UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# EVAPOTRANSPIRATION LOSSES FROM FLOOD-PLAIN AREAS IN CENTRAL ARIZONA

Open-File Report 76-864

Prepared in cooperation with the Arizona Water Commission

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Tucson, Arizona
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Santa Maria River about 21 mi (34 km) southwest of Bagdad. In the upstream reach spring runoff moves out of the area as surface flow; in the downstream reach, however, the runoff is stored as ground water in the thick alluvial deposits of large areal extent.

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## CONVERSION FACTORS

Factors for converting English units to metric units are shown to four significant figures. In the text, however, the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

| Multiply English unit | By | To obtain metric unit |
|---|---|---|
| acres | 0.4047 | hectares (ha) |
| acre-feet (acre-ft) | .001233 | cubic hectometers ($hm^3$) |
| cubic feet per second ($ft^3/s$) | .02832 | cubic meters per second ($m^3/s$) |
| feet (ft) | .3048 | meters (m) |
| inches (in) | 25.4 | millimeters (mm) |
| miles (mi) | 1.609 | kilometers (km) |

# EVAPOTRANSPIRATION LOSSES FROM FLOOD-PLAIN AREAS IN CENTRAL ARIZONA

By

T. W. Anderson

## ABSTRACT

The present (1975), near-future, long-term future, and potential evapotranspiration losses from flood-plain areas are estimated for most streams in central Arizona. It is assumed that the near-future and long-term future evapotranspiration losses will change as a result of a change in the surface-water flow regimen; although the surface-water flow regimen may change owing to any water-augmentation scheme, the most probable source of additional water will be from vegetation modification in the watershed. The stream channel from the point of introduction of additional water to the downstream user site is the area for which the present, near-future, long-term future, and potential evapotranspiration losses are estimated. The total stream length included in the study is 1, 287 miles (2, 071 kilometers) and includes perennial and intermittent streams. The estimates of present evapotranspiration losses were determined by an integration technique based on areal mapping of vegetation types and

densities and on relations between water use by different types of vegetation and depth to ground water. Several methods were used to check the results, including a base-flow method and a water-budget method. Near-future evapotranspiration losses were estimated using the integration method, and the increase in loss is attributed to shallower depths to water; it is assumed that long-term future losses will increase further owing to an increase in riparian vegetation density. Empirical methods were used to estimate the potential evapotranspiration losses.

Many of the streams included in the study are perennial; the near-future and long-term future increases in evapotranspiration losses are estimated to be negligible for the perennial streams. The streams for which large increases in evapotranspiration losses are predicted are generally in the west-central part of the State, where the environment is desert to semidesert.

The report gives a summary of the general hydrologic, vegetative, and geomorphic conditions for most streams in the study area. In addition the present, near-future, long-term future, and potential evapotranspiration losses and the estimated increase in evapotranspiration losses are presented.

# INTRODUCTION

An average of 80 million acre-ft (98,600 $hm^3$) per year of water falls as rain and snow in Arizona; however, more than 95 percent is consumed by evaporation and transpiration (Harshbarger and others, 1966, p. 4-5). At the present time (1975), the remaining 5 percent is available for man's use; however, this small amount of water is poorly distributed in time and space. Several potential sources of water augmentation and methods for better water management have been suggested in an attempt to increase the available supply, including water importation, interbasin transfer, cloud seeding, augmentation by ground-water pumpage, and vegetation modification in the watershed.

Vegetation modification is considered to be the prime possibility in the search for additional water. The modification process involves either the thinning of present watershed vegetation or the replacement of present watershed vegetation with types having lower consumptive use. One of the benefits would be an increase in runoff by decreasing the consumptive use and amount of interception losses attributed to the native vegetation in the watershed.

In order to accrue a beneficial value any additional streamflow, regardless of source, must reach a downstream user. The assumption is made that natural channels would be the means of conveyance, and, therefore, some of the streamflow may be lost in transit. The reach of channel from the point of introduction of additional streamflow to the downstream user site is the area of interest in this report. The study was undertaken by the U.S. Geological Survey in cooperation with the Arizona Water Commission.

