U.S. DEPARTMENT OF COMMERCE
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TECHNICAL PAPER NO. 37

Evaporation Maps for the United States

U.S. DEPARTMENT OF COMMERCE
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EVAPORATION MAPS FOR THE UNITED STATES

INTRODUCTION

Since evaporation inevitably extracts a portion of the gross water supply to a reservoir, the estimation of this loss is an important factor in reservoir design. In arid regions, the evaporation loss actually imposes a ceiling on the water supply obtainable through regulation. Speaking of storage on the main stem of the Colorado River, Langbein[1] states that "The gain in regulation to be achieved by increasing the present 29 million acre-feet to nearly 50 million acre-feet of capacity appears to be largely offset by a corresponding increase in evaporation."

In the final stages, the design of major storage projects requires detailed study of all data available, including observations made at the proposed reservoir sites. However, generalized estimates of free-water evaporation are invaluable in preliminary design studies of major projects, and are often fully adequate for the design of lesser projects. The maps presented herein have been prepared to serve these purposes, primarily, but they should be of value in other studies. For example, free-water evaporation (Plate 2) is a good index to potential evapotranspiration, or consumptive use, and the pan coefficient (Plate 3) is indicative of an aspect of climate.*

The following series of maps is presented for the United States (except Alaska and Hawaii):

Plate 1 - Average Annual Class A Pan Evaporation,

Plate 2 - Average Annual Lake Evaporation,

Plate 3 - Average Annual Class A Pan Coefficient,

Plate 4 - Average May-October Evaporation in Percent of Annual,

Plate 5 - Standard Deviation of Annual Class A Pan Evaporation.

In 1942, A. F. Meyer[2] published a map comparable to that in Plate 2, and in the following year R. E. Horton[3] published a map of Class A pan evaporation similar to Plate 1. Subsequent to 1942, there has been a substantial increase in the Class A pan station network and significant progress in the development of techniques for estimating lake evaporation. However, the maps prepared by Horton and Meyer were carefully studied in the preparation of the new series -- any pronounced differences are considered to be reasonably substantiated by data now available.

Plate 3 shows the ratio of annual lake evaporation to that from the Class A pan. It can be used to estimate free-water evaporation for any site for which representative pan data are available. Plate 4 has been included to assist in the extrapolation of seasonal pan evaporation data to annual values, as well as to provide an indication of the seasonal distribution of evaporation from a shallow free-water body. Plate 5 shows the variability of pan evaporation, year-to-year, and can be used to estimate the frequency distribution of annual lake evaporation. The correct interpretation and use of these three plates are discussed later in the report.

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* If solar radiation, wind, dew point, and air temperature are such that water in an exposed Class A pan is warmer than the air, the coefficient is greater than 0.7, and vice versa.

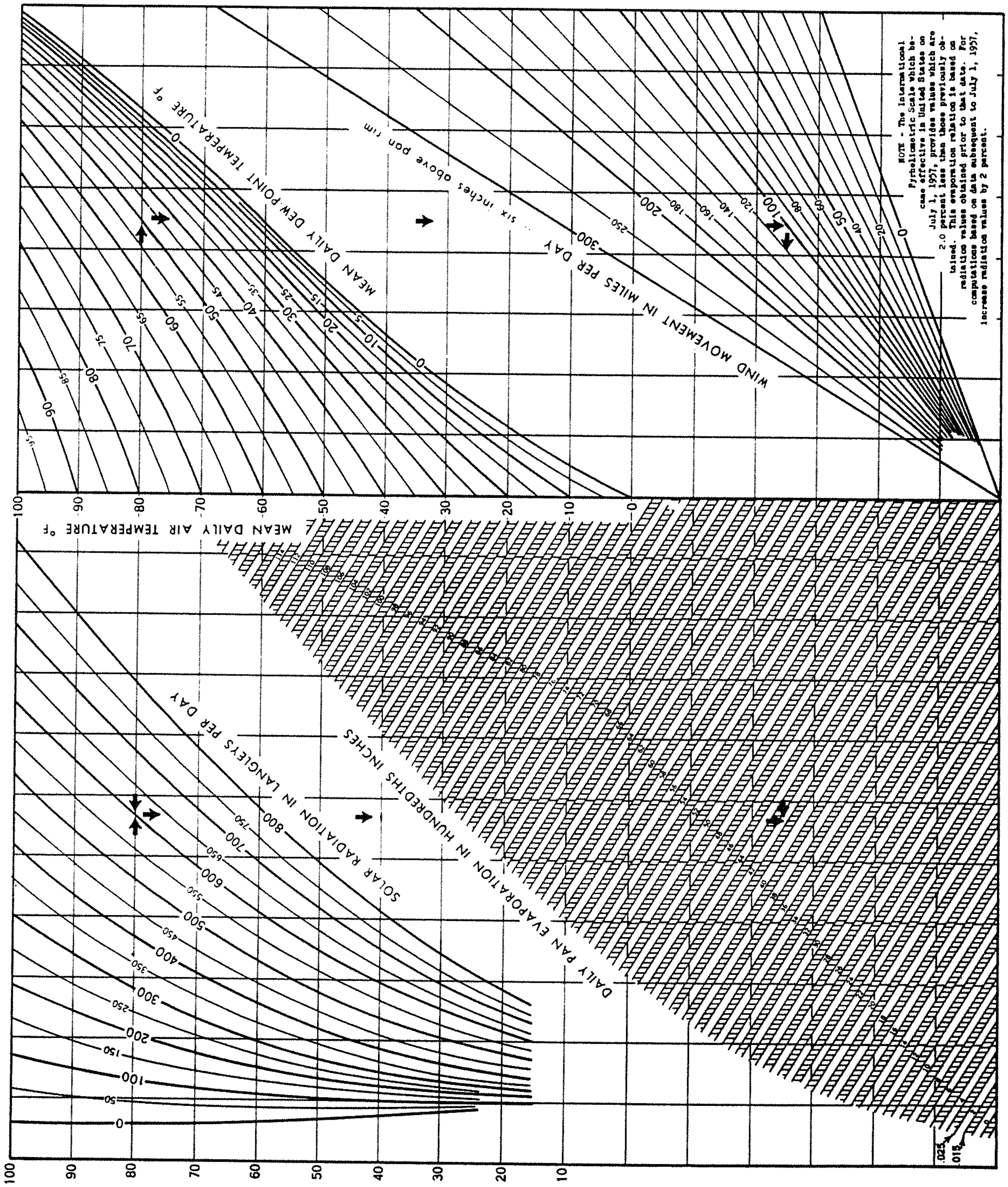


Figure 1. - Class A pan evaporation relation. (Adapted from fig. 2 of reference 6.)

