U.S. Weather Bureau.

Research paper no. 38.

U. S. DEPARTMENT OF COMMERCE

SINCLAIR WEEKS, *Secretary*

WEATHER BUREAU

F. W. REICHELDERFER, *Chief*

RESEARCH PAPER NO. 38

EVAPORATION FROM PANS AND LAKES

by

M. A. KOHLER, T. J. NORDENSON, and W. E. FOX

WASHINGTON
May 1955

WEATHER BUREAU RESEARCH PAPERS

No. 1 **Progress Report on Development of an Electronic Anemometer.* W. R. Thickstun, July 1943.

No. 2 **A Project to Test the Potential Usefulness of Pressure Patterns for Forecasting.* H. W. Norton, G. W. Brier, and R. A. Allen, January 1944.

No. 3 **Preliminary Report on Duration of Stormy Periods at Selected Localities and Intervals Between Periods.* L. L. Weiss, January 1944.

No. 4 **Some Relationships Between Five-Day Mean Surface Maps and Their Component Daily Maps.* C. B. Johnson, January 1944.

No. 5 **Improvement of Trend Methods of Forecasting.* P. F. Clapp, July 1943.

No. 6 (Unassigned.)

No. 7 **Formation of New Moving Centers South of Deep Lows.* R. C. Gentry, January 1944.

No. 8 **An Investigation of a Trajectory Method of Forecasting Flow Patterns at the 10,000-Foot Level.* H. G. Dorsey and G. W. Brier, January 1944.

No. 9 **Preliminary Report on Stagnant Highs Over Greenland, Iceland, and England, and Over the Bering Sea and Alaska in July and August.* R. C. Gentry and L. L. Weiss, January 1944.

No. 10 **Persistence in London Temperatures.* H. W. Norton and G. W. Brier, January 1944.

No. 11 **Skill in Selecting the "Best" Forecast.* G. W. Brier, January 1944.

No. 12 *Notes on Interdiurnal Pressure and Temperature Changes in the Upper Air.* R. C. Gentry, January 1944. (Unpublished.)

No. 13 *Investigation and Practical Use of a Method for Constructing Six-Hour Isallobars on Upper Level Charts.* E. M. Cason and P. F. Clapp, January 1944. (Unpublished.)

No. 14 *Weight Changes for the Atmosphere Divided Into Three Layers.* L. L. Weiss, February 1944. (Unpublished.)

No. 15 **Some Notes on Forecasting for Atlanta and Miami Districts (North and South Carolina, Georgia, and Florida).* Grady Norton, February 1944.

No. 16 **Verification of a Forecaster's Confidence and the Use of Probability Statements in Weather Forecasting.* G. W. Brier, February 1944.

No. 17 **Pressure Patterns Accompanying Cyclonic Activity in the Azores Area.* R. L. Pyle, March 1944.

No. 18 **Normal Mean Virtual Temperatures and Weights of the Air Column Between Sea Level and 10,000 Feet.* Staff, Extended Forecast Section, July 1944.

No. 19 **Temperature Changes During Formation and Dissipation of West Coast Stratus.* Morris Neiburger (University of California at Los Angeles), July 1944.

No. 20 *Empirical Studies of the Motion of Long Waves in the Westerlies.* P. F. Clapp, July 1944. (Unpublished.)

No. 21 **A Collection of Reports on the Preparation of Prognostic Weather Charts.* J. R. Fulks, H. B. Wobus, and S. Teweles, Edited by C. P. Mook, October 1944.

No. 22 **Relationship Between Surface Temperature and Mean Virtual Temperature in the Lower Troposphere.* W. M. Rowe, November 1944.

No. 23 **Forecasting the Time of Formation of Stratus Cloud Ceiling at Oakland, California, Airport.* Edward M. Vernon, April 1945.

No. 24 **Investigation of Polar Anticyclogenesis and Associated Variations of the Zonal Index.* Jerome Namias, September 1945.

No. 25 **Progress Report on Objective Rainfall Forecasting Research Program for the Los Angeles Area.* J. C. Thompson, July 1946.

No. 26 *A Study of Quantitative Precipitation Forecasting in the TVA Basin.* Glen W. Brier, November 1946. $0.25

No. 27 *Objective Methods of Forecasting Weather Minimum Temperatures at Washington, D. C.* C. P. Mook and Saul Price, August 1947. $0.35

No. 28 **Possibility of Long Range Precipitation Forecasting for the Hawaiian Islands.* Samuel B. Solot, January 1948.

No. 29 *An Objective Method of Forecasting Five-Day Precipitation for the Tennessee Valley.* William H. Klein, July 1948. $0.30

No. 30 *First Partial Report on the Artificial Production of Precipitation: Stratiform Clouds—Ohio, 1948.* Richard D. Coons, R. C. Gentry, and Ross Gunn, August 1948. $0.30

(*Continued on page 21*)

---

*Out of print.

NOTE.—Nos. 2, 3, 4, 7, 8, 9, 10, and 11 are included in one publication under the title *A Collection of Reports on Extended Forecasting Research*, Weather Bureau, 1944.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

a	constant or coefficient (empirical)
b	constant or coefficient (empirical)
e	water vapor pressure
e_a	atmospheric water vapor pressure
e_0	water vapor pressure at water surface
e_s	saturation water vapor pressure at T_a
n	exponent (empirical)
u_p	daily wind movement at Class A pan (6 inches above rim)
u_4	daily wind movement 4 meters above surface
A_p	effective area, outer face of Class A pan
A_w	water-surface area of Class A pan
E	daily evaporation
E_a	daily pan evaporation assuming $T_0=T_a$
E_L	daily lake evaporation (adjusted for advection)
E_p	daily pan evaporation
E_p'	computed Class A pan evaporation
K_a	air temperature, degrees Kelvin (° C. absolute)
K_0	water-surface temperature, degrees Kelvin (° C. absolute)
P	atmospheric pressure
Q_{bs}	long-wave radiation emitted by the body of water (also referred to as back radiation)
Q_h	sensible heat transfer from water surface
Q_h'	sensible heat transfer from Class A pan, excluding that from the water surface
Q_n	net radiation exchange
Q_s	solar radiation on horizontal surface
Q_v'	net energy advected into lake (including negative advection of evaporated water)
Q_ϑ	increase in energy storage
R	Bowen's dimensionless ratio
T	temperature
T_a	air temperature
T_d	dewpoint temperature
T_0	water-surface temperature
α	proportion of advected energy (lake) used for evaporation
α_p	proportion of advected energy (Class A pan) used for evaporation
γ	factor defined by equation for Bowen's ratio, equation (3)
γ_p	empirical factor (comparable to γ, but for Class A pan)
σ	Stefan-Boltzman constant for black-body radiation
Δ	slope of saturation vapor-pressure curve at T_a
*	used as a superscript in denoting an incremental change, for example, $E_L^*-E_L$ signifies the incremental change in evaporation brought about by an assumed change in water temperature.

EVAPORATION FROM PANS AND LAKES

M. A. Kohler, T. J. Nordenson, and W. E. Fox

Hydrologic Services Division, U. S. Weather Bureau, Washington, D. C.

[Manuscript received January 6, 1955; revised April 4, 1955]

ABSTRACT

Development of improved methods for estimating annual lake evaporation from pan observations and related meteorological data has been the primary objective of Weather Bureau evaporation studies. The authors show that use of the customary 0.7 coefficient for converting Class A pan evaporation to lake evaporation can lead to appreciable error unless the effects of advected energy into the lake and heat transfer through the pan are taken into consideration. Techniques are derived to adjust for these effects, and computations of evaporation are made for six reservoirs where estimates from water budget computations are also available.

Another objective of the Weather Bureau evaporation studies has been the development of a universally applicable relation for computing pan evaporation from meteorological data. A relation of this type has considerable application for estimating the winter season evaporation records, which are generally missing in most parts of the United States, and to compute pan evaporation at first-order Weather Bureau stations for strengthening the areal coverage of the network of Class A evaporation pans. Computations are made from the pan evaporation relation for 21 Class A stations well distributed over the United States and one Alaskan station. The results indicate that the relation is universally applicable.

INTRODUCTION

During the period April 1950 through August 1951 a comprehensive interagency [1] evaporation experiment was conducted at Lake Hefner, Okla. Major and immediate results of this study [17] [2] were released in 1952, and summarized tabulations of the observations [18] were subsequently published in 1954. The data collected at Lake Hefner will undoubtedly form the basis of many analyses, developments, and conclusions for years to come, and the work reported herein is, in many respects, a continuation of that described in one section of the Lake Hefner Report [17].

Continuing evaporation studies conducted by the Weather Bureau have been aimed primarily toward the development of improved methods for estimating annual lake evaporation from pan observations and related meteorological data normally collected in its established observational programs. Since the network of pan stations is quite sparse and the records are notably incomplete—usually seasonal in nature—the development of a universally applicable procedure for extrapolating and interpolating pan evaporation has also been a major objective. This paper presents the results of these studies, including examples of suggested methods of computing reservoir evaporation, given selected combinations of basic data.

Much of the material presented can be considered as only preliminary—the basic approach to the problem is believed sound, but some of the empirical aspects are based on rather meager data. It is hoped the observations from current and planned projects will provide a basis for reliable confirmation or modification. In the meantime, there appears little doubt that one can improve upon the "0.7 pan coefficient" where the required data are available.

[1] Collaborating agencies were: U. S. Department of the Navy, Bureau of Ships and Navy Electronics Laboratory; U. S. Department of the Interior, Bureau of Reclamation and Geological Survey; U. S. Department of Commerce, Weather Bureau.

[2] Numbers in brackets designate references listed on p. 20.

LAKE HEFNER PAN RELATIONS

It was shown in the Lake Hefner Report [17] that the daily evaporation (inches) from the Class A pan can be reliably estimated from the equation

$$E_p=(e_0-e_a)(0.42+0.0040u_p) \tag{1}$$

where e_0 and e_a are vapor pressures (inches of mercury) of the water surface and over-lying air, respectively and u_p is the wind movement (standard pan installation) in miles per day.[3] When the water temperature is observed, pan evaporation is measured as well, so this equation is of little practical value. Penman [10] has shown that the need for water temperature observations can be eliminated, however, through simultaneous solution of an aerodynamic equation, such as equation (1), and one expressing an energy balance. Assuming the change in heat storage of the water body and the heat conducted through the walls of the container to be negligible, Penman derived the equation

$$E=\frac{1}{\Delta+\gamma}(Q_n\Delta+\gamma E_a) \tag{2}$$

where Δ is the slope of the saturation vapor-pressure vs temperature curve (de_s/dT) at the air temperature T_a; E_a is the evaporation given by the aerodynamic equation, assuming water temperature (T_0) equal to air temperature; Q_n is the net radiant energy expressed in the same units as those of E; and γ is defined by the equation

$$R=\gamma\left(\frac{T_0-T_a}{e_0-e_a}\right) \tag{3}$$

in which R is Bowen's [1] dimensionless ratio. If evaporation and convective transfer of sensible heat are restricted to equivalent, identical surfaces, Bowen has derived a value for γ of 0.000339 P, where P is the atmospheric pressure in inches of mercury, and γ has the units of inches of mercury per degree F. Using mass-transfer concepts, D. W. Pritchard (unpublished notes) derived Bowen's ratio for both a smooth and a rough[4] surface, the corresponding values of γ being 0.000317 P and 0.000367 P, respectively. For a wet-bulb temperature of 32° F., the standard psychometric equation gives a γ of 0.000367 P. This value changes slightly with the wet-bulb temperature, becoming 0.000378 P when the wet-bulb temperature is increased to 80° F. In view of these findings, it was decided to use $\gamma=0.000367\ P$ for the studies reported herein.

