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A COMPARISON OF MASS-TRANSFER AND CLIMATIC-INDEX EVAPORATION COMPUTATIONS FROM SMALL RESERVOIRS IN TEXAS

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TABLE OF CONTENTS

TABLES

FIGURES

TABLE OF CONTENTS (Cont'd.)

A COMPARISON OF MASS-TRANSFER AND CLIMATIC-INDEX EVAPORATION COMPUTATIONS FROM SMALL RESERVOIRS IN TEXAS

ABSTRACT

The mass-transfer method of determining evaporation is utilized as the control method in an evaluation of climatic-index evaporation data provided by the Texas Water Rights Commission for eight floodwater-retarding reservoirs in Texas. Data were collected at each reservoir at various times during the period 1960-68 by the U.S. Geological Survey.

A t-test for the comparison of means of two sets of independent observations was used to determine if a significant difference existed between monthly evaporation rates for bimonthly periods beginning with January as computed by the mass-transfer method and by the climatic-index method. No significant difference at the 5 percent level was found between the two sets of data during any of the 2-month periods.

Exclusion of the inconsistent Calaveras Creek data increased the correlation coefficient between mass-transfer and climatic-index evaporation data from 0.81 to 0.86.

Because the t-tests showed no significant differences between the mass-transfer and climatic-index data, both methods are assumed to provide an equally good estimate of evaporation from small reservoirs. Therefore it is concluded that the climatic-index evaporation data, as supplied by the Texas Water Rights Commission, provide a reliable estimate of evaporation for use in hydrologic studies of small reservoirs in Texas.

A COMPARISON OF MASS-TRANSFER AND CLIMATIC-INDEX EVAPORATION COMPUTATIONS FROM SMALL RESERVOIRS IN TEXAS

INTRODUCTION

The purpose of this report, which was prepared by the U.S. Geological Survey in cooperation with the Texas Water Development Board, is to compare monthly evaporation by 2-month periods beginning with January-February as computed by the empirical climatic-index method, E_{CI}, (furnished by the Texas Water Rights Commission) to evaporation as calculated by the mass-transfer method, E_{MT}. The comparisons will show whether or not E_{CI} is significantly different from E_{MT}. In the keeping with this purpose, this report presents:

1. the mass-transfer coefficients and standard error of each as determined for eight floodwater-retarding reservoirs;

2. the results of t-tests used to compare E_{CI} and E_{MT}; and

3. recommended coefficients if necessary to adjust E_{CI} to E_{MT}.

As of September 30, 1969, the Soil Conservation Service of the U.S. Department of Agriculture had completed 1,355 floodwater-retarding structures in Texas. Definition of the hydrologic effects of these structures is requisite to the development of practical water-planning and management programs. Definition of the hydrologic effects is dependent upon an accurate evaluation of the following variables: (1) net inflow, (2) outflow, (3) rainfall on the pool, (4) change in storage, and (5) consumption.

Consumption includes evaporation from the free water surface, evaporation from the soil surface adjacent to the pool, transpiration, and percolation to the ground-water reservoir. Generally, percolation to the ground-water reservoir is not considered as consumption. However, in the study areas of this investigation, the water table normally does not intersect the surface streams anywhere near the floodwater-retarding reservoirs. Therefore, percolation to the ground-water reservoir is not recoverable as a "surface-water resource" in the basin and is considered as a loss. Because consumption includes components that are difficult to measure, it is the variable most difficult to evaluate. Gilbert and Sauer (1970, p. 31-37) present data and analyses which show consumption from floodwater-retarding reservoirs to exceed evaporation losses associated with the surface storage of water.

METHODS OF DETERMINING EVAPORATION

There are five basic methods that can be used to estimate evaporation from lake surfaces. These five methods are discussed briefly in the following sections of this report.

Water-Budget Method

The water-budget method results in the determination of evaporation from a reservoir by measuring inflow, outflow, seepage, and change in storage. The results of water-budget studies made on Lake Hefner in Oklahoma (Marciano and Harbeck, 1954) indicate that this method yields realistic results provided that inflow, outflow, change in storage, and seepage are measured accurately. In instances where transpiration, "bank" storage, or ground-water storage affects the water loss from a reservoir, the water-budget method may not provide accurate evaporation data.