## Purpose and Scope of Investigation

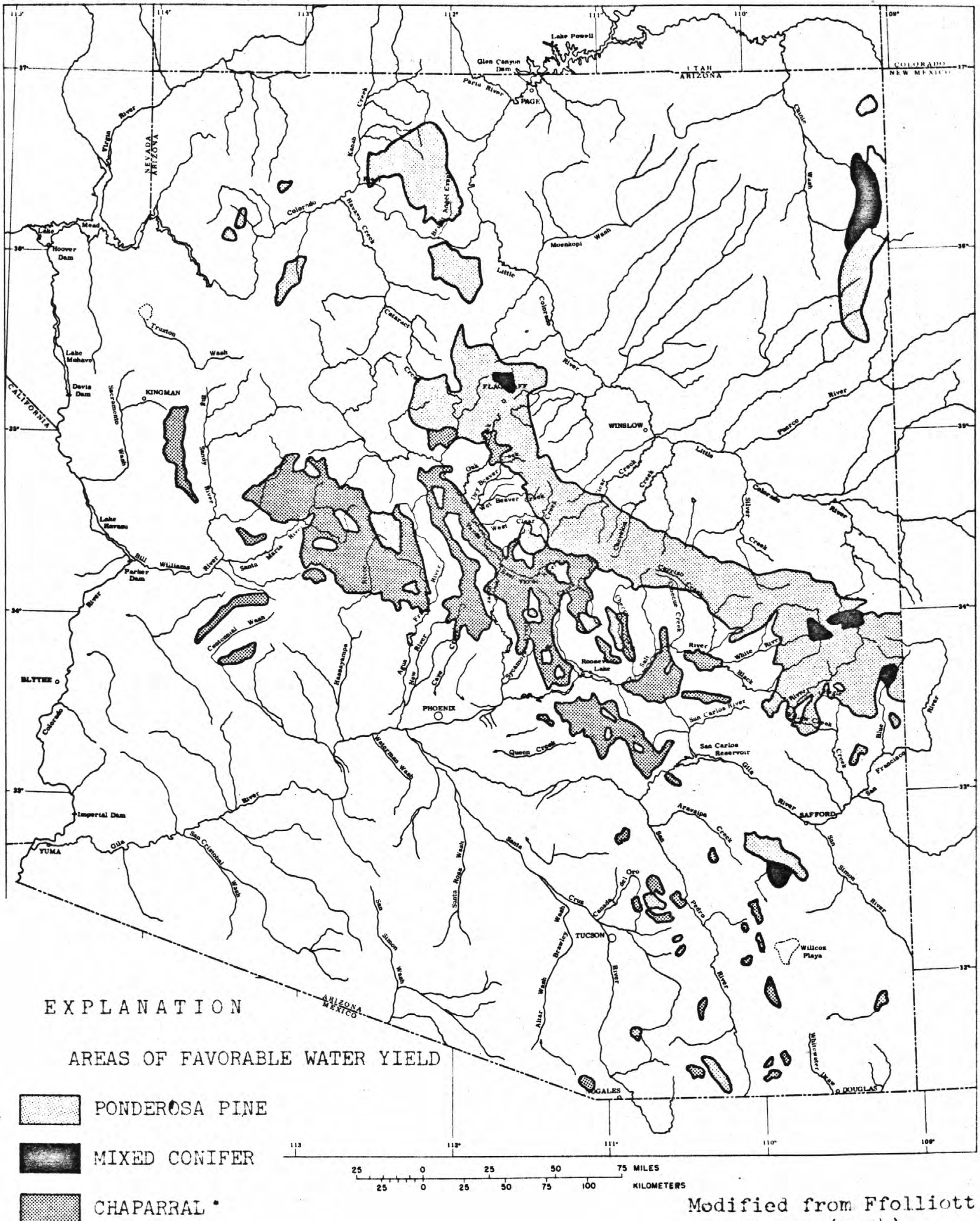
The purpose of this investigation was to estimate the possible increase in transitory water losses that may occur as a result of an increase in the availability of water at the upstream end of selected streams in central Arizona. The losses are attributed largely to transpiration by vegetation in the riparian zone and to evaporation from soil and open-water surfaces along the stream channels that may receive additional water as the result of some future water-augmentation scheme. Loss estimates were made using the existing flow conditions and assumed future increased flow conditions. The estimates of evapotranspiration losses are based on consumptive use rates derived from other studies (Gatewood and others, 1950; Rantz, 1968; van Hylckama, 1970) and, therefore, serve only to show the possible increase in losses that may occur along the stream channels assuming an increase in the flow regimen. Estimates of present losses were made using an inventory of existing vegetation in the riparian zone determined from aerial photographs and using empirical data on consumptive use for different vegetation types, densities, and depths to water. Estimates of future losses were made based on the assumption that more water will be available in the stream channels. The difference between present and future evapotranspiration losses for any reach will equal the amount of water that can be lost in transit if sufficient water to cause perennial flow throughout the reach were introduced into the stream. Although the source of additional water was not of particular concern in this study, it is assumed that the most probable source will be as a result of vegetation modification in the watershed; this assumption greatly influenced the areal extent of the investigation.

