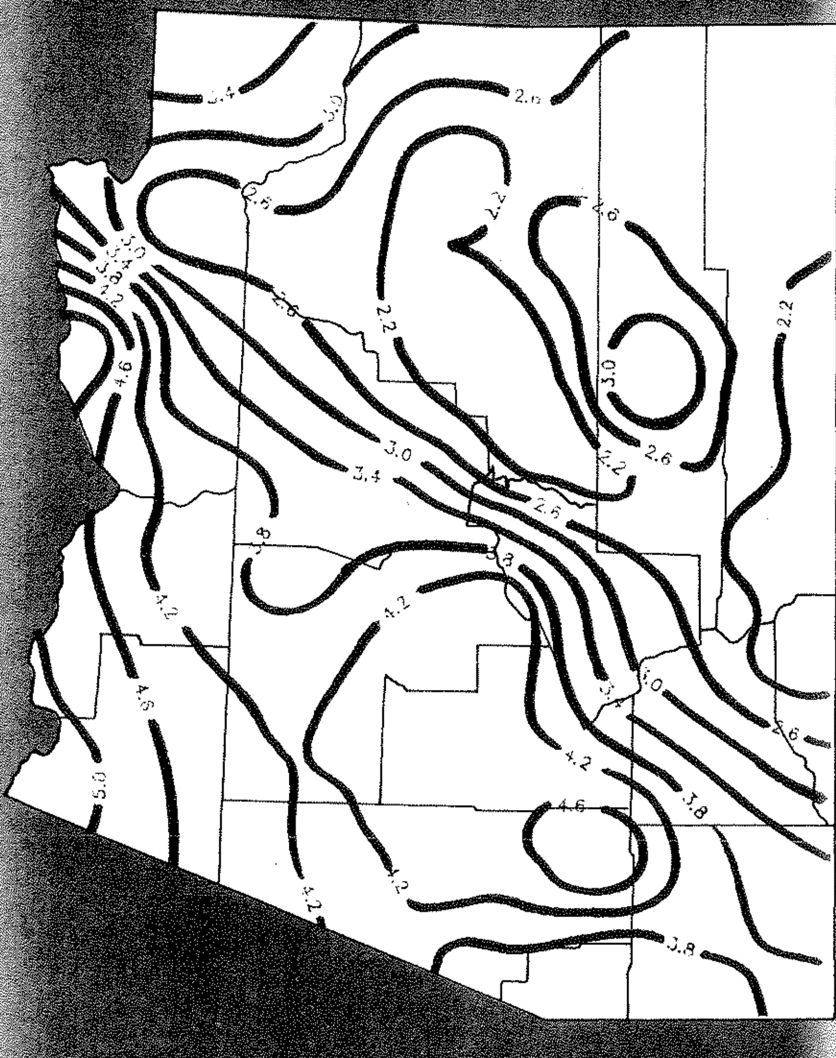
REFERENCE EVAPOTRANSPIRATION ESTIMATES FOR ARIZONA



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Agricultural Experiment Station
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Acknowledgements

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Introduction

Irrigated agriculture is the largest single user of available water in Arizona. Present estimates show water use at about 85 percent of the available water with the major portion coming from groundwater reserves. The state has been facing an estimated overdraft of two million acre-feet per year from groundwater aquifers. As a result, the 1980 Groundwater Management Code is forcing the agricultural sector to manage and use the available water more efficiently. The second Groundwater Management Plan is about to start and it has a more stringent requirement for water conservation than did the first plan.

Farmers and The Arizona Department of Water Resources should have information concerning the amount of irrigation water needed for satisfactory crop production. Water requirements of crops are necessary in order to calculate system capacities and to schedule irrigations. They are also needed by engineers and hydrologists for the planning of new irrigation projects, for the apportionment of available water supplies, for the development of new sources, and as a basis for hydrologic balance studies.

Recognizing the importance and the need for irrigation water requirement data, various state and federal agencies have been working to estimate crop water requirements of irrigated crops in Arizona. The work of Erie et al. (1965) is a milestone in this effort. Recently, the Arizona Cooperative Extension Service has established a network of climatic stations in order to provide the basic weather-based information essential for irrigation management. This is an important development but requires time and an extensive number of stations in order to cover the whole state.

The first step in quantifying irrigation water requirements is the establishment of relationships between evaporative demand of the soil-plant-atmosphere system i.e., the evapotranspiration needs of crops. Crop evapotranspiration (ETc) can be directly measured using field water balance techniques, lysimeters, energy balances, or mass transfer methods. These methods can provide accurate values for ET but they involve expensive and time-consuming experiments over a long time period and in each area for which information is needed. Because of these difficulties, the methods have been confined to research studies and have had limited field application. Thus, scientists have developed empirical relationships for predicting evaporation from water and land surfaces, and transpiration by plants (evapotranspiration). These relationships are based on climatological data. The climatological variables most commonly used are temperature, humidity, wind, and solar radiation. Jensen (1966) justified the use of emperical methods when; 1) there are inadequate climatological and soil-crop data available to apply complete rational equations based on the physical processes involved; 2) the absolute accuracy of the data needed may be adequate using simple emperical equations that require much less time and effort to solve; and 3) complete rational equations often require greater technical ability and experience in meteorology, physics, and agronomy that many users of evapotranspiration data have or can justify.

The approach that has gained widest acceptance for estimating actual evapotranspiration of a crop is the use of reference evapotranspiration (ETo). This approach is based on determining the upper limit of water use (potential evapotranspiration) by a reference plant (such as alfalfa or pasture) under non-water-limiting conditions and relate this value to actual crop evapotranspiration (ETc) by way of experimentally determined coefficients. These coefficients are multiplicative correction factors known as crop coefficients (Kc) which account for differences in physiology, canopy architecture, and stage of development of crops, and therefore, are crop specific (Doorenbos and Pruitt, 1977).

The concept of reference evapotranspiration was first introduced by Thornthwaite (1948), improved by Penman (1956) and further refined by Doorenbos and Pruitt (1977).

There are several models available for estimating reference evapotranspiration. These models involve the use of correlations of temperature (Blaney and Criddle, 1962), of solar radiation (Doorenbos and Pruitt, 1977), of temperature and radiation (Jensen and Haise, 1963), of net radiation (Priestley and Taylor, 1972), and a combination of energy and mass transfer principles (Penman, 1948). The models differ widely in complexity and consistency of evapotranspiration estimation. In the absence of any standard, selection of a particular model is dependent upon data available, geographical area in question, and other information available pertaining to the methods reliability in a given region.

This report presents reference evapotranspiration maps for the state of Arizona using data from 50 climatic stations. They are spread throughout Arizona and one is in Las Vegas, Nevada (Figure 1). These climatic data enable calculation of ETo using Blaney-Criddle model.

Maps of mean daily ETo for each month, elevation, annual ETo, and coefficient for extrapolating Mesa values of ETo to other sites are provided.

Motivation for this study came from the desire to provide farmers, extension advisors, engineers, and water resource planners a normal-year ETo (i.e., one with average weather conditions) estimates for use in calculating crop water requirements, defining water duties, and for planning water resource projects. The normal-year ETo data presented are particularly valuable for areas in which no research activities on water requirement has been conducted.

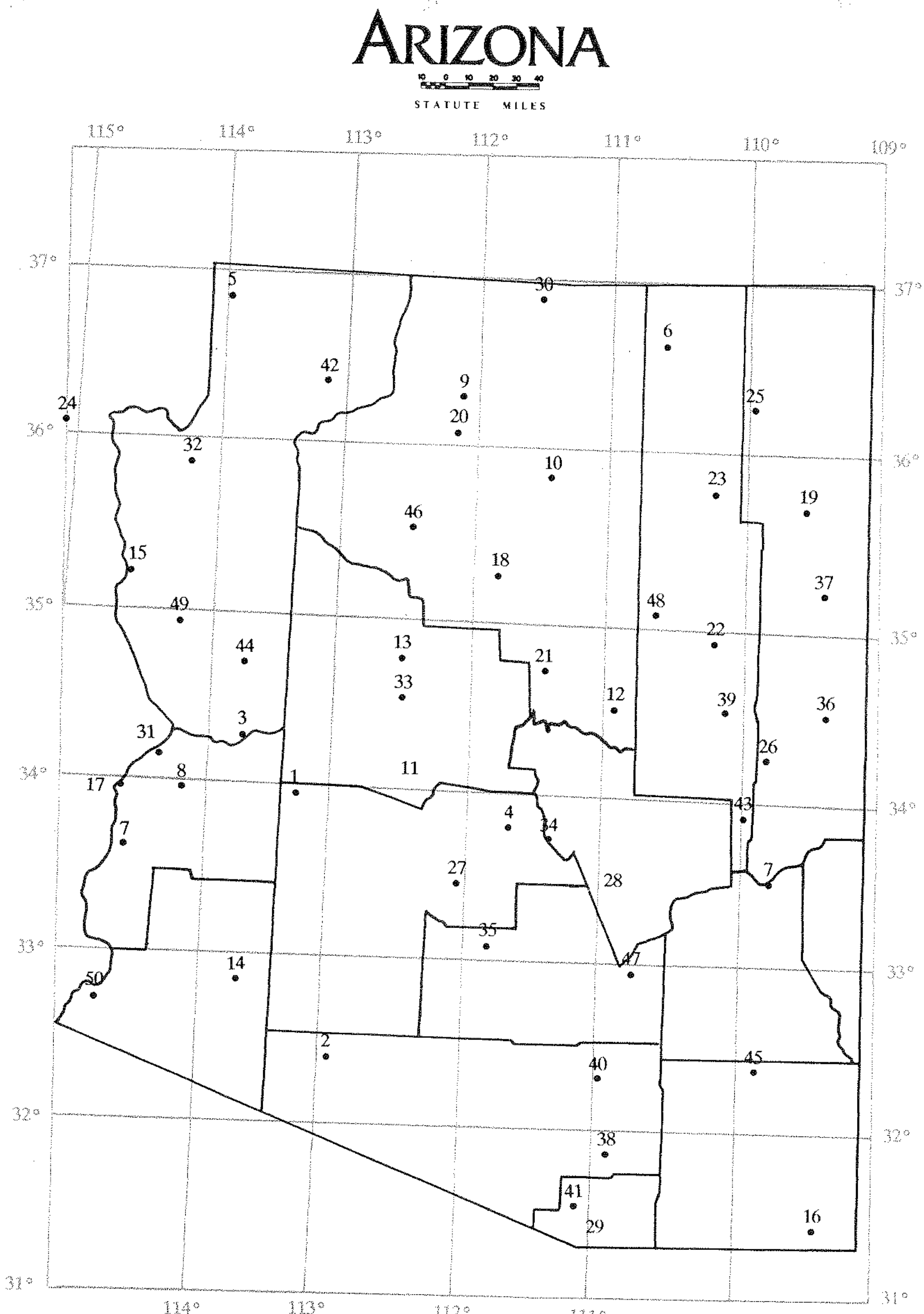

Figure 1. Station Locations

Procedure

Data Collection

Historical data from the 50 stations representing seven regions (northwest, southwest, south central, southeast, east central, north central, and northeast, Figure 1) were used to calculate ETo. The record length at each of the 50 stations varied from 5 to 30 years. The number of climatological variables recorded at each station varied from just minimum and maximum temperatures to radiation, wind run, minimum and maximum relative humidity, and sunshine hours. Table 1 presents the sites selected based on record length and representativeness for a region.