Energy-Budget Method

The energy-budget method is based on the principle of conservation of energy. Incoming, outgoing, and stored energy are measured over some finite period and related to the amount of energy required for the evaporation process. Anderson (1954) used the energy-budget method to compute evaporation from Lake Hefner. Harbeck and others (1958) used the energy-budget method as a control for calculations made during the Lake Mead studies.

The energy-budget method, from a physical point of view, appears to be the most accurate method of computing evaporation. Use of the method, however, is generally limited to the calibration of other methods of determining evaporation because of the relatively high instrumentation cost.

Pan-to-Lake Coefficients

The evaporation pan is currently the most widely used instrument to determine evaporation. Reservoir evaporation is determined by application of pan-to-lake coefficients to the pan-evaporation values. The method is simple to use, required data are generally available, and the results are reasonably accurate on an annual basis.

The primary objectives of evaporation studies by the U.S. Weather Bureau are the development of improved methods for estimating lake evaporation from a network of climatological observations (Kohler and Parmele, 1967). Monthly values of pan-to-lake coefficients vary considerably, depending on lake characteristics and local climate. Unless the effects of advected energy into the lake and the effects of heat transfer through the pan are taken into account, appreciable error can be introduced by the use of the customary 0.7 annual coefficient.

Mass-Transfer Method

The mass-transfer method of deriving evaporation equations is based on the concepts of discontinuous and continuous mixing applied to the transfer of mass or water vapor in the boundary layer. Nearly all mass-transfer equations have one common factor—that evaporation is directly proportional to the product of vapor-pressure difference and wind speed. Wind speed, in some of the equations, has been assigned an exponent between 0.75 and 1.00. Marciano and Harbeck (1954) present a physical and mathematical review of mass-transfer equations.

The following quasi-empirical mass-transfer equation (Harbeck, 1962) was used in this study as the control method to determine evaporation from a free water surface:

$$E_{MT} = Nu\ (e_o - e_a) \qquad (1)$$

where E_{MT} = evaporation in inches per day,

N = the mass-transfer coefficient, a coefficient of proportionality,

u = wind speed, in miles per hour, at 2 meters above the water surface,

e_o = saturation vapor pressure, in millibars, corresponding to water-surface temperature, and

e_a = vapor pressure of the air, in millibars.

Harbeck (1962) states that the mass-transfer coefficient, N, generally represents a combination of many variables, such as the size of the lake; roughness of the water surface; manner of variation of wind with height; atmospheric stability; barometric pressure; and density and kinematic viscosity of the air. Gilbert and others (1964) and Harbeck (1962) present three methods that can be used to determine the mass-transfer coefficient.

An evaporation-seepage technique presented by Harbeck and previously described by Langbein, Hains, and Culler (1951) is used in this report to determine N. Application of the technique is based on the following assumptions:

1. The decline in reservoir stage during periods when there is no surface inflow or outflow is composed of two parts, evaporation and seepage.

2. When the product $u(e_o - e_a)$ is zero, evaporation is negligible.

The evaporation-seepage technique is applied as follows in the determination of a composite N for a reservoir. Determine the change in stage (ΔH) and the average values of wind speed and vapor pressure differences for 3- to 5-day periods of no inflow or outflow. The values of these variables are then plotted with (ΔH), in feet per day, as the ordinate, and the product of $u(e_o - e_a)$, where u is expressed in miles per hour and $(e_o - e_a)$ in millibars, as the abscissa. A least-squares line is then fitted to the data. The slope of this line is the mass-transfer coefficient.

Initially, an attempt was made to determine a mass-transfer coefficient for each 2-month period at each reservoir. However, the lack of data prevented a least-squares determination of N for the 2-month periods. Consequently, a composite N based on all data was calculated for each reservoir. Had it been possible to determine a mass-transfer coefficient for each 2-month period, any seasonal variation in the intercept, which is indicative of other consumptive losses such as seepage, would have been shown.

The composite N value with the humidity, temperature, and wind speed data were used in equation (1) to compute monthly evaporation from each reservoir.

Climatic-Index Method

Veihmeyer (1964) presents a summary of selected evaporation equations based on Dalton's Law, which is the basis of most empirical equations. Other than the vapor-pressure differential, wind movement is generally the most important factor in the equations.