## Area-Selection Criteria

The selection of the areas and stream channels for this study was controlled by several factors. The principal factors were vegetation climax, average annual and seasonal precipitation characteristics, and downstream water use. Secondary factors were geology, potential sediment yield, and land ownership. Although the secondary factors were considered during the investigation, they proved to be nonlimiting because the areas in which one of the factors might be critical are small. All the factors considered as criteria for determining the extent of the study area are interrelated; however, the principal criterion was the vegetation climax, which is defined by the dominant mature vegetation type in the watershed.

The vegetation climax is dependent primarily on the climate, altitude, soil, and topography in the area. The reason for selecting areas of a particular vegetation type is the potential for water-yield improvement through vegetation modification. Figure 1 shows areas of favorable water yield based on vegetation climax. The vegetation types considered most favorable for increasing water yield through vegetation modification are ponderosa pine, mixed conifer, and chaparral. According to Hibbert and Ingebo (1971, p. 26) ". . . conversions in the pinyon-juniper type have shown little promise of increasing water yield."

The average annual and seasonal precipitation characteristics were another principal criterion used in establishing the limitations on the extent of the study area assuming that the prime source of additional water will be from vegetation modification. "Average annual precipitation of 16 inches (406 mm) is considered as the minimum for possible increased yield, with average winter precipitation of 10 inches (254 mm) to assure a reasonable increase" (Lower Colorado Region State-Federal Interagency Group for the Pacific Southwest




Modified from Ffolliott and Thorud (1974)