All 50 stations have daily and monthly records of both minimum and maximum temperatures. Only Tucson, Mesa, and Yuma had daily wind records for the entire period covered in the study. Winslow had some daily and monthly values for a few years. For all other stations, available long-term average monthly temperature values reported for different periods were used. Table 1 also presents the number of years of data, and types of data available for calculating ETo. The weather parameters came from both state and federal sources (Table 2).

Tucson, Mesa, Yuma, Winslow, and Flagstaff had long-term daily and monthly relative humidity data. Long-term monthly average values available from different sources were used for the other stations. Isolines of monthly mean values of both minimum and maximum temperature, and minimum and maximum relative humidity, were developed for the state for each month of the year. These figures allow interpolation of parameters for sites with no long-term data. Figure 2 is an elevation map, useful in making adjustments for elevation, as required by the model used.

Solar radiation values were the least reported data, yet they are very important in some models. Only seven stations in the state have long-term solar radiation data (Table 3). Interpolation of data for other stations was made using the closest station's data and adjusting them for the difference in altitude and latitude. For Blaney-Criddle model radiation is used to get the ratio of actual to maximum possible sunshine hours. In the absence of measured ratio the function given by FAO (Doorenbos and Pruitt, 1977) was used to estimate this value. The lack of reliable solar radiation data for the state was the basis for chosing the Blaney-Criddle model for estimating ETo. This model is the least dependent on radiation data among the ones considered for this study.

Table 1. Summary of Stations: Observed Periods and Type of Data Used.

No.	Station	Region	Year	Wind	Temperature
1	Aguila	SC	1974-83	1	3
2	Ajo	SE	1973-82	1	3
3	Alamo Dam	SW	1973-81	1	3
4	Bartlett Dam	SC	1978-82	2-Long term	3
5	Beaver Dam	NW	1974-83	1	3
6	Betatakin	NE	1972-81	1	3
7	Black R. Pump	SE	1969-78	2-Long term	3
8	Bouse	SW	1971-80	1	3
9	Bright Angel	NE	1974-83	1	3
10	Cameron	NE	1974-83	1	3
11	Castle Hot Spring	NC	1974-81	1	3
12	Chevelon Range	NE	1975-83	1	3
13	Chino Valley	NC	1973-81	2	3
14	Dateland	SW	1972-81	1	3
15	Davis Dam #2	NW	1968-77	2-Long term	3
16	Douglas	SE	1974-83	2-Long term	3
17	Ehrenberg	SW	1974-81	1	3
18	Fort Valley	NE	1973-82	2-Long term	3
19	Ganado	NE	1973-82	1	3
20	Grand Canyon	NE	1974-83	2-Long term	3
21	Happy Jack	NE	1974-83	1	3
22	Holbrook	NE	1974-83	1	3
23	Keams Canyon	NE	1974-83	1	3
24	Las Vegas	NW	1964-83	0-1964-83	3
25	Many Farms	NE	1965-74	2-Long term	3
26	McNary	NE	1971-80	1	3
27	Mesa	SC	1950-83	0-1950-83	3
28	Miami	EC	1973-81	1	3
29	Nogales	SE	1964-83	2-Long term	3
30	Page	NE	1964-83	2-Long term	3
31	Parker	SW	1972-81	1	3
32	Pierce Ferry	NW	1974-83	1	3
33	Prescott	NC	1974-83	2-Long term	3
34	Roosevelt	SC	1974-83	2-Long term	3
35	Sacaton	SC	1972-81	2-Long term	3
36	Saint Johns	NE	1973-82	1	3
37	Sanders	NE	1973-82	1	3
38	Santa Rita	SE	1973-82	1	3
39	Snowflake	NE	1973-82	2-Long term	3
40	Tucson	SE	1964-82	0-1964-82	3
41	Tumacacori	SE	1974-82	1	3
42	Tuweep	NW	1971-80	1	3
43	Whiteriver	EC	1964-83	2-Long term	3
44	Wikieup	NW	1976-83	1	3
45	Willcox	SE	1972-81	2-Long term	3
46	Williams	NE	1974-80	1	3
47	Winkelman	SC	1970-79	2-Long term	3
48	Winslow	NE	1964-83	0/2-1979-64, Long term	3
49	Yucca	NW	1974-83	1	3
50	Yuma	SW	1964-83	0-1964-83	3

0 - Daily wind values available.
1 - No daily or long term wind values available.
2 - No daily records for wind, only long term averages available.
3 - Daily maximum and minimum temperatures were available and used.

EC = East Central
NC = North Central
NE = North East
NW = North West
SC = South Central
SE = South East
SW = South West

Table 2. Major Sources of Data

Climatological Variable	Source
Temperature	Bulk, H.C. (No date) Climate & Energy Series #7
	Sellers, *et al.* (1985)
	US Department of Commerce, NOAA
Relative Humidity	Bulk, H.C. (No date) Climate and Energy Series #7
	Sellers (1974)
	US Department of Commerce, NOAA
Wind	Sellers (1974)
	US Department of Commerce, NOAA
Solar Radiation	Durrenberger (1980)
	Hamdy and Durrenberger (1976)
	Knapp *et al.* (1980)
	US Department of Commerce, NOAA

Data Processing

Reference evapotranspiration calculations were made using a modified version of the FAO computer program developed by Gupta et al. (1977). The original program allows computation of ETo using Blaney-Criddle, radiation, Penman, and pan evaporation methods. The program was modified to include the modified Jensen-Haise, Net Radiation, and Hargreave's models. The pan evaporation method was not used because there was an insufficient amount of pan data.

To date there is only one site in the entire state, that at the U.S. Water Conservation Laboratory in Phoenix, that has a lysimeter which can be used to check the accuracy and the reliability of empirical models. In view of the lack of sufficient lysimeter or other reliable field data on ETo, no attempt was made to calibrate the model for the various regions of the state.

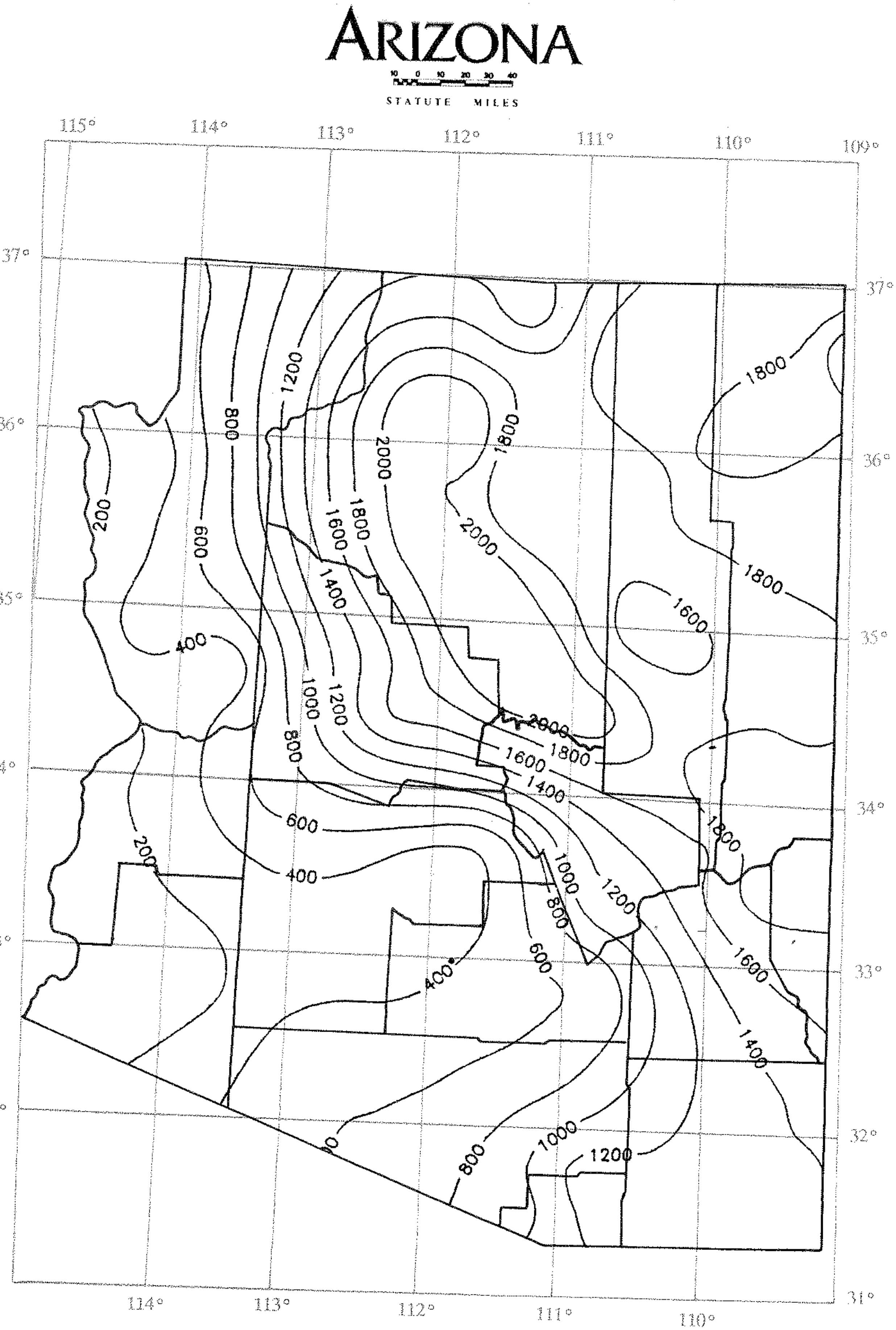

Figure 2. Contour map developed from 50 reported site elevations (meter)

Table 3. Average Solar Radiation Data (After Hamdy and Durrenberger, 1976)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Las Vegas	265	355	477	633	687	718	651	604	526	394	289	234
Page	229	321	424	560	637	645	592	538	490	346	272	231
Yuma	292	384	488	616	684	700	626	591	520	419	320	262
Phoenix	282	369	470	618	683	678	622	554	500	397	306	247
Castle Creek	240	328	417	552	594	574	453	434	416	342	253	197
Seven Springs	209	285	372	470	487	478	367	337	317	275	227	196
Tucson	299	371	476	605	642	667	603	568	502	413	325	266
Fort Huachuca	324	397	506	631	680	669	549	553	495	430	344	288

All values are in Langleys/Day (1 Langley/day = 1 cal/cm^2/day)

A brief description of the Blaney-Criddle model used for this study follows.