METHODS FOR COMPUTING EVAPORATION

The various methods for computing pan and lake evaporation are described in the Lake Hefner[4] and Lake Mead[5] Water-Loss Investigations Reports, and in Weather Bureau Research Paper No. 38[6]. There are four generally accepted methods of computing lake evaporation: (1) water budget, (2) energy budget, (3) mass transfer, and (4) lake-to-pan relations. Very few reliable water-budget estimates are available because small errors in volume of inflow and outflow usually result in large errors in the residual evaporation value. The energy-budget approach requires such elaborate instrumentation that it is only feasible for special investigations. The mass-transfer method requires observations of lake surface-water temperature, dew point, and wind movement which are available for only a very few reservoirs. Methods (1), (2), and (3) are only applicable for existing lakes and reservoirs, and cannot be used in the design phase.

The few lake-evaporation determinations that have been made using water-budget, energy-budget, and mass-transfer methods were used in preparing Plates 2 and 3. However, from a practical point of view, the lake-evaporation map is based essentially on pan evaporation and related meteorological data collected at Class A evaporation and first-order synoptic stations.

DEVELOPMENT OF MAPS

Average Annual Class A Pan Evaporation. The Class A pan-evaporation data were obtained from all available sources: Weather Bureau, Corps of Engineers, Bureau of Reclamation, State and private organizations. The required 10-year (1946-1955) average values were compiled for 146 stations with complete annual records, and for 151 stations with seasonal records.

Average monthly values of air temperature, dew point, wind movement, and solar radiation (or percent sunshine) were computed for 255 first-order Weather Bureau stations. The percent sunshine values were converted to solar radiation using the relation developed by Hamon, Weiss, and Wilson[7]. Observed wind movement was adjusted to pan height by the power law

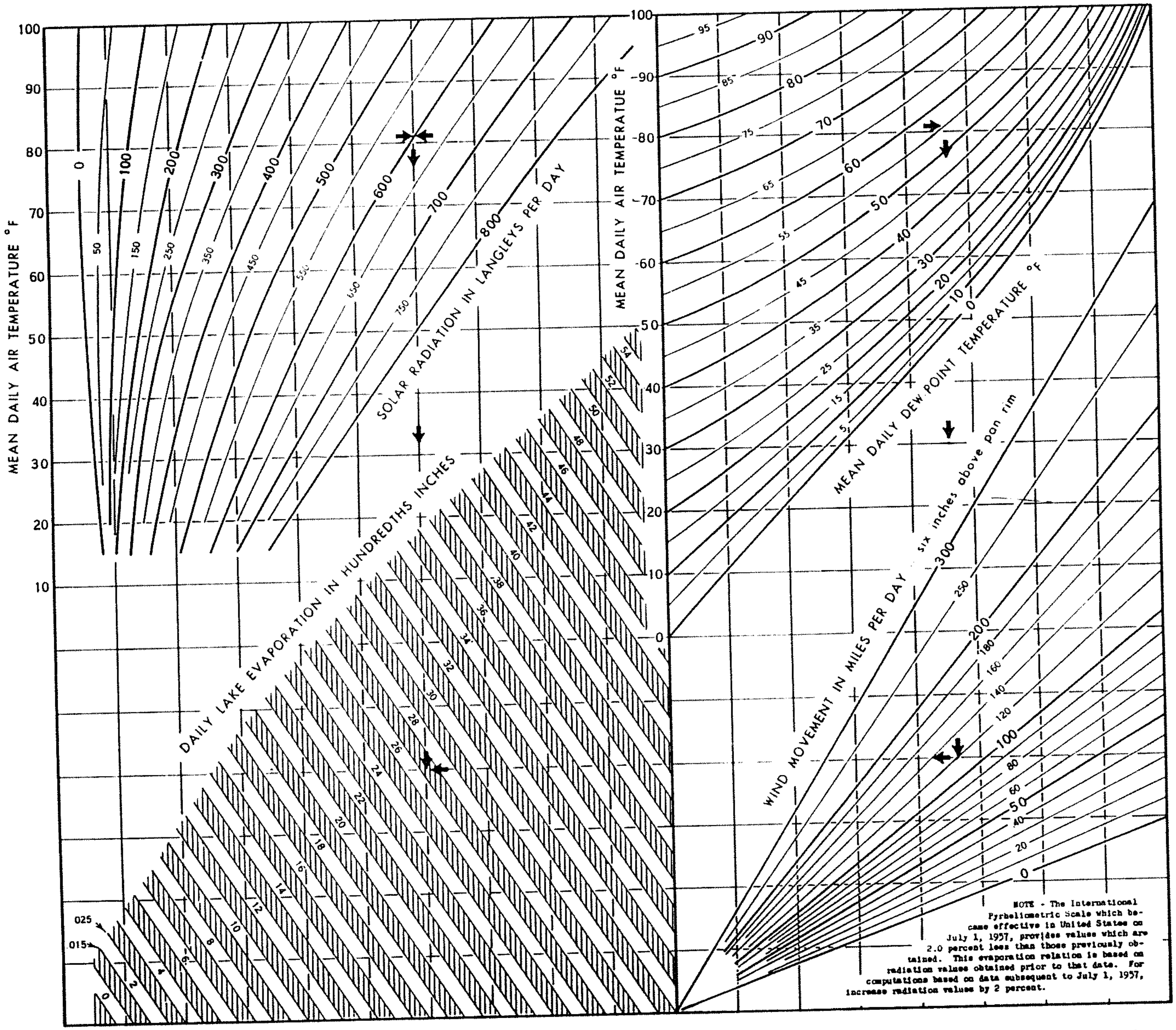
$$\frac{U_1}{U_2} = \left(\frac{Z_1}{Z_2}\right)^{0.3}$$

where U_1 = wind movement at pan height; U_2 = wind movement at station anemometer height; Z_1 = height of pan anemometer (2 feet above ground); and Z_2 = height of first-order station anemometer. In some cases a further refinement of pan-wind estimates was made by comparing computed April-October pan-wind movement with that observed at nearby Class A pan evaporation stations. The dew point data were reduced when necessary to the 6-foot level (above the ground) using the correction graph in A. F. Meyer's Evaporation from Lakes and Reservoirs [2].