Equation (2) is not strictly applicable to the Class A pan, but assuming the form to be adaptable, the relation shown in figure 1 (also presented as figure 96 in the Lake Hefner Report) was derived by the graphical, coaxial technique [8]. Since evaportaion occurs only from the water surface, while convective transfer of sensible heat takes place at the sides and bottom of the Class A pan as well, γ for the pan (γ_p) was found to exceed the theoretical value, being 0.025 (0.000871 P) at the elevation of Lake Hefner.

APPLICABILITY OF LAKE HEFNER PAN RELATION

As contemplated in Volume 1 of the Lake Hefner Report, the relation of figure 1 was subsequently tested on the records for seven stations and the results of the tests are shown in table 1. The data for all stations except Boulder City and Grand Junction were punched on cards; classified by air temperature, dewpoint, wind, and radiation; and class averages were used in the analysis in the interest of conserving time. Such grouped data do not lend themselves to the computation of correlation coefficients and standard errors, but examination of the computed and observed evaporation did show a high degree of correlation to exist.

[3] List of symbols appears on p. iv.

[4] According to the mass-transfer studies in the Lake Hefner Report, the lake surface was aerodynamically rough at all times.

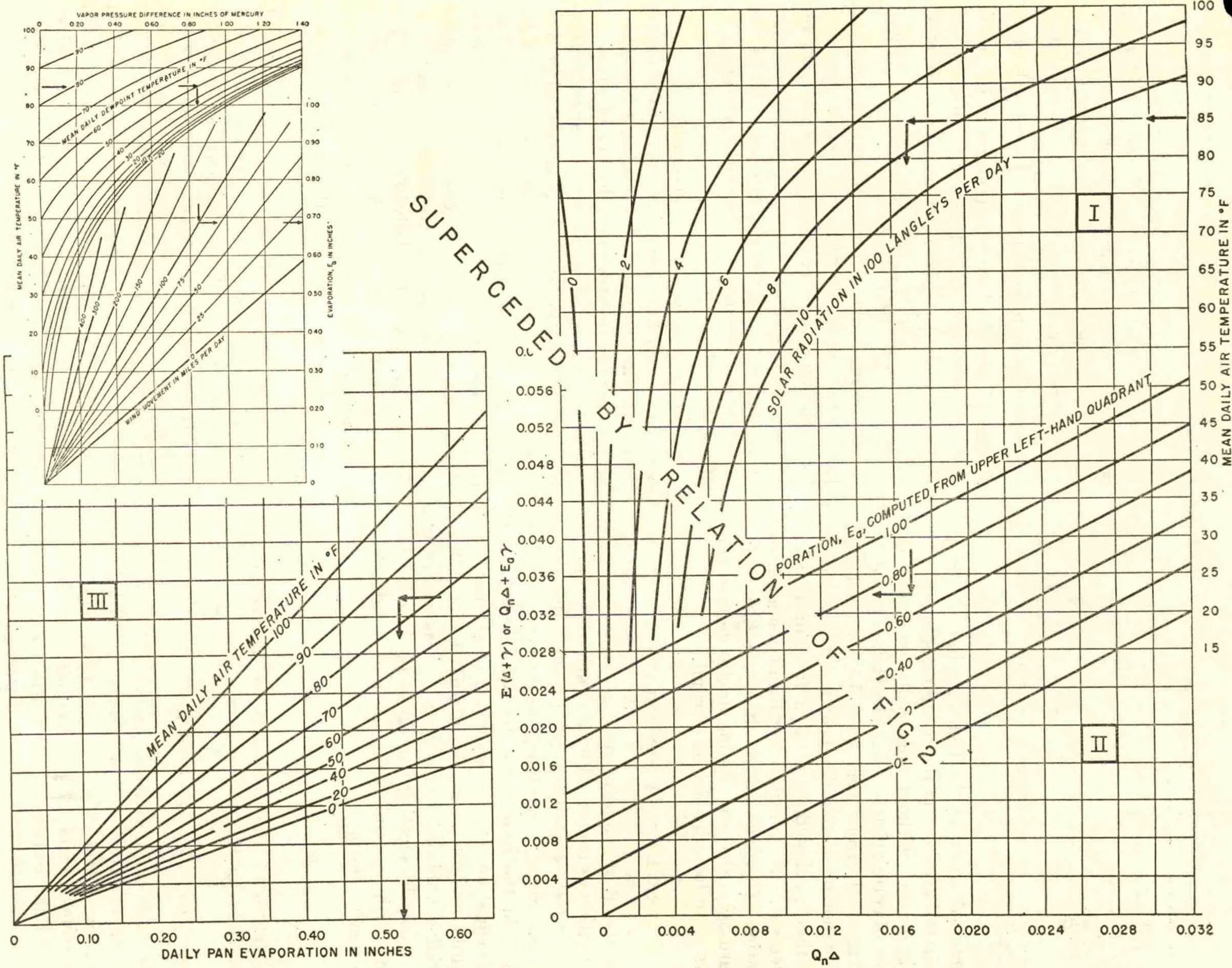

FIGURE 1.—Relation for Class A pan, based only on observations from Lake Hefner South Station.

TABLE 1.—*Verification of Lake Hefner Class A pan relation (fig. 1)*

Station	Days of record	Total evaporation (in.)		Bias (percent)
		Observed	Computed	
Austin, Tex	1,021	264.30	287.18	+8.7
Boulder City, Nev.[1]	537	185.82	196.40	+5.7
Evansville, Ind	639	124.18	127.03	+2.3
Grand Junction, Colo	100	36.53	36.94	+1.1
Lake Hefner, Okla	246	73.01	73.38	+0.5
New York City, N. Y	572	104.91	104.28	+0.6
Springfield, Ill	586	166.48	162.48	−2.4
Vicksburg, Miss	1,393	219.12	237.12	+8.2

[1] Radiation data used were obtained in connection with the interagency water-loss investigations conducted at Lake Mead (see section headed "Future Studies").

Detailed study of the test data indicated that the overall accuracy of the relation could probably be improved without materially affecting the degree of correlation for the Lake Hefner pan data. The residual errors were quite highly correlated with vapor-pressure difference, and it appeared at first that γ_p should be made a function of wind movement. It later developed that the apparent variation of γ_p was the result of the bias in E_a. Accordingly, the pan relation finally derived considers γ_p to be independent of wind.

REVISION OF PAN RELATION

As stated previously, residual errors in daily evaporation as computed from figure 1 were found to be correlated with vapor-pressure difference (e_s-e_a). Since the vapor-pressure bias was also present in the basic water-temperature relationship, equation (1), it seemed logical that the required revision be made in this relation, thus providing unbiased values of E_a. This was done graphically by plotting (e_0-e_a) vs E_p, labeling the points with u_p, and fitting a smooth family of curves of the form

$$E_p=(e_0-e_a)^n(a+bu_p) \tag{4}$$

The values of the constants so derived were: $a=0.37$, $b=0.0041$, and $n=0.88$. Thus,

$$E_a=(e_s-e_a)^{0.88}(0.37+0.0041u_p) \tag{5}$$

Although the derived constants a, b, and n of equation (4) are based on data from Vicksburg, Miss., Silver Hill, Md., Boulder City, Nev., and Lake Hefner, Okla., the correlation index for 266 days of Lake Hefner (South Station) data is only slightly lower than was obtained with equation (1) (0.91 as compared to 0.92), which had been based entirely on those data. Moreover, the revised relation actually fits the data from the Lake Hefner Northeast Station better than equation (1).

Most investigators have found that evaporation is proportional to the difference in vapor pressure between air and water, other factors being equal [2]. However, Himus [6] found the evaporation to be proportional to $(e_0-e_a)^{0.83}$, and Millar [9] states that evaporation is proportional to the difference in vapor concentration rather than the vapor-pressure difference. The difference in vapor concentration is proportional to $\left(\frac{e_0}{K_0}-\frac{e_a}{K_a}\right)$, where K_0 and K_a are absolute temperatures of the water and air, respectively. The vapor-pressure difference raised to the 0.83 power is approximately proportional to $\left(\frac{e_0}{K_0}-\frac{e_a}{K_a}\right)$, according to Millar. On the other hand, if the exponent has physical justification, it should appear in similar equations for both pan and lake. Analysis of the data for Lake Hefner, although inconclusive, shows that no significant improvement results when an exponent is introduced on the vapor-pressure term of the lake relation.

The derived exponent in equation (4) ($n=0.88$) may, of course, have been influenced by observational and instrumental deficiencies. The measured water temperature may be biased, since the temperature element measures the average temperature of the top layer of water instead of that at the surface. Bias may also be occasioned by use of average daily water temperatures and dewpoints to obtain (e_0-e_a) inasmuch as the relationship between temperature and saturation vapor pressure is curvilinear. No claim is made that equation (4) with its derived constants is the equation that would be obtained if there were no instrumental, observational, or averaging errors—it is the empirical equation that best fits the observed data.

Equation (4) was derived from data for Class A pan stations at low elevations, and thus there is some question as to whether it is equally applicable at high elevations. Accurate water temperature and dewpoint data were not available for any standard Class A installations above 5,000 feet m. s. l. With the available data, no elevation effect could be detected. Inspection of data given for sunken pans by Rohwer [11] at various elevations indicates that his apparent elevation effect can be minimized by use of an exponent for (e_0-e_a), since the vapor-pressure difference decreases with pressure. However, equation (4) was not fitted to data from sunken pans and further data from Class A pans are needed before the effect of pressure can be definitely determined.

Having revised the equation (5) for E_a, it was deemed advisable to check remaining features of the original relation (fig. 1), again using all readily available data. This phase of the study was based on data from Lake Hefner (Northeast and South Stations), Silver Hill, and Boulder City. Assuming [5] $\gamma_p=0.025$ as originally concluded (fig. 1), and using equations (2) and (5), daily values of Q_n were computed. These, in turn, were graphically correlated (see p. 134 of [17]) with air temperature and solar radiation and the resulting curves were converted to yield values of $Q_n\Delta$. A further approximation of γ_p confirmed the 0.025 value within the limits of precision warranted. The revised relation is presented in figure 2.

RELIABILITY OF REVISED RELATION

Much effort has been devoted to checking the reliability of the relation shown in figure 2, making every attempt to determine under what climatic regimes it may or may not be applicable. Since the study was in many respects a continuation of the Lake Hefner analysis, and since the relation published in the Lake Hefner Report could serve as a yardstick of reliability, initial comparisons were derived for this station. Based on 246 days of record without rain, the correlation coefficient for the relation of figure 2 was found to be 0.96, while the standard error was 0.039 inches. In spite of the fact that other stations were given considerable weight in deriving the relation of figure 2, it is as reliable as the original relation (fig. 1) when applied to data collected at Lake Hefner (South Station).