Use of pan-to-lake coefficients, without accounting for advected energy into the lake and heat transfer through the pan, can introduce considerable error into estimates of evaporation. Kohler, Nordenson, and Fox (1955) developed the "theoretical" pan concept, in which sensible heat transfer through the pan and the part available for use in the evaporation process is determined. The Texas Water Rights Commission has adopted the method presented by Kohler, Nordenson, and Fox (1955). The method, as applied by the Commission is entitled the *climatic-index method*.

The Texas Water Rights Commission utilizes the composite relation between air temperature, dew-point temperature, wind movement, and solar radiation as shown in Figure 1 for the determination of monthly lake-surface evaporation (E_{CI}). Figure 1 is based on equation 10 in the U.S. Weather Bureau Research Paper No. 38 by Kohler, Nordenson, and Fox (1955).

COLLECTION OF DATA

The data necessary to compute mass-transfer evaporation values were collected on one floodwater-retarding reservoir in each of the eight watersheds shown on Figure 2. The subwatershed reservoirs and the periods during which data were collected are given in Table 1.

The data used in this study are wind movement, mean daily air and water temperatures, relative humidity, rainfall, and change in stage. A raft supporting a 28-day thermograph and a totalizing anemometer was anchored at midlake. The thermograph provided water-surface temperature data and the anemometer provided wind-movement data at 2 meters above the water surface (Figure 3). Air-temperature and relative-humidity records were obtained weekly from hygrothermograph installations (Figure 3) near each reservoir.

Change in stage and rainfall data were provided by a continuous-stage recorder and a recording rain gage. Figure 4 shows part of a typical well and gage house used to obtain stage and rainfall records (note receiver for recording rain gage on top of the gage house).

Climatic-index data were obtained from the Environmental Science Services Administration first-order synoptic stations. Values of the climatic data at a specific reservoir site are determined by interpolation of the data from surrounding stations.

ANALYSES OF DATA

Method of Analyses

The monthly evaporation data for all reservoirs were plotted prior to statistical evaluation to determine if inconsistencies existed. E_{CI} was plotted against E_{MT}. The points were random about the line of equal evaporation for all reservoirs except the Calaveras Creek reservoir, where E_{MT} was consistently greater than E_{CI}. The Calaveras Creek data were omitted from the statistical evaluation except in computing a correlation coefficient to show the effect of the inconsistent data.

Change in stage and wind-speed records on Calaveras Creek were generally poor during the study period. New equipment was tried, but was not dependable (written communication, Kennon, 1965). The reservoir also contained a luxuriant growth of weeds. These circumstances provided sufficient reasons to question the accuracy of the evaporation data.

A t-test for the comparison of means of two sets of independent observations was used to determine if any significant difference exists between the monthly evaporation rates of E_{CI} and E_{MT}. Statistical evaluation of the monthly data was made for the 2-month periods.

Wine (1964) gives the following formula for the computation of the t statistic:

$$t_c = \frac{\overline{X} - \overline{Y}}{s_p \sqrt{1/n_1 + 1/n_2}} \qquad (2)$$

where t_c is the value used to judge statistical significance or insignificance when compared to a t-value table,