Average monthly Class A pan evaporation was computed for all first-order Weather Bureau stations by entering the graphical relation of Figure 1 with corresponding values of air temperature, dew point, solar radiation, and wind movement. The seasonal Class A pan-evaporation records were extrapolated to obtain annual values by using ratio of annual to seasonal computed pan evaporation for nearby first-order Weather Bureau stations.

The final average annual Class A pan evaporation map, Plate 1, is based on the observed and extrapolated annual pan evaporation for 297 Class A pan stations and the computed annual Class A pan evaporation for 255 first-order Weather Bureau stations. In addition, data from numerous Bureau of Plant Industry (BPI) pan stations, adjusted by appropriate coefficient to obtain estimated Class A pan evaporation, were considered.

Average Annual Class A Pan Coefficient. The average annual Class A pan coefficient map, Plate 3, was the second map to be developed. Average monthly values of lake evaporation were computed from Figure 2 for 255 first-order Weather Bureau stations, using the air temperatures, dew point, solar radiation, and wind data described in the previous section. The



NOTE - The International Pyrheliometric Scale which became effective in United States on July 1, 1957, provides values which are 2.0 percent less than those previously obtained. This evaporation relation is based on radiation values obtained prior to that date. For computations based on data subsequent to July 1, 1957, increase radiation values by 2 percent.

Figure 2. - Lake evaporation relation. (Adapted from fig. 6 of reference 6.)

annual values were then divided by the annual pan evaporation values previously derived for the same stations to obtain the lake-to-pan ratios (pan coefficients). In addition, lake evaporation and pan coefficients were computed for all Class A pan stations with water-temperature observations, using the relations shown in Figures 3 and 4. The derivation of Figures 3 and 4 is fully discussed in reference 6 . This approach to the computation of lake evaporation assumes that the Class A pan coefficient is 0.70 when air and water temperatures are equal, and adjusts for heat transfer through the pan when the temperatures are different.

The isopleths of Plate 3 were then drawn on the basis of the coefficients computed for the first-order Weather Bureau stations, the selected Class A pan stations with water temperature observations, and those derived in other studies that were considered reliable.

Average Annual Lake Evaporation. By definition, the product of the pan evaporation (Plate 1) and the pan coefficient (Plate 3) yields the corresponding lake evaporation. The isopleths of Plate 2 were thus first drawn to be consistent with Plates 1 and 3, and the results were reviewed in the light of all available lake values, i.e.,

first-order Weather Bureau stations - - - - - - - - - - - - - - - - - - 255,

Class A stations with water temperature- - - - - - - - - - - - - - - - 48,

sunken pans 12 feet or more in diameter- - - - - - - - - - - - - - - - 7,

miscellaneous (energy budget, water budget, and mass transfer)- - - 10.

As a final step, it became necessary to reconsider the data plotted on all three maps, subjectively evaluating the reliability of each item.

Average May-October Evaporation in Percent of Annual. Although the data required to derive the isopleths of Plate 4 are sparse, they are consistent, station to station. Over much of the country Class A pans are not in operation during the winter months because of freezing weather. In such areas, the map is based entirely on the ratios (May-through-October to annual evaporation) computed from data collected at first-order Weather Bureau stations. In the warmer sections of the country, where pan observations are made throughout the year, ratios based on observed pan data were also used in the development.

Standard Deviation of Annual Class A Pan Evaporation. For many purposes, the magnitude of the average annual or seasonal evaporation is sufficient. In other cases, however, knowledge of the variability or the frequency distribution of evaporation is required. To serve these purposes, the map of Plate 5, showing the standard deviation* of annual Class A pan evaporation, was prepared. Mass plottings of evaporation were first made for each station having more than 15 years of record to check the consistency of the data. In several cases these plottings indicated that some change (exposure, location, etc.) had occurred during the period and, in such cases, the standard deviation was based on only the longer, consistent portion of the record. The standard deviations computed from seasonal records were adjusted to annual values by use of the relation shown in Figure 5, derived from data for 38 Class A pan stations with complete annual records. The correlation coefficient between the observed standard deviation of annual evaporation and that computed from the relation is 0.85. The reliability of this relation and Plate 5 could be improved if time and manpower were available to compute the evaporation for each year of record for all the first-order Weather Bureau stations.

The standard deviation and the mean determine the normal frequency distribution and Plates 1 and 5 can be used to estimate the frequency curve of annual pan evaporation if it can be assumed that the data follow the normal distribution. Accordingly, tests were made to see if the distribution of annual (or seasonal) Class A pan evaporation is significantly different than

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* Computed by the equation $S = \sqrt{\frac{\Sigma(X - \overline{X})^2}{n - 1}}$, where X is annual or seasonal evaporation in inches, $\overline{X}$ is the mean of X, and n is the number of years of record.