Table 2 summarizes verification for stations and data comparable to table 1. While the data presented in these two tables are far from conclusive, when considered along with reduced correlations between residual (daily) errors and vapor-pressure difference there seems little doubt that the revised relation of figure 2 will yield more reliable results than that of figure 1 when applied under widely varying conditions.

To delineate conditions under which figure 2 may be expected to provide reliable estimates obviously requires more verification than that

TABLE 2.—*Verification of revised Class A pan relation (fig. 2) for stations and periods shown in table 1*

Station	Days of record	Total evaporation (ins.)		Bias (percent)
		Observed	Computed	
Austin, Tex	1,021	264.30	275.00	+4.0
Boulder City, Nev	537	185.82	186.63	+0.4
Evansville, Ind	639	124.18	121.49	−2.2
Grand Junction, Colo	100	36.53	35.48	−2.9
Lake Hefner, Okla	246	73.01	72.96	−0.1
New York City, N. Y	572	104.91	97.97	−6.6
Springfield, Ill	586	166.48	156.84	−5.8
Vicksburg, Miss	1,393	219.12	218.92	−0.1

presented in table 2. For this purpose it seemed that testing the relation for relatively short periods on a rather large number of stations would provide more conclusive results than if the same working time were spent on analyzing all data for only a few stations. Accordingly, the correlation coefficient and standard error were computed from 100 days of record for 13 additional stations well distributed over the United States, and 1 Alaskan station. Verification results are tabulated in table 3, and are also plotted on the map of figure 3. All computations for table 3 were made using figure 2, with $\gamma_p=0.025$. Possible errors in neglecting the variation of γ_p with pressure are discussed later in this section.

Examination of figure 3 could easily lead one to suspect that climatic, or geographic, variations are still evidenced in the plotted bias. To adequately appraise the results presented in tables 2 and 3 and figure 3, however, some of the deficiencies in the basic data should be considered, namely:

1. Times of observation of the pertinent elements are frequently out of phase, e. g., in all cases it was necessary to use calendar-day solar radiation data, whereas observations of evaporation are made virtually any time between sunrise and sunset. Such variations in timing have no material effect on bias, but do reduce the correlation index.
2. Very few stations have observations of all required elements (particularly dewpoint and solar radiation), and in such cases it was necessary to use data collected at a nearby first-order Weather Bureau station.
3. In 7 of the 22 cases, solar radiation data were necessarily estimated from observations of percent sunshine [3].
4. Variations in time of evaporation observation, when taken by lay observers, are frequently 1 or 2 hours. Thus, 22- to 26-hour "days"

[5] Although $\gamma_p=0.000871\ P$ (corresponding to 0.025 at elevation of Lake Hefner) could have been used to account for differences in elevation, this refinement did not appear justified.

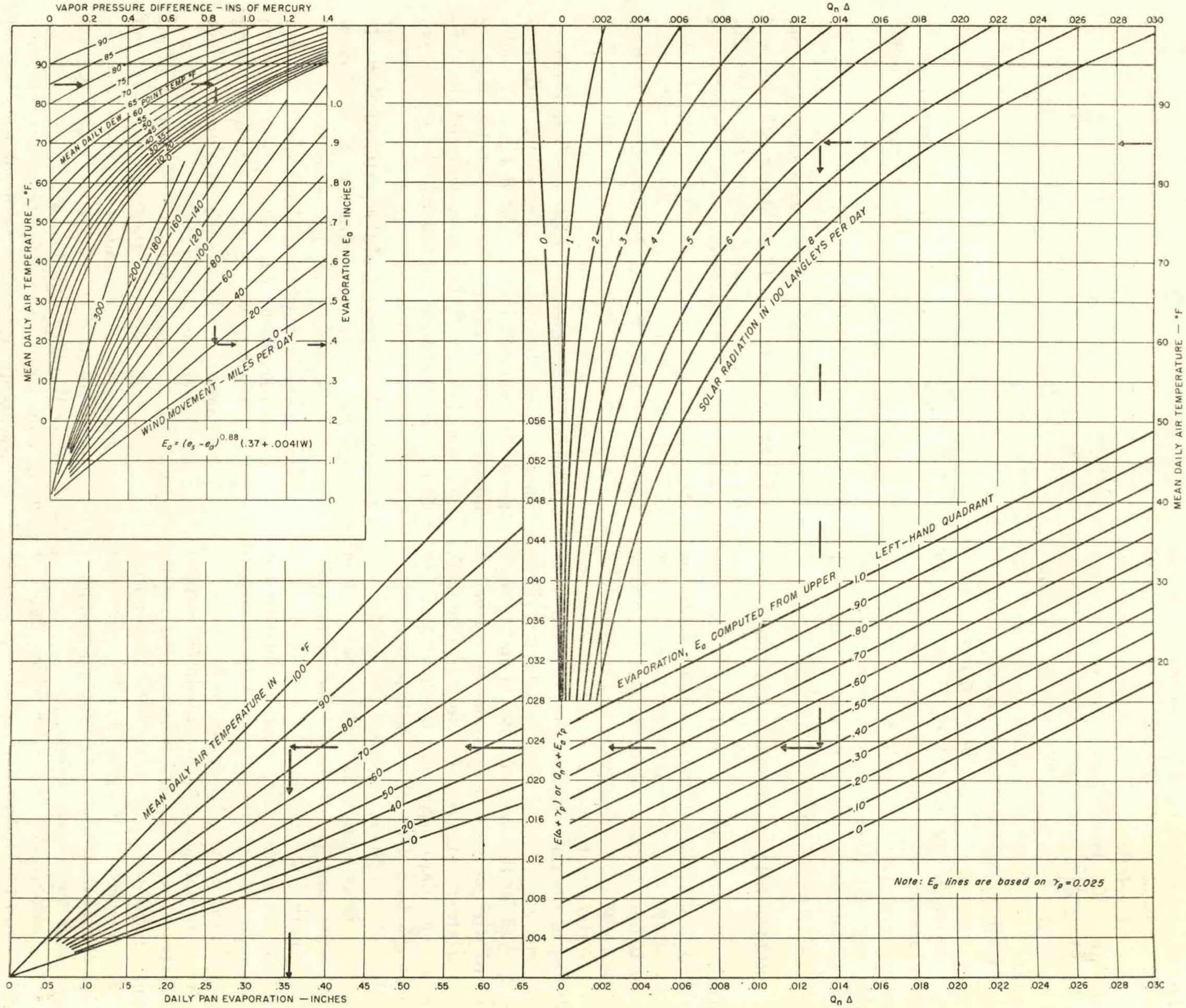

FIGURE 2.—Revised relation for Class A pan.

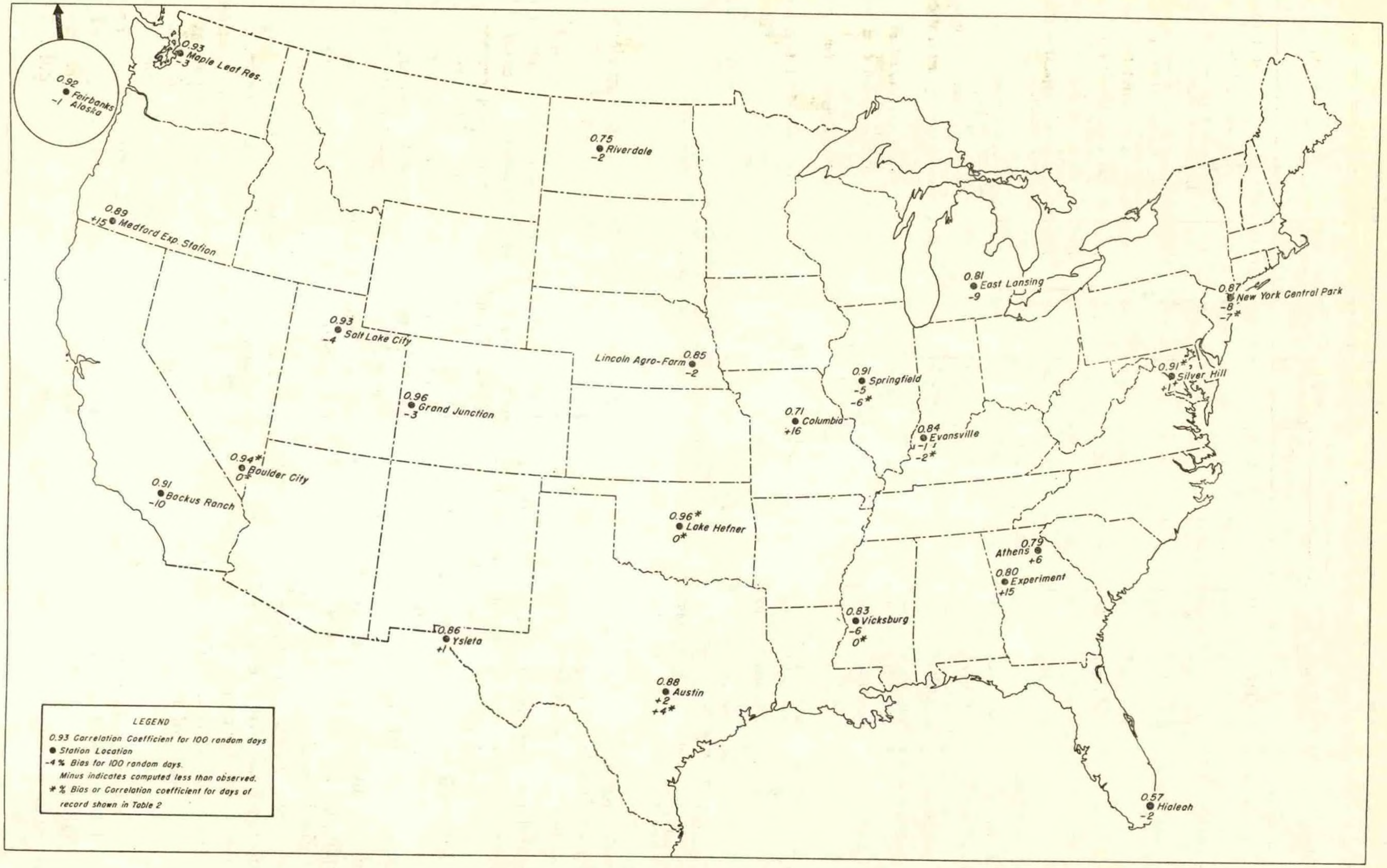

FIGURE 3.—Verification data for relation given in figure 2.