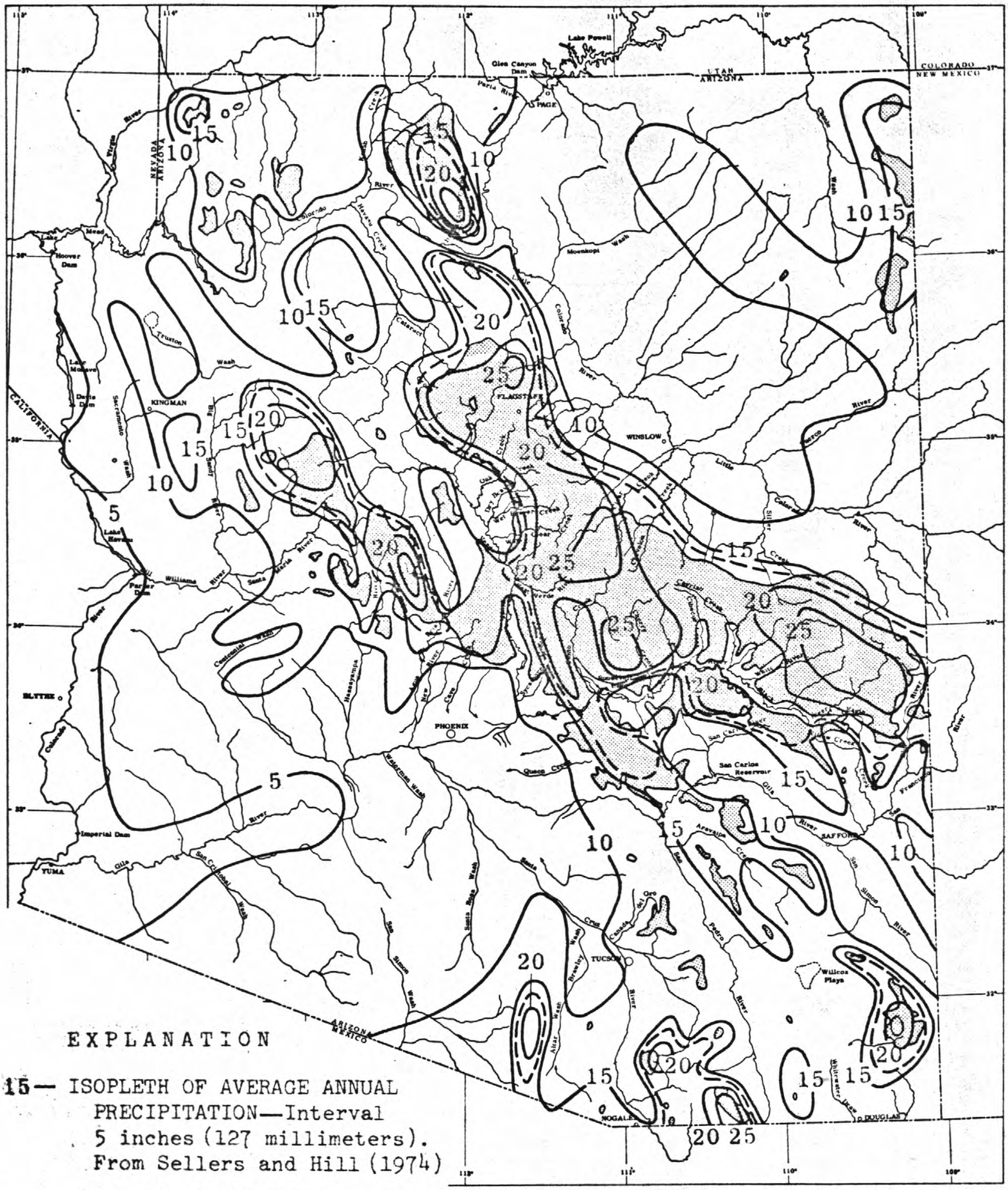
Figure 1.--Areas of favorable water yield based on the distribution of ponderosa pine, mixed conifer, and chaparral vegetation in Arizona.

Interagency Committee, 1971, p. 141). Figure 2 shows the areas in the State that meet these criteria.

Downstream water use is an important consideration in vegetation management or for any water-import scheme because the value of additional water must justify the cost of the project. Any existing or potential use—irrigation, public supply, recreation, and other uses—was considered as a partial justification for inclusion of a channel reach in this study.

## Location and Extent of Area

Most of the areas in Arizona that meet all the aforementioned criteria are along the south side of the Mogollon Rim in the Central highlands water province (fig. 3). The areas include the flood plains of the major streams that drain the central part of the State. The streams drain a broad west-northwest-trending band that extends from the Arizona-New Mexico State line on the east to near the Colorado River on the west (fig. 4); the band is south of the Mogollon Rim, which is about coincident with the dividing line between the Plateau uplands and the Central highlands water provinces in Arizona (fig. 3). The streams that drain the area in the extreme north-central part of the State (fig. 3) and those that drain northeast from the Mogollon Rim




EXPLANATION

—15— ISOPLETH OF AVERAGE ANNUAL PRECIPITATION—Interval 5 inches (127 millimeters). From Sellers and Hill (1974)

----- ISOPLETH OF 16 INCHES (406 MILLIMETERS) AVERAGE ANNUAL PRECIPITATION

AREA IN WHICH NORMAL OCTOBER-APRIL PRECIPITATION EXCEEDS 10 INCHES (254 MILLIMETERS)—From University of Arizona (1965)

Figure 2.--Average annual and normal October-April precipitation in Arizona.