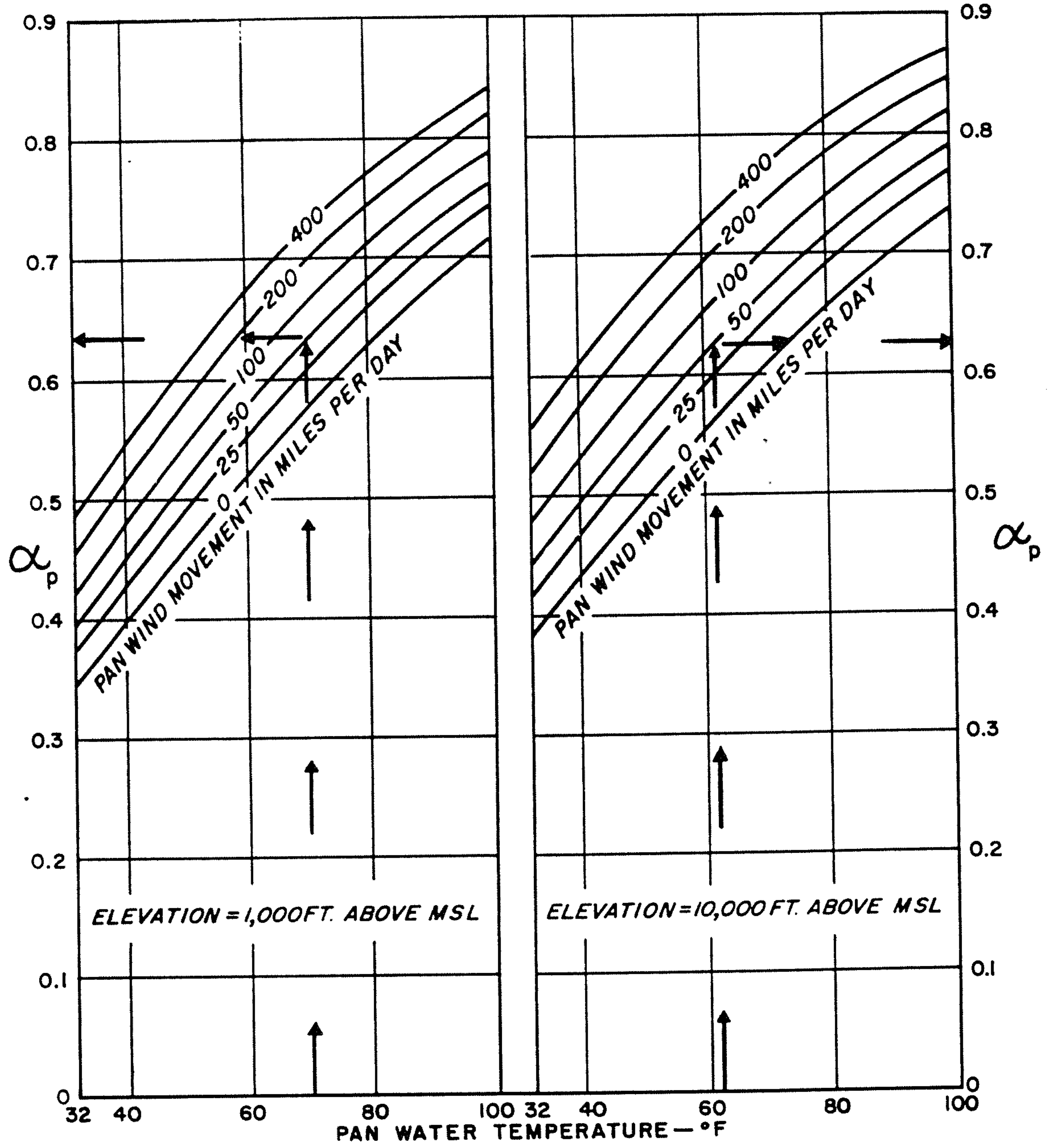

Figure 3. - Proportion of advected energy (into a Class A pan) utilized for evaporation. (From reference 6)

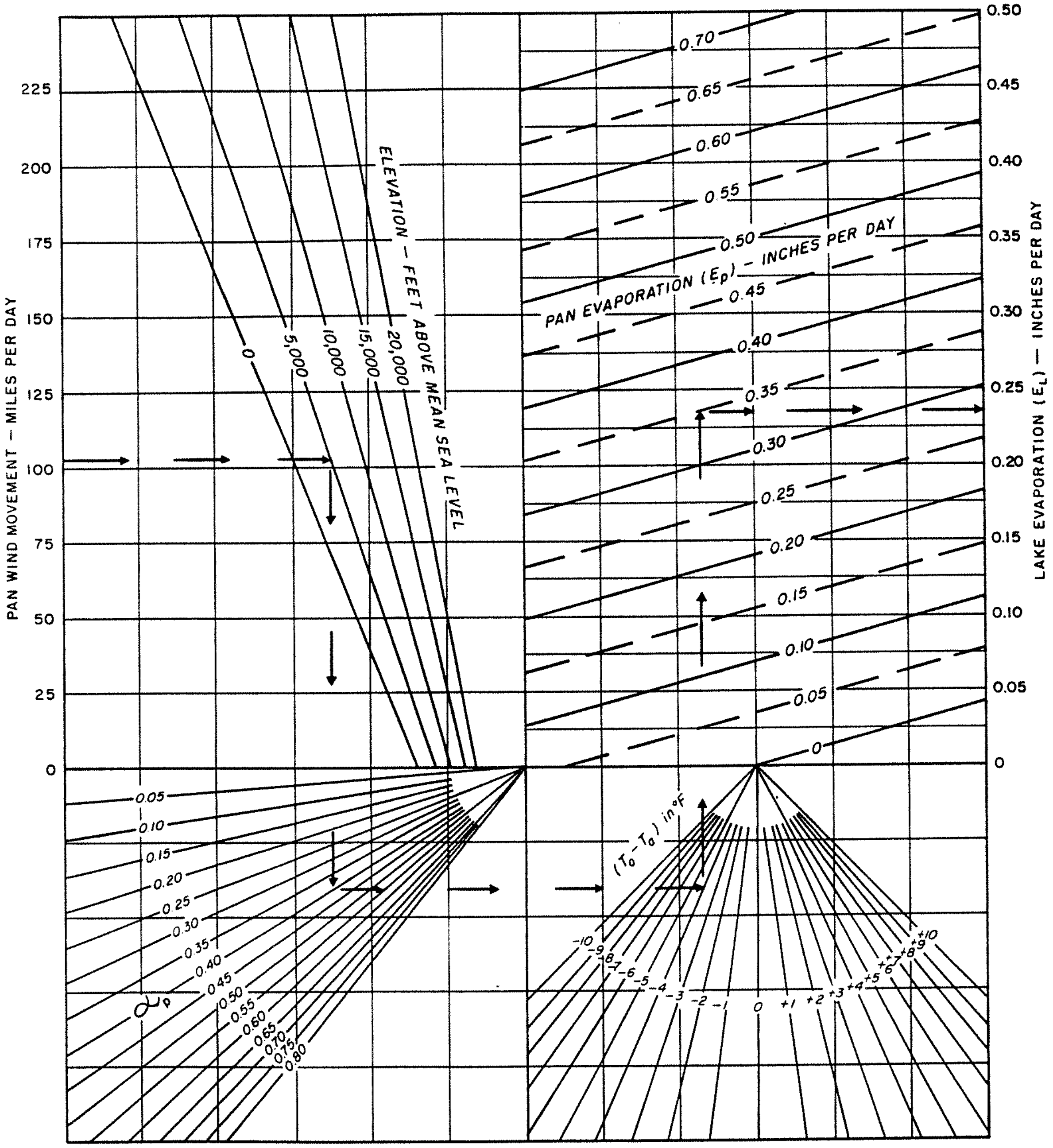

Figure 4. - Conversion of Class A pan evaporation to lake evaporation. (From reference 6)