TABLE 3.—*Verification of revised Class A pan relation (fig. 2)*

Station	Period of record	Number of days [1] selected	Total evaporation (in.)		Bias (percent)	Correlation index	Standard error	Remarks
			Observed	Computed				
Athens, Ga	3/51–12/53	100	20.43	21.58	+6	0.79	0.061	Radiation and dewpoint at Atlanta W. B. Airport Station.
Austin, Tex	12/46–12/49	100	23.31	23.76	+2	.88	.053	Radiation computed from percent sunshine.
Backus Ranch, Calif	1/52–10/52	100	33.64	30.32	−10	.91	.071	Radiation at Inyokern or Santa Maria.
Boulder City, Nev	3/52– 9/53	537	185.82	186.63	±0	.94	.056	Radiation at Boulder Island in Lake Mead.
Columbia, Mo	4/53–10/53	100	23.39	27.08	+16	.71	.059	
East Lansing Exp. Farm, Mich.	6/51–10/52	100	20.04	18.33	−9	.81	.055	Dewpoint at Lansing W. B. Airport Station. Radiation computed from percent sunshine.[2]
Evansville, Ind	4/46–11/50	100	18.67	18.50	−1	.84	.046	Radiation computed from percent sunshine.
Experiment, Ga	1/51– 5/53	100	15.72	18.02	+15	.80	.054	Radiation and dewpoint at Atlanta W. B. Airport Station.
Grand Junction, Colo	9/47–11/53	100	36.53	35.48	[3]−3	.96	.045	Radiation computed from percent sunshine prior to 1953.
Hialeah, Fla	1/51– 5/53	100	20.96	20.44	−2	.57	.085	Radiation and dewpoint at Miami W. B. Airport Station.
Lake Hefner (South Sta.), Okla.	6/50– 8/51	246	73.01	72.96	±0	.96	.039	
Lincoln Agro. Farm, Nebr	5/50– 4/54	100	20.97	20.53	−2	.85	.042	Radiation and dewpoint at Lincoln W. B. Airport Station.
Maple Leaf Res., Wash	4/53– 6/54	100	14.40	14.03	−3	.93	.028	Radiation at University of Washington. Dewpoint at Seattle W. B. Airport Station.
Medford Exp. Sta., Oreg	6/50– 4/53	100	14.40	16.51	+15	.89	.041	Radiation and dewpoint at Medford W. B. Airport Station.
New York Central Park, N. Y	7/44– 9/49	100	17.70	16.24	−8	.87	.037	
Riverdale, N. Dak	7/50–10/53	100	23.99	23.43	−2	.75	.073	Radiation and dewpoint at Bismarck W. B. Airport Station.
Salt Lake City Airport, Utah	8/29–11/32	100	31.07	29.70	−4	.93	.060	Radiation computed from percent sunshine.
Silver Hill, Md	9/53– 9/54	221	47.95	48.22	+1	.91	.036	
Springfield, Ill	7/46–10/50	100	22.40	21.18	−5	.91	.039	Radiation computed from percent sunshine.
University Exp. Sta., Alaska	6/53– 6/54	100	14.28	14.19	−1	.92	.028	
Vicksburg, Miss	9/43– 6/46	100	14.79	13.85	−6	.83	.044	Radiation computed from percent sunshine.
Ysleta, Tex	11/50– 5/53	100	26.22	26.38	+1	.86	.080	Radiation and dewpoint at El Paso W. B. Airport Station.

[1] Days randomly selected except for Boulder City, East Lansing, Lake Hefner, Maple Leaf Res., University Exp. Sta., and Silver Hill. For these stations all days without rain during the designated period were used in the computations, except when data were missing.
[2] Observed radiation at East Lansing appeared to be biased when compared with other stations in the area and, therefore, values computed from percent sunshine were used in the evaporation computations.
[3] Bias subsequent to 1951 is appreciably greater than that for previous years.

are not uncommon. As in 1 above, this deficiency of data tends to reduce the correlation index, but has no material effect on the bias.

5. Non-standard operation of pans is always a source of concern. Some pans are cleaned frequently and maintained at proper level, while at other stations infrequent cleaning and filling of the pan may have a significant effect on observed evaporation.
6. Measures of bias and correlation computed from samples of 100 items or less are subject to appreciable random errors.

These facts are presented to emphasize the futility of detecting any pattern of climatic bias from the computations thus far completed. It does seem, on the other hand, that the verification presented indicates deficiencies of the relation to be rather minor.

It is believed that the verification results presented justify a high degree of confidence in the general reliability of the derived pan relation. Nonetheless, little data are available to substantiate its applicability to the higher elevations experiencing much reduced pressures. The value of E_a is purported to increase with increasing elevation, other factors remaining the same. The value of γ_p is directly proportional to pressure, but the effect of such variation on pan evaporation depends upon the relative values of Q_n and E_a. When water temperature exceeds air temperature ($Q_n > E_a$) one effect augments the other, while with the reverse temperature gradient ($Q_n < E_a$) the two effects tend to compensate. Computations for cases with extreme temperature differences at Salt Lake City and Grand Junction indicate that figure 2 can be used to elevations as high as 5,000 feet m.s.l. without appreciable error.

There are not a great number of locations where all required data for computing pan evaporation are observed—solar radiation observations are even now being made at only about 60 stations throughout the United States. There are reasonably reliable means of estimating this factor [3], however, and sufficiently accurate estimates of the other required elements can usually be made.

TABLE 4.—*Variation of pan evaporation with related factors*

Case No.	T_a (°F.)	Percent error per °F. change in T_a	T_d (° F.)	Percent error per °F. change in T_d	Q_s (langleys per day)	Percent error per percent change in Q_s	u_p (miles per day)	Percent error per percent change in u_p	E_p (inches per day)
1	91	1.8	41	0.4	700	0.7	50	0.2	0.51
2	91	2.3	63	.8	700	.8	50	.1	.46
3	84	3.8	75	2.7	600	.9	50	.1	.28
4	66	6.0	55	4.0	300	.6	50	.2	.12
5	45	6.3	28	2.9	250	.3	50	.3	.09
6	91	1.8	41	.3	700	.6	100	.3	.60
7	91	2.3	63	1.0	700	.7	100	.2	.52
8	84	4.4	75	3.1	600	.8	100	.2	.31
9	66	6.2	55	4.6	300	.5	100	.4	.15
10	45	6.2	28	3.1	250	.3	100	.5	.11

Table 4 is included to assist in the evaluation of evaporation errors brought about by errors of estimation in other elements for selected reasonable combinations of the pertinent factors.

Examination of the table shows that errors in dewpoint (T_d) have less effect on computed evaporation than do corresponding errors in air temperature (T_a). Particularly when the data must be estimated, errors of 10 percent in solar radiation (Q_s) are not uncommon and it will be seen that such errors can, under some circumstances, result in as much as 10 percent error in the computed evaporation. In view of some mass-transfer equations, one might gain the impression that doubling the wind (u_p) doubles the evaporation. That this is not the case is borne out by the data in table 4. This does not invalidate mass-transfer equations, but simply demonstrates that changes in windspeed are accompanied by changes in water temperature and other elements.

Although the relation of figure 2 was derived from daily observations, experience has shown that only minor errors result when monthly evaporation (i. e., mean daily value for the month) is computed from monthly averages of the daily values of T_a, T_d, Q_s and u_p. In fact, the use of mean annual data is usually satisfactory, provided (e_0-e_a) is computed from monthly values of air and dewpoint temperature.

APPLICATION OF PAN RELATION

A means of computing pan evaporation from meteorological factors can serve a variety of purposes. Moreover, as discussed in a subsequent section, figure 2 can form the basis of a technique for estimating annual reservoir evaporation from the same meteorological factors. Evaporation pans are normally withdrawn from operation during the winter period when freezing temperatures would result in damage to the pan. Accordingly, as much as 6 months of record are missing, year after year, at some high-latitude stations. The utility of such seasonal records is increased considerably if reliable estimates can be made for the missing periods. Relatively few meteorological stations are equipped with evaporation pans so that the rather meager pan network can, in effect, be strengthened by computing evaporation at those first-order stations not equipped with pans. Through comparisons of observed and computed evaporation, tests can be made of the reliability and representativeness of observed data. The reliability of pan evaporation as observed during periods of appreciable rain is always open to question, since one can never be certain that splashout and spillover have not introduced serious errors.

ESTIMATION OF ANNUAL LAKE EVAPORATION

Mass-transfer and energy-budget approaches (as well as empirical equations) can be used to estimate evaporation from existing reservoirs and lakes, but their application has yet been very limited. However, as a result of the Lake Hefner studies, these techniques are being applied to Lake Mead and several small reservoirs. On the other hand, these methods are not directly applicable to design problems, since water temperature data are required for their use. Virtually all estimates of reservoir evaporation—both design and operational—have been made by applying a "pan coefficient" to observed or computed pan evaporation.

Coefficients determined from water-budget estimates of lake evaporation show appreciable variation of a somewhat geographical nature, but since the cause of such variation has not been thoroughly understood, use of an average value has been the customary practice. In 1932, for example, an evaporation subcommittee of the American Society of Civil Engineers presented table 5 as a part of their report [16].

TABLE 5.—*ASCE recommended coefficients and observed range* [1]

Type of pan	Coefficient	Reasonable range of coefficient
Class A land pan	0.70	0.60 to 0.82.
Colorado "buried" pan	.78	0.75 to 0.86.
U. S. G. S. "floating" pan	.80	0.70 to 0.82.

[1] Recommended by Subcommittee on Evaporation of the Special Committee on Irrigation Hydraulics of the American Society of Civil Engineers, 1932.

It is not clear by what reasoning process it was conceived that lake evaporation should be proportional to that observed in a nearby pan, and there is little to be gained through speculation at this time. It will suffice to state that the important differences between pan and lake are such that their combined effect is closely approximated by the assumed ratio as is borne out by observation. On the premise that annual pan data can be converted to evaporation data from an adjacent lake by applying a coefficient, it follows that two adjoining lakes should experience the same evaporation—a consequence which bears consideration.

Assuming two lakes to be represented by a single pan experience, the same wind and net incoming radiation, and that the overrunning air is the same for both, what factors could cause evaporation (inches depth) to differ from one lake to the other? Surface area has been advanced as such a factor on a theoretical basis, but experimental evidence [14] (p. 142 of [17]) seems to indicate that the effect is not appreciable within the range of interest. Quality of water, depth, and other factors may have minor effect, but the one most important item to be considered has, for some reason, been overlooked in applying pan data—that is, advected energy. If water discharged from a reservoir is replaced by relatively hot water, then there is a net increase of energy which is dissipated partially by evaporation [4]. This item is discussed in detail in the following section.

Having concluded that advected energy to a lake can have an important effect upon the pan coefficient, the question arises as to the magnitude of similar effects for the pan. Cursory examination shows that advection by means of water added is normally unimportant, but that advection of sensible heat at the pan-air interface is sufficient to produce moderate variation in any conceived "pan coefficient," particularly under varying climatic regimes. This subject is also discussed in subsequent sections.

EFFECT OF ADVECTED ENERGY ON LAKE AND PAN

If an evaporation pan is to be used as an index to reservoir evaporation, then adjustment for factors affecting only the pan or the lake should improve the relationship. Unlike a lake, the Class A pan permits considerable transfer of heat to and from its sides and bottom due both to radiation exchange and to transfer of sensible heat caused by a difference in water and air temperature. Although variations in the altitude of the sun may cause slight variations in seasonal coefficients, preliminary studies indicate that the radiation exchange for the sides and bottom can be treated as a part of the net radiation exchange for the pan, having a direct but essentially invariable effect on the annual pan coefficient. Observations demonstrate that the annual sensible heat transfer across the pan-air interface can be appreciable, and that it may flow in either direction, depending upon the relative magnitudes of meteorological and radiation factors. Since corresponding annual heat transfer through the bottom of a lake is essentially zero, pan data should logically be adjusted for advection through the pan before applying a coefficient. Similarly, advection (and energy storage) in the lake is independent of pan behavior and proper adjustments should be made to the computed evaporation.