FAO Blaney-Criddle Model

The recommended relationship for this method is (Doorenbos and Pruitt, 1977, see page 110)

$$ETo = a_b + b_b[P\ (0.46T + 8.0)] \qquad (1)$$

where:

ETo = reference crop evapotranspiration ET, clipped grass, mm day^{-1}

a_b and **b_b** = adjustment factors

P = mean daily percentage of total annual daylight hours for a given month and latitude

T = mean daily temperature, °C.

The adjustment factor a_b depends upon minimum relative humidity and sunshine as given by:

$$a_b = 0.0043(RH_{min}) - \left(\frac{n}{N}\right) - 1.41 \quad (2)$$

where:

RH_{min} = minimum relative humidity.
n/N = ratio of actual to maximum possible sunshine hours. This value, in the absence of measured data, is estimated by:

$$\frac{n}{N} = 2\frac{R_s}{R_a} - 0.5 \quad (3)$$

R_s = solar radiation in mm day^{-1}
R_a = extraterrestrial radiation (depends on the month of the year, and latitude).

The adjustment factor b_b depends on $U_{day}(ms^{-1})$, n/N, and RH_{min}. It is calculated by interpolation from values in a table included in the program. P is also calculated from values in a table included in the program. Its value depends on the month of the year and latitude.

The mean daily temperature T, °C is an input data to the program calculated as:

$$T = [T_{max} + T_{min}]/2 \quad (4)$$

For more detail on the Blaney-Criddle and the other models considered, the reader is referred to Doorenbos and Pruitt (1977), Burman, *et al.* (1983), and Hill, *et al.* (1983).

ETo Maps

Mean monthly values of ETo calculated using the model described above were recorded for 50 sites on maps of Arizona plus Las Vegas, Nevada for each month of the year. A computer program called *SURFER* (Golden Software Inc., 1987) was employed to draw the isolines of ETo as well as minimum and maximum temperature, minimum and maximum relative humidity, elevation, and the transformation coefficient on the map using a three-step procedure. It operates on the data as follows. First the program develops a grid system by transforming the known longitude and latitude for each site into an x-y coordinates measured from a specified origin. Next, subroutine GRID creates regularly spaced data points from the irregularly spaced points on the coordinate system. Subroutine TOPO then creates the contour map using ETo as the z-coordinate based on the file developed by GRID. Finally, a plotting subroutine sends a file to a plotter. Since the program uses a rectangular boundary system, the irregular boundaries of the state had to be plotted manually.

Only one set of ETo maps based on Blaney-Criddle model (Figures 3 to 14) is presented for three reasons. First, of all the models tried, Blaney-Criddle was the only one for which data for calculating ETo, (i.e., temperature) was available for all stations (Table 1). Second, despite the acknowledged accuracy of Penman and the other complex models, the required long-term solar radiation and wind speed records are simply not available in Arizona. Finally, most earlier works on consumptive use of crops in Arizona which used the Blaney-Criddle model (Erie et al. 1965) and presented crop coefficients can be used with the maps in this report provided necessary adjustments are made. ETo maps based on Penman, Jensen-Haise, and the average of six models are available from the author upon request.

Figure 15 is also provided to present ETo on an annual rather than monthly basis. This will give a good estimate of ETo for use in project planning.

