NOAA Technical Report NWS 33

Evaporation Atlas for the Contiguous 48 United States

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NWS 13 The March-April 1969 Snowmelt Floods in the Red River of the North, Upper Mississippi, and Missouri Basins. Joseph L. H. Paulhus, Office of Hydrology, October 1970, 92 p. (COM-71-50269)

NWS 14 Weekly Synoptic Analyses, 5-, 2-, and 0.4-Millibar Surfaces for 1968. Staff, Upper Air Branch, National Meteorological Center, May 1971, 169 p. (COM-71-50383)

NWS 15 Some Climatological Characteristics of Hurricanes and Tropical Storms, Gulf and East Coasts of the United States. Francis P. Ho, Richard W. Schwerdt, and Hugo V. Goodyear, May 1975, 87 p. (COM-75-11088)

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Evaporation Atlas for the Contiguous 48 United States

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EVAPORATION ATLAS FOR THE CONTIGUOUS 48 UNITED STATES

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ABSTRACT. Maps are presented showing the areal distribution in the contiguous 48 states of evaporation (1) observed from Class A pans from May through October, (2) estimated for a free water surface (FWS) with negligible heat storage from May through October, and (3) estimated for an FWS for the entire year. A map is presented of coefficients to convert from pan evaporation to FWS evaporation. Sources of data, analyses of the maps, and limitations on their use are described.

1. INTRODUCTION

Evaporation information collected by the National Weather Service (NWS) from Class A pans and synoptic and basic observation stations (NOAA-NWS 1979) in the contiguous 48 states has been processed and analyzed, and the analyses are presented on four maps.

The maps, printed on a scale of 1/4,800,000, are:

Map 1: Class A pan evaporation (average for May through October),

Map 2: Shallow lake or free water surface (FWS) evaporation (average for May through October),

Map 3: Shallow lake or free water surface (FWS) evaporation (average annual), and

Map 4: Map of coefficients to convert Class A pan evaporation to FWS evaporation (for period May through October).

Map 1 represents the evaporation during May through October from a Class A pan situated in an open area subject to representative humidities and wind exposures, i.e., not protected by shelter-belt trees or buildings and not located in a heavily irrigated field.

Maps 2 and 3 represent growing season (May through October) and annual evaporation, respectively, from a shallow lake or a free water surface (FWS). FWS evaporation, which these maps display, is primarily estimated from observed pan data and is considered by many hydrologists to be equivalent to potential evaporation or the evaporation expected from a natural water surface or very wet soil. The values are also considered a good index to potential evapotranspiration or potential consumptive use.

Map 4 represents the coefficient required to convert Class A pan evaporation to FWS evaporation (May through October).

Detailed information on the sources, limitations, and adjustments of the data and on the techniques used in analyzing the maps are referenced or explained in this report.

This publication updates Technical Paper No. 37, Evaporation Maps of the United States (Kohler et al., 1959) published by the Weather Bureau [now the National Weather Service (NWS)].

Records of evaporation data were rather limited when the maps in Technical Paper No. 37 were prepared. However, the maps have served well the needs for general information on evaporation. The number of stations reporting pan evaporation generally increased until the late 1970's, when there was a substantial decrease in the official NWS evaporation network. In the preparation of the current maps, earlier maps were carefully studied, and differences in the analyses are considered to be reasonably substantiated by the data now available. Major changes in the maps may be noted for the mountainous West, where the earlier records available for Technical Paper No. 37 were extremely sparse.

The data for the analysis on map 1 are primarily observed evaporation measurements from Class A pans adjusted to the period 1956-70. (See the listing Climatological Data in the references.) Additional estimates were developed from meteorological measurements by a method based on eq. 10 of U.S. Weather Bureau Research Paper No. 38 (Kohler et al., 1955) using a program developed by Lamoreux (1962).

Additional data not published in Climatological Data were also collected and used in the analyses. An extensive literature search was conducted, and State Climatologists from many Central and Western States were consulted to obtain all possible information on Class A pan and free water evaporation, especially for the more arid areas of the country.

2. BASIC DISCUSSION

2.1 Pan Evaporation

Pan evaporation is used in this report to mean evaporation observed at a standard NWS Class A pan installation by observers following standard techniques. These installations and techniques are described in the NWS Observing Manual No. 2--Substation Observations (NOAA-NWS, 1972). The Class A pans are generally of monel metal, unpainted, 47.5 inches in diameter, 10 inches deep, and mounted on a platform a few inches above the surrounding soil. Most observations are now made using a fixed-point gage (a pointed shaft, extending vertically from the bottom of the pan, surrounded by a stilling well). The top or point is fixed so that when the water surface just meets the point, the surface is 2 inches below the rim of the pan. Measured amounts of water are added, or removed in the case of rain, to maintain the water surface 2 inches below the rim of the pan.

Measurements using nonstandard pans or measurement methods may differ from those using standard pans and techniques. Use of nonstandard pans in California is described in section 6.5. There are a large number of nonstandard pans (for example, painted pans or sunken pans) in the United States. Because measurements from nonstandard pans are difficult to compare with those from standard pans, NWS policy is to publish only data from the standard installations.

High winds, heavy rains, and below-freezing temperatures often prevent reliable measurements with a pan. Several equations have been developed to allow computation of estimated evaporation when such conditions occur. These equations may also be used to compute "pan" evaporation from meteorological data when no pan is present. An example of such an equation (Penman, 1948) is

$$E_p = \frac{Q_n \Delta + E_a \gamma_p}{\Delta + \gamma_p} , \tag{1}$$

where E_p is the estimated daily pan evaporation in inches, Q_n is the net radiation in langleys per day, Δ is the slope of the curve relating saturation vapor pressure to temperature at air temperatures (T_a), γ_p is the constant in the psychrometric equation generally given as 0.025 inches of Hg/°F for a pan, and E_a is the evaporation computed in inches when the measured air temperature is considered the same as the temperature of the water surface if a Class A pan were physically present. E_a is given in inches by the equation,

$$E_a = (e_s - e_a)^{0.88} \; [0.37 + 0.0041 \; U_p] , \tag{2}$$

where U_p is the daily wind movement measured by the pan anemometer in miles per day and $e_s - e_a$ is the difference in inches of Hg between the vapor pressure of the air and the saturated vapor pressure of air at the temperature of the water surface.

The solution of eqs. (1) and (2) requires measurement of wind movement, mean air temperature, mean dew point, and daily solar radiation. There are only a limited number of solar radiation stations in the United States. Hamon et al. (1954) developed a technique for estimating solar radiation from percent sunshine as reported by a large number of stations. Thompson (1976) derived a relationship between percent cloud cover and solar radiation.

The wind movement required for use in eqs. (1) and (2) is that measured at the anemometer height for a Class A pan (nearly 2 feet above the ground level). Most wind records from meteorological stations are for much higher levels. The formulas normally used in reducing the wind to the anemometer height are exponential or logarithmic in form, and no one formula has been found that is completely adequate for estimating values at levels near the surface of the ground. Thus, error may be introduced into the pan evaporation estimates based on meteorological parameters when the station anemometer height is significantly higher than 2 feet.

2.2 Free Water Surface Evaporation

"Free water surface" (FWS) evaporation is defined to mean evaporation from a thin film of water having no appreciable heat storage. While it is a somewhat theoretical term, it can be practically approximated and is determined most commonly by multiplying the observed pan evaporation by a coefficient described in more detail later. FWS evaporation is of great interest to users because it closely represents the potential evaporation from adequately watered natural surfaces such as vegetation and soil. In the literature (for example, USWB Technical Paper No. 37), the term "lake" evaporation has been used with the same meaning; however, this usage has led to some confusion. The evaporation from a real lake may differ significantly from FWS evaporation during a given month because of a change in heat storage in the lake. Only when the change in heat storage is negligibly small will FWS be a good estimation of the evaporation from the lake. For any period other than an exact year, estimates of actual evaporation from a lake surface (based on estimates of FWS evaporation) are bound to be biased by the hysteresis effect of heat storage in the lake. During the spring, heat is stored in the waters of a lake, and generally, the actual lake evaporation is much less than the computed FWS evaporation. During the fall, the stored energy in the lake is released and the actual lake evaporation is much greater than the FWS evaporation. For example, on the Great Lakes in the United States the maximum lake evaporation may occur during the late autumn months of October, November, or December, while the maximum pan and FWS evaporation occurs some time from June to August.

Techniques for computing FWS evaporation from meteorological factors and from Class A evaporation pans equipped to measure water temperatures are described in Weather Bureau Research Paper No. 38 (Kohler et al., 1955). The required input measurements when pan evaporation (E_p) observations are available are: mean air temperature in °F (T_a), mean water surface termperature in °F (T_o), and wind travel (U_p) in miles per day over the pan. FWS evaporation is given by eq. 14 in the reference,

$$\text{FWS (inches)} = 0.70\ [E_p + 0.00051\ P\alpha_p\ (0.37 + 0.0041\ U_p)\ (T_o - T_a)^{0.88}]\ , \quad (3)$$

where P is the mean station pressure in inches of Hg and α is the ratio of the advected energy used in (or not available for) evaporation to the total advected energy into (or out of) the water body. [In eq. (3), α is designated with a subscript p to indicate that it is used as the fraction of the total energy loss associated with evaporation from a pan.] The general form for α for a shallow lake is

$$\alpha = \frac{E_L^* - E_L}{(E_L^* - E_L) + (Q_{bs}^* - Q_{bs}) + (Q_h^* - Q_h)}\ , \quad (4)$$

where $E_L^* - E_L$ is the incremental change in energy used in evaporation for an incremental increase in the surface water temperature $T^* - T$, $Q_{bs}^* - Q_{bs}$ is the corresponding incremental change in the energy radiated from the surface of the water, and $Q_h^* - Q_h$ is the corresponding change in advected energy. α_p has the same form with E_p replacing E_L.