If we assume that an incremental change in the surface water temperature of a lake has no significant effect on the net incoming radiation or vapor pressure of the air above the lake, and since appreciable annual transfer of heat occurs only at the water surface, then the effect on evaporation of advected energy [6] can be approximately evaluated by assuming a change in the average water temperature and computing the corresponding changes in evaporation, energy advected by the evaporated water, outgoing long-wave (back) radiation, and conduction of sensible heat [4, 5]. The incremental change in evaporation (in inches) can be computed by means of the equation [7]

$$E^*_L - E_L = (e^*_0 - e_0)(0.00304u_4) \tag{6}$$

where e^*_0 and e_0 are the saturation vapor pressures in inches of mercury for the assumed and observed

[6] In reality, net advected energy, or advection less change in storage. Unless stated otherwise, the change in energy storage is assumed to be zero throughout this section of the paper.

[7] This relation is derived from equation (3) in table 27 of the Lake Hefner Report.

water temperatures, respectively, and u_4 is the 4-meter wind speed in miles per day. Computations indicate that the incremental change in energy advected by the evaporated water is of a magnitude such that it can be neglected. The incremental change in back radiation (equivalent inches of evaporation per day) can be computed from the equation

$$(7) \qquad Q_{bs}^* - Q_{bs} = \frac{0.97\sigma}{1500}\,[K_0^{*4} - K_0^4]$$

where 0.97 is the emissivity of the water, σ is the Stefan-Boltzman constant (11.71×10^{-8} cal. cm.$^{-2}$ °C^{-4} day^{-1}) and K_0^* and K_0 are the respective water temperatures (absolute, °C.). The conversion factor, 1500, assumes 590 cal./cm.^{3} for the heat of vaporization. The incremental change in sensible heat transfer (equivalent inches of evaporation) can be computed using Bowen's ratio (R) from the equation

$$(8) \qquad Q_h^* - Q_h = 0.000367P(E^*R^* - ER) = 0.000367P\,(T_0^* - T_0)(0.00304u_4)$$

where P is the atmospheric pressure in inches of mercury and temperatures are in degrees F.

The proportion (α) of advected energy utilized in (or not available for [8]) evaporation then becomes

$$(9) \qquad \alpha = \frac{E_L^* - E_L}{(E_L^* - E_L) + (Q_s^* - Q_{bs}) + (Q_h^* - Q_h)}$$

Figure 4, derived from equations (6), (7), (8), and (9) assuming an incremental temperature change of 1° F., provides a convenient solution for α. Since α varies with atmospheric pressure (P), two charts are shown in figure 4—one for an elevation of 1,000 feet m. s. l., and the other for 10,000 feet m. s. l. For comparison with pan evaporation, the observed lake evaporation should be corrected by addition of the quantity $\alpha\,(Q_\vartheta - Q_v')$ where Q_ϑ is the change in energy storage and Q_v' is the net advected energy into the lake (both in equivalent inches of evaporation). A similar analysis was made for the Class A pan (making reasonable assumptions for the relation of e_a to e_0 and T_a to T_0) with the results shown in figure 5. Reasonable changes in the assumed temperatures and vapor pressures would have only minor effect on α_p and no significant effect on the adjusted pan evaporation.

[8] If the net advection is out of the body of water, the evaporation is decreased.

It should be emphasized that the derivation of figures 4 and 5 is not rigorous in every respect, since certain assumptions are required in the development. However, it is believed that experimental data could provide a basis for evaluating the reliability of the relations. Since the advocated use of figures 4 and 5 is for the determination of corrections seldom in excess of 15 percent of the total evaporation, they should be adequate for the purpose. Attention is directed to the fact that sensible heat transfer from the water surface of the pan is assumed to be proportional to $(T_0 - T_a)^{0.88}$ as must be the case if Bowen's ratio concept and equation (4) are theoretically sound. Whether or not the use of this exponent on the temperature term is valid depends on its source in the vapor-pressure term. In estimating annual lake evaporation from pan data, it makes little difference whether unity or 0.88 is used.

"THEORETICAL" PAN CONCEPT

Although reliable data are notably limited, such data as are available indicate that the ratio of Class A pan to lake evaporation is for practical purposes [9] 0.70, provided

1. Any net advection into the lake is balanced by the change in energy storage.
2. The net transfer of sensible heat through the pan is negligible.
3. The pan exposure is representative [10].

The relationship of figure 2 yields estimates of evaporation from the Class A pan with its consequent boundary losses—that is, $\gamma_p = 0.025$ as derived empirically in effect adjusts for sensible heat transfer through the pan. If, then, the theoretical value, γ, is substituted into the relation, computed values of evaporation should correspond to those observed in a "hypothetical" or "theoretical" pan which has the radiation characteristics of the Class A pan, but which permits no sensible heat transfer through the walls of the pan. On the basis of data now available, it is evident that the annual coefficient for this "hypothetical" pan is near 0.70, and is essentially independent of

[9] A value of 0.69 was originally derived for Lake Hefner neglecting items 1 and 2. Considering these factors yields a value closer to 0.70, although such small differences are obviously of no real significance.

[10] In the light of the source data, particularly that of the Lake Hefner experiment, air passing over the pan should be free of influence by the lake, and the pan should be freely exposed to direct sunshine throughout the day and should not be unduly protected from the wind. The pan wind at Lake Hefner averaged about one-half that at 4 meters over the lake, but it is believed this ratio can vary appreciably without materially affecting the results.

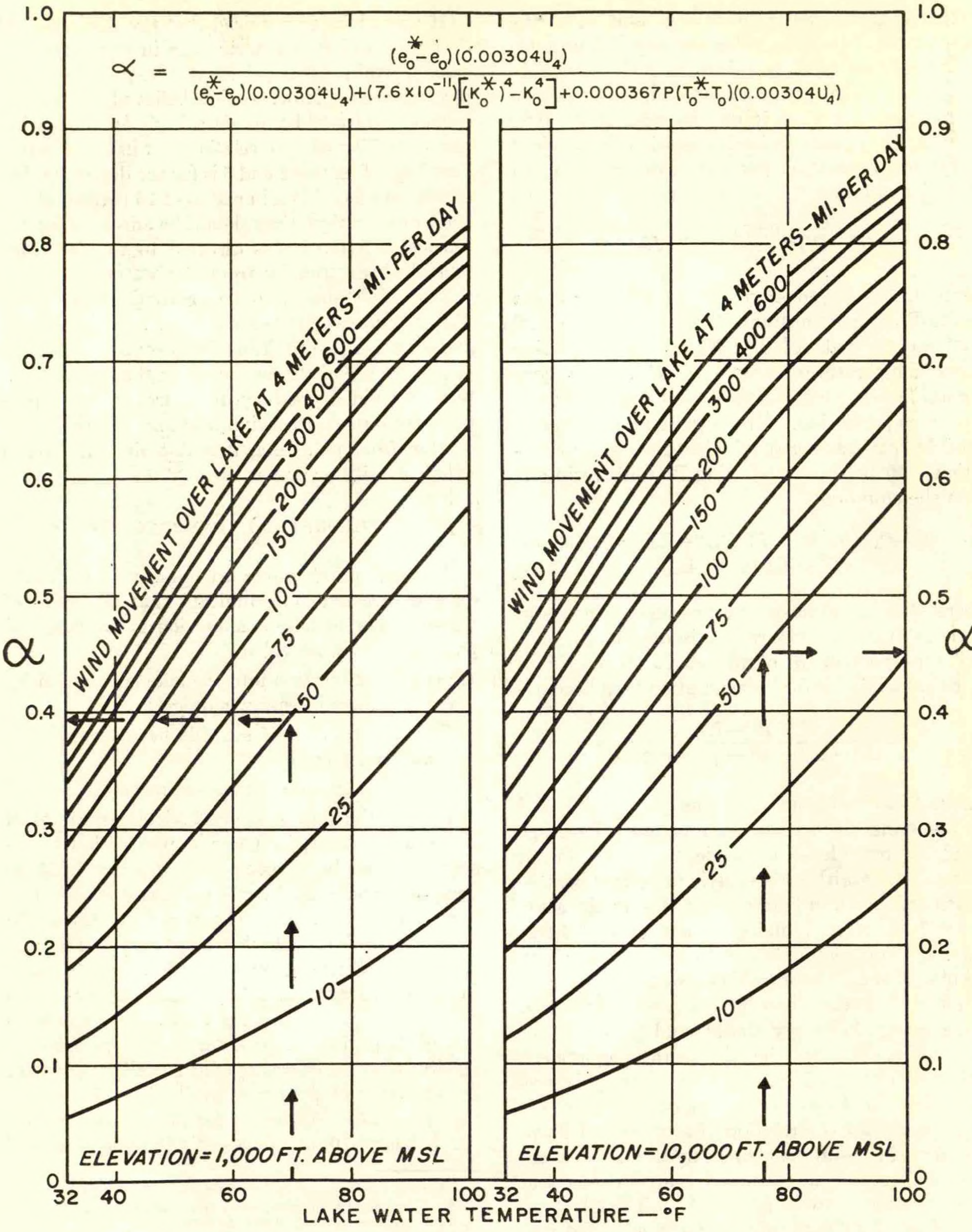

FIGURE 4.—Proportion of advected energy (into a lake) utilized for evaporation.

