A Practical Field Technique For Measuring Reservoir Evaporation Utilizing Mass-Transfer Theory

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STUDIES OF EVAPORATION

GEOLOGICAL SURVEY PROFESSIONAL PAPER 272-E

Evaporation from many reservoirs can be computed from records of reservoir stage, wind speed, humidity, and water-surface temperature

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
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By G. Earl Harbeck, Jr.

ABSTRACT

Studies of evaporation made in recent years have provided values of the mass-transfer coefficient, N, in the equation $E=Nu_2(e_o-e_a)$ for reservoirs having surface areas ranging from 1 to nearly 30,000 acres. The apparent correlation of N with reservoir surface area may in large part be associated with variations in the shape of the wind profile near the surface resulting from differences in surface roughness.

It appears that evaporation from many reservoirs can be determined with acceptable accuracy with a fairly simple system of instrumentation, data processing, and analysis.

INTRODUCTION

The active participation of the Geological Survey in studies of evaporation from water surfaces began with the Lake Hefner study (U.S. Geol. Survey, 1954). The principal objectives of that study were to test the validity of the energy-budget and mass-transfer theories for the measurement of evaporation from lakes and reservoirs. The energy-budget method is based upon an accounting of all incoming and outgoing energy, the residual being the energy available for evaporation; the Lake Hefner study showed that this method is suitable for measurement of evaporation for periods of 10 days or longer. The mass-transfer method relates the exchange of water vapor between a water surface and the atmosphere on the basis of measurements of certain related parameters; the study showed that certain mass-transfer equations gave results of acceptable accuracy.

During the Lake Mead study (Harbeck and others, 1958) the energy budget was the basic method used. A simple quasi-empirical equation previously derived for Lake Hefner was found to give satisfactory results on an annual basis at Lake Mead, a much larger lake, although there was a pronounced seasonal variation in the results, owing presumably to the effects of atmospheric stability. The seasonal variation could be minimized by using wind speeds measured near the surface of the lake. Two of the mass-transfer equations that gave acceptable results at Lake Hefner did not prove satisfactory at Lake Mead, nor did another previously untested equation.

Following the Lake Mead study, the energy-budget method has been used to determine evaporation from many lakes in the United States. A simpler method based upon mass-transfer theory, which was also successful, will be described in a section to follow. The results of all these determinations indicate that a practical and reasonably accurate method of determining reservior evaporation is now available if certain conditions can be met.

MASS-TRANSFER THEORY

A complete description of mass-transfer theory is beyond the scope of this report. A simple example of the same type as the Lake Hefner quasi-empirical equation is

$$E=Nu(e_0-e_a), \qquad (1)$$

in which E = evaporation, in inches per day;

N = a coefficient of proportionality, hereafter called the mass-transfer coefficient;

u = wind speed, in miles per hour, at some height above the water surface; a numerical subscript, if used, indicates the height in meters;

e_0 = saturation vapor pressure in millibars, corresponding to the temperature of the water surface;

e_a = vapor pressure of the air, in millibars; a numerical subscript, if used, indicates the height in meters.

Nearly all the mass-transfer equations to be found in the literature have one thing in common: evaporation is considered to be proportional to the product of the wind speed, u, times the vapor-pressure difference, e_0-e_a. In a few equations, the wind speed, u, has an exponent, usually less than unity.

The mass-transfer coefficient, N, represents a combination of many variables in the published mass-transfer equations. Among these are the manner of the variation of wind with height, the size of the lake, the roughness of the water surface, atmospheric stability, barometric pressure, and density and kinematic viscosity of the air. In some of the mass-transfer equations these variables are combined into extremely complicated mathematical expressions. For some of them a direct solution is impossible, and indirect methods must be used. As none of the many published equations that were tested gave acceptable results under all conditions, the emphasis in the Geological Survey was placed upon the use of the energy-budget method for the measurement of evaporation, and further studies of mass-transfer theory were abandoned.

ENERGY-BUDGET STUDIES

After the Lake Mead study the energy-budget method was used to measure evaporation from selected reservoirs in the West, principally in Texas, Arizona, and California. The procedure was usually as follows: A group of 3 or 4 vicinal reservoirs for which evaporation data were desired was selected. The basic requirement was that net incoming radiation measured at one centrally located radiation station could be considered representative of the radiation received at all reservoirs. Thermal surveys to determine the changes in energy storage were made at each reservoir at regular intervals (usually about 1 month). The amount of energy brought into each reservoir in inflow and removed in outflow was computed. A raft supporting an anemometer and a water-surface temperature recorder was moored at the approximate center of each reservoir.