FWS is estimated from meteorological factors by eq. 10 in Research Paper No. 38,

$$\text{FWS (inches)} = 0.70 \; \frac{Q_n \Delta + E_a \gamma}{\Delta + \gamma} \, , \tag{5}$$

where all terms except γ are defined as in eq. (1). $\gamma = 0.000367P$ where P is the station pressure as defined for eq. (3). In this paper, γ is taken to equal 0.0105 inches of Hg/°F. These equations were adapted for computer use by Lamoreux (1962).

Many factors are involved in the relationship of FWS evaporation (potential evaporation) to actual evaporation (or, more exactly, evapotranspiration). Direct measurements of actual evaporation from a lake surface or evapotranspiration from a watershed are almost impossible. The FWS evaporation or potential evaporation can be estimated with reasonable accuracy. Many studies have been conducted to develop seasonal or monthly factors to adjust FWS evaporation to estimates of actual evaporation or evapotranspiration (Pruitt, 1966; Mustonen and McGuinness, 1968).

2.3 Pan Coefficients

The pan coefficient, a ratio of FWS evaporation to observed pan evaporation, has been determined at a few locations by comparing pan evaporation with direct estimation of lake evaporation (corrected for heat storage to obtain potential evaporation) from a detailed water budget (USGS, 1954). More often, however, the coefficient for a given location is computed by taking either the ratio of FWS evaporation to observed pan evaporation, where FWS evaporation is computed by using the pan observation with measured water temperature and daily wind movement (eqs. 3 and 4) or, for synoptic weather stations, the ratio of FWS/E_p, where FWS is estimated using eq. (5) and E_p is estimated using eqs. (1) and (2).

The pan coefficient commonly used to compute FWS evaporation from Class A pan measurements is 0.7. As seen in map 4, the pan coefficients in the United States vary from 0.64 to 0.88 for the May through October period. The value of the pan coefficient is dependent upon the average climatic condition for the area. (When climatic conditions are such that the water in the exposed pan is warmer than the air, the coefficient is greater than 0.7, and vice versa.) The coefficient for a particular location may also change from the warmer months (May through October) to the colder months (November through April). In general, the tendency for most locations is for winter coefficients to be lower than those for summer months. For an extreme example, pan coefficient values along the coast of southern California range from 0.88 for the warmer months to 0.64-0.68 for the colder months.

Pan coefficients computed on a monthly basis may show significant variability. Areas with mild winters show less variability than stations subject to freezing temperatures. Generally, coefficients are most stable in summer and most variable in spring and fall. In a large part of the country, a major percentage of the annual evaporation occurs in the summer; therefore, reasonable estimates of yearly FWS evaporation can be obtained using average pan coefficients for the warm season (map 4). Areas subject to freezing generally have no pans in service during the winter, so winter coefficients are not needed. However, winter pan or lake evaporation can be computed from meteorological data.

The primary reason for variations in pan-to-lake coefficients is the energy exchange through the sides and bottom of the Class A pan. The technique (eq. 3) of Kohler et al., 1955, discussed earlier in this section, was derived for adjusting such energy exchange and for computing FWS evaporation on a daily basis. In this way, the pan-to-lake coefficient for a particular location and time period can be determined.

3. SELECTION OF BASE PERIOD

Early in the 1970's it was planned to update the evaporation maps. Considerable work was done to adjust all data to the 15-year period 1956-70. However, the actual development of the maps was delayed. When analyses of the maps began in 1980, consideration was given to using a longer and/or later time base. However, no compelling reason could be found to change the selected base period. Reasons for retaining the base period are (1) the average evaporation for periods longer than 10 years shows little change with time (table 2) and (2) cutbacks in the evaporation network and conversion to nonstandard equipment and nonstandard observing techniques occurred at many stations in the 1970's. Thus, while use of a longer base period that is later in time or compatible with a 30-year climatic base might provide small changes in estimated mean evaporation, it would reduce the number of stations having complete records for the selected time base.

4. BASIC DATA SOURCES

The primary source of pan evaporation data was the Climatological Data series for 1956-70. (See references.) From that source, over 400 stations had measured water temperatures together with pan evaporation and wind movement measurements (figure 1). An additional group of about 170 stations (figure 2) recorded only pan evaporation and, in some cases, wind movement. (Some of these stations added temperature and wind sensors during the base period, but the length of record was inadequate for use on the maps.) Additional data were obtained from State Climatologists and other sources. The publication, Evaporation from Water Surfaces in California, was furnished by the State Climatologist for California (Goodridge, 1979). This publication contained 478 evaporation records as measured by 30 different types and sizes of evaporation pans. Of these, 261 were from Class A pans, and 64 of the 261 records were published in Climatological Data. These Class A pan station locations are included in the stations plotted in figures 1 and 2. In addition to the above mentioned publication, the State Climatologist provided a computer tape containing all of the California data, which made the handling of these data very convenient.

The total number of Class A pan records from all sources used in the analysis was approximately 800. Of these, approximately 210 were from stations that had observed data for the entire year.

Meteorological data from synoptic/basic NWS weather stations comprised a second major source of information. Where temperature, humidity, and wind measurements were available with some estimate of solar radiation, pan evaporation and FWS evaporation could be computed from techniques described in Research Paper No. 38 (Kohler et al., 1955). There were 225 synoptic/basic meteorological network stations (without pan evaporation records) for which estimates of pan and FWS evaporation were computed. The distribution of the stations is shown in figure 3. The estimated solar radiation used in these computations included measured incoming solar radiation records for 18 percent of the stations, sunshine data for 39 percent, cloud cover for 34 percent, and a combination of data types for the remaining 9 percent.

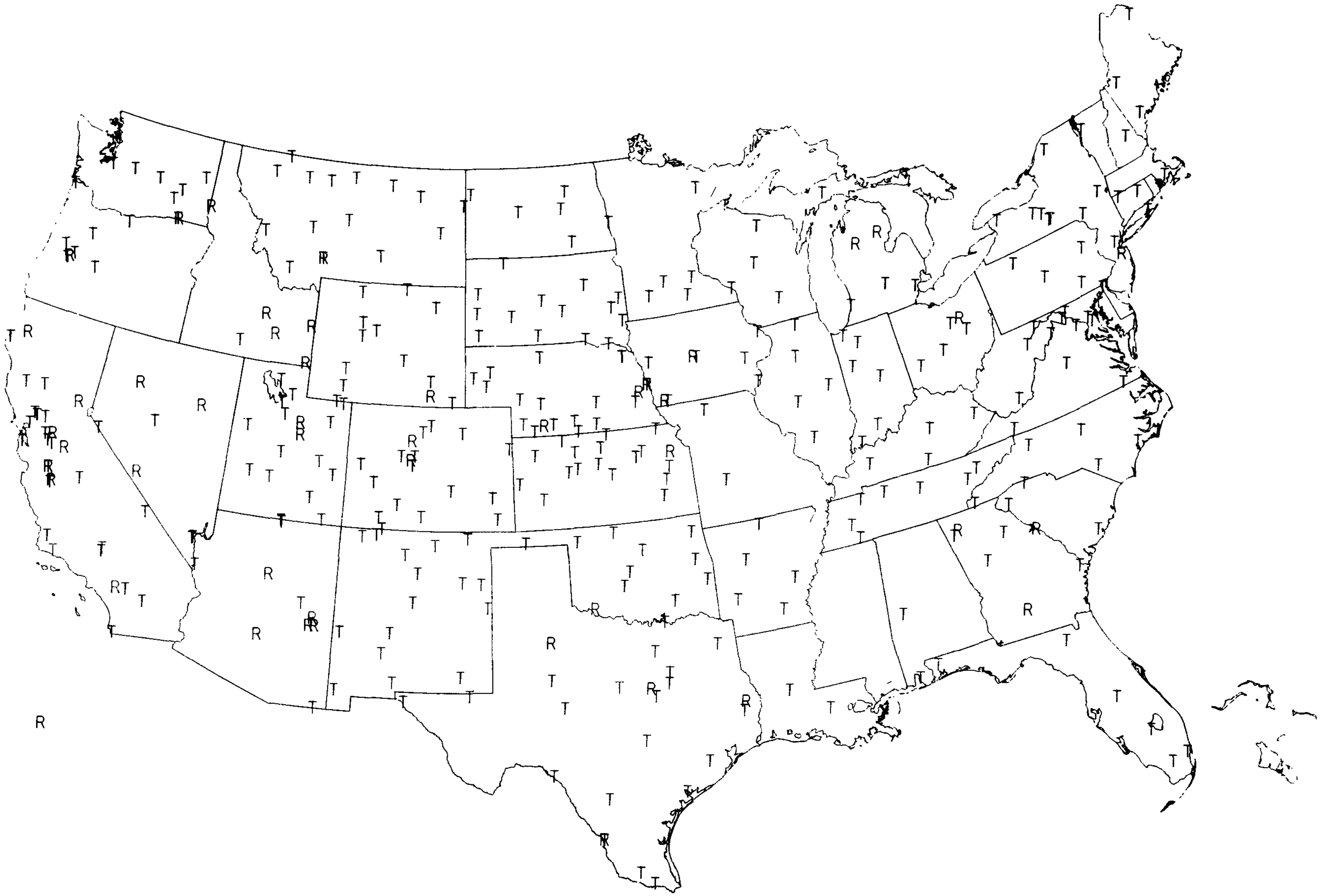

Figure 1--Distribution of Class A pan stations which make concurrent measurements for computing FWS evaporation by equation 3. Stations identified by an R were not equipped with sensors to record additional data until the latter part of the 1956-70 time base.