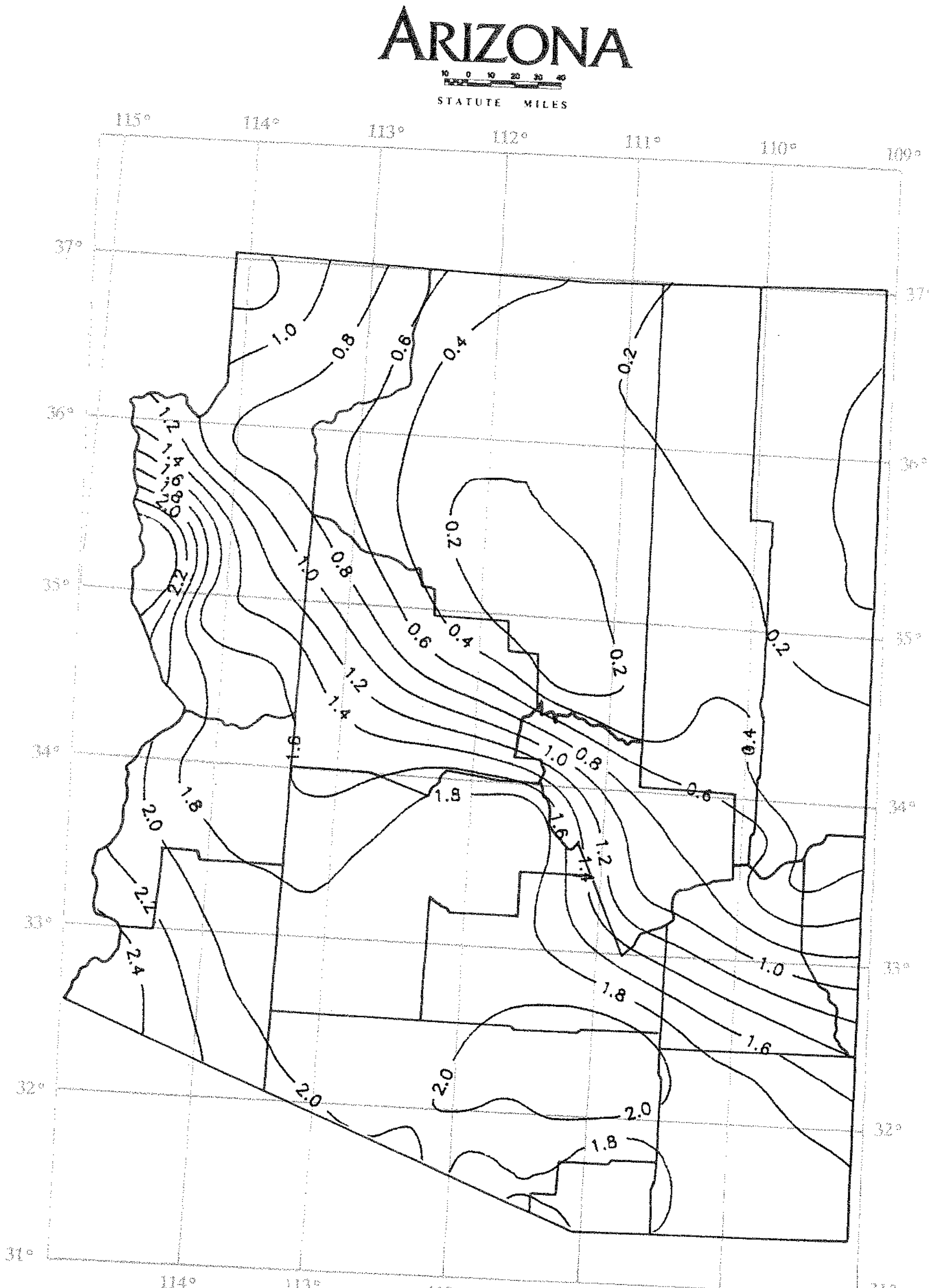

Figure 3. Reference Evapotranspiration (ETo) in millimeters per day – January

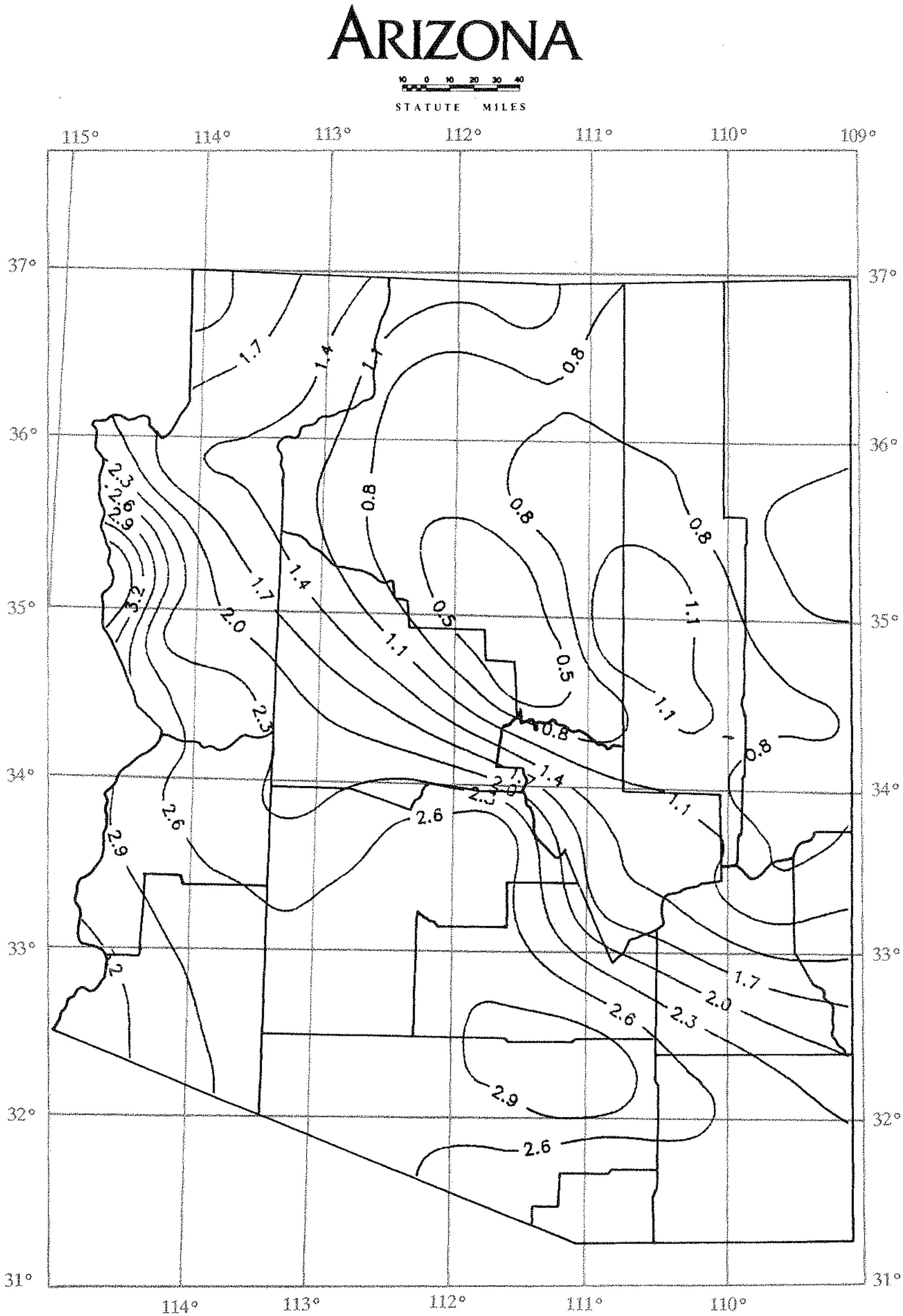

Figure 4. Reference Evapotranspiration (ETo) in millimeters per day – February

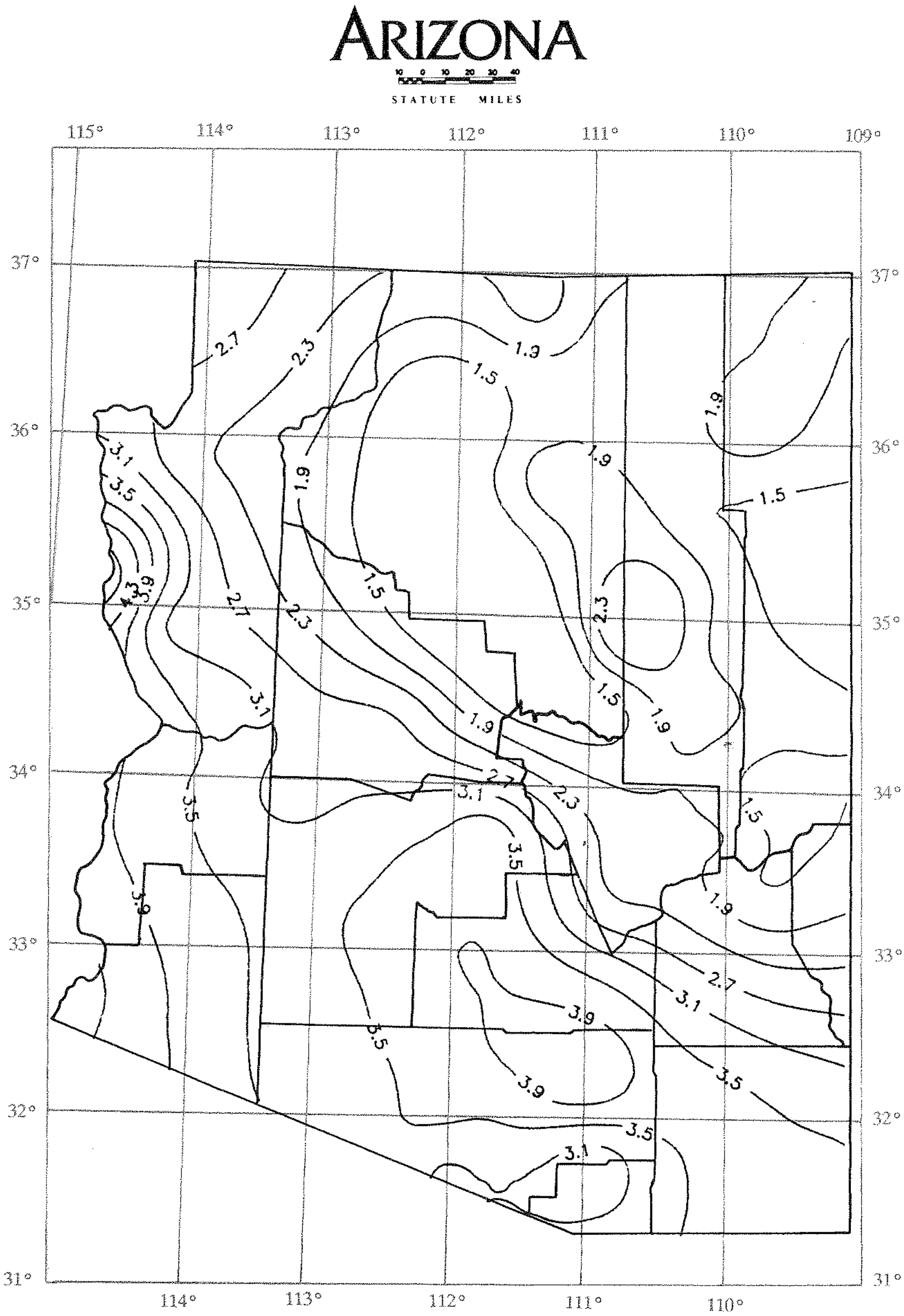

Figure 5. Reference Evapotranspiration (ETo) in millimeters per day – March

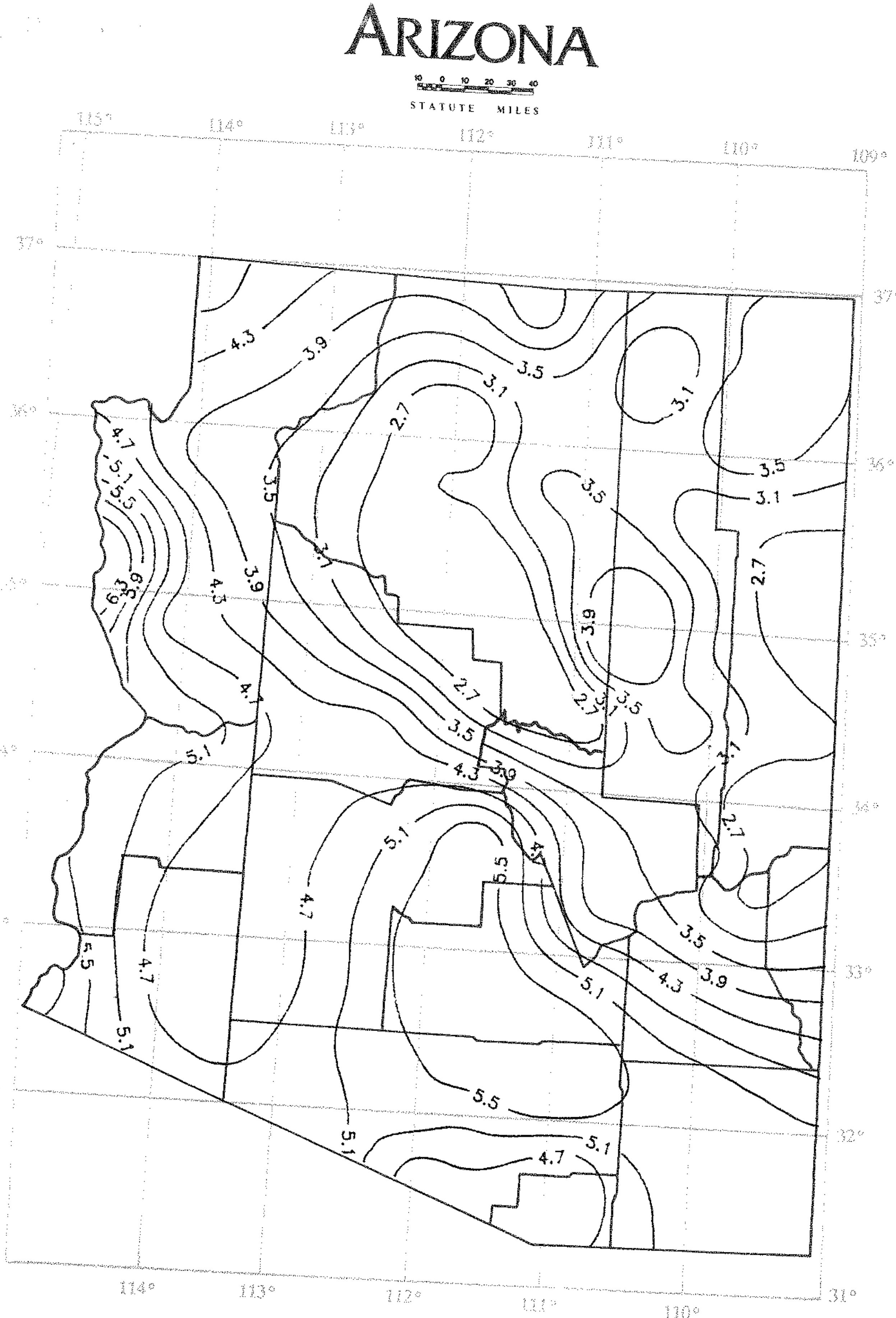

Figure 6. Reference Evapotranspiration (ETo) in millimeters per day – April