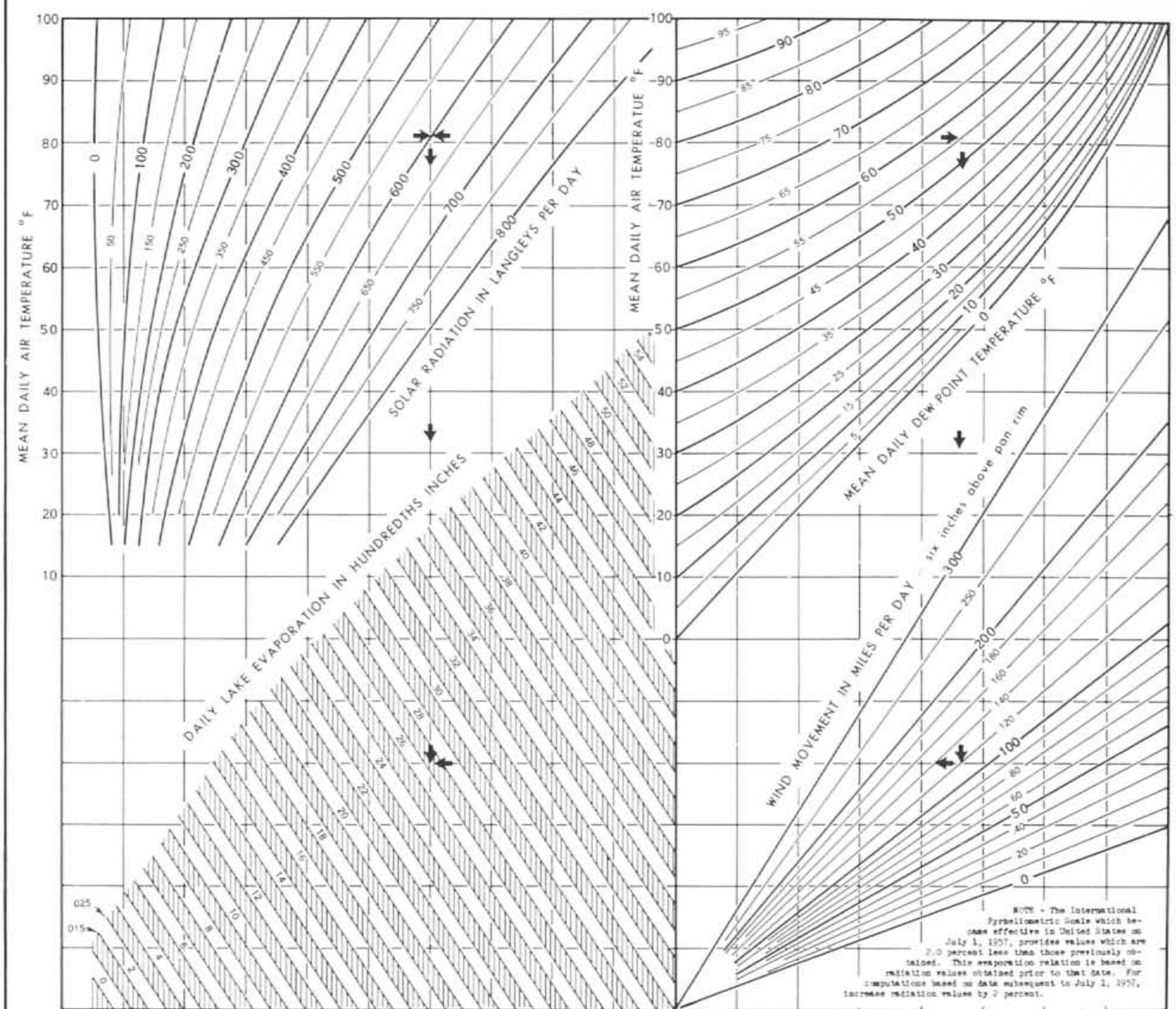
$\overline{X}$ is the mean of the monthly mass-transfer evaporation data for a 2-month period,

$\overline{Y}$ is the mean of the monthly climatic-index evaporation data for a 2-month period,

s_p is the pooled standard deviation for samples of equal size computed as

$$s_p = \sqrt{\frac{s^2_{MT} + s^2_{CI}}{2}} \qquad (3)$$

where s^2_{MT} and s^2_{CI} are the variances of the mass-transfer and climatic-index data, respectively, and



Adapted from U.S. Department of Commerce Weather Bureau Technical Paper No. 37

Figure 1

Lake Evaporation Relations Used by the Texas Water Rights Commission in Climatic-Index Computations