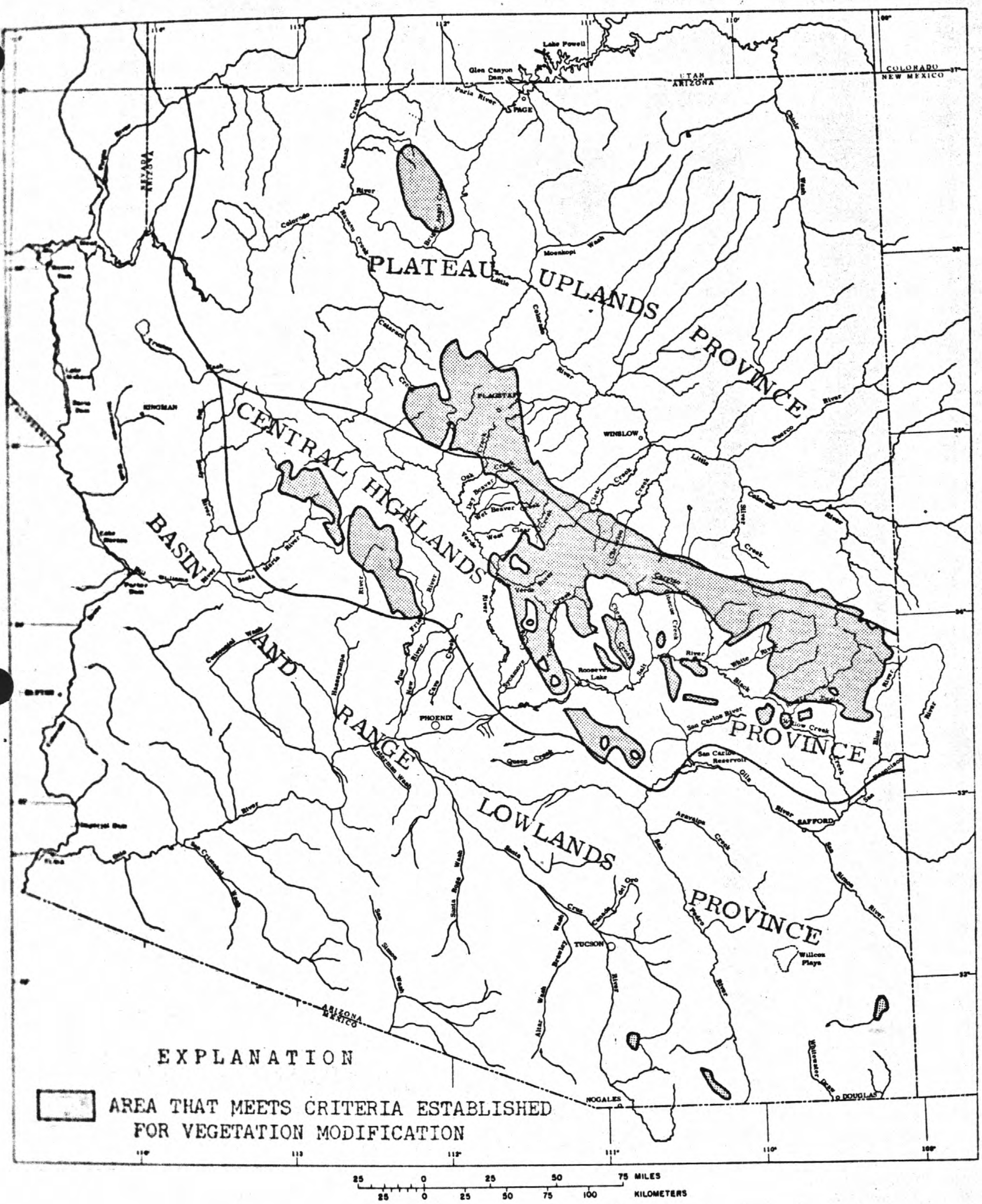



**Figure 3.**--Arizona's water provinces and areas that meet criteria established for vegetation modification to increase water yield.