Figure 2--Distribution of Class A pan stations reporting observed evaporation only (water temperature not measured or measured for an insufficiently long period of record).

Figure 3--Distribution of weather stations measuring a form of air temperature, humidity, wind movement, and radiation, where evaporation can be estimated by the Penman (1948) equation.

An attempt was made to locate additional information that would be of value in the development of the evaporation maps. A computer search was made of the literature files available to NOAA's Atmospheric Sciences Library for all article abstracts containing the words "evaporation" and "lake." Several bibliographies on evaporation were also searched (Robinson and Johnson, 1961). The number of reports that contained additional data on pan evaporation or estimates of lake evaporation were limited. In most cases, the records were for relatively short periods (from a few months to 2 years) and were not sufficient for determining a long-term average. In most cases, these records compared favorably with the analysis based on the available data. When there was an apparent difference, an effort was made to obtain additional information from the State Climatologist or governmental agencies.

In addition to the pan evaporation and estimates from meteorological factors, other information relating to pan and FWS evaporation were obtained from State Climatologists and other sources. For example, estimates of consumptive use, as calculated by the Soil Conservation Service (SCS) for locations in New Mexico (SCS, 1972), were used as a guide for the final positioning of isopleths in areas with sparse data. A map of potential evapotranspiration furnished by the State Climatologist was helpful in defining the seasonal FWS evaporation in Montana (Caprio, 1973).

5. DATA PRESENTATION

Maps of average monthly evaporation are of greater interest than annual or semiannual maps. However, the problems involved in developing consistent monthly maps for all the climates and physiographic regions of the contiguous United States made the preparation of such maps infeasible. It was decided that the most useful maps that could be prepared were those based on estimates of FWS evaporation for May through October and for the entire year.

In determining the order in which to prepare the selected maps, it was clear that the most reliable evaporation map would be that of pan evaporation for the warmer months (map 1). The period of May through October was selected since most reporting stations had observed data for these months and these months represent the growing season for much of the country.

The May through October pan coefficient map (map 4) was the second map to be drawn. It was based primarily on the coefficients determined for approximately 400 stations having pan water temperature and wind movement measurements. In addition, pan coefficients were determined for the 225 synoptic/basic stations using methods discussed in section 2.2.

Map 2, the May-October FWS evaporation, was primarily defined by multiplying the May-October pan evaporation values (map 1) by the appropriate coefficient from map 4. In addition, point values estimated by eqs. (1), (2), and (5) were considered in the analysis.

No simple relationship exists between the evaporation during May through October and that for the entire year. For that reason, a map of FWS evaporation was prepared for the winter season (November through April, not published). This map was developed using data and techniques equivalent to those used for the May-October maps. The final FWS evaporation map (map 3) was then developed by graphical addition of the two seasonal maps.

6. PAN EVAPORATION MAP

6.1 Period Adjustment of Observed Pan Station

Only 27 percent of the nearly 800 Class A pans had a full 15-year (1956-70) record for May through October. The remainder of the stations were each adjusted to the 15-year period by prorating data from a station with an incomplete 1956-70 record against data from a nearby station which (1) was in a compatible climatic regime, (2) had data in the similar incomplete period, and (3) had a computed or actual average for the 1956-70 period. The following equation was used:

$$E_{ssa} = \frac{E_{ssm}}{E_{\ell sm}} \times E_{\ell s56-70} , \qquad (6)$$

where E_{ssa} is the adjusted 1956-70 average for a station having a nonstandard period, E_{ssm} is the average for the same station for the nonstandard period, and $E_{\ell sm}$ is the average for the same nonstandard period for a nearby station that also has an average ($E_{\ell s56-70}$) for the base period.

6.2 Map Preparation

The average values of computed and observed pan evaporation for the 1956-70 period were used in preparing the May through October pan evaporation maps. For areas of low relief in the central and eastern areas of the United States, the values were plotted on a base map with a scale of 1 to 4,800,000 and the analyses were made directly from those data.

For locations in mountainous areas (the 11 Western States and the Appalachian area of the Eastern United States), USGS maps with a scale of 1 to 500,000 were used to provide detailed topographic information for the analyses.

For many areas in the western United States, the relationship between evaporation and elevation has been found to be good (Blaney, 1958). Graphs of pan evaporation versus elevation were drawn by eye for selected physiographic regions of the mountainous areas. (See figure 4.) These graphs showed reasonably good relationships, with evaporation decreasing as elevation increased. Examples of these plots are shown in figures 5 and 6. Figure 5 is the graph

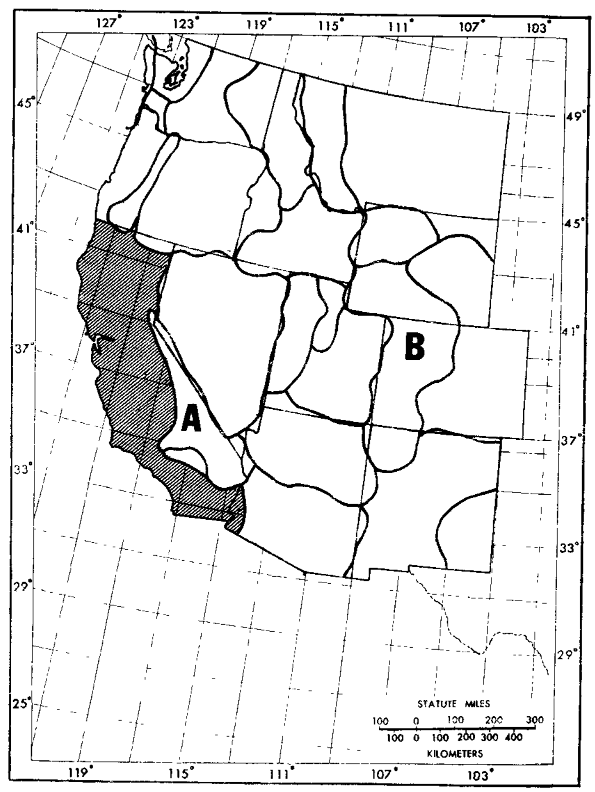

Figure 4--Outlines of regions used in developing pan evaporation vs. elevation relations.

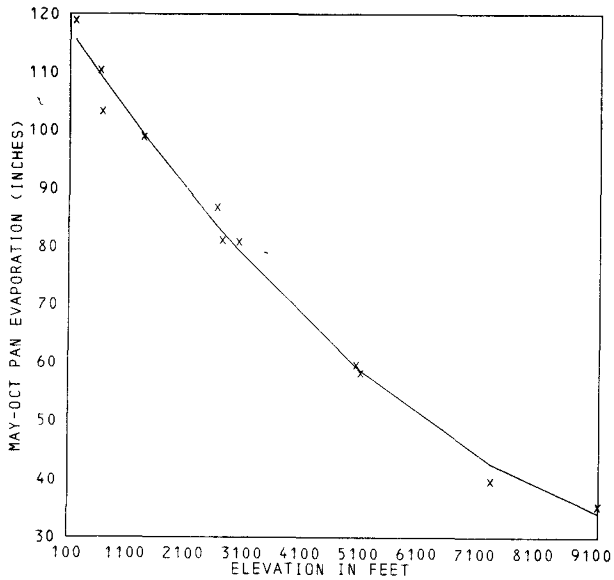

Figure 5--Pan evaporation vs. elevation curve for Region A on figure 4 (California).