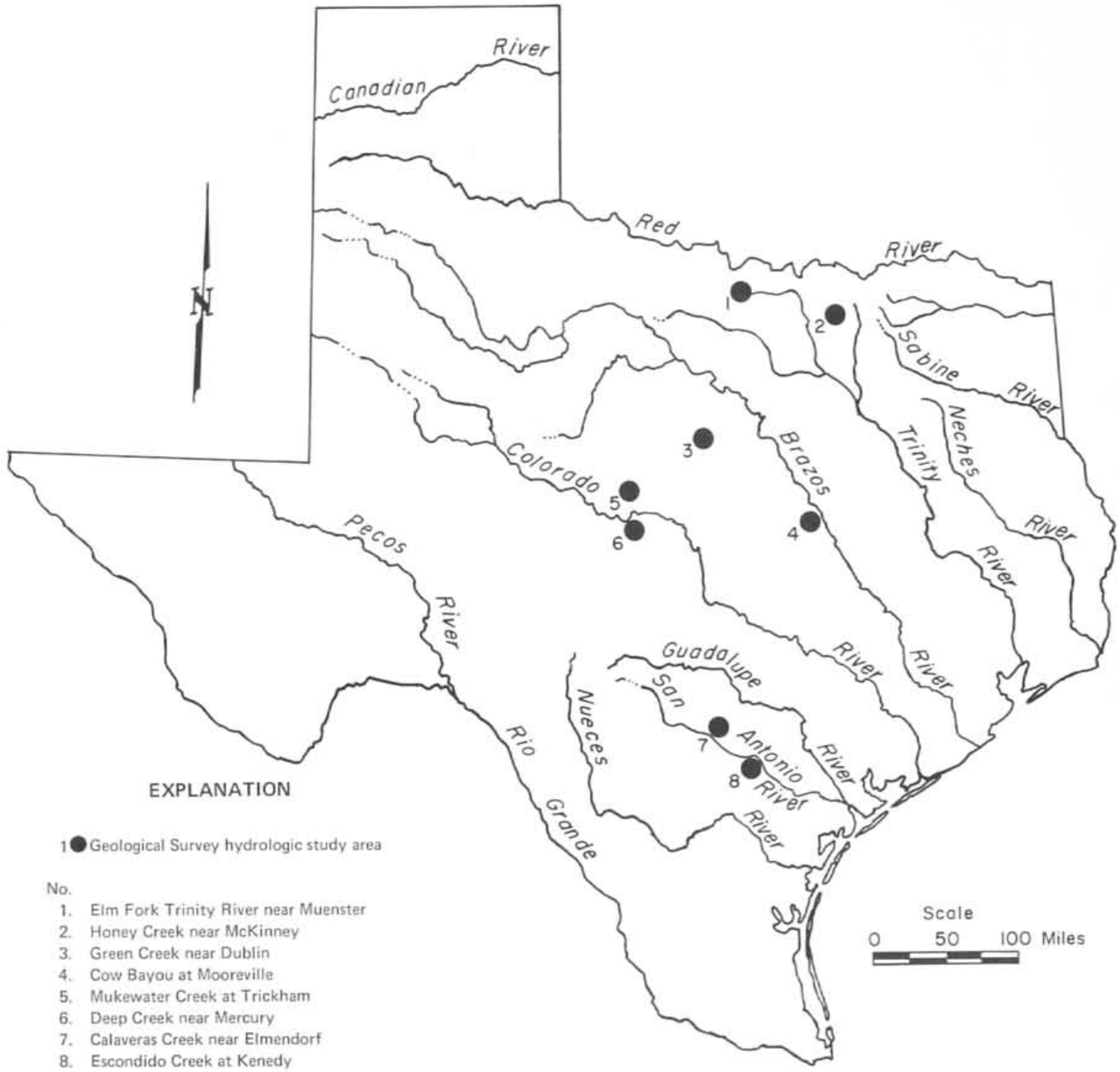
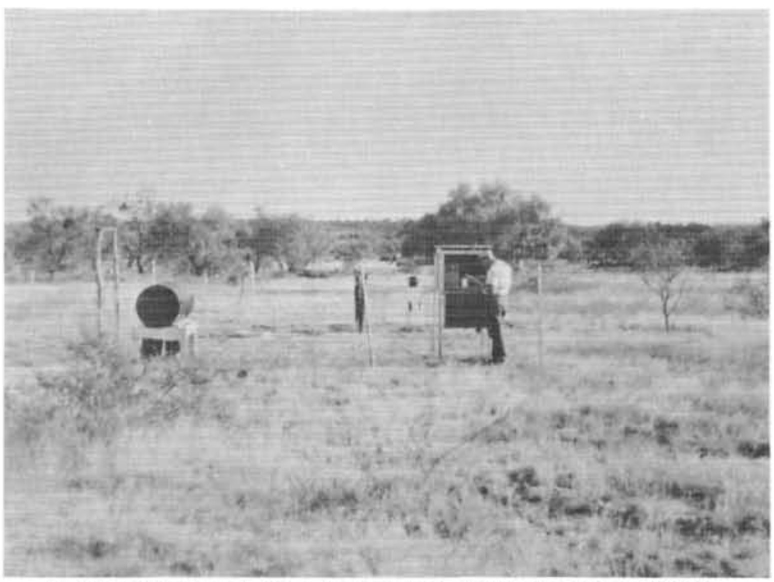