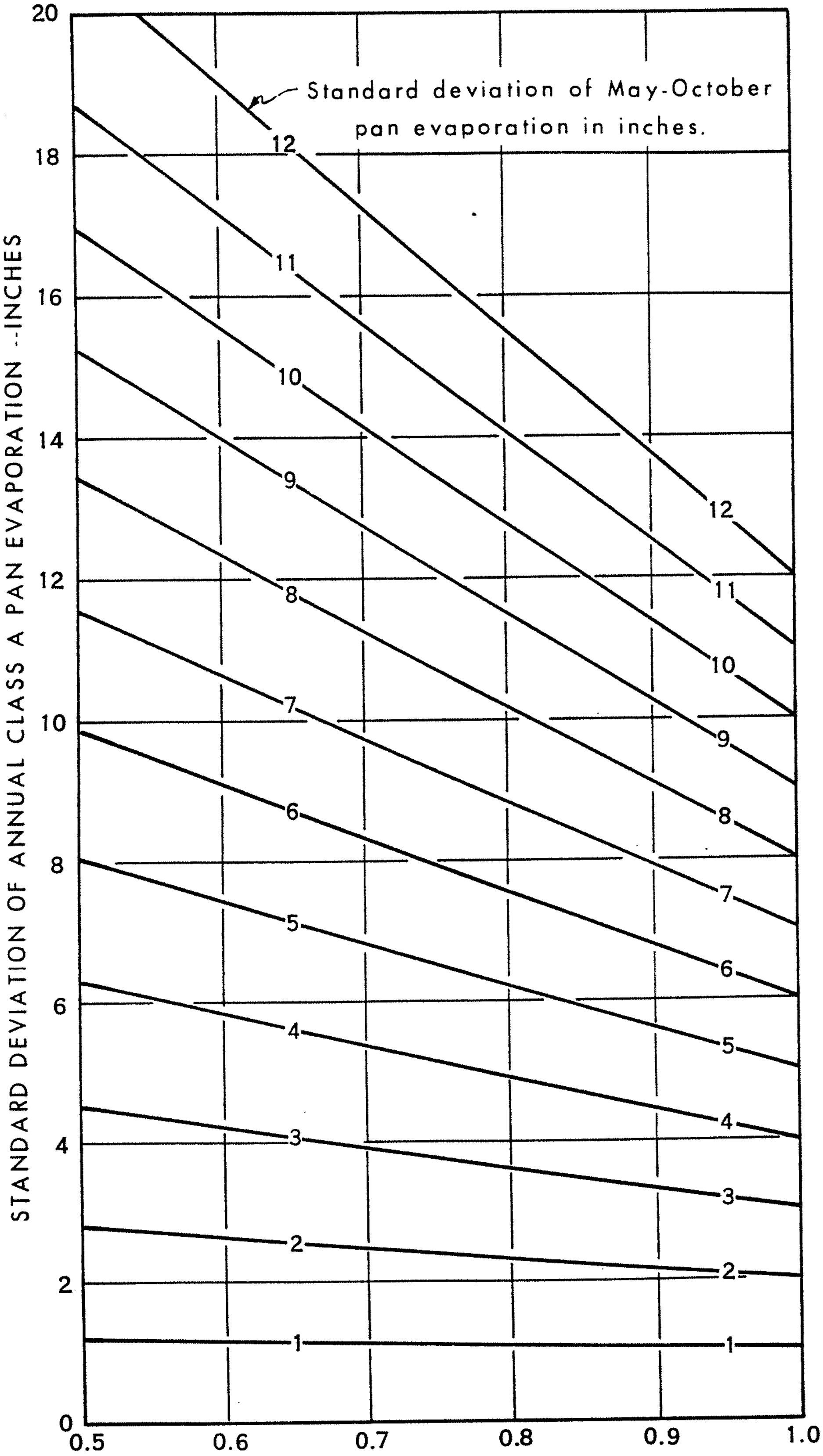

Figure 5. - Ratio $\frac{\text{May-October Class A pan evaporation}}{\text{Annual Class A pan evaporation}}$

normal. Twenty-one long record Class A pan stations were selected for tests of normality using methods of Geary and Pearson[8]. Length of record ranged from 24 years to 40 years but with a preponderance in the 30-40 year range. Skewness and kurtosis coefficients were computed for the 21 stations. Three stations had skewness coefficients which fell outside of the 90% acceptance region and one station had a kurtosis coefficient outside the 90% acceptance region. The data for each station were also plotted on normal probability paper for visual evaluation. It will be seen from Figure 6 that there is no tendency for a characteristic or consistent departure from the fitted straight lines. It is concluded, therefore, that a normal distribution can be assumed in applying Plates 1 and 5.

Interpretation, Use, and Limitations of Maps. Although the utility of the derived maps hinges largely on their reliability, it is virtually impossible to make any meaningful generalizations in this respect. In deriving Plates 1, 2, and 3, all available pertinent data were utilized to the greatest extent feasible with present-day knowledge of the relationships involved. It can be reasonably assumed, therefore, that the maps provide the most accurate generalized estimates yet available. The reliability of the maps is obviously poorer in the areas of high relief than in the plains region, and the density of the observation network is an important factor throughout.

It is known that some of the data collected over the years are from sheltered sites which are not representative. Through subjective evaluation of the station descriptions and wind data, an attempt was made to derive pan evaporation and coefficient maps indicative of a representative exposure, reasonably free of obstructions to wind and sunshine. Variations in the data were smoothed to a considerable extent, and it is entirely possible that the true areal variation in evaporation exceeds that shown on the maps. For example, a pan or small reservoir located in a canyon of northerly orientation and partially shielded from the sun would experience considerably less evaporation than indicated by the maps.

The effect of topography has been taken into account only in a general way, except where the data provided definite indications. Thus it will be noted that the isopleths tend to follow closely the topographic features in some portions of the maps while the resemblance is more casual in other areas. Both Class A pan and lake evaporation were assumed to decrease with elevation[9, 10], but the decrease assumed for lake evaporation is less. With an increase in elevation, dew point and air temperatures tend to decrease, while wind movement usually increases. Solar radiation, on the other hand, increases up-slope during cloudless days and may otherwise increase or decrease depending on the variation of cloudiness with elevation. There are but few reliable observations of the variation of all these factors up mountain slopes, but it is probable that the effect of these changes is less for lake evaporation than for pan evaporation.