During a calibration period of a little more than 1 year (it was considered desirable that the period include 2 summers), evaporation was determined using the energy-budget method for each reservoir. During this period conterminous records of wind speed and water-surface temperature were obtained at each raft and the vapor pressure of the air was obtained from meteorological data recorded at the radiation station or from U.S. Weather Bureau records at a nearby station. Then the mass-transfer coefficient, N, was obtained by dividing the energy-budget evaporation, E, by the product $u(e_0-e_a)$. The aim was to determine N for each reservoir so that the expensive radiation equipment could be moved to another group of reservoirs. Evaporation could be computed on a continuing basis for each of the first group of reservoirs using the experimentally determined mass-transfer coefficient, windspeed, water-surface temperature and humidity of the air.

A so-called "standard" raft was designed using empty steel drums to provide buoyancy. The anemometer was approximately 2 meters above the water surface. Because of practical considerations the standard raft design was not used at a few reservoirs. For example, at one large reservoir high waves were expected frequently, so that a larger-than-standard raft was used, and because the lake was extensively used for boating, the raft was moored near the shore where it would not be as dangerous to navigation as if it were anchored in midlake. At another reservoir, no observer was available to visit the raft weekly and change the water-surface temperature chart; therefore, water-surface temperatures were measured at the edge of the lake and recorded on the radiation recorder. Wind speeds were measured on shore also. Although the mass-transfer coefficients thus determined were suitable for obtaining continuous records of evaporation at these reservoirs, they were later found to be in poor agreement with the coefficients based on data obtained at the standard midlake rafts.

EVAPORATION-SEEPAGE MEASUREMENTS

A simple technique for measuring seepage and evaporation losses from small lakes and reservoirs was first described by Langbein, Hains, and Culler (1951). The two basic assumptions of the method are (1) during periods of no surface inflow or outflow, the fall in reservoir stage is composed of two parts, evaporation and seepage; and (2) when the product $u(e_0-e_a)$ is zero, evaporation is negligible.

In most instances, restriction of the analysis to periods of no surface inflow or outflow is preferable, though not necessary. If inflow and outflow are measured, the observed change in stage can be adjusted accordingly, but ordinarily even small errors in measuring inflow and outflow may make the adjusted change in stage of questionable accuracy.

The second assumption is reasonable because, in the absence of wind and vertical convection, evaporation proceeds only by molecular diffusion, an extremely slow process. Even with convection resulting from substantial differences between air and water temperature, evaporation in the absence of wind is quite small, as shown by an analysis by Marciano and Harbeck (1954) of an equation developed by Yamamoto (1950). Also, if the second term of the product $u(e_0-e_a)$ is zero, the air is saturated and evaporation is zero.

The method is simple to use. A totalizing anemometer is mounted at a height of 2 meters above the water surface on a standard raft anchored in midlake. A spring-driven or battery-powered water-temperature recorder designed for either 7-day or 28-day operation is also mounted on the raft. An auxiliary marginal pen records units of wind movement; the size of the unit may be varied to suit local conditions. A tipping-bucket rain gage is operated in conjunction with the water-stage recorder; each increment of rainfall is recorded by a pen marking in the margin of the water-stage recorder chart. Periods of rainfall may thus be excluded from the analysis by scanning the chart. The beginning and end of each period should be chosen so that reservoir stages at these times are accurately defined. Times when the recorder chart indicates the occurrence of wind-induced surges or oscillations of the water surface should be avoided. Winds need not necessarily be light during the entire period; in fact, some periods having windy spells within them should be selected purposely so that as wide a range as possible of the product $u(e_0-e_a)$ is obtained. The periods may be of variable length as long as the same units are used. The change in stage, ΔH, is usually computed in feet per day, and average values of wind speed and vapor-pressure difference are computed for the same period.

Data obtained at Deep Creek Reservoir No. 3 near Placid, Tex., are shown in figure 30. It is apparent that the Y intercept of a least-squares line would not differ from zero by a statistically significant amount, which indicates that the net seepage is zero. The slope of the best fitting line is N, the mass-transfer coefficient. This method has been used to determine N for many small ponds in Texas. Some were flood-detention reservoirs for which area and capacity curves were available. Some, however, were small ponds in south Texas that were used only for evaporation-suppression studies and therefore were not mapped. Surface areas of these ponds were estimated.