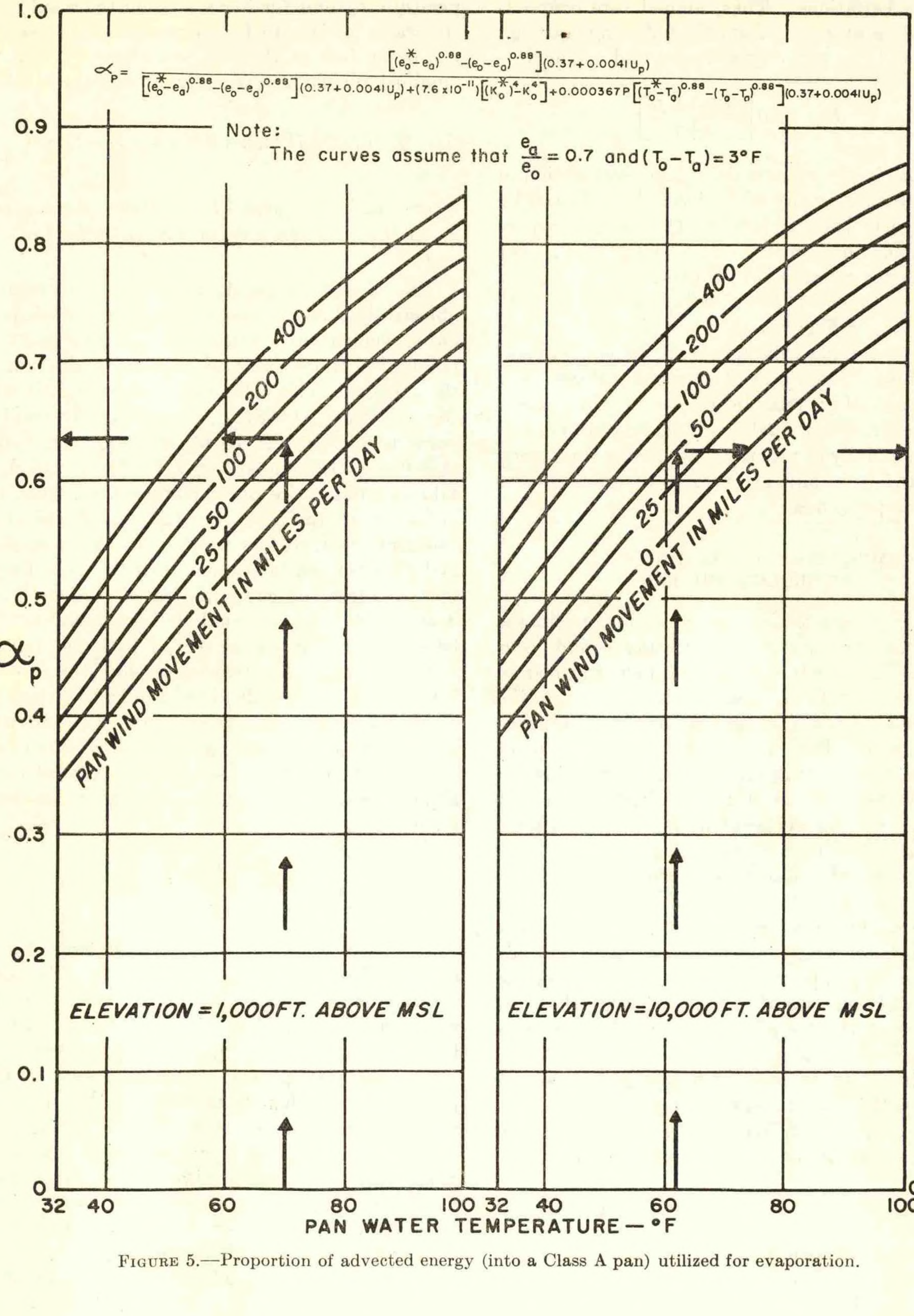

FIGURE 5.—Proportion of advected energy (into a Class A pan) utilized for evaporation.

climatic variations. Thus, annual lake evaporation can be estimated from the following equation (using daily or monthly averages and accumulating):

$$E_L=0.70\left[\frac{Q_n\Delta+E_a\gamma}{\Delta+\gamma}\right] \tag{10}$$

where E_L is the average daily lake evaporation in inches (assuming any advection to be balanced by a change in energy storage), $Q_n\Delta$ and E_a are as determined in figure 2, and $\gamma=0.000367P$. For convenience equation (10) is presented graphically in figure 6 for $\gamma=0.0105$. Although equation (10) is strictly applicable only for daily data, use of monthly averages will, in general, cause no appreciable bias. Even annual averages will generally give reasonably reliable results if the vapor-pressure difference used in the E_a relation is averaged from daily or monthly data rather than being computed from annual averages of air and dew-point temperatures.

COMPUTATION OF HEAT TRANSFER THROUGH THE PAN

The previous section described one technique for estimating the evaporation which would occur from a "hypothetical" Class A pan designed to eliminate transfer of sensible heat through the sides and bottom. A second and more obvious approach involves the direct computation of transfer through the pan and the determination of that portion which was utilized in (or not available for) the evaporation process as discussed in the section on advection.

Unfortunately, observations required for determining the temperature gradient through the pan proper are not available—in fact, the only pertinent data generally available are wind and air temperature supplemented by temperature of the water surface at some stations. Nonetheless, an estimate of the transfer can be made, if certain assumptions are adopted.

From Bowen's ratio concept and equation (4), it will be seen that the transfer of sensible heat from the water surface of a Class A pan (in equivalent inches of evaporation) is given by

$$Q_h=0.000367P(0.37+0.0041u_p)(T_0-T_a)^{0.88} \tag{11}$$

It can be shown that the difference in mean daily temperature at the inner and outer faces of a pan does not exceed a fraction of a degree F. Assuming the outer face of the pan to be at temperature T_0, and further assuming the wind over the water surface to be representative of the entire outer face of the pan, equation (11) can be modified to yield heat transfer through the pan, i. e.,

$$Q_h'=0.000367P(0.37+0.0041u_p)(T_0-T_a)^{0.88}\left(\frac{A_p}{A_w}\right) \tag{12}$$

where A_w is the area of the water surface and A_p is the effective area of the outer face of the pan.

The effective area A_p is difficult to evaluate objectively since it must account for variations in air movement and other factors from point to point over the surface as well as conduction to the support. The value of γ_p derived empirically (fig. 2) was $0.000871P$, while the theoretical value is $0.000367P$. In other words, $(A_p+A_w)/A_w=0.000871/0.000367$, or $A_p=1.37A_w$. If A_p is taken as the entire outer surface then, from the geometry of the pan $A_p=1.83A_w$. Eliminating the upper 2½ inches normally above the waterline and that portion in contact with the 2-by-4 supports reduces the computed ratio to about 1.10. The actual value would be expected to fall between these two extremes of 1.83 and 1.10.

Though not wholly independent, still another insight into the magnitude of A_p can be gained by simultaneous solution of equation (12) and that given in figure 5. Taking cases where lake evaporation is known and assuming the 0.7 coefficient applicable when air and pan-water temperatures are equal,

$$\alpha_p Q_h'=\frac{E_L}{0.7}-E_p \tag{13}$$

The value of α_p can be obtained from figure 5 and, having lake and pan evaporation, Q_h' can be computed. Solution of equation (12) then provides an estimate of A_p. This approach was attempted for Fullerton, Calif. [12], for the years 1935 and 1936 (taking evaporation from a 12-foot sunken pan to be equivalent to that from a lake) and the derived values of A_p were $1.34A_w$ and $1.25A_w$, respectively. The only annual period at Lake Hefner with significant difference between pan-water and air temperatures (0.7° F. as compared to about 4° F. at Fullerton) was the period September 1, 1950, through August 31, 1951. Even this difference is so small as to cast doubt upon the result, but the value of A_p derived for this period is $1.58A_w$.

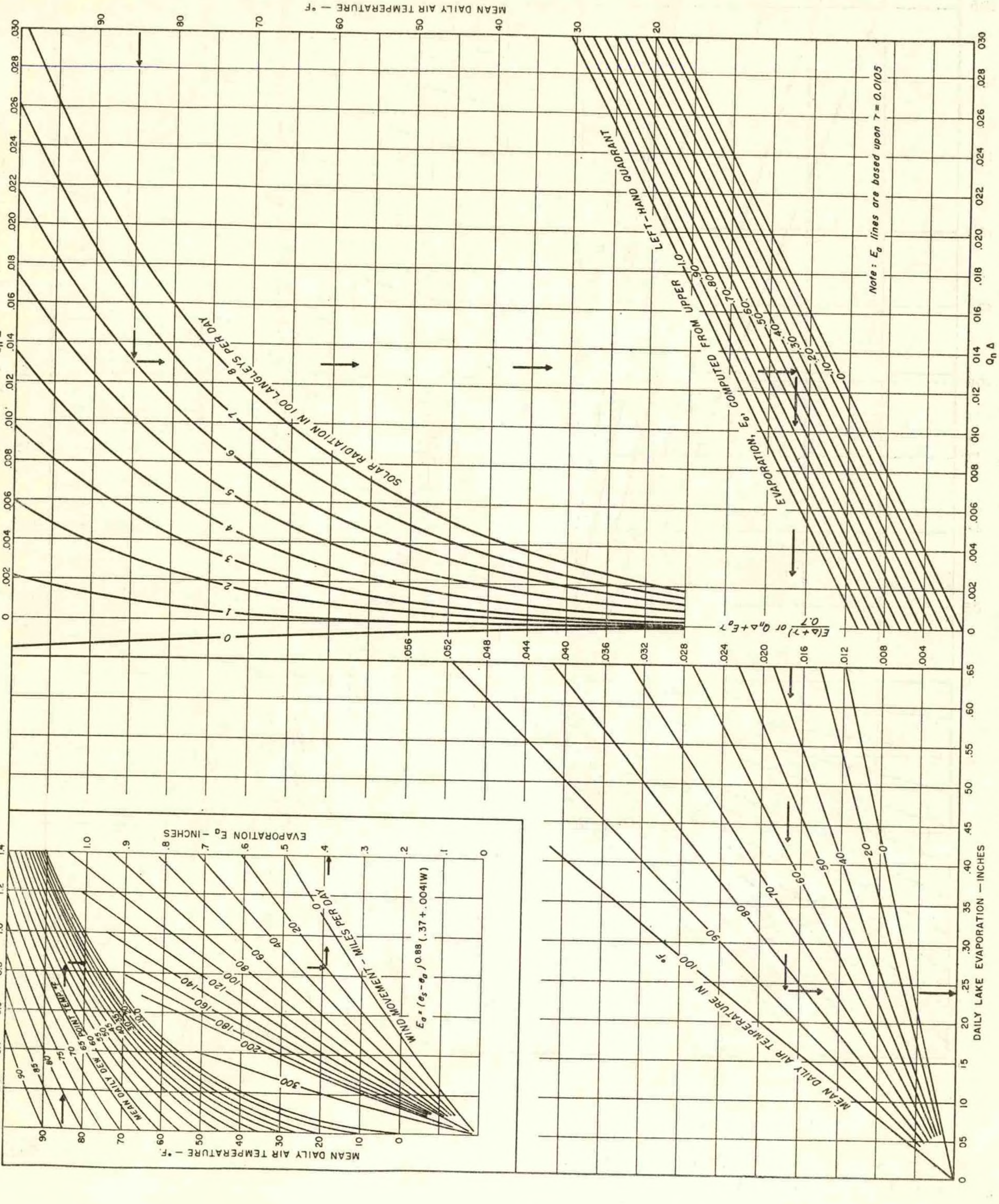

FIGURE 6.—Graphical presentation of equation (10).