Figure 2.—Location of the Eight Watersheds Where Evaporation Data Were Collected

Table 1.—Period During Which Climatic Data Were Collected for the Evaporation Study on Each Subwatershed Reservoir

WATERSHED	SUBWATERSHED NUMBER	PERIOD OF DATA COLLECTION				
Elm Fork Trinity River	6- 0	Oct.	1965	to	Aug.	1968
Honey Creek	11	Oct.	1965	to	Aug.	1967
Green Creek	1	Aug.	1964	to	Aug.	1966
Cow Bayou	4	Mar.	1964	to	Dec.	1965
Mukewater Creek	9	Mar.	1963	to	Feb.	1965
Deep Creek	3	Jan. Mar.	1960 1965	to to	Jan. Feb.	1962; 1966
Calaveras Creek	6	Nov.	1963	to	Sept.	1965
Escondido Creek	11	Oct.	1963	to	Nov.	1964

A. Standard Raft with Thermograph and Totalizing Anemometer



B. Hygrothermograph, Young Screened Pan, and Nonrecording Rain Gage

Figure 3

Climatological Instruments That Provide Data for Use in Mass-Transfer Computations.

Figure 4.—Typical Gage Installation at a Floodwater-Retarding Reservoir

n_1 and n_2 are the sample sizes of the mass-transfer and climatic-index data, respectively.

The t-test provides a valid comparison of the two sets of evaporation data because the variables used for computation of E_{CI} and E_{MT} are derived independently. There is no common measurement of any climatic factor. Coefficients (K) to adjust the climatic-index data to the mass-transfer data for each 2-month period were computed as the ratio of $\overline{X}_{MT}/\overline{Y}_{CI}$.

The 95 percent confidence interval was computed to show the magnitude of the difference in means of E_{MT} and E_{CI} that could be expected for any 2-month period. The limits of the confidence interval of two means are given by Li (1964) as follows:

$$(\overline{X} - \overline{Y}) \pm t_{.025} \sqrt{s_p^2 \left(\frac{1}{n_1} + \frac{1}{n_2}\right)} \qquad (4)$$

where $t_{.025}$ is the 2.5 percent point of the t distribution with $(n_1 + n_2 - 2)$ degrees of freedom. Definitions of the other terms are as given previously.

Results of Analyses

The mass-transfer coefficient, intercept, and the standard error of estimate of the mass-transfer coefficient for each reservoir are shown in Table 2. The average standard error expressed as a percentage (excluding data from the Calaveras Creek reservoir) is 10 percent. The range is 5 percent to 17 percent. The correlation coefficients between E_{MT} and E_{CI} with the data from the Calaveras Creek reservoir included and excluded were 0.81 and 0.86, respectively.

The results of the t-test between the two sets of data, the adjustment coefficients, and the 95 percent confidence intervals for the difference in means are given in Table 3 for each 2-month period. There is no significant difference between E_{MT} and E_{CI} at the 5 percent level. The confidence intervals given in the last column of Table 3 show the range within which the difference in monthly mean evaporation, as determined by the two methods, falls 95 percent of the time.