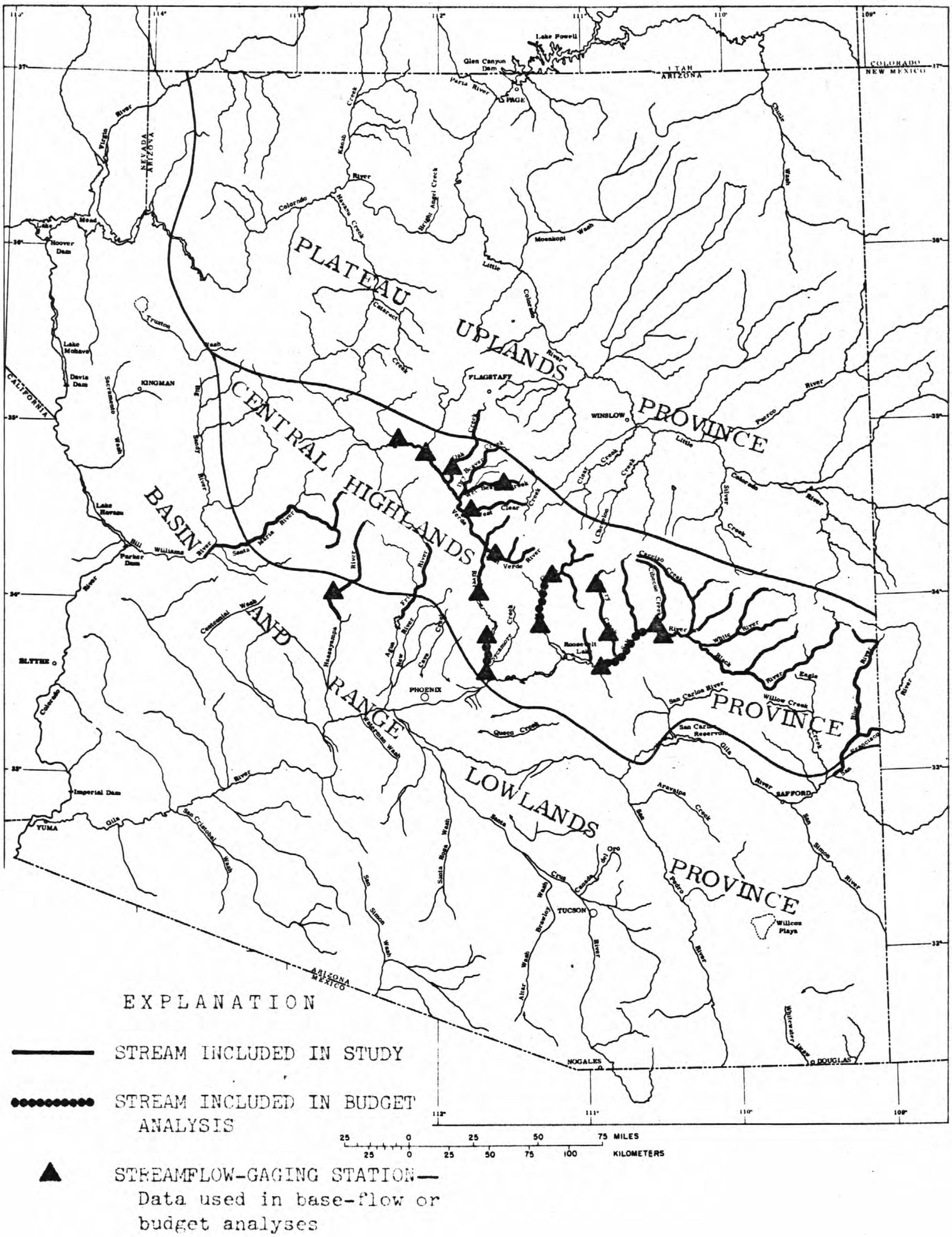



Figure 4.--Streams included in the study, streams included in the budget analysis, and streamflow-gaging stations from which data were used in the base-flow or budget analyses of evapotranspiration losses.

were not included in this investigation. The evapotranspiration losses for the Agua Fria River drainage have been described by Anderson (1970) and are summarized in this report.

The total stream length included in the study is about 1, 287 mi (2, 071 km). (See table 1 and fig. 4.) The streams flow generally toward the south or southwest and include intermittent and perennial streams. The altitude of the flood plains ranges from about 1, 100 ft (340 m) above mean sea level near Alamo Reservoir on the Bill Williams River to more than 7, 500 ft (2, 300 m) near the headwaters of Black River, White River, Blue River, and Big Bonita Creek.