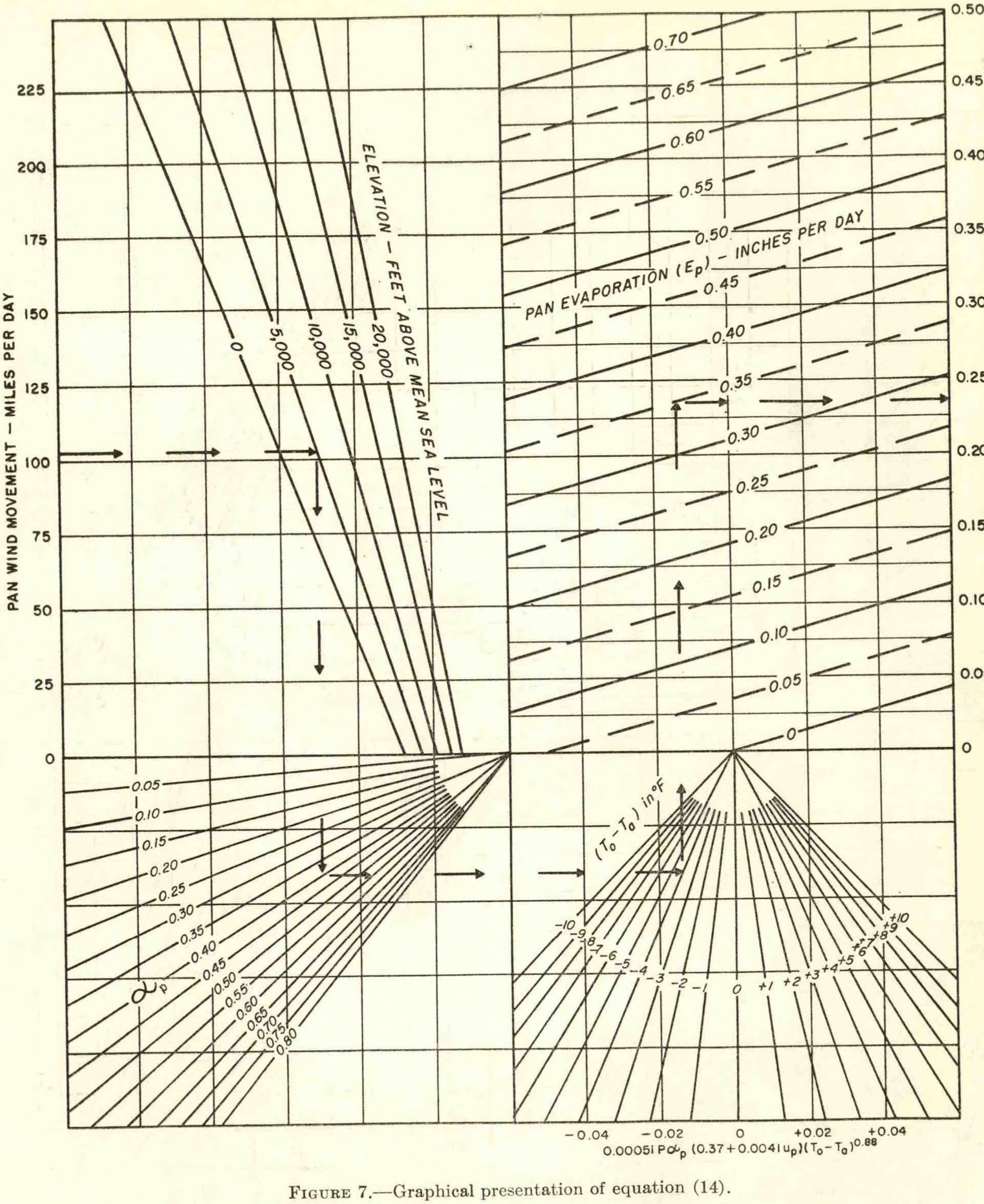

FIGURE 7.—Graphical presentation of equation (14).

Data are admittedly insufficient to determine A_p accurately at the present time, but additional data are being collected which should prove of value in this regard. Considering the above computations, however, it appears that the use of $1.4A_w$ for A_p should be satisfactory. Thus, annual lake evaporation (inches per day) can be estimated from the following equation

$$E_L = 0.70\,[E_p + 0.00051 P\alpha_p(0.37 + 0.0041u_p)\,(T_0 - T_a)^{0.88}] \qquad (14)$$

where α_p is determined from figure 5. This equation assumes that any advected energy into the lake is balanced by a change in energy storage and that the pan exposure is representative. Graphical solution of equation (14) is shown in figure 7.

EVALUATION OF SUGGESTED PROCEDURES

A study of the material presented in the foregoing sections will reveal several approaches to the estimation of reservoir evaporation—the method to be used in a specific case hinging largely upon the data available for the purpose and the quality of such data. To avoid confusion, the ensuing discussion of the several methods is restricted to the estimation of natural lake evaporation, uninfluenced by advection of energy into the lake. As previously emphasized, data are, up to the present time, extremely limited and of such reliability as to preclude any conclusive analysis of the various techniques. For what value they may have for the purpose, but more to demonstrate application of techniques, table 6 lists pertinent data and results of the computations. Columns 17 through 25 are to be compared with column 16. To demonstrate the relative accuracy achieved with monthly as compared to annual data, the computed values shown in columns 18–21 are based on the mean data given in columns 4–11, while those shown in columns 22–25 are based on an accumulation of computed monthly evaporation.

Over much of the United States there is not appreciable transfer of heat through the Class A pan (on an annual basis), and the use of the 0.7 coefficient in these areas should provide reliable results when representative pan observations are available. If water temperature data are available in addition to the observations normally made at a Class A installation, it is believed equation (14) constitutes the most reliable approach. Even though the factor α_p and the ratio A_p/A_w cannot yet be determined with precision, the results shown in columns 16 and 23 of table 6 are extremely encouraging.

In those cases where representative pan data are not available, it appears that interpolation of related causal factors followed by computation of pan evaporation (fig. 2) should be preferable to direct interpolation from surrounding pans. That is, application of a coefficient to the computed pan evaporation should yield more reliable estimates of lake evaporation than application of the same coefficient to interpolated pan evaporation. Use of equation (10) should provide further improvement since it tends to account for heat transfer through the pan.

If representative pan evaporation observations are available in addition to the data required for equation (10), several possibilities are apparent. That portion of the right-hand member of equation (10) in parentheses represents the evaporation from the "hypothetical" pan and, assuming the error in computed evaporation from the Class A and the hypothetical pans to be proportional, equation (10) becomes

$$(15) \qquad E_L=0.70\left[\frac{Q_n\Delta+E_a\gamma}{\Delta+\gamma}\times\frac{E_p}{E'_p}\right]$$

where E'_p is the Class A pan evaporation computed from figure 2. Equation (15) can be readily solved by multiplying E_L as obtained from figure 6 by the ratio E_p/E'_p.

If, on the other hand, it is believed that little reliance can be attached to derived solar radiation data, $Q_n\Delta$ as estimated by entering figure 2 in reverse fashion can be applied to figure 6. That is,

$$(16) \qquad E_L=0.70\left[\frac{E_p(\Delta+\gamma_p)+E_a(\gamma-\gamma_p)}{\Delta+\gamma}\right]$$

$$=0.70\left[\frac{(\Delta+0.000871P)E_p-0.000504PE_a}{\Delta+0.000367P}\right]$$

An objective appraisal of the techniques summarized in this section is hardly possible; first, because so much depends upon the relative accuracy (and representativeness) of the data used and, second, because of the limited experimental data available for comparative analysis. Nevertheless, table 6 does indicate that equation (14) provides the most reliable estimate of lake evaporation, with equations (10), (15), and (16) giving results slightly less accurate. It also appears that better results are obtained with monthly data than with annual, and further improvement might be expected if daily values are used. In addition to the reservoirs given in table 6, 19 months of data are available for Lake Mead (above Hoover Dam on the Colorado River). Complete analysis of these data will be given in a report now in preparation by the cooperating agencies, but preliminary computations, using

TABLE 6.—*Computation of lake evaporation by suggested methods*

Class A pan station	Lake	Period (pan and meteorological data)	Observed Class A pan evaporation (inches)	Mean air temperature (°F.)	Mean [1] (e_o-e_a) (inches of mercury)	Mean water surface temperature in pan (°F.)	Mean daily pan wind movement (miles)	Mean daily solar radiation (langleys)	Mean [2] station pressure (inches of mercury)	Mean lake surface temperature (°F.)	Mean daily wind movement over lake at 4 meters (miles)	Q'_v (equivalent inches of evaporation) [3]	Q_θ (equivalent inches of evaporation) [3]	Lake evaporation in inches: Water budget: Observed	Lake evaporation in inches: Water budget: Adjusted [16]	Computed from pan and related data using averages for entire period: 0.7 pan evaporation	Computed from pan and related data using averages for entire period: Eq. (10)	Computed from pan and related data using averages for entire period: Eq. (14)	Computed from pan and related data using averages for entire period: Eq. (15)	Computed from pan and related data using averages for entire period: Eq. (16)	Computed from pan and related data using monthly averages and accumulating: Eq. (10)	Computed from pan and related data using monthly averages and accumulating: Eq. (14)	Computed from pan and related data using monthly averages and accumulating: Eq. (15)	Computed from pan and related data using monthly averages and accumulating: Eq. (16)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Lake Hefner, Okla. (South Station) [17]	Hefner	5/1/50–4/30/51	78.7	59.3	0.206	59.1	138	436	28.7	58.8	300	−1.0	+0.8	[4] 52.5	53.5	55.1	48.6	54.5	51.3	52.6	50.7	55.5	52.6	53.2
Lake Hefner, Okla. (South Station)	do	9/1/50–8/31/51	83.9	60.1	.239	59.4	135	456	28.7	58.8	299	−1.0	−0.5	[4] 57.0	57.3	58.7	53.9	57.2	54.5	54.6	54.8	57.9	56.0	56.3
Fullerton, Calif. [12]	12-foot pan	1/1–12/31/35	66.2	61.1	------	64.8	61	------	29.8	67.2	------	------	------	51.0	51.0	46.3	------	51.0	------	------	------	51.1	------	------
Fullerton, Calif.	do	1/1–12/31/36	72.4	62.0	------	65.7	66	------	29.8	68.3	------	------	------	55.3	55.3	50.7	------	55.6	------	------	------	55.5	------	------
Lake Elsinore, Calif. [13]	Elsinore	1/1–12/31/40	78.0	65.2	[5] .271	------	52	------	28.5	------	------	------	------	59.3	59.3	54.6	------	------	------	57.6	------	------	------	57.4
Lake Elsinore, Calif.	do	1/1–12/31/41	66.7	63.2	[5] .215	------	46	------	28.5	------	------	------	------	52.0	52.0	46.7	------	------	------	51.0	------	------	------	50.7
Fort Collins, Colo. [11]	85-foot res	[6] 4/6–11/29/27	39.6	57.7	.223	59.0	53	------	25.0	62.2	------	------	------	27.4	27.4	27.7	------	28.6	------	28.8	------	28.5	------	28.8
Fort Collins, Colo.	do	[7] 4/5–11/27/28	39.2	56.2	.212	58.4	50	------	25.0	61.0	------	------	------	27.0	27.0	27.4	------	28.8	------	29.3	------	28.8	------	29.6
Belle Glade Experiment Station, Fla.	Okeechobee	1/1–12/31/52	64.1	71.6	[8] .244	------	[9] 50	[10] 488	29.9	------	------	------	------	[11] 48.0	48.0	44.9	53.7	------	47.9	46.0	54.9	------	47.9	46.5
Red Bluff Dam, Tex.	Red Bluff	1/1/40–12/31/47	[12] 106.2	64.3	[13] .435	------	67	[14] 520	27.0	------	------	------	------	[15] 76.8	76.8	74.3	67.0	------	70.3	72.1	67.0	------	70.7	72.5

Numbers in brackets indicate references, p. 20.