The data used to derive Plates 1, 2, and 3 were limited to the recent 10-year period to reduce the time required for processing and also to increase areal coverage. One might reasonably ask if the selected 10-year period is representative, and the data in Table 1 have been compiled to shed light on this question. The examination of Table 1 indicates that for the most part the average for 1946-1955 is consistent with the averages for other selected periods of record.

There is good reason to expect that Plate 4, showing seasonal distribution of pan evaporation, is more reliable than any other map in the series. Plate 5, on the other hand, is based on a sparse network, and time trends resulting from changes in site, exposure, etc., may have caused some bias in the derived values of standard deviation. Data which were obviously inconsistent were eliminated from the analysis, but any undetected inconsistencies result in values which tend to be too high. Even so, any bias in the final, smoothed isopleths should be small.

The use of Plates 1-5 is self-evident in most respects and need not be considered further here. Certain limitations and less obvious features are discussed in the following paragraphs.

Plates 1, 2, and 3. Unless the user has at hand pan-evaporation data not considered in the development of this series of maps, average annual lake evaporation can be taken directly from Plate 2. The value so determined will also suffice if pan-evaporation data collected at the site substantiate that given by Plate 1. If the pan evaporation at the site exceeds that given by

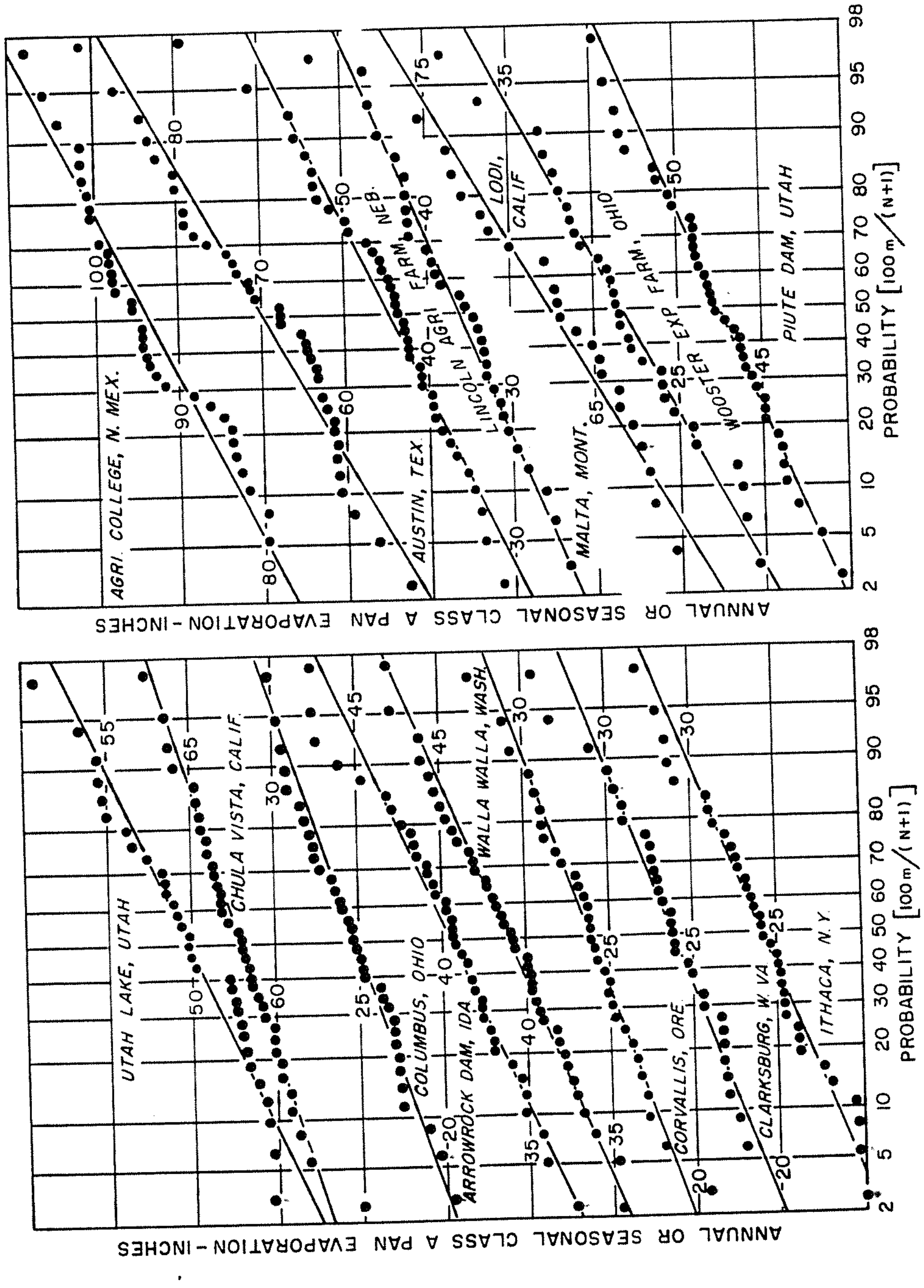

Figure 6. - Frequency curves - selected class A pan evaporation stations.