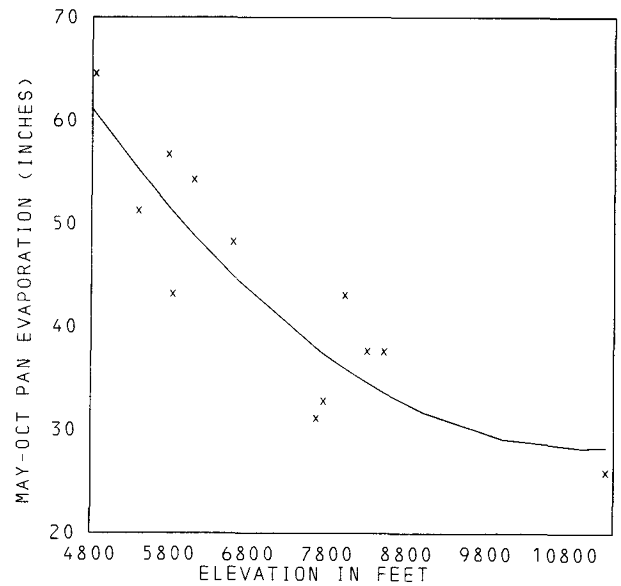

Figure 6--Pan evaporation vs. elevation curve for Region B on figure 4 (New Mexico, Colorado, and Wyoming).

for the mountain and desert areas of southeastern California (marked A on figure 4). The data used for this curve are discussed further in section 6.3. This curve is the best fit of any of the physiographic regions, with the square of the correlation coefficient (R^2) equaling 0.99. The curve shows the tendency, reported by Peck (1967), of these relations to become fairly flat at high elevations in the Western United States, with little or no further decrease in evaporation with increased elevation. Figure 6 shows the pan evaporation-elevation relation for the area of the western slopes of the central Rockies (Region B on Figure 4). This relation is more typical of those for the Western United States. Region B is larger than Region A and represents a larger spread in latitude. The correlation ($R^2 = 0.73$) indicates that elevation accounts for approximately 70 percent of the variability for the entire area. Many of the evaporation sites represented in figure 6 are in relatively open areas (Farmington and Navajo Dam in New Mexico and Pathfinder Dam in Wyoming) and others are in confined or protected areas (Green Mountain, Vallecito, Wagon Wheel Gap, and Climax in Colorado). Thus, the scatter of points around the curve is to be expected. The plotted data points within each physiographic region generally were found to be close to the smooth curve drawn by eye through the data. In some cases, however, individual points were found to deviate considerably from the general relationship. In several of those cases, the deviating points were later identified with stations that had a painted pan or nonstandard conditions, situations that were unknown to the authors until the deviations were investigated. In other cases, especially for those stations that were found to have less evaporation than the average curve would indicate, the stations were found to be extremely sheltered or affected by irrigated areas (not meeting the exposure criteria specified in Observing Handbook No. 2--NOAA-NWS, 1972).

The pan evaporation vs. elevation curves were of great value in defining isopleths in the lower valley and bench lands in the mountainous areas. For the transition zones across physiographic boundaries, the topography and climate (for instance, the temperature versus elevation curves on the boundary between Idaho and Montana) were considered in the analyses.

6.3 California Area

The average pan values for the Sacramento and San Joaquin River drainages in California were found to have little or no consistent relationship with elevation. In fact, for many areas, the pan values had essentially zero correlation with elevation (crosshatched areas of figure 4). However, for stations on the eastern slopes of the Sierra Mountains, a single relationship with elevation (figure 5) was found to represent all of the area from the Mojave Desert to the area north of Lake Tahoe. The fit of data for this large expanse of area was one of the best for the entire West.

The analysis of the seasonal (May through October) pan evaporation values for the Sacramento and San Joaquin River drainages in California showed centers of very low and high evaporation. Sufficient data were found to support this unusual analysis. The centers of low values seemed to be correlated with possible mesoclimatological regimes induced by meteorological and environmental conditions.

Study of the initial analyses of the seasonal pan evaporation data for the Central Valley area did lead to the conclusion that many of the pans must be affected by moisture conditions from irrigation in the immediate area of the pan. The authors consulted with Mr. James Goodridge, the State Climatologist for California, on this problem. The report on evaporation records for the State of California (Goodridge, 1979) contains environmental classification for most pan evaporation stations. It was assumed that those having Classification A (agroclimatic station, irrigated) were affected by higher atmospheric moisture conditions and should have less average pan evaporation than other stations. (Environmental classification A should not be confused with Class A pans.)

Because the humidity associated with irrigation is induced and subject to nonclimatic variations, an attempt was made to determine how much these records might be affected. The work by Pruitt (1966) and others has shown that evaporation pans having a moist upwind fetch may have as much as 26 percent less evaporation than similarly located pans with a dry upwind fetch. Isopleths were redrawn for the Central Valley without consideration of 50 stations having the environmental classification A. A comparison of the redrawn map values with the observed pan values showed that the effect of irrigation had reduced the evaporation by 14.2 percent. (Standard deviation of the individual deviation values is 4.12 inches.) This adjustment was taken into account when records from stations with Classification A were used for developing the isopleths for the Central Valley and Pit Valley areas.

6.4 Other Types of Pans

Map 1 of pan evaporation is based primarily on observed and computed Class A pan evaporation records. However, in many areas of the country, the network of Class A stations is not adequate to define the regional variability that occurs in pan evaporation.

Measurements are available from a large number of different types of pans and are published in the State of California report (Goodridge, 1979). This report contains 10 records from Bureau of Plant Industry pans, 14 from floating pans, 33 from sunken pans (USGS land pan or Colorado pan), and 53 from the Young pan. Many coefficients have been published for converting records from other types of pans to Class A pan or to lake evaporation (Goodridge, 1979; Nordenson and Baker, 1962; Young, 1945). These coefficients vary greatly from pan to pan, and the actual values are not constant for different climatic regimes and vary with the seasons of the year. However, several of the stations in southern California have concurrent records for different types of pans. There were over 20 stations operating a Class A pan concurrently with other pans, the most prominent of these other pans being the Young screened pan. Concurrent periods of record vary from 1 to over 20 years. More than half of these stations had records for 10 years or more. These records were reviewed along with published coefficients from the literature, and general relations were developed for specific regions of California. For example, for the Young screened pan it was evident from the comparison data that the difference in the evaporation of the Class A and Young pans was related to the climate of the area. Since the pan-to-lake coefficient (map 4) is a climatic indicator, it was used as a parameter in a statistical relation for estimating Class A pan evaporation. The goodness of fit of this relation is shown by an $R^2 = 0.89$. The relation is shown in the following equation:

$$E_{cA} = 37.05 + 0.825\, E_{ys} - 0.45\, C_{map\ 4}\ , \qquad (7)$$

where

E_{cA} is average May-Oct Class A pan evaporation (inches),

E_{ys} is average May-Oct Young screened pan evaporation (inches), and

$C_{map\ 4}$ is May-Oct pan-to-lake coefficient (from map 4).

The 15 stations listed in table 1 were used to develop the relationship. These vary in elevation from 96 feet above MSL to over 9,100 feet above MSL.

Table 1.--Stations used to develop Class A pan estimates from Young pan

Station	Period of Record
Baldwin Park	22
Encino Reservoir	28
Florence Lake	12
Foreman Creek	4
Fullerton	4
Huntington Lake	12
Kaiser Pass	12
Oroville Dam	10
Redinger Lake	12
San Jacinto Reservoir	11
Shaver Lake	12
Silver Lake	14
Thermalito	6
Thousand Oaks	5
Yuma, Arizona	3

All but one of these stations are found in three clusters in the central and southern parts of the state.

This and other relations served as a guide in the analysis of the isopleths for the various locations in California where they were applicable.

6.5 Estimates from Meteorological Factors

Comparison of meteorological estimates of pan evaporation, throughout the country, with observed pan evaporation data indicated a slight overall negative bias. In the Central United States, pan evaporation estimates from synoptic/basic station meteorological data seemed to be significantly lower than pan data observed nearby. This discrepancy tended to indicate a regional bias in the meteorological estimates.

A map of differences between the isopleth values from a preliminary pan evaporation map and the computed estimates from meteorological data from the synoptic/basic stations verified the regional biases for the western Great Plains. Corresponding differences were also observed between the estimates of FWS evaporation based on pan data (map 2) and those computed from meteorological data. A map of these differences for FWS estimates for the May-October period is shown in figure 7. For most of the country, little bias is apparent in the meteorological estimates. However, for the area of the western Great Plains, a strong negative regional bias ranges up to more than 13 inches. No definite reason has been determined for this bias. It is postulated that the clear air instability during the summer period could be a contributing factor. Since there are some apparent reasons that the estimates based on meteorological data should be biased and no obvious reasons that estimates based on pan data should be biased, the assumption was made that the pan measurement is the more nearly correct. Regardless of the causative factor, the map was valuable in using the meteorological estimates for the Central United States.

7. PAN COEFFICIENT MAP

The map (map 4) for pan coefficients was based on approximately 400 coefficients determined from pans equipped to measure water temperatures and on the coefficients derived using meteorological data from the 225 synoptic/basic weather stations. The period May through October was selected as the most beneficial for users since the coefficients are applied primarily to data collected during these months of greatest evaporation. In addition, a basic purpose of this pan coefficient map is to aid in developing the May through October FWS map.

For the areas of low relief, the map was analyzed directly from the plotted data. In the mountainous areas, topography (elevation) appeared to be related to pan coefficients.

8. FREE WATER SURFACE EVAPORATION MAPS

8.1 May Through October Map

FWS evaporation (map 2) exhibits a pattern similar to that of pan evaporation (map 1) with regional variations related to the values on the pan coefficient map.

The primary method of analysis used for deriving the May through October map (map 2) was the application of the coefficient values (map 4) to the pan evaporation values (map 1). Individual values of FWS evaporation computed by eq. (3) and values derived from meteorological factors computed by eq. (5) were plotted on preliminary copies of map 2 as a check on the analysis.