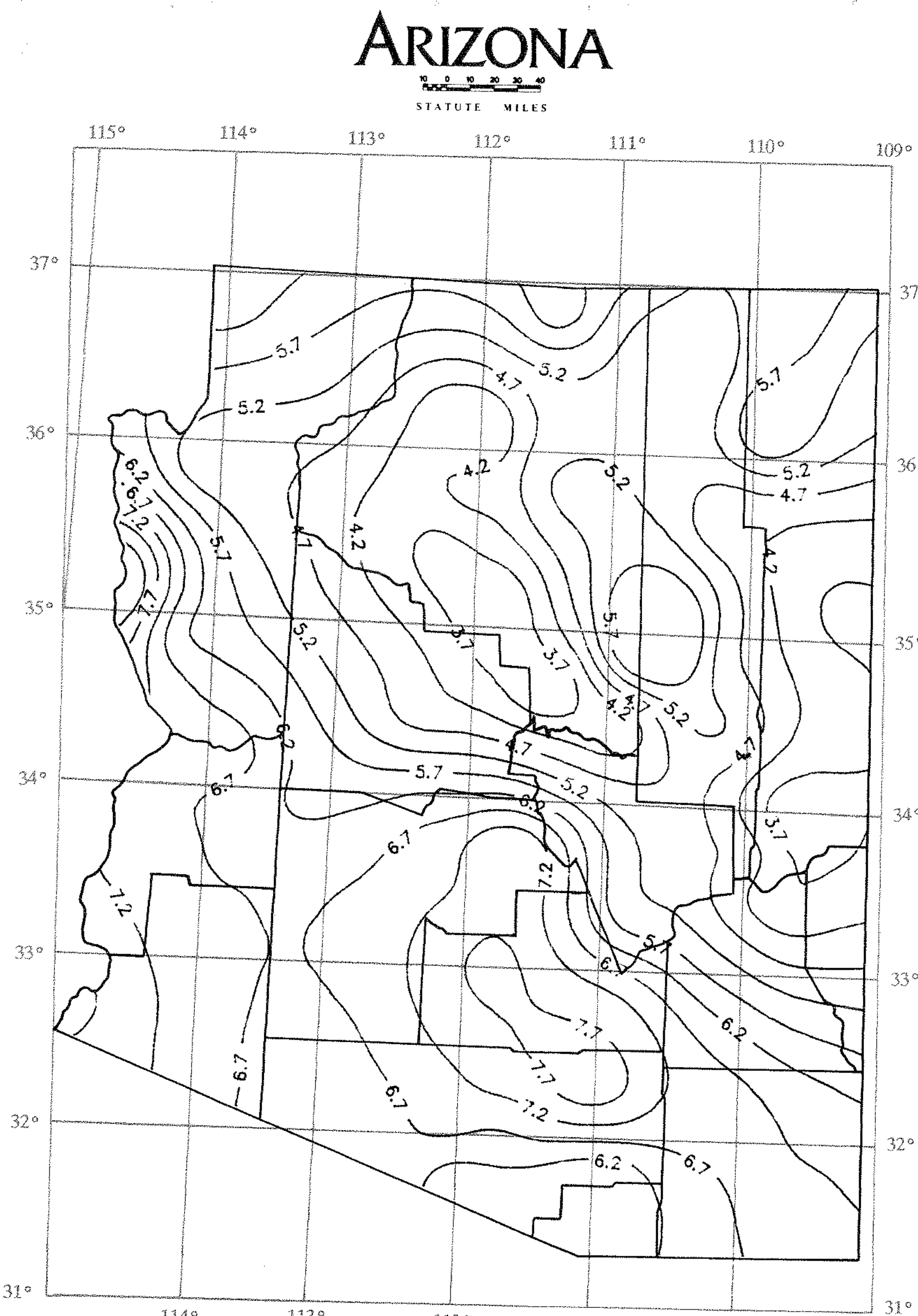

Figure 7. Reference Evapotranspiration (ETo) in millimeters per day– May

ARIZONA

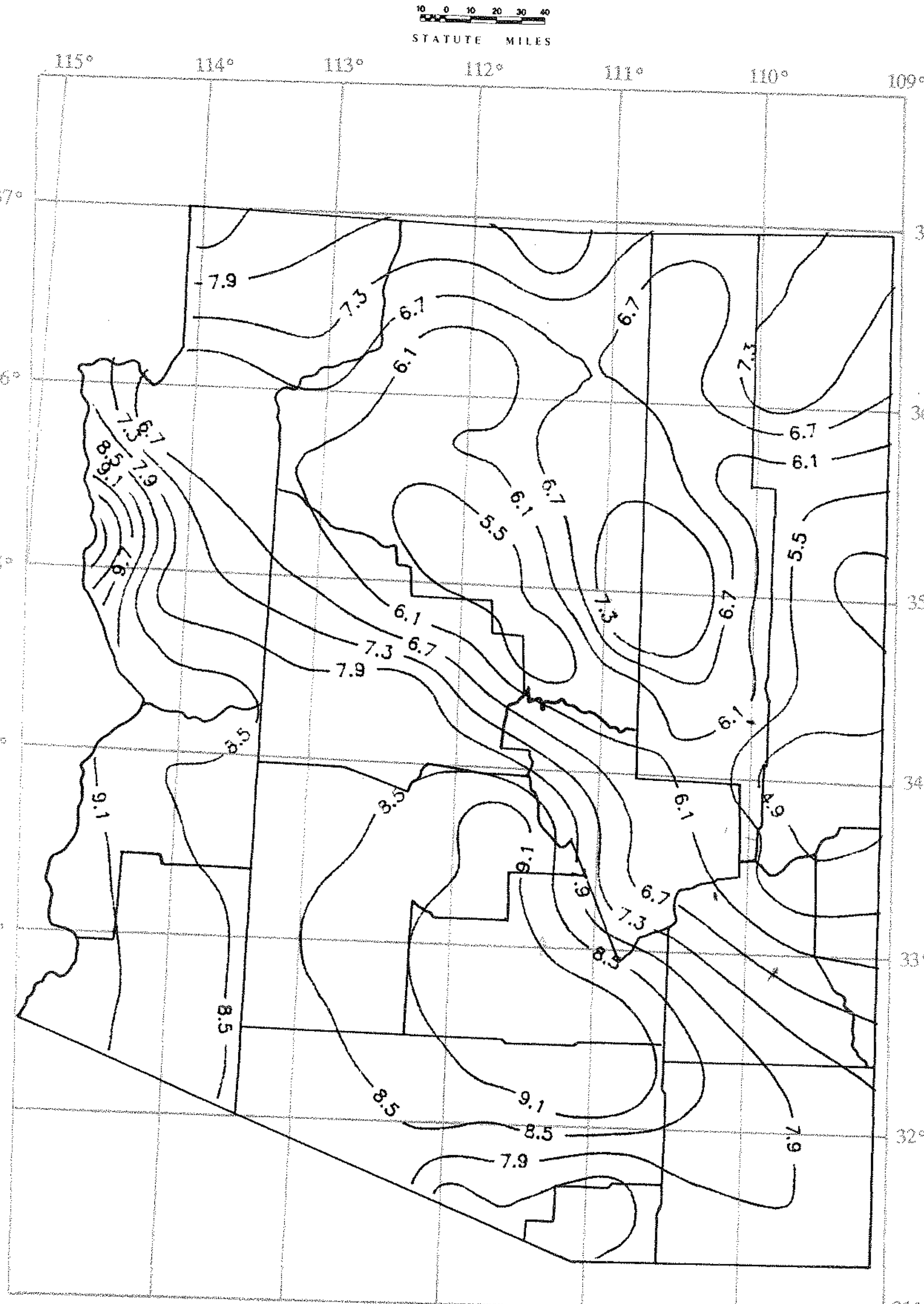

Figure 8. Reference Evapotranspiration (ETo) in millimeters per day – June

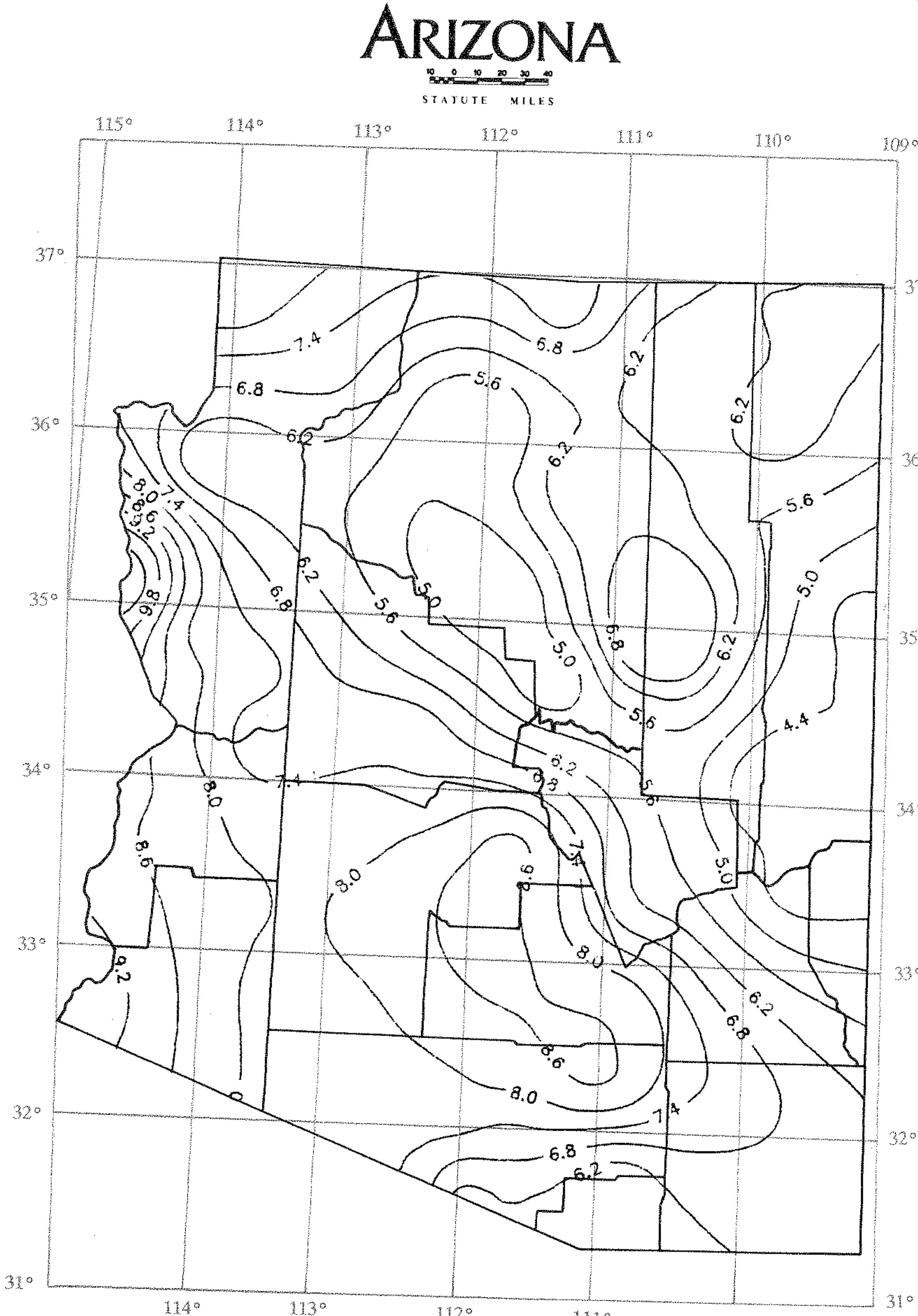

Figure 9. Reference Evapotranspiration (ETo) in millimeters per day -- July

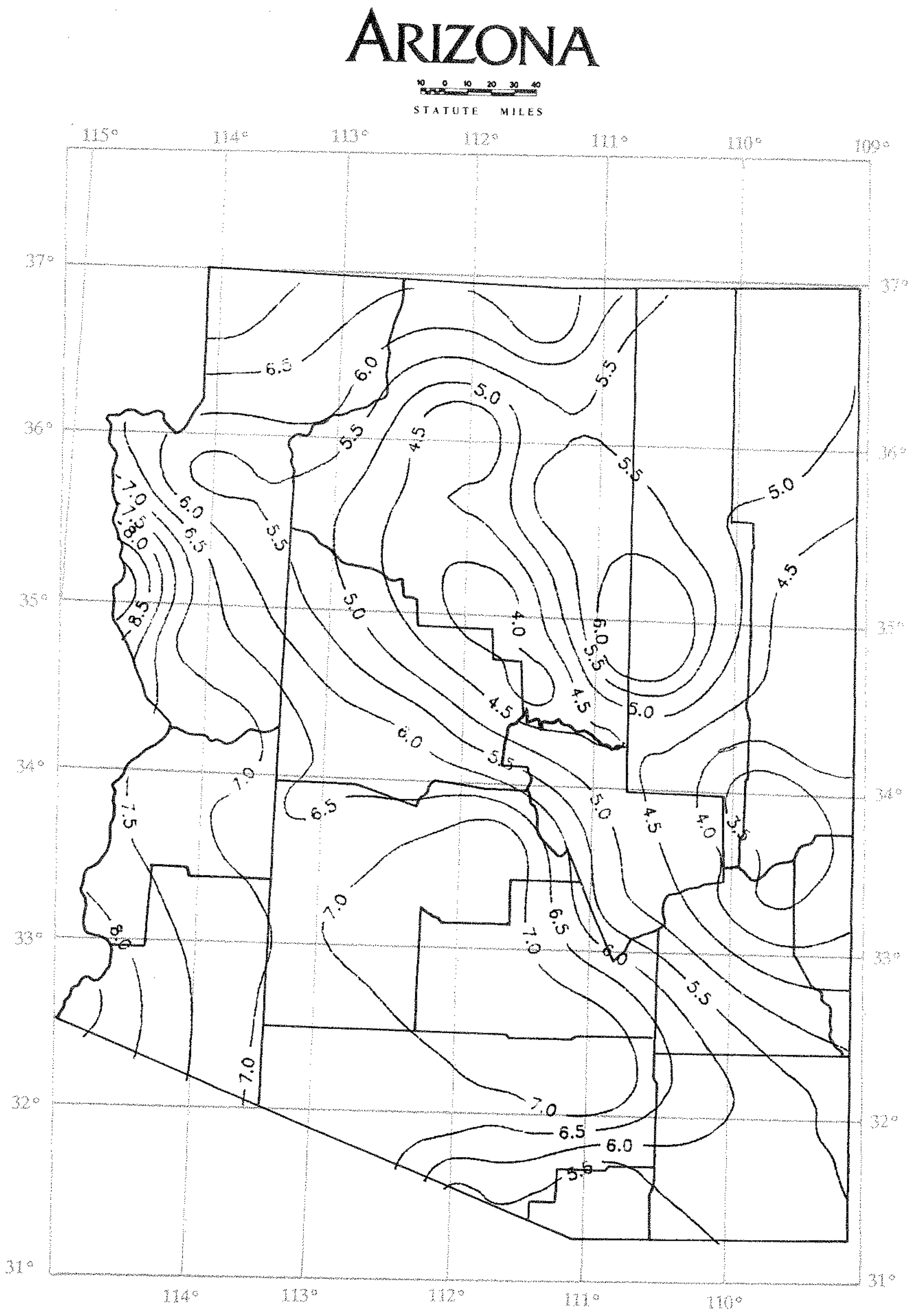