The riparian vegetation along the streams includes desertscrub, weeds, grass, mesquite, saltcedar, cottonwood, willow, and large deciduous trees, such as alder, sycamore, walnut, and ash. Evergreen vegetation—such as ponderosa pine, juniper, and pinyon—was not mapped with the riparian vegetation.

## General Hydrogeologic Setting

Central Arizona receives the largest amount of precipitation of any area in the State. Most of the streams are tributary to either the Salt or Verde Rivers. The reservoirs on the rivers impound water for the Salt River Project—the irrigation project that serves the Phoenix area.

Table 1.--Approximate length of stream channels included in the study in central Arizona

[Listed in general east to west order]

| Stream name | Length, in miles |
|---|---|
| Blue River | 49 |
| San Francisco River | 43 |
| Black River | 111 |
| Big Bonita Creek | 26 |
| White River-North Fork | 20 |
| -East Fork | 21 |
| -Main Stem | 16 |
| Salt River | 87 |
| Carrizo Creek | 56 |
| Corduroy Creek | 22 |
| Cedar Creek | 22 |
| Cibecue Creek | 43 |
| Canyon Creek | 46 |
| Cherry Creek | 44 |
| Salome Creek | 12 |
| Tonto Creek | 59 |
| Haigler Creek | 19 |
| Spring Creek | 17 |
| Verde River | 159 |
| East Verde River | 40 |
| Pine Creek | 13 |
| Fossil Creek | 20 |
| West Clear Creek | 32 |
| Wet Beaver Creek | 27 |
| Dry Beaver Creek | 32 |
| Oak Creek | 47 |
| Agua Fria River | 44 |
| Hassayampa River | 47 |
| Bill Williams River | 5 |
| Santa Maria River | 49 |
| Kirkland Creek | 37 |
| Skull Valley Creek | 22 |
| Total | 1,287 |

The general hydrologic cycle in and along the streams is depicted in figure 5. Although the geology is diverse, the basement rock is generally granite or gneiss, and large parts of the area are overlain by basalt. The flood plains are from a few tens of feet to more than 1 mi (1.6 km) wide, and the stream gradients also have a wide range. The alluvium along the flood plains consists of silt to cobbles, and the thickness ranges from zero to more than 100 ft (30 m). The presence of large stands of riparian vegetation is dependent mainly on the presence of a ground-water reservoir along the channel. Large pockets of alluvium sufficient in size to contain a significant amount of ground water are generally along the reaches having a shallow slope. Therefore, the geomorphic characteristics of a reach control many factors.

## Geomorphic Setting

Considerable information can be inferred about a stream, especially as it relates to the evapotranspiration potential, by observing the general geomorphic setting. A stream valley is in one of three general stages of geomorphic development—young, mature, or old age (Thornbury, 1956, p. 101). Each stage has certain physical characteristics associated with it, and many of the conditions