TABLE 1 - COMPARISON OF AVERAGE CLASS A PAN EVAPORATION FOR 1946-55 PERIOD TO AVERAGE FOR OTHER PERIODS

Class A Pan Station	Average Annual Evaporation 1946-55	Mean Annual Evaporation Ratio				Record Period	Season
		1940-57 / 1946-55	1935-57 / 1946-55	1930-57 / 1946-55	Record Period / 1946-55		
Fairhope, Ala.	50.2	0.99	1.00				
Bartlett Dam, Ariz.	126.4	0.98^a					
Mesa Experiment Farm, Ariz.	86.9	0.99	0.98^a	0.97	0.95	1917-57	
Sierra Ancha, Ariz.	76.0	0.98	0.98^a				
Hope, Ark.	56.9	1.00^a	1.03^c				
Backus Ranch, Calif.	113.0	1.00	1.01^b				
Baumberg, Calif.	57.3	0.99^b					
Beaumont, Calif.	85.6	1.00^a					
Boca, Calif.	47.8*	0.97^a					May-Oct
Chula Vista, Calif.	62.9	1.00	1.00	1.00	0.99	1919-57	
Davis Agricultural College, Calif.	71.4	0.97	0.97	0.97	0.96	1927-57	
Fall River Mills Intake, Calif.	50.0*	0.98	0.99	1.01	1.02	1926-57	May-Oct
Friant Government Camp, Calif.	89.6	0.98					
Lodi, Calif.	65.2	1.00	1.02^a	1.03^b			
Tanbark Flat, Calif.	64.1	1.01	1.02^a				
Conejos, Colo	47.2*	0.94					May-Oct
John Martin Dam, Colo.	67.7*	0.96^b					Apr-Oct
Montrose No. 1, Colo.	60.3	0.98^a					
Pueblo City Reservoir, Colo.	63.8*	0.96^b					Apr-Oct
Wagon Wheel Gap, Colo.	28.0*	0.99					Jun-Sep
Belle Glade Experiment Station, Fla.	63.2	1.01					
Hialeah, Fla.	67.8	1.00^a					
Loxahatchee, Fla.	60.1	1.04^a					
Tamiami Trail, Fla.	62.6	1.02^c					
Experiment, Ga.	57.0	1.03					
Tifton Experiment Station, Ga.	54.9	1.06^a					
Aberdeen Experiment Station, Idaho	40.7*	0.99^b	1.00^b				May-Oct
Lifton Pumping Station, Idaho	39.9*	0.99	1.01				May-Oct
Moscow, Idaho	32.7*	0.99^b					Apr-Sep
Ames, Iowa	42.7*	1.00	1.03	1.04^c			Apr-Oct
Norwich SCS Experiment Farm, Iowa	43.2*	0.98	1.00^c				May-Oct
Hays, Kans.	79.9*	0.96	0.98^c				Apr-Oct
Beltsville, Md.	33.2*	1.02^b					May-Oct
Germfask Wildlife Refuge, Mich.	27.1*	0.99					May-Oct
Lakeside, Mo.	44.7*	0.99^c	1.02^c				Apr-Nov
Washington University, St. Louis, Mo.	34.9*	1.00	1.02^c				Apr-Oct
Bozeman Agriculture College, Mont.	31.4*	1.05	1.08				May-Oct
Malta, Mont.	29.9*	1.05	1.15	1.20	1.21	1926-57	May-Oct
Bridgeport, Nebr.	41.0*	0.96	0.97	0.98^a			May-Oct
Kingsley Dam, Nebr.	45.4*	0.99^a					May-Oct
Lincoln Agronomy Farm, Nebr.	38.1*	1.02	1.09	1.16	1.16	1917-57	May-Oct
Rye Patch Dam, Nev.	59.5*	1.02^a					May-Oct
Pleasantville, N. J.	29.3*	1.04^b					May-Oct
Agricultural College, N. Mex.	98.8	0.98	0.98	0.98	0.95	1919-57	
Almogorda Dam, N. Mex.	113.4	0.98					
Conchas Dam, N. Mex.	74.7*	0.99	1.01^b				Apr-Oct
Elephant Butte Dam, N. Mex.	123.6	0.97	0.96				
Jornado Experiment Range, N. Mex.	88.5	1.02					
Portales, N. Mex.	92.3	1.00^b	0.99^b				
Alcove Dam, N. Y.	25.1*	1.01^b					May-Oct
Ithaca, N. Y.	26.2*	1.01	1.04	1.00^a	0.97^a	1919-57	May-Oct
Murphy, N. Car.	40.4	1.01^a	1.02^a				
Charles Mill Dam, Ohio	33.8*	1.02^a					Apr-Oct
Columbus, Ohio	24.3*	1.03^b	1.02^b	1.04^b	1.05^b	1919-57	May-Oct
Dayton, Ohio	35.2*	1.02	1.02^b				Apr-Oct
Senecaville Dam, Ohio	35.0*	0.95					Apr-Oct
Fort Supply Dam, Okla.	63.2*	0.99^a					May-Oct
Tipton, Okla.	69.5*	1.00					Apr-Oct
Corvallis State College, Oreg.	23.8*^c	1.02^d	1.04^d	1.05^d	1.10^d	1920-57	May-Sep
Medford, Oreg.	41.0*	1.02					Feb-Nov
Warm Springs Reservoir, Oreg.	47.4*	0.99	1.02	1.07	1.04	1927-57	Apr-Sep
Wickiup Dam, Oreg.	34.4*^a	1.00^b					May-Sep
Hawley Dam, Pa.	24.9*	1.02^a	1.00^c				May-Sep
Jamestown, Pa.	24.0*	0.98^b					May-Sep
Jefferson City, Tenn.	41.1	1.01^b					
Neptune, Tenn.	41.9*	1.02^a	1.02^c				Mar-Nov
Austin, Texas	81.2	0.97^b					
Denison Dam, Texas	80.0*	0.97^a					Feb-Dec
Ysletta, Texas	105.0	0.98					
Piute Dam, Utah	44.9*	1.01^a	1.03^a	1.04^a	1.06^a	1918-57	May-Sep
Utah Lake, Utah	58.6*	0.99	1.00	1.01	1.01	1923-57	Mar-Oct
Quincy, Wash.	54.1*	1.02^a					Apr-Oct
Seattle Maple Leaf Reservoir, Wash.	29.2*	0.99^b					Apr-Oct
Walla Walla, Wash.	44.8*	0.98	1.02	1.02	1.02	1916-57	Apr-Oct
Wind River, Wash.	24.2*	1.01^a	1.03^b	1.05^b	1.08^b	1924-57	May-Sep
Clarksburg, W. Va.	23.0*	1.04	1.06-	1.12	1.13	1923-57	May-Oct
Wardensville R. M. Farm, W. Va.	31.0*	1.01					May-Oct
Trempealeau Dam, Wisc.	37.2*	0.97^a					May-Oct

* - Indicates seasonal value   a - 1 year missing   b - 2 years missing   c - 3 years missing   d - 4 years missing

Plate 1, application of the pan coefficient (Plate 3) will probably provide a better estimate of lake evaporation than that given by Plate 2. If, on the other hand, observed pan evaporation is less than that given by Plate 1, a value of lake evaporation less than given by Plate 2 should be accepted only after it has been determined that the pan site is reasonably free of obstructions to wind and sunshine. This is to say that pan evaporation and the pan coefficient are both dependent upon exposure.

Figures 2 and 4 are not entirely free of exposure effects, but if all the data required for use of either of these relations are available at the project site, they should provide a value of lake evaporation of comparable reliability to that given by Plate 2.