Figure 10. Reference Evapotranspiration (ETo) in millimeters per day – August

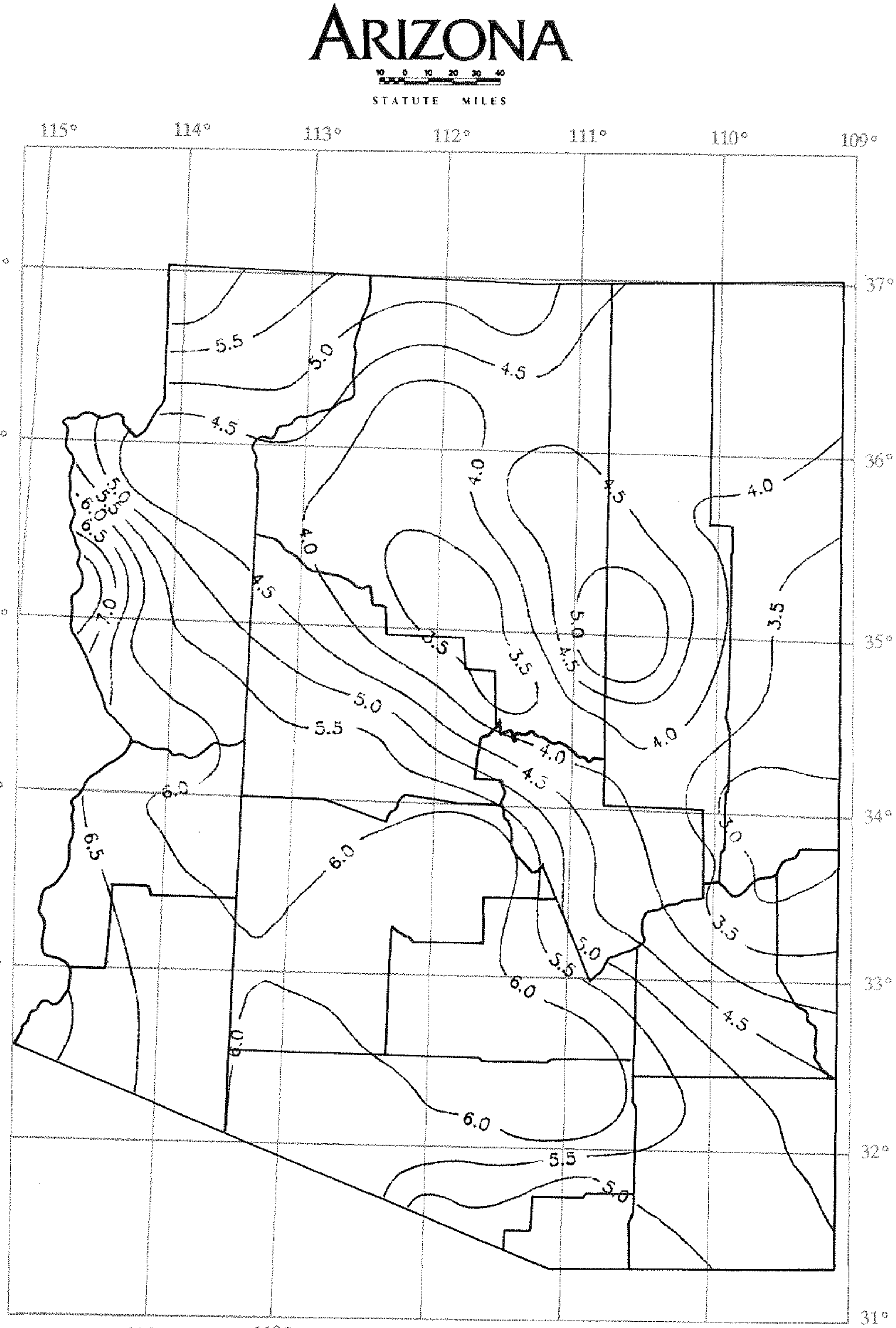

Figure 11. Reference Evapotranspiration (ETo) in millimeters per day – September

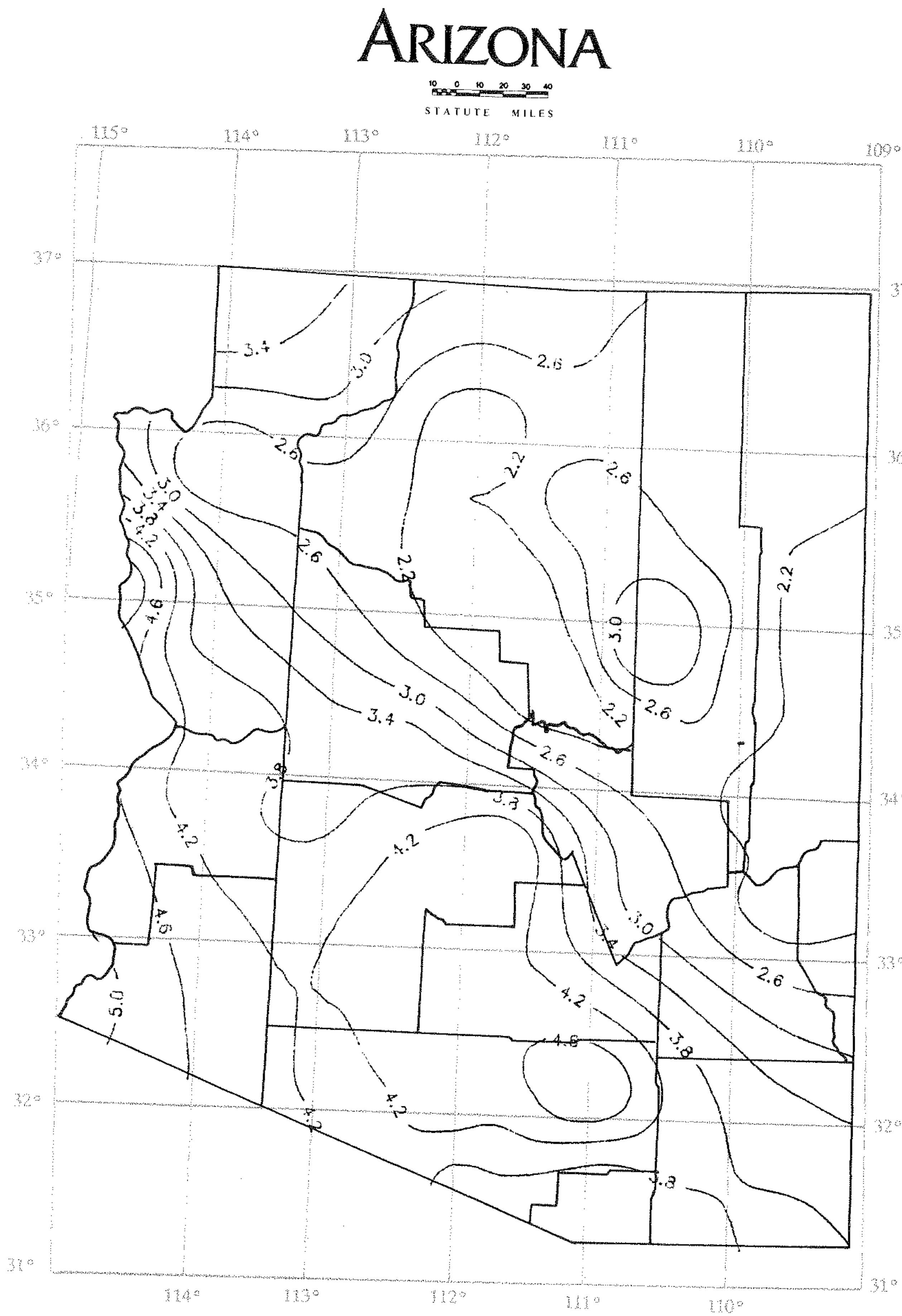

Figure 12. Reference Evapotranspiration (ETo) in millimeters per day – October

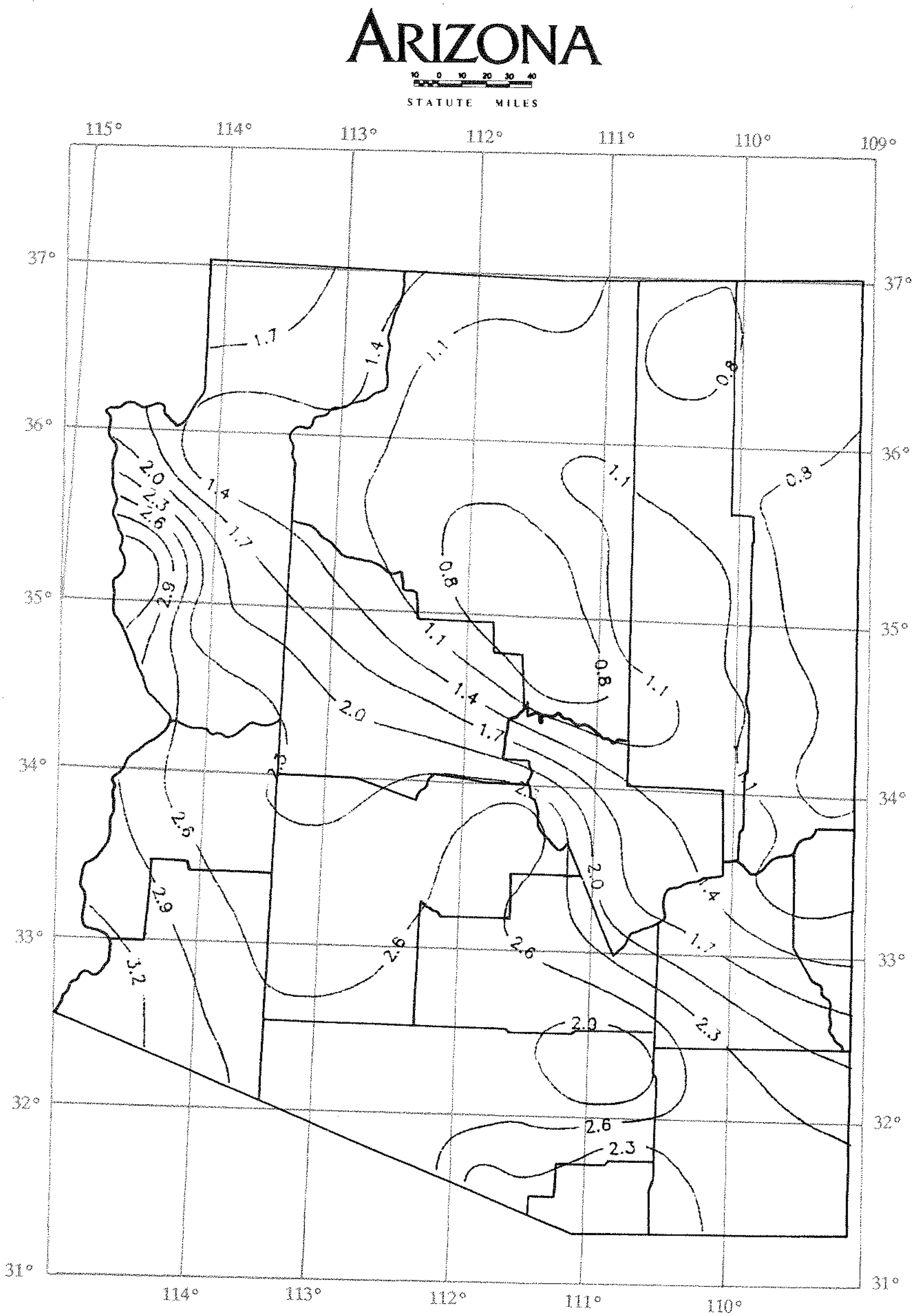

Figure 13. Reference Evapotranspiration (ETo) in millimeters per day – November