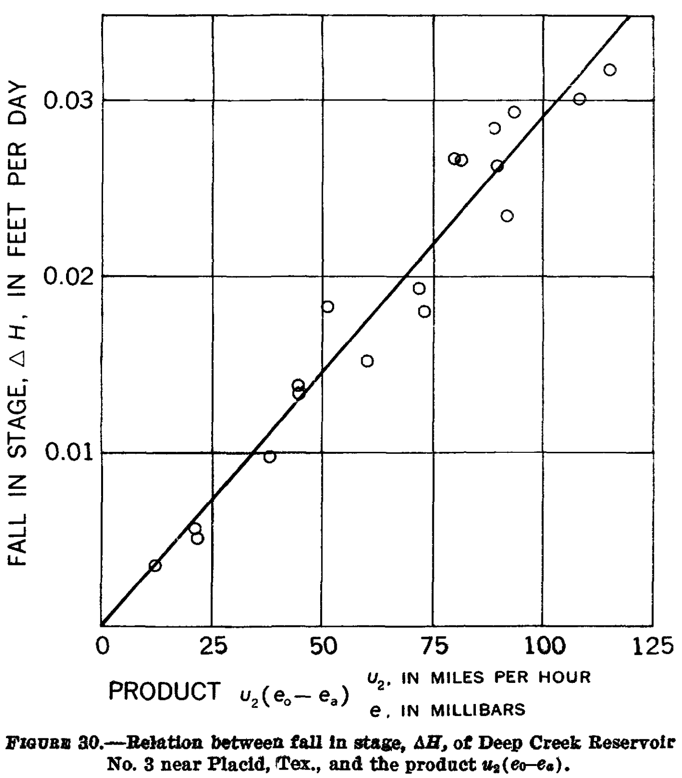


FIGURE 30.—Relation between fall in stage, ΔH, of Deep Creek Reservoir No. 3 near Placid, Tex., and the product $u_2(e_0-e_a)$.

MASS-TRANSFER COEFFICIENTS

The mass-transfer coefficients obtained in the course of the energy-budget studies and the evaporation-seepage studies are considered to be comparable. In both studies, the wind speeds at a height of 2 meters above the surface and the water-surface temperature were measured in midlake. Air temperature and humidity were measured at a site usually several miles away from the lake, so that the vapor pressure thus computed is considered to be representative of the natural humidity of the air unmodified by passage over a body of water.

For Lake Hefner, the vapor pressure measured at the 8-meter level in midlake was used in the previously mentioned quasi-empirical equation (Marciano and Harbeck, 1954, eq 58). The authors concluded that the upper limit of the vapor blanket was at a height of about 8 meters above the surface in midlake. The vapor pressure at 8 meters could therefore be considered to represent the water-vapor content of the unmodified air at Lake Hefner. In this equation the wind speed used was that recorded at 8 meters. The wind speed was also recorded at 2 meters and the average ratio of the two, u_8/u_2, was 1.237 (Harbeck and others, 1958, table 10). In order that the mass-transfer coefficient given in equation 58 (Marciano and Harbeck, 1954) could be compared with other coefficients, the units were changed and the 8-meter wind speed was replaced by the 2-meter wind speed on the basis of the above ratio.

At Lake Mead, both wind speed and vapor pressure at the 2-meter level were used in a similar equation (Harbeck and others, 1958, eq 20). Because Boulder Basin of Lake Mead is much larger than Lake Hefner, the upper limit of the vapor blanket was believed to be probably above 8 meters, but no data were obtained above that level. The vapor pressure at 8 meters was not considered to be representative of the unmodified air, but at least it was closer to it than the 2-meter vapor pressure was. Accordingly, equation 20 was modified by changing units and by replacing the 2-meter vapor pressure with the 8-meter vapor pressure, using the ratio $(e_0-e_8)/(e_0-e_2)=1.105$ (Harbeck and others, 1958, table 10).

The mass-transfer coefficients obtained from energy-budget and evaporation-seepage studies are shown in figure 31. The coefficient for Lake Mead was considered representative of Boulder Basin (29,000 acres at the time of the study) rather than of the entire lake, as Boulder Basin, where the meteorological data were obtained, is connected to the main part of the reservoir by only a narrow channel.