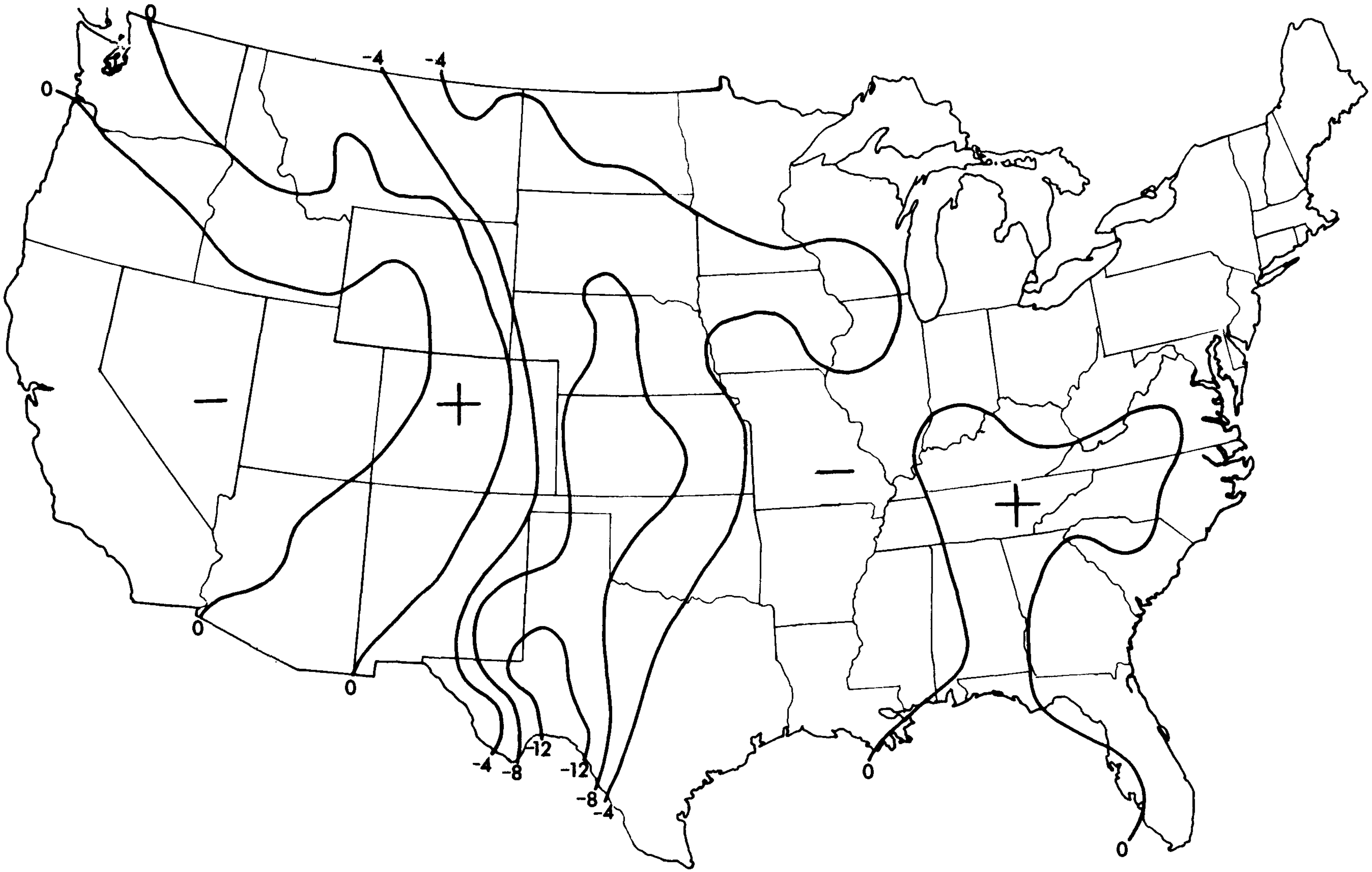

Figure 7--Deviation in inches of May-October free water surface evaporation E_{mf} (computed using meteorological factors) from equivalent map points E_{m2} (station point values from map 2) derived from the analysis of observed values. Map value = $E_{mf} - E_{m2}$

8.2 Annual Map

Two seasonal FWS evaporation maps (May through October and November through April) were graphically added to obtain the annual FWS map. The regional variability of evaporation is proportionally greater in the winter than in the summer because of freezing conditions at higher elevations and in the northern latitudes. A November through April map (not published) of FWS evaporation was prepared using techniques similar to those used in developing the summer seasonal maps. In some areas, it was first necessary to prepare a winter pan evaporation map to develop the November through April FWS map as was done for the summer season. For other areas where there were more computed November through April FWS evaporation values, the map was prepared directly using eqs. (3) and (4) where there were pan records and eq. (5) for synoptic weather stations.

For the more northern part of the country, and especially in the higher western areas, the limited data available suggest that winter evaporation is very very small. However, at the suggestion of the State Climatologist for Montana, Mr. Joseph Caprio, a minimum value of 7 inches was established for the November through April FWS evaporation. The Climatic Atlas of the United States (ESSA-EDS, 1968) shows winter temperatures and dewpoints to be nearly as low in the mountainous areas of Montana as anywhere else in the United States. With this justification, the 7 inch value was assumed to hold as a minimum everywhere on the November to April map.

9. ADDITIONAL INFORMATION

9.1 Long-Term Variability

Table 2 lists average 1956-70 pan evaporation for specific stations and the comparison of these 15-year averages with averages for other periods during the past 34 years. The table provides some information for the long-term variability of evaporation data.

9.2 Monthly Values

A recommended method for distributing the seasonal values from the evaporation maps to monthly values is to use the monthly distribution of observed pan data from stations in the immediate area. Mean monthly pan evaporation data (for Class A pan stations in the United States with at least 10 years of data) fill many pages of tables and will be found in a forthcoming NOAA Technical Report. A very brief sample of these data for the 1956-70 base period is presented in table 3. Data in the report just mentioned are presented in inches of evaporation, as are seasonal and annual values in table 3. However, the monthly data are presented in table 3 as the mean percent of annual evaporation. These 40 stations were chosen to generally show how the annual distribution of evaporation varies throughout the 48 states. They do not form a large enough sample to show local variations. Plots of these data are shown in figure 8.

9.3 Selected Values for Map Isopleths

The intervals between isopleths on the three maps (maps 1, 2, and 3) were based on the variability and magnitude of the values on the maps. In the Eastern United States, multiples of 4 inches were selected. In some areas, in which additional information could be provided to the user, isopleths at 2 inch intervals have been added. For the 11 Western States, a spacing of 5 inches was

Table 2.--Comparison of evaporation

CLASS A PAN STATION	STATION INDEX STATE-STATION (a)	SEASON COMPARED	ADJUSTED AVERAGE EVAP. 1956-70
Fairhope 2NE, Ala.	1-2813	Annual	51.0
Bartlett Dam, Ariz.	2-0632	Annual	121.3[d]
Mesa Exp. Farm, Ariz.	2-5467	Annual	88.4
Chula Vista, Calif.	4-1758	Annual	65.8
Davis 2WSW, Calif.	4-2295	Annual	76.7
Friant Govt Camp, Calif.	4-3261	Annual	89.2
Lodi, Calif.	4-5032	Annual	68.0[h]
Montrose No. 1, Colo.	5-5717	Annual	58.4
Wagon Wheel Gap, Colo.	5-8742	Jun-Sept	26.9[d]
Belle Glade E. S., Fla.	8-0611	Annual	61.6
Tifton E. S., Ga.	9-8703	Annual	56.9
Moscow, Idaho	10-6152	Apr-Sept	37.6[d]
Ames 3SW (Ames), Iowa	13-0205	Apr-Oct	43.1[k]
Bozeman Agric. Col., Mont.	24-1044	May-Oct	36.8[h]
Bridgeport, Nebr.	25-1145	May-Oct	40.7
Elephant Butte Dam, N.Mex.	29-2848	Annual	116.9[k]
Jornada Exp. Range, N.Mex.	29-4426	Annual	87.2[k]
Charles Mill Lake, Ohio	33-1466	Apr-Oct	31.4
Fort Supply Dam, Okla.	34-8304	May-Oct	63.1[h]
Tipton 4S, Okla.	34-8379	Apr-Oct	74.4[h]
Medford Exp. Sta., Oreg.	35-5424	Feb-Nov	43.4[h]
Wickiup Dam, Oreg.	35-9316	May-Sept	32.7
Denison Dam, Tex.	41-2394	Feb-Dec	73.2[d]
Ysletta, Tex.	41-9966	Annual	108.8
Wardensville RM Farm, W.Va.	46-9281	May-Oct	31.6[h]

Notes:

a - Additional information such as latitude, longitude, and elevation can be obtained from State Station Index in NOAA EDIS Climatological Data.
b - No ratios are computed when more than 3 years of a 15-year period are missing.
c - The left-hand number indicates the number of years in the record for the month-of-the-year with the least data. The right hand number indicates the maximum length of record for months with the most complete record.
d - 13-year record of base period adjusted to 15 years.

