approach to meeting the requirement in the future.

The last evaporation maps of the United States prepared by the U. S. Weather Bureau were based on 1946–1955 data [*Kohler et al.*, 1959]. It is apparent that these maps can be much improved using data collected during the past ten years, and this project is now under way. Evaporation will be computed from equation 6 for all first-order stations in the process.

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