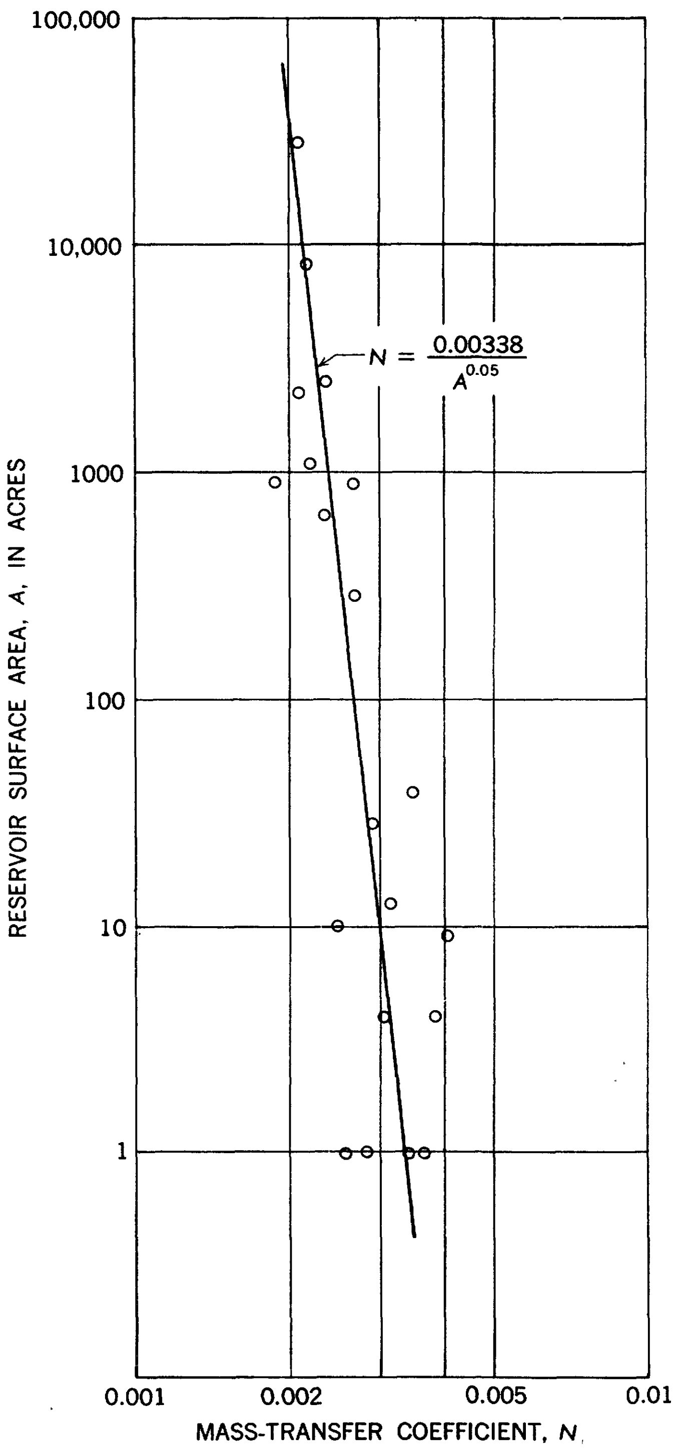


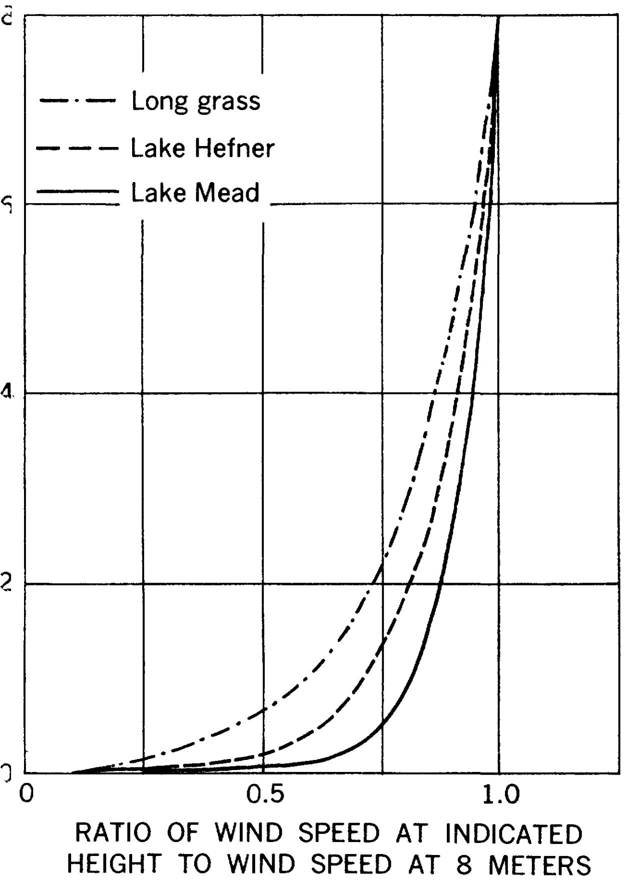
FIGURE 31.—Relation between mass-transfer coefficient, *N*, and reservoir surface area.