for 15-year base period with other periods

AVERAGE EVAPORATION RATIO (b)				PERIOD OF RECORD	
1946-55 / 1956-70	1950-64 / 1956-70	1965-79 / 1956-70	Full Record / 1956-70	DATES	YEARS(c)
0.98	0.99		0.98	8/34-12/79	42-46
1.04	1.03	0.99[e]	1.01	6/40-12/79	38-40
1.02	1.00		0.99	11/16-12/79	61-64
0.96	1.02	1.02	0.96	9/18-12/79	61-62
0.93	0.94[f]	1.04[e]	0.93	5/26-12/79	49-54
1.00	1.04	0.88[g]	0.96	5/39-10/79	39-41
0.96	1.04		1.00	1/31-12/79	27-49
1.03[j]	1.05	0.98[g]	1.01	1/41-10/79	15-39
1.04	1.08[e]		1.02	6/40- 9/71	30-32
1.03	1.00[g]	1.03	1.02	3/40-12/79	37-39
0.96	1.00[g]		1.00	5/37-12/79	36-42
0.87	0.94[e]		0.97	6/39- 9/79	26-41
0.99	0.98		1.02	4/33-10/70	35-38
0.85	1.03		0.96	5/35-10/79	42-44
1.01	1.01		1.02	5/31- 9/78	45-48
1.06	1.05[f]	0.95	0.94	4/16-12/79	62-64
1.01			1.05	1/53-12/79	21-27
1.08	1.06	0.96	1.04	4/39-10/79	39-41
1.00	1.03	1.01[g]	0.98	7/40-10/79	39-40
0.93	1.00		0.96	7/38-10/78	38-41
0.94	0.98		0.99	9/37-10/79	32-43
1.05	1.02	0.97	1.00	5/41-10/79	35
1.09[j]	1.07[e]		1.02	10/40-11/79	29-40
0.97	1.01	0.97[e]	0.96	2/39-12/79	39-41
0.98	1.07		0.98	8/39- 9/79	37-41

e - Numerator of ratio is a 13-year record adjusted to 15 years.
f - Numerator of ratio is a 12-year record adjusted to 15 years.
g - Numerator of ratio is a 14-year record adjusted to 15 years.
h - 14-year record of base period adjusted to 15 years.
j - 1946-55 mean is for 9 years.
k - 12-year record of base period adjusted to 15 years.

Table 3.--Adjusted mean monthly

Station Name	Map ID*	State Index No.**	Station Index No.**	Percent Jan	Feb	Mar	Apr
Fairhope 2NE, Ala.	1	1	2813	3.7	4.8	7.8	9.8
Bartlett Dam, Ariz.	2	2	0632	3.5	4.0	6.1	8.7
Bacus Ranch, Calif.	3	4	418	3.0	3.5	6.6	8.7
Sacramento, Calif. (Met)	4	4	7630	1.8	3.1	5.4	8.4
Wagon Wheel Gap, Colo.	5	5	8742				14.0
Hartford, Conn. (Met)	6	6	3456	2.6	3.1	5.8	10.1
Tamiami Trail, Fla.	7	8	8780	5.3	5.9	8.4	10.4
Experiment, Ga.	8	9	3271	4.1	4.5	7.3	10.0
Moscow, U of I, Idaho	9	10	6152				6.8
Pocatello, Idaho	10	10	7211	1.6	2.3	5.8	8.1
Ames, Iowa	11	13	205				10.0
Toronto Dam, Kans.	12	14	8191	2.3	3.4	6.6	10.3
Tribune, Kans.	13	14	8235				9.0
Madisonville, Ky.	14	15	5067				11.1
Urbana, Ill.	15	11	8750				8.6
Woodworth State Forest, La.	16	16	9865	3.4	4.4	7.3	9.4
Caribou, Maine (Met)	17	17	1175	1.8	2.4	5.0	8.3
Rochester, Mass.	18	19	6938				8.1
East Lansing Hort. Farm, Mich.	19	20	2395				9.4
Scott, Miss.	20	22	7886	3.0	3.4	6.8	9.6
Weldon Springs Farm, Mo.	21	23	8805				9.5
Bozeman Agric. Col., Mont.	22	24	1044				7.8
Medicine Creek Dam, Nebr.	23	25	5388				9.9
Boulder City, Nev.	24	26	1071	3.1	3.7	6.4	8.9
Topaz Lake, Nev.	25	26	8186				8.4
Elephant Butte Dam, N. Mex.	26	29	2848	2.9	4.3	7.5	11.1
El Vado Dam, N. Mex.	27	29	2837			9.9	10.4
Aurora Research Farm, N.Y.	28	30	331				12.5
Chapel Hill, N.C.	29	31	1677	3.1	4.7	7.8	10.5
Wooster Exp. Sta., Ohio	30	33	9312				9.1
Canton Dam, Okla.	31	34	1445	2.6	4.0	6.8	9.9
Detroit Power House, Oreg.	32	35	2292	.4	2.2	4.4	6.4
Redfield, S. Dak.	33	39	7052				9.6
Neptune, Tenn.	34	40	6454	2.4	3.7	6.8	10.5
Grapevine, Tex.	35	41	3691	3.1	4.0	7.2	8.7
Welasco, Tex.	36	41	9588	4.1	4.8	7.3	9.3
Ysletta, Tex.	37	41	9966	3.6	4.9	7.7	13.3
Utah Lake, Utah	38	42	8973			5.7	9.1
Templeau Dam, Wis.	39	47	8589				14.3
Heart Mountain, Wyo.	40	48	4411				6.9

* Plot identification number for figure 8
** NOAA-EDIS Climatological Data

Class A pan evaporation for selected stations
1956-70

of Annual										
May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	May thru Oct	Nov thru Apr	Annual Inches
12.5	12.5	12.3	11.1	9.3	7.6	4.8	3.8	65	35	50.97
12.0	13.8	13.7	11.6	10.1	7.9	4.9	3.9	69	31	121.3
11.5	14.0	14.5	14.7	10.0	7.1	3.6	2.7	72	28	120.56
11.9	15.4	16.2	14.5	11.0	7.2	3.3	1.8	76	24	69.70
16.0	14.1	12.0	10.7	7.1				74	26	50.95
13.3	14.3	15.1	13.7	9.0	6.4	4.0	2.5	72	28	42.52
10.9	10.2	10.6	10.1	8.8	8.2	6.0	5.2	59	41	56.48
12.3	12.6	12.4	11.4	9.3	6.7	5.1	4.2	65	35	64.65
12.0	14.1	19.3	17.7	11.6	6.0			81	19	45.25
11.9	14.5	19.1	15.1	10.5	6.5	2.9	1.7	78	22	60.98
14.6	15.8	15.5	13.3	9.3	7.6	3.4		76	24	50.10
12.6	12.5	15.0	14.3	9.5	7.6	4.1	1.7	72	28	61.19
11.8	13.9	15.7	13.9	9.9				73	27	92.98
13.1	13.9	14.6	13.2	9.6	7.8			72	28	55.26
13.3	15.0	15.2	13.6	10.3	7.3	3.8		75	25	49.46
12.1	13.1	13.0	12.5	9.2	7.7	4.5	3.4	68	32	48.86
15.4	16.0	16.4	13.9	9.0	6.5	3.2	2.1	77	23	22.25
13.0	15.0	14.6	13.0	8.7	5.4			70	30	35.71
13.7	15.3	16.2	14.0	9.6	6.4	2.3		75	25	44.53
12.9	13.8	13.4	11.9	9.2	7.0	4.3	3.1	68	32	60.99
11.9	13.7	14.5	13.5	10.5	7.5	4.0		72	28	48.08
12.6	13.9	19.0	16.6	10.3	5.9			78	22	47.06
12.4	14.2	15.5	14.4	10.5	7.5			74	26	70.60
12.4	14.3	14.8	12.9	9.9	6.9	3.8	2.8	71	29	109.73
11.8	13.6	15.6	14.5	10.9	7.2	3.3		74	26	82.07
13.7	14.8	12.5	10.6	8.5	6.8	4.2	2.8	67	33	116.86
15.1	14.4	14.5	11.5	9.3	6.1			71	29	57.91
15.4	16.7	14.3	10.1	6.8				76	24	41.08
12.3	12.6	13.2	11.8	9.3	6.9	4.7	3.2	66	34	52.89
12.6	15.1	15.5	13.7	9.9	7.1			74	26	46.12
11.5	12.5	14.2	13.6	9.3	7.5	4.6	3.4	69	31	77.51
11.8	15.7	21.8	17.9	11.0	5.2	2.4	1.1	83	17	39.74
13.3	14.5	16.9	15.9	11.0	7.2			79	21	51.83
12.0	13.8	14.0	12.5	9.3	7.1	4.2	3.5	69	31	46.47
10.3	12.4	14.5	13.9	9.8	7.4	4.9	3.9	68	32	84.81
10.7	11.3	13.2	12.8	9.4	7.3	5.4	4.2	65	35	85.70
13.9	12.9	10.1	8.8	6.6	4.3	3.1		65	35	108.76
13.3	15.4	17.7	15.3	10.7	6.6			79	21	56.12
15.8	16.5	13.6	9.6	8.2				78	22	39.29
13.5	13.9	16.3	14.8	9.5	6.4			74	26	49.36