1 Obtained from averaging monthly values.

2 From NACA standard atmosphere-pressure tables [15], except for Fort Collins where observed value was used.

3 Assumed to be zero when data are missing.

4 Corrected values as listed in table 28 of Lake Hefner Report [17].

5 Computed from average monthly relative humidity.

6 8 days missing during period.

7 7 days missing during period.

8 Dewpoint temperature assumed to be same as minimum temperature. A study of Florida data showed this to be a reasonable assumption.

9 Pan wind movement estimated from observed wind movement on 50-foot tower.

10 Assumed to be same as observed radiation at Miami. Value is probably too high as afternoon cloudiness tends to increase inland from the coast.

11 Average annual value for period (1940–46) as given in [7]. Accuracy is questionable due to doubt as to seepage loss. Meteorological data for 1952 are assumed applicable for 1940–46 since the 1952 pan evaporation is same as annual average for the above 7-year period.

12 Average annual evaporation. Data missing for some months during period.

13 Dewpoint temperature assumed to be same as that observed at El Paso.

14 Estimated from average percent of possible sunshine at El Paso and [3].

15 Average annual value for 6 years (1944–49) as given in [7].

16 Observed water budget evaporation as adjusted for effect of advected energy and change in energy storage. Obtained by solving equation (17) for E_L.

Boulder City pan data in equation (14), give a value of evaporation from Lake Mead within about 10 percent of that obtained by the U. S. Geological Survey with energy budget and mass-transfer methods, even though the pan is at an elevation 1,300 feet higher than the lake and is affected by local watering. Adjusting air and dewpoint temperatures to lake elevation and applying equation (10) yields a value of evaporation within 3 percent for the 19-month period, with an average error of only one-half inch on a monthly basis. Thus, it would appear from the Lake Mead results that the techniques suggested herein can be used to compute monthly lake evaporation when advection and energy storage terms can be evaluated.

ADJUSTMENT FOR ENERGY ADVECTION AND STORAGE IN THE LAKE

All equations (10, 14, 15, and 16) and computations for deriving the estimates of lake evaporation given in columns 18–25 of table 6 are based on the somewhat idealized assumptions that

(1) any energy advected into the lake is balanced by a change in energy storage;
(2) the 0.7 coefficient is applicable to the Class A pan when average air and pan-water temperatures are equal.

It will be seen that these two qualifications are not independent in the strictest sense—the method of adjusting for advected energy should provide for "zero" adjustment when circumstances duplicate those accompanying the experiments in which the 0.7 value was found to apply. From the practical viewpoint there is advantage in the concept that no adjustment is required when evaporation is balanced by inflow of the same temperature and the outflow is zero. In addition, advection computations should be based on a balanced water budget to provide results which are independent of the temperature base used. It takes only a few selected computations to show that advection adjustments can be neglected except when inflow and outflow are large relative to the volume of evaporation, and even then the temperatures of inflow and outflow must be appreciably different. It will also be found that errors in items such as precipitation and evaporation are of little importance so long as the advection computations are based on a balanced water budget.

In table 6 the observed water budget evaporation is adjusted (as shown in column 16) for energy advection and change in energy storage for comparison with E_L as computed from equations (10), (14), (15), and (16). When computing actual lake evaporation, the adjustment would be made to E_L as shown in the following equation:

(17) $$\text{Lake Evaporation}=E_L+\alpha(Q_v'-Q_\theta)$$

It is obvious that adjustment must be made for the change in energy storage as well as advected energy (previously discussed). If the energy advection is zero and the energy storage is observed to decrease in a given period, then the energy released is dissipated through back radiation, evaporation, and transfer of sensible heat. Conversely, the evaporation will be decreased if part of the energy imparted to the water is used to increase the energy storage.

SUMMARY AND CONCLUSIONS

The first part of this research paper describes the development of an empirical relation for estimating pan evaporation from pertinent meteorological factors and discusses the reliability and applications of the derived relation. Although further verification analysis seems justified, results presented are believed to be sufficiently good to instill a high degree of confidence in the accuracy of the relation, except possibly when applied for high elevations.

The second part of the report treats the problem of estimating reservoir evaporation from pan and related meteorological data. It may appear that much of the material is presented prematurely in view of the extremely limited substantiative evidence now available, and this may well be the case. On the other hand, there can be little doubt that the use of the customary 0.7 Class A pan coefficient, without consideration of advected energy to either the pan or the lake, may lead to appreciable error. Assumptions must be made in deriving the techniques for making adjustments, but any deficiencies in this connection are believed to be of much lower order than the required advection adjustments.

Required advection adjustments for reservoirs do not portray any reasonable geographic pattern since they are the direct outcome of the plan of operation. Extrapolating such adjustments therefore requires thorough study of operational procedures. Adjustments for heat transfer through the pan are influenced by climatological factors only and therefore display a geographical pattern consistent with that of the pertinent climatological factors. In flat terrain, variations in the required adjustment are gradual and extrapolation should be reasonably reliable.

FUTURE STUDIES

IMMEDIATE OBJECTIVES

As emphasized in the previous section, some phases of the procedures described herein for estimating lake evaporation do not have the benefit of adequate supporting data. Reliability of the procedures should improve materially with each experiment, or "test case," and every attempt will be made to conduct continued analyses along these lines. Further verification of the pan relation (fig. 2) is also warranted and it is hoped that this work can proceed rather rapidly. The effects of non-standard operational practices at pan stations, and the relative merits of different types of pans are also under continued investigation.

PROJECTS

Upon completion of the Lake Hefner observational program, interagency activities (Geological Survey, Bureau of Reclamation, Navy, and Weather Bureau) were shifted to Lake Mead where observations were made for the period March 1, 1952, through Sept. 30, 1953. A report of the Lake Mead water-loss studies is now in preparation.

A similar project is now underway at Felt Lake on the campus of Stanford University. This work is being conducted by Stanford under contract with the Weather Bureau, with some of the instrumental equipment being furnished by the Geological Survey and Bureau of Reclamation. The Weather Bureau is also conducting an experimental pan program at its Silver Hill Observatory near Washington, D. C. In addition to these experimental projects, data provided by the network of Class A stations is gradually being augmented in several respects, namely, (1) establishment of new stations, (2) implementing observations of dewpoint and water temperature at existing stations, and (3) adding pan observations to the observational program at those first-order stations where solar radiation data are available.

REFERENCES

1. I. S. Bowen, "The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface," *Physical Review*, Ser. 2, vol. 27, June 1926, pp. 779–787.
2. J. Dalton, "Experimental Essays on the Constitution of Mixed Gases; on the Force of Steam or Vapour from Water and Other Liquids in Different Temperatures, Both in a Torricellian Vacuum and in Air; on Evaporation; and on the Expansion of Gasses by Heat," *Memoirs*, Manchester Literary and Philosophical Society, Series 1, vol. 5, Part 2, 1802, pp. 535–602.
3. R. W. Hamon, L. L. Weiss, and W. T. Wilson, "Insolation as an Empirical Function of Daily Sunshine Duration," *Monthly Weather Review*, vol. 82, No. 6, June 1954, pp. 141–146.
4. G. E. Harbeck, Jr., "The Use of Reservoirs

and Lakes for the Dissipation of Heat," U. S. *Geological Survey Circular* 282, 1953.
5. G. E. Harbeck, Jr., "The Effect of Salinity on Evaporation," U. S. Geological Survey *Professional Paper* No. 272-A, 1955.
6. G. W. Himus, "The Evaporation of Water in Open Pans," *Transactions*, Institution of Chemical Engineers, vol. 7, 1929, pp. 166–177.
7. W. B. Langbein, "Research on Evaporation from Lakes and Reservoirs," *Transactions* of meeting of International Association of Hydrology, Brussels, 1951, pp. 9–11.
8. R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus, *Applied Hydrology*, McGraw-Hill Book Co., New York, 1949, pp. 650–655.
9. F. Graham Millar, "Evaporation from Free Water Surfaces," Canada Department of Transport, Division of Meteorological Services, *Canadian Meteorological Memoirs*, vol. 1, No. 2, 1937, p. 47.
10. H. L. Penman, "Natural Evaporation from Open Water, Bare Soil, and Grass," *Proceedings of the Royal Society of London*, Ser. A, vol. 193, No. 1032, April 1948, pp. 120–145.
11. C. Rohwer, "Evaporation from Free Water Surfaces," U. S. Department of Agriculture, *Technical Bulletin* No. 271, December 1931.
12. A. A. Young, *Evaporation Investigations in Southern California*, U. S. Department of Agriculture, Soil Conservation Service, Division of Irrigation, April 1945.
13. A. A. Young, *Evaporation Studies at Lake Elsinore, California*, U. S. Department of Agriculture, Soil Conservation Service, Division of Irrigation, 1942.
14. Water-Loss Investigations: Lake Mead Studies (Inter-agency report now in preparation).
15. Smithsonian Institution, *Smithsonian Meteorological Tables*, 6th Revised Edition, 1951, p. 267.
16. Subcommittee on Evaporation of the Special Committe on Irrigation Hydraulics, Final-Report, "Standard Equipment for Evaporation Stations," *Transactions*, American Society of Civil Engineers, vol. 99, 1934, pp. 716–718.
17. U. S. Geological Survey, "Water-Loss Investigations: Volume 1—Lake Hefner Studies," *Geological Survey Professional Paper* No. 269, 1954. (A reprint of U. S. G. S. *Circular* No. 229, 1952.)
18. U. S. Geological Survey, "Water-Loss Investigations: Lake Hefner Studies, Base Data Report," *Geological Survey Professional Paper* 270, 1954.

WEATHER BUREAU RESEARCH PAPERS

(*Continued from page ii*)

No. 31 *Second Partial Report on the Artificial Production of Precipitation: Cumuliform Clouds—Ohio, 1948.* Richard D. Coons, Earl L. Jones, and Ross Gunn, January 1949. $0.30

No. 32 *Further Studies in Hawaiian Precipitation.* Samuel B. Solot, January 1950. $0.30

No. 33 *Artificial Production of Precipitation. Third Partial Report: Orographic Stratiform Clouds—California, 1949. Fourth Partial Report: Cumuliform Clouds—Gulf States, 1949.* Richard D. Coons, Earl L. Jones, and Ross Gunn, September 1949. $0.40

No. 34 *Predicting the Runoff From Storm Rainfall.* M. A. Kohler and R. K. Linsley, September 1951. $0.05

No. 35 *The Application of the Hydraulic Analogy to Certain Atmospheric Flow Problems.* Morris Tepper, October 1952. $0.35

No. 36 *Cloud Seeding Operations in the Bishop Creek, Calif., Watershed.* Ferguson Hall, T. J. Henderson, and Stuart A. Cundiff, January 1953. $0.25

No. 37 *Pressure Jump Lines in Midwestern United States, January–August 1951.* Morris Tepper, June 1954. $0.45

No. 38 *Evaporation from Pans and Lakes.* M. A. Kohler, T. J. Nordenson, and W. E. Fox, May 1955. $0.20

Weather Bureau Research Papers for sale by Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

U. S. GOVERNMENT PRINTING OFFICE: 1955

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. - Price 20 cents