Table 2.—Mass-Transfer Coefficient, Intercept, and Standard Error of Estimate of the Mass-Transfer Coefficient for Each Reservoir Utilized in the Study

WATERSHED AND RESERVOIR	MASS-TRANSFER COEFFICIENT	INTERCEPT	STANDARD ERROR, S_b, OF MASS-TRANSFER COEFFICIENT	S_b EXPRESSED AS PERCENT
Elm Fork Trinity River, 6-0	$2.66 \cdot 10^{-4}$	$3.0 \cdot 10^{-3}$	$2.97 \cdot 10^{-5}$	11
Honey Creek, 11	$2.27 \cdot 10^{-4}$	$2.8 \cdot 10^{-3}$	$2.66 \cdot 10^{-5}$	12
Green Creek, 1	$2.62 \cdot 10^{-4}$	$2.5 \cdot 10^{-3}$	$1.79 \cdot 10^{-5}$	7
Cow Bayou, 4	$1.90 \cdot 10^{-4}$	$1.1 \cdot 10^{-2}$	$3.23 \cdot 10^{-5}$	17
Mukewater Creek, 9	$2.39 \cdot 10^{-4}$	$6.0 \cdot 10^{-3}$	$1.21 \cdot 10^{-5}$	5
Deep Creek, 3	$2.29 \cdot 10^{-4}$	$4.5 \cdot 10^{-3}$	$1.17 \cdot 10^{-5}$	5
Calaveras Creek, 6	* $4.43 \cdot 10^{-4}$	$1.2 \cdot 10^{-2}$	$2.74 \cdot 10^{-5}$	6
Escondido Creek, 11	$2.22 \cdot 10^{-4}$	$2.1 \cdot 10^{-2}$	$3.27 \cdot 10^{-5}$	15

* Kennon (written communication, 1965) computed a mass-transfer coefficient of 2.28×10^{-4} by weighting the bimonthly coefficients. Because of this and other discrepancies, Calaveras Creek data were not used in the study.

Table 3.—Results of the Analyses by 2-Month Periods for the Comparison of Mass-Transfer and Climatic-Index Evaporation Data From Seven Small Reservoirs in Texas

Period	Computed t value	$\pm t_{.025}$ with (n_1+n_2-2) degrees of freedom (df) (that value which computed t value must exceed to show significance)	Adjustment coefficient (climate-index evaporation times coefficient = mass-transfer evaporation)	95 percent confidence interval (95 percent of the time the difference in means lies within this interval) Units = feet per month
Jan. -Feb.	1.63	±2.00 with 56 df	1.11	$0 < \bar{X} - \bar{Y} < 0.04$ [a]
Mar. -Apr.	0.32	±2.00 with 56 df	1.03	$-0.05 < \bar{X} - \bar{Y} < 0.07$
May -June	-0.65	±2.00 with 54 df	0.96	$-0.08 < \bar{X} - \bar{Y} < 0.04$
July -Aug.	-1.87	±2.00 with 56 df	0.92	$-0.10 < \bar{X} - \bar{Y} < 0$
Sept. -Oct.	0.38	±2.01 with 50 df	1.03	$-0.04 < \bar{X} - \bar{Y} < 0.06$
Nov. -Dec.	0.73	±2.00 with 60 df	1.06	$-0.02 < \bar{X} - \bar{Y} < 0.04$

a/ $\bar{X}$ is the mean of E_{MT}. $\bar{Y}$ is the mean of E_{CI}.

The coefficients for adjustment of the climatic-index data (Table 3) can be applied for each 2-month period. However, because the t-tests showed no significant differences between the two methods, no greater accuracy can be achieved by their application.

SUMMARY AND CONCLUSIONS

Mass-transfer evaporation data collected at various periods between 1960 and 1968 from seven floodwater-retarding reservoirs in Texas have afforded data to which climatic-index evaporation data supplied by the Texas Water Rights Commission could be readily compared.

Determination of a mass-transfer coefficient (N) was required for computation of mass-transfer evaporation for each reservoir. N was determined as the slope of the least-squares line for a plot of $u(e_o - e_a)$ versus ΔH for each reservoir. The average standard error of estimate of N for the seven reservoirs was 10 percent. The range was 5 percent to 17 percent.

A t-test was used to determine if a significant difference existed between monthly E_{MT} and monthly E_{CI} for 2-month periods. No significant difference at the 5 percent level was found for evaporation during any 2-month period as determined by the two methods.

Because there is no significant difference in the evaporation rate as determined by the mass-transfer and climatic-index methods, both methods are assumed to provide an equally good estimate of evaporation. On the basis of the data available for analysis in this report, it is concluded that the climatic-index evaporation data as supplied by the Texas Water Rights Commission can be used without application of a coefficient to estimate evaporation from small reservoirs in Texas.

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