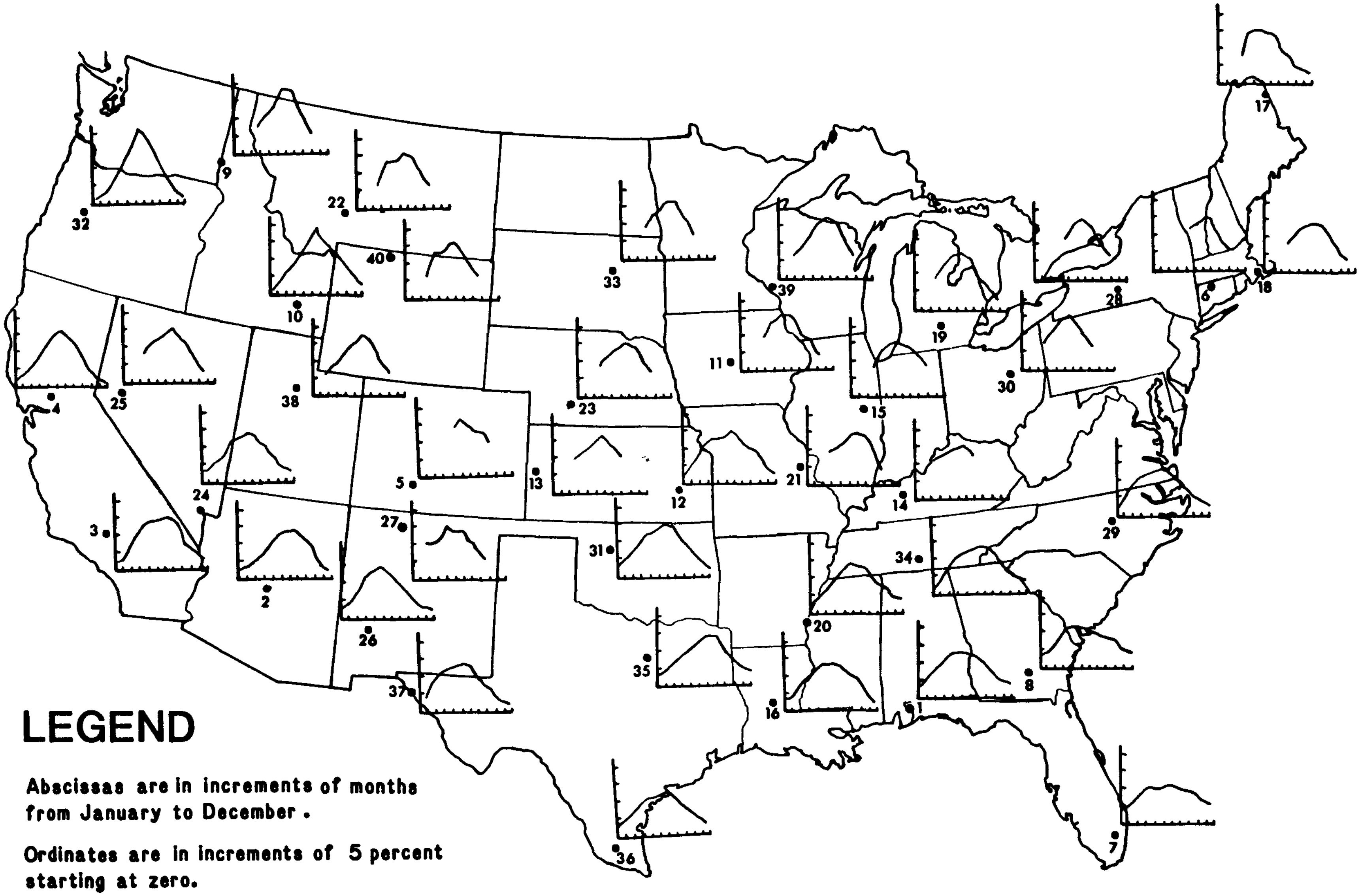

Figure 8--Graphs of mean monthly percent of annual evaporation for 40 selected stations. The numerical data for these stations are shown in table 3.

selected. In the desert areas of the Southwest, the interval was increased to 10 inches when the values exceeded 80 inches.

10. LIMITATION ON USE OF MAPS

10.1 Distribution of Stations

Although the current maps are based on more than 1,000 data points, the distribution of stations is not uniform (figures 1 through 3). Thus, the accuracy of the map is also not uniform. In those areas in which there are sharp gradients in the isopleths, the density of stations required for a given accuracy may increase greatly.

The pan evaporation vs. elevation relations were used to a great extent in the Western United States for extrapolating isopleths to high elevation areas and to areas with sparse data.

Dashed lines have been used to indicate where the isopleths were extended at least two isopleth intervals beyond the values of the last data point on the pan evaporation vs. elevation relation. The dashed isopleths were also used for those areas with extremely sparse data where, in the judgement of the authors, the analyses were much less certain.

10.2 Use of Maps for Estimating Actual Lake Evaporation

Values of FWS evaporation from map 3 can be used as estimates of the average annual lake evaporation for those lakes for which (1) there is only a negligible change in heat storage and (2) the heat content of inflow waters is essentially the same as that for outflow waters. Seasonal values cannot be used for estimating actual lake evaporation unless the changes in heat storage and the difference in heat inflow and outflow are properly accounted for.

11. SUMMARY

Pan evaporation data and other estimates of pan evaporation and FWS evaporation were used to prepare maps of average Class A pan evaporation and FWS evaporation for the 48 contiguous United States. FWS evaporation is considered to be approximately equivalent to potential evaporation from a shallow water surface and to potential evapotranspiration from a vegetative surface with an unlimited supply of water.

In the mountainous areas of the Western United States and in the Appalachian region of the Eastern United States, relationships of the estimated values with elevation were used in the preparation of the maps.

A map of coefficients for use in adjusting May-October seasonal Class A pan evaporation to FWS evaporation was also prepared.

The publication of these maps serves to update the maps published in Technical Paper No. 37, <u>Evaporation Maps of the United States</u>, by the Weather Bureau (now the National Weather Service, NOAA) in 1959 (Kohler et al.).

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Climatologists in the Western States were contacted because the large variations in relief influence evaporation patterns and the semiarid and arid climates in the West have resulted in their longtime interest in pan and potential evaporation.

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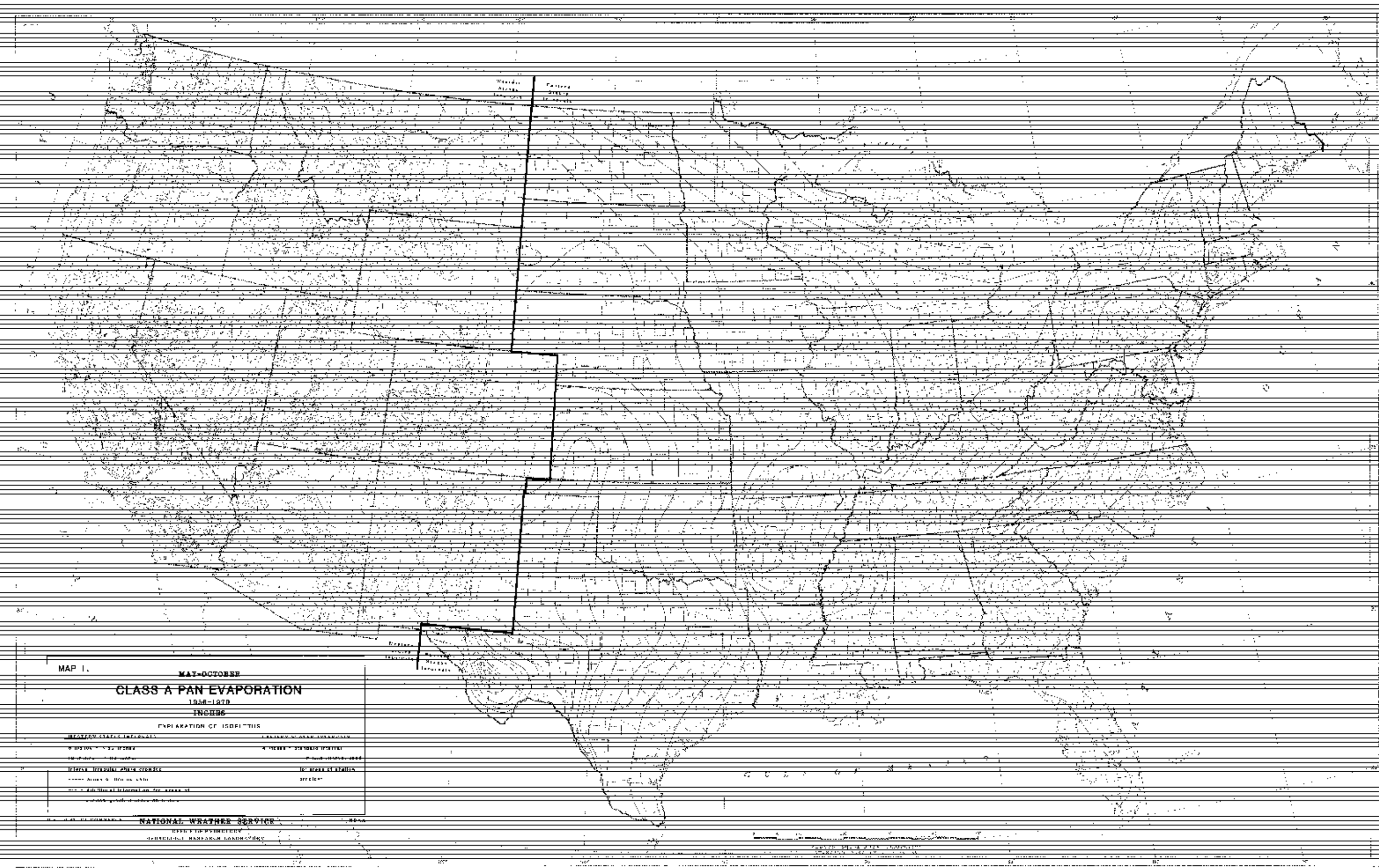