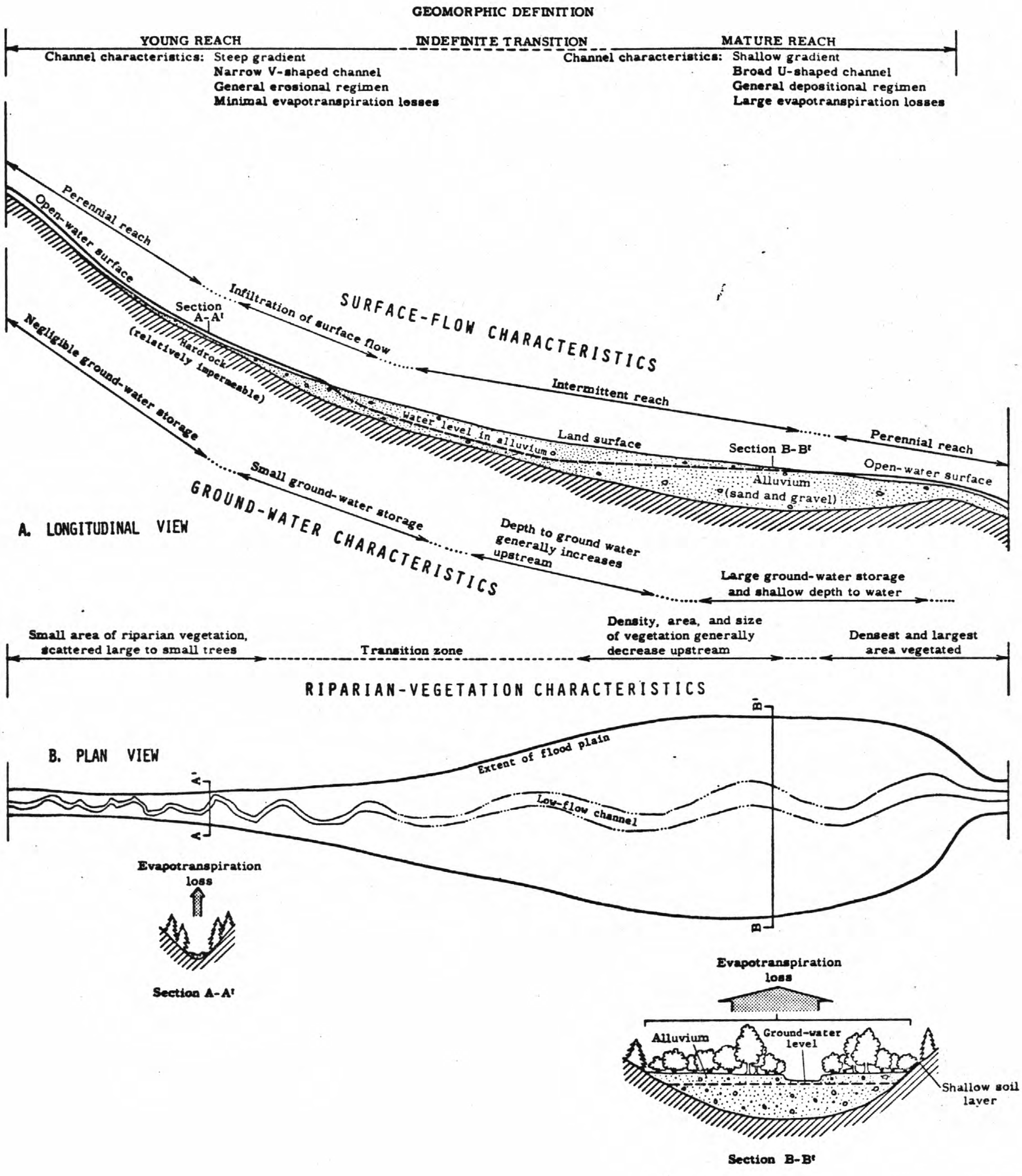



Figure 5.--General hydrologic system and geomorphic conditions along stream channels in central Arizona.

that affect evaporation and transpiration in a stream valley are related to the geomorphology of the valley. In general, where a stream valley has a particular geomorphic history or exhibits particular geomorphic characteristics, one or several typical evapotranspiration conditions may be predicted.

Arizona has no truly old age streams; therefore, a comparison of the physical characteristics of youthful and mature valleys provides a usable contrast of features as they relate to evapotranspiration by riparian vegetation. A summary of the major controlling features is given below.

| Feature | Characteristic of feature | |
|---|---|---|
| | Young | Mature |
| Gradient of valley | Steep | Mild |
| Shape of valley cross section | V-shaped | U-shaped |
| Width of valley floor | Narrow | Wide |
| Longitudinal shape of channel | Nearly straight or jagged | Subrounded |

Based on a knowledge of these features, other characteristics may be inferred, such as location of reach on longitudinal stream profile, erosional and depositional characteristics; surface-water flow characteristics, and ground-water characteristics.

Figure 5 illustrates the contrast in characteristics between young and mature reaches. The part of the valley classified as young is the headwaters reach. The slope is steepest in the upstream reach and gradually decreases in the downstream direction, which gives a general concave upward shape to the