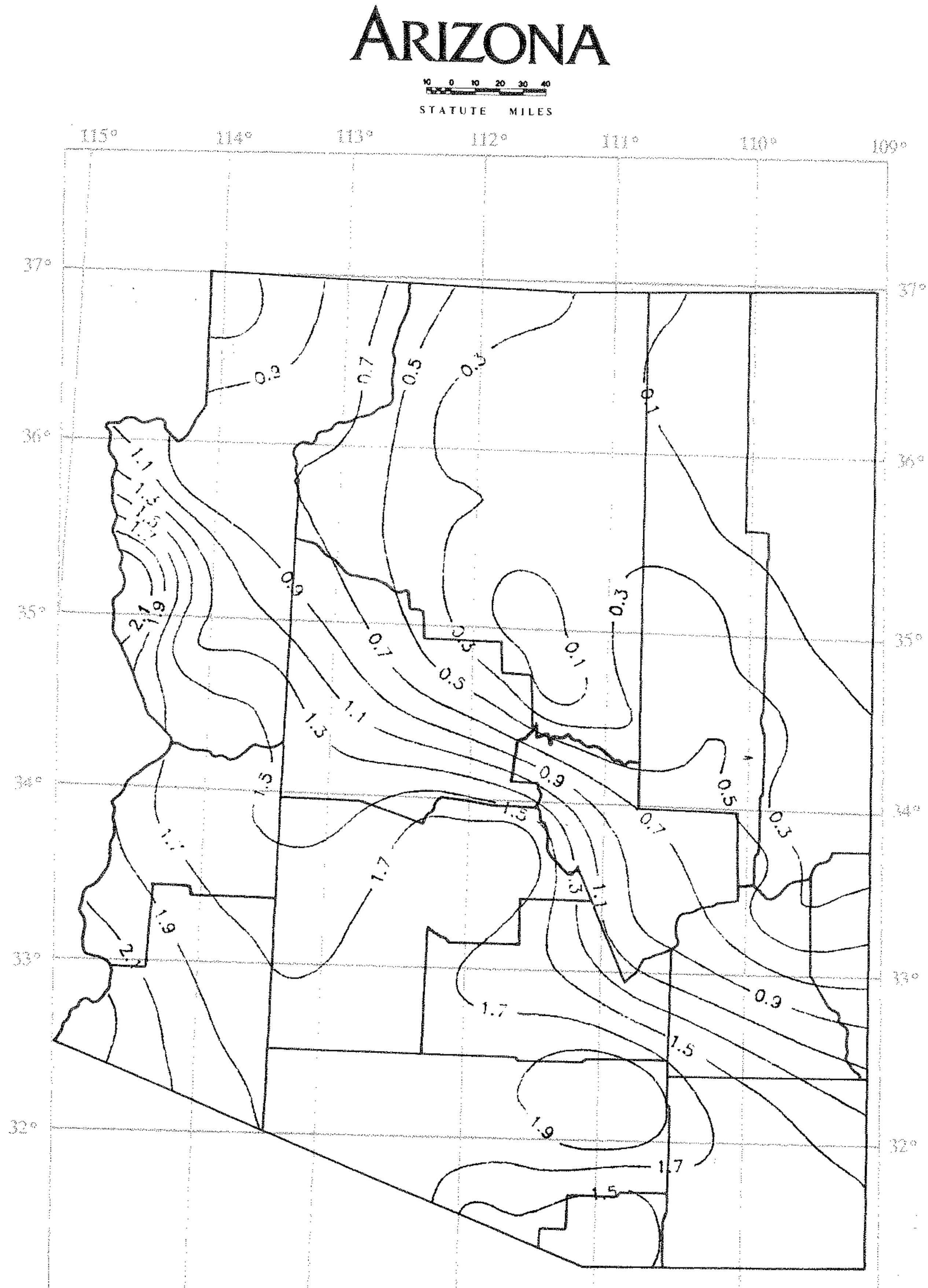

Figure 14. Reference Evapotranspiration (ETo) in millimeters per day – December

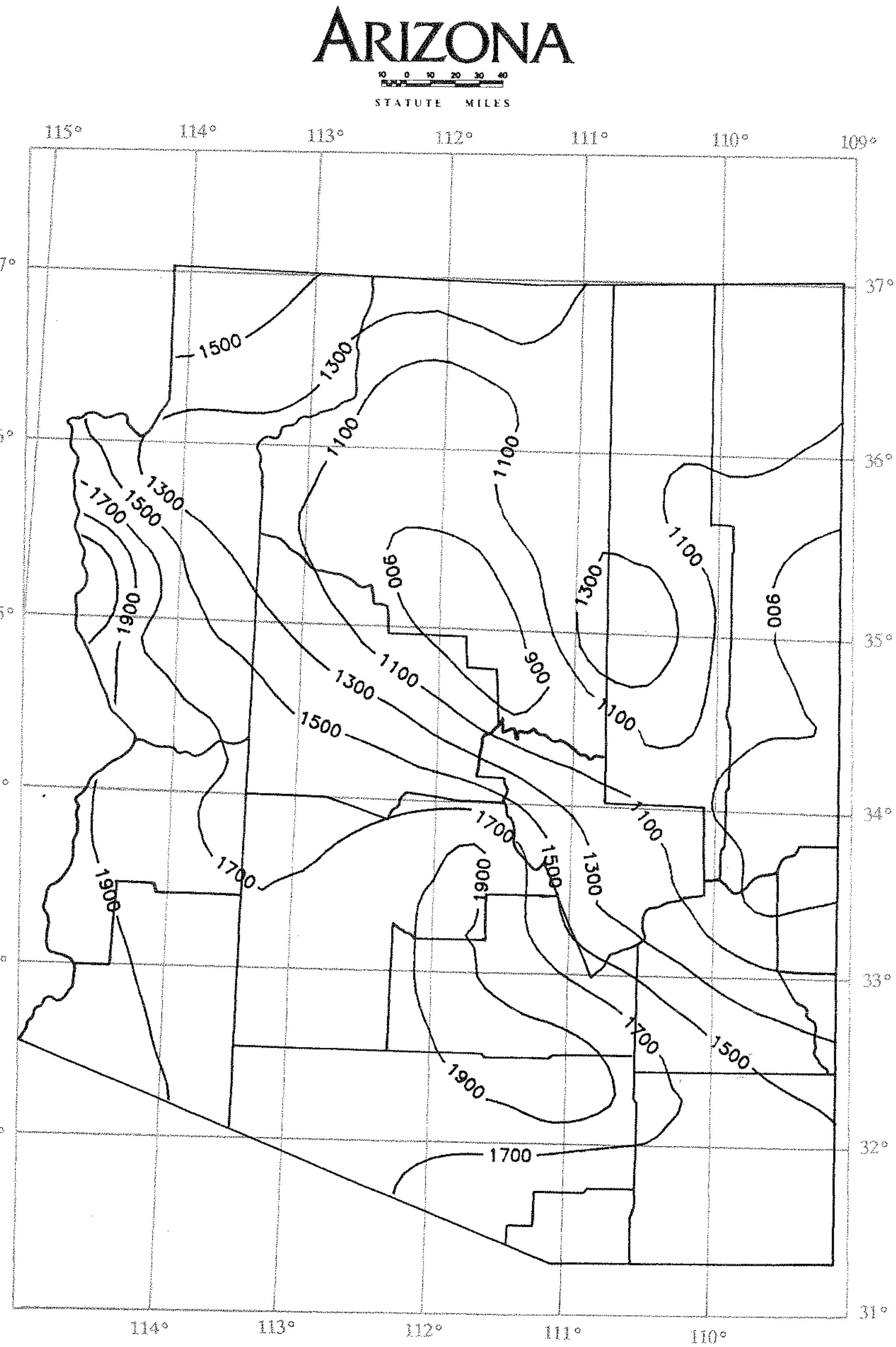

Figure 15. Annual ETo in millimeters

Use of ETo Maps

Maps of ETo provided herein can be used as a data base for long-term mean monthly values for most of the areas of the state. Users are required to know only the latitude and longitude of the locations they are interested in to use the maps.