It should be emphasized that values of free-water evaporation given by Plate 2 (or Plates 1 and 3) assume that there is no net advection (heat content of inflow less outflow) over a long period of time. The average annual advection is usually small and can be neglected, but this is not always the case. It was found at Lake Mead, for example, that advection results in a 5-inch increase in average annual evaporation. If the advection term is appreciable, adjustment should be made as discussed in references 5 and 6.

Plate 4. The Class A pans are not in operation during the winter months over much of the country because of freezing weather. Plate 4 provides means of estimating average annual evaporation from that observed during the open season, May through October. When used in conjunction with Plate 1, it also provides a means of estimating average growing-season evaporation (Class A pan) which is so important in some studies.

Although the seasonal ratios of Plate 4 are based on Class A pan data, it is believed that they are equally applicable to free-water evaporation for shallow lakes. The ratios based on monthly computed lake evaporation for the first-order stations showed no significant deviation from those based on the pan values. It should be emphasized that the seasonal ratios can be applied to annual lake evaporation only in case of shallow lakes where energy storage can be ignored. In deep lakes, the energy storage becomes an important factor in determining seasonal or monthly evaporation. For example, at Lake Mead the maximum lake evaporation occurs in August, but maximum Class A pan evaporation is observed in June; for Lake Ontario, the maximum lake evaporation is in September, and maximum pan evaporation in July[11]. Corrections can be made for changes in energy storage and heat advection into or out of the lake in the manner described in references 5 and 6.

Plate 5. The standard deviation of annual Class A pan evaporation can be obtained for any selected site directly from Plate 5. If the annual pan coefficient were constant, year-to-year, then the standard deviation of lake evaporation would be the product of that for pan evaporation and the pan coefficient. Because of variation in the annual pan coefficient, the standard deviation computed in this manner may be a few percent too low. Since the values given by Plate 5 are probably biased on the high side (discussed previously), the two possible errors tend to compensate.

Having obtained the mean and standard deviation, the frequency distribution of annual lake (or pan) evaporation can be derived, assuming the data are normally distributed. If it is further assumed that the annual evaporation totals occurring in successive years are independent, the frequency distribution of n-year evaporation can also be derived[12].

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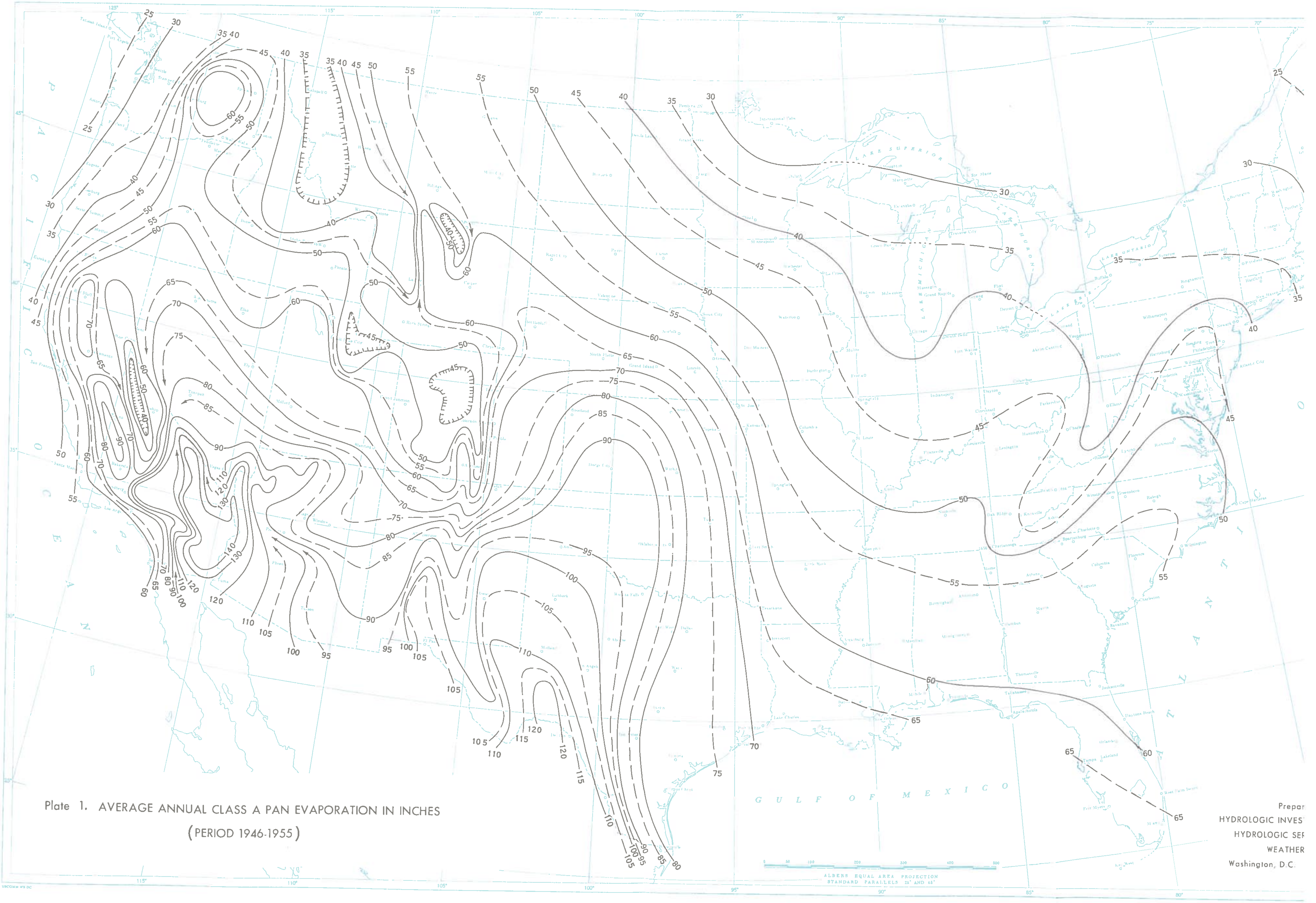

Plate 1. AVERAGE ANNUAL CLASS A PAN EVAPORATION IN INCHES
(PERIOD 1946-1955)

Prepar
HYDROLOGIC INVES
HYDROLOGIC SE
WEATHER
Washington, D.C.

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