Part of the scatter about the best fitting line is attributable to physiographic differences between reservoirs, particularly exposure to wind. Consider two nearby small ponds having the same surface area, one in flat terrain with no shoreline vegetation and the other surrounded by hills and dense shoreline vegetation. The wind profile over the 2 ponds will not be the same even though the windspeed at some height, such as 8 meters, may be the same. As the standard error of estimate of the regression shown in figure 31 is approximately 16 percent, the coefficient *N* should be determined for each reservoir individually, but the basic relation illustrated in figure 31 should serve to prevent gross errors.

The apparent significant correlation between *N* and reservoir surface area warrants further study. It was stated earlier that on an annual basis the mass-transfer coefficients for Lake Hefner and Lake Mead agreed closely, which would indicate no correlation between *N* and surface area, at least for surface areas of between 2,000 and 30,000 acres. Wind speeds used in this equation (Marciano and Harbeck, 1954, eq 58) were measured at 8 meters, however, not at 2 meters, and the ratio u_8/u_2 for Lake Hefner was quite different from the ratio for Lake Mead. The ratio u_8/u_2 is proportional to the wind shear resulting from surface drag. Consider a very small pond in a forested area. The time of passage over the pond is too short to permit significant modification of the wind profile, and the surface drag is therefore representative of the upwind terrain, not the pond surface. Consider also a water surface having an infinite fetch and uniform wind conditions. Surface drag will approach but never reach zero, because some energy is expended in maintaining wave form and motion. At Boulder Basin of Lake Mead the ratio u_8/u_2 was 1.145, and at Lake Hefner it was 1.237 (Harbeck and others, 1958, table 10). The area of Boulder Basin was 29,000 acres, which is equivalent to a circular area having a radius of approximately 4 miles. Similarly, the equivalent radius of Lake Hefner was approximately 1 mile.

If a pond is so small that it has no appreciable effect on the wind profile, the ratio u_8/u_2 could be about 1.375, which corresponds to a wind profile that might be observed over a field of long grass or perhaps a wheatfield. These three wind ratios were used as a basis for the profiles shown in figure 32.

Wind speeds at 8 meters were assumed to be the same over all 3 surfaces, and the wind speeds at other heights are shown relative to the 8-meter wind for the 3 different surfaces. The 2-meter wind at Lake Hefner is 12



32.—Representative wind profiles over grass and water surfaces.

nt less than the 2-meter wind at Lake Mead, so the mass-transfer coefficient for Lake Hefner d be greater than for Lake Mead. The 2-meter d over a grassfield is about 24 percent less than at e Mead. The increase in mass-transfer coefficient n Lake Mead to a small pond is more than 24 per-, and it is likely that other factors are involved, as the decrease in evaporation with distance r wind. Results of investigations agree that evapo-on rates should decrease downwind. There is no ement as to the manner of variation, however, and therefore concluded that the apparent relation een N and surface area illustrated in figure 31 is in part to the use of wind data at the 2-meter level n part to the downwind decrease in evaporation rates. In other words, the apparent relation between N and surface area is due in part to the relation between the ratio u_8/u_2 and the surface area.

Measurement of the wind speed at the 2-meter level in midlake is important, if the coefficient N is to be in reasonable agreement with the curve shown in figure 31. If wind speeds are measured at some other location, such as on shore, the coefficients thus determined cannot be expected to agree with those on figure 31. Wind speeds measured at heights of 2 meters on shore will be substantially less than those measured at the same height in midlake.

CONCLUSIONS

Expansion of the present program of evaporation measurement in the United States is practicable. The evaporation-seepage method can be used at a reasonable cost. The data required are wind speed at the 2-meter level and water-surface temperature in midlake, vapor pressure of the unmodified air, and change in lake stage. The change in stage is then separated into its two components, seepage and evaporation. A mass-transfer coefficient, N, can be determined for each reservoir for use in the equation $E=Nu_2(e_0-e_a)$.

The energy-budget method, which requires much more expensive equipment and an elaborate data-processing and analysis procedure, can be reserved for measurements of evaporation from the larger lakes and reservoirs, or from any reservoirs for which it may be impracticable to use the mass-transfer method because inflow and outflow cannot be measured with sufficient accuracy.

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