It should be noted that these values are estimates based on reasonably sound data and assume a normal year with an average condition. The ETo values are accurate within the assumptions made. The ETo values do not reflect short-term variations nor do they represent the actual and complete picture of the complex soil-plant-environment interactions. The values do not account for the effects of slope and aspects since horizontal surfaces were assumed in all of the models. In view of the above facts and because no calibrations were made for regional variations, data presented herein should be used as a first approximation or as a guide, with modification to be made for local, site-specific information.

It should also be emphasized that the maps were not developed to answer detailed questions such as those associated with agricultural water duty. The values presented here may be far from the water duties required or allotted by Arizona Department of Water Resources (ADWR). ETo is only one component of water duty and the other components and factors influencing water duty must be addressed separately.

Calculation of Crop Evapotranspiration (ETc)

It has been pointed out that no local calibration of ETo values were made due to lack of appropriate data. One way by which an adjustment to local variations can be made is through the use of appropriate crop coefficients. Crop coefficient (Kc) is the ratio of the actual crop evapotranspiration to that of the reference evapotranspiration. As such, as pointed out earlier, Kc reflects the capability of the crop-soil system to meet evaporative demand for a general (estimated) climatic condition and at a given stage of growth of a crop. This value is normally developed experimentally by simultaneous measurement of both crop evapotranspiration and reference crop evapotranspiration.

In Arizona, crop evapotranspirations were established for the most common field crops in the state by Erie et al. (1982) using data from the Salt River Valley. There were no simultaneous measurements of reference crop evapotranspiration. This makes it necessary to develop crop coefficients for the crops grown in the state if the ETo values are to be useful. Recognizing this fact, research priority in ET was given to the development of Kc values (Brown and Yitayew, 1988). Presently, Kc values are available for a limited number of Arizona crops. Some of the Kc values being used are adapted from California information. These values will give reasonable actual crop ET values for California (Pruitt et al. 1987) but may need to be verified for Arizona conditions. To this end applied research should be conducted both for validation of California-based Kc values and the development of new ones.

Figure 16 shows ETo and ETc for alfalfa at Mesa, Arizona as functions of time. The ETc values were taken from Erie et al. 1982. As expected, the crop evapotranspiration values are higher than the reference evapotranspiration values by as much as 15 percent depending upon the time of the year. This is consistent with reported values of crop coefficients that reflect this relationship between crop and reference evapotranspiration for alfalfa (Doorenbos and Pruitt, 1977). The figure clearly indicates the reliability of the map values for estimating reference evapotranspiration (ETo).

To use Erie, et al. (1982) values for sites other than Mesa without proper adjustment will result in over- or under-estimation of ETc. Therefore a transformation coefficient map based on the ratio of the annual ETo of the fifty stations to that of Mesa's is provided in Figure 17.

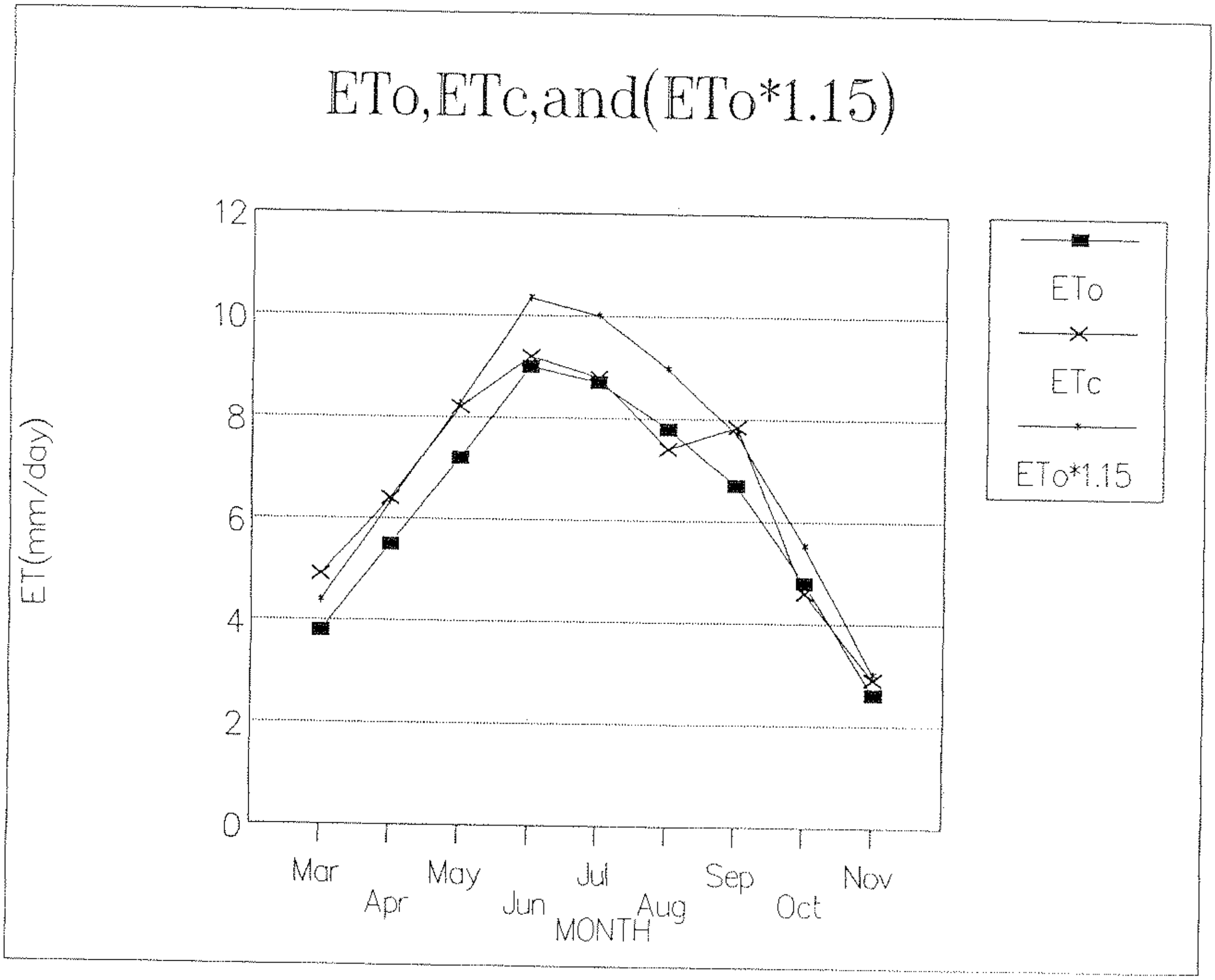

Figure 16. ETo alfalfa, ETc, and (ETo*1.15)

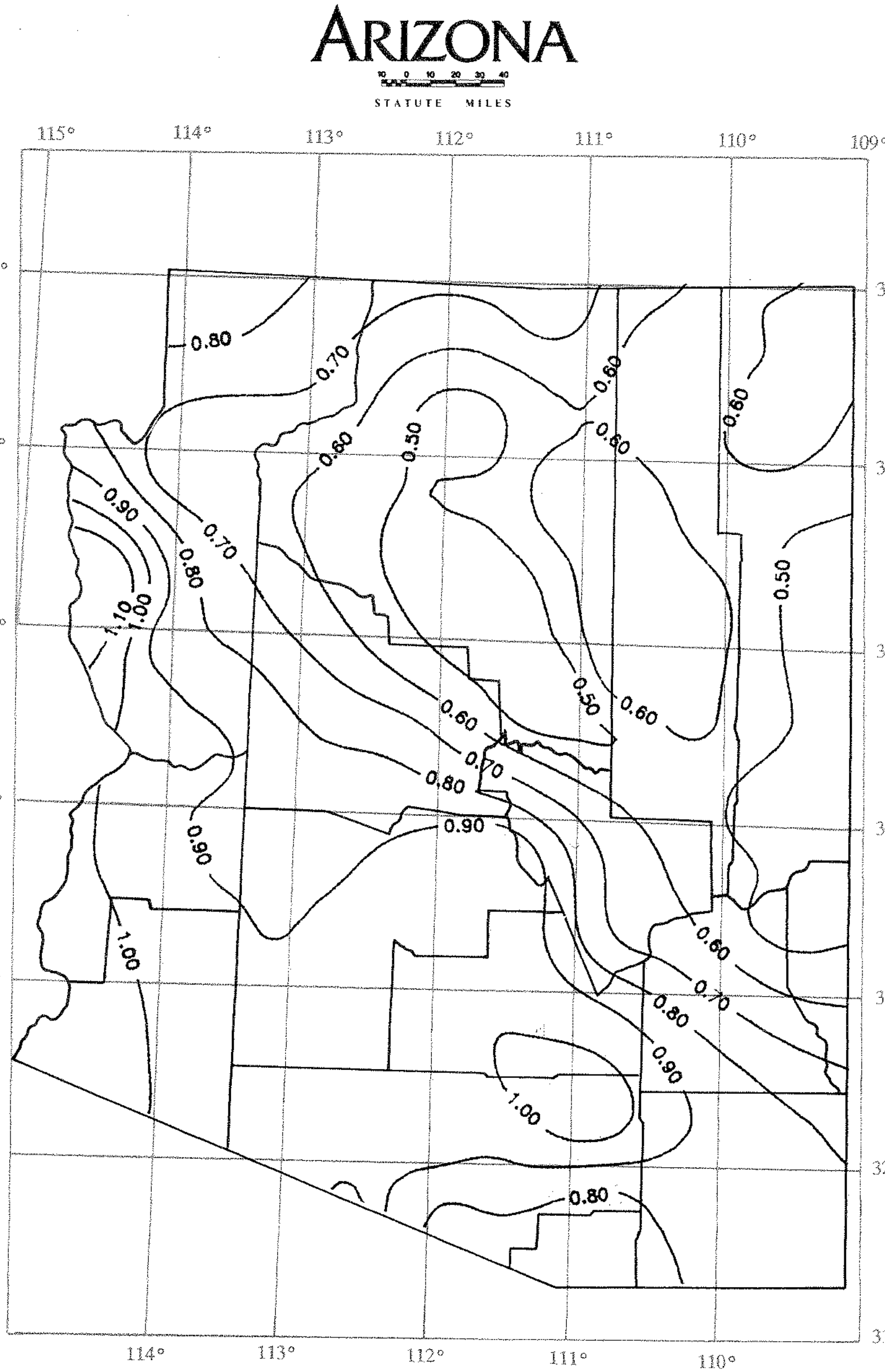

Figure 17. Transfer Coefficient: Ratio of ETo of a Site to that of ETo of Mesa

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