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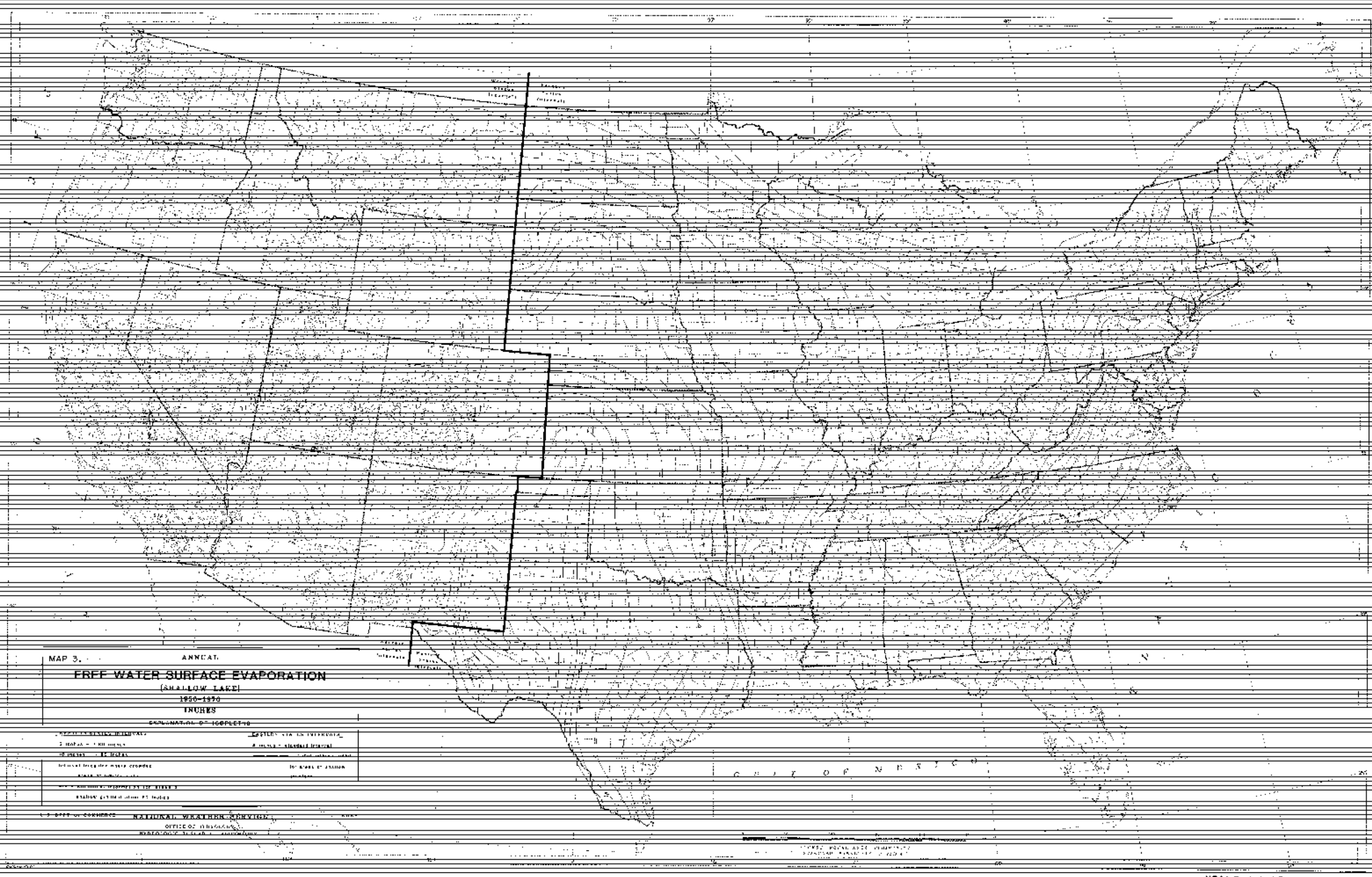
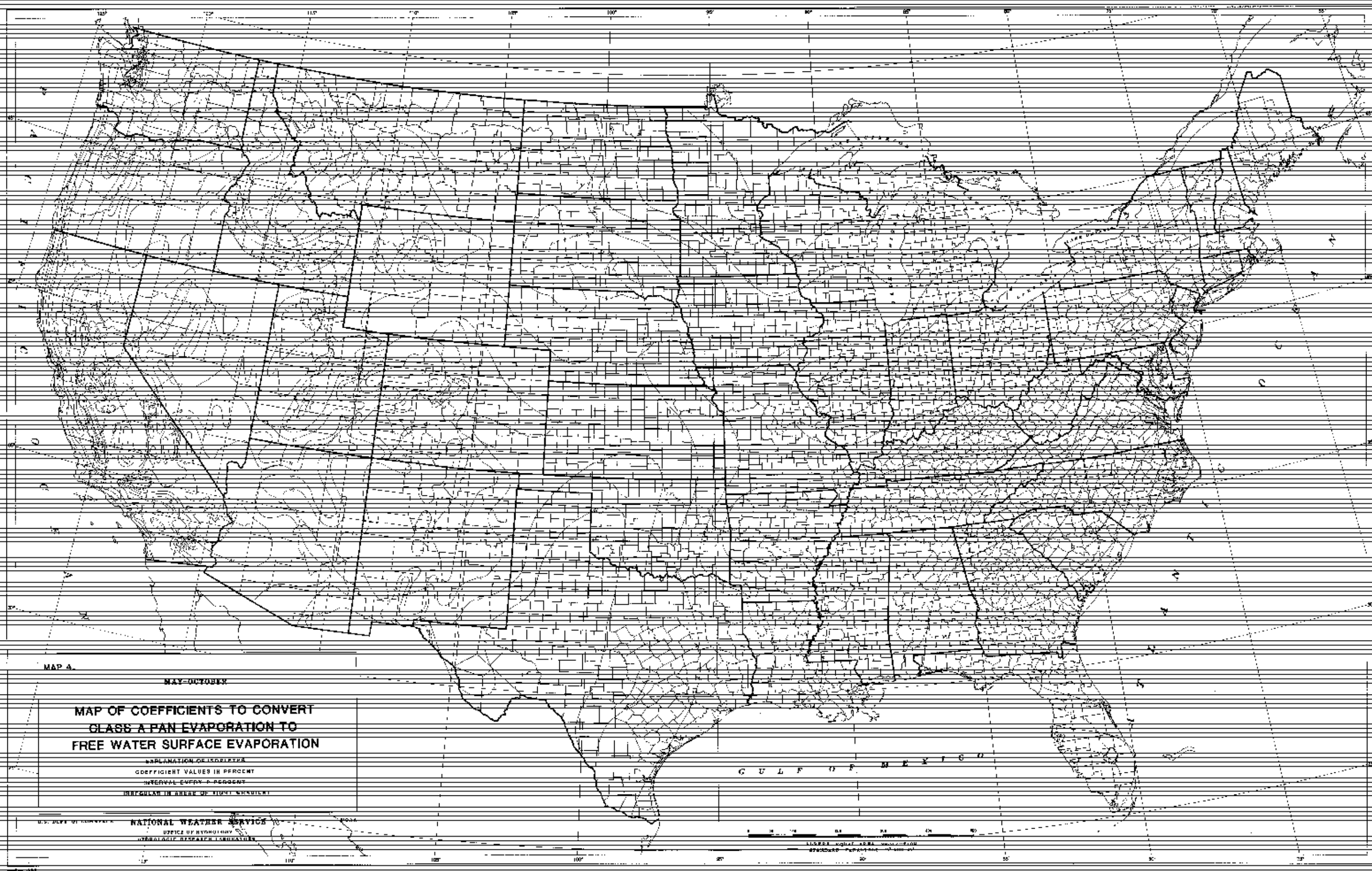
Map 1 of 4: May-October Pan Evaporation

MAP 2.
MAY-OCTOBER
FREE WATER SURFACE EVAPORATION
(SHALLOW LAKE)
INCHES
NATIONAL WEATHER SERVICE
G U L F O F M E X I C O


MAP 3.
ANNUAL
FREE WATER SURFACE EVAPORATION
(SHALLOW LAKE)
1956-1970
INCHES
NATIONAL WEATHER SERVICE


MAP 4.
MAY-OCTOBER
MAP OF COEFFICIENTS TO CONVERT
CLASS A PAN EVAPORATION TO
FREE WATER SURFACE EVAPORATION
COEFFICIENT VALUES IN PERCENT
NATIONAL WEATHER SERVICE
G U L F O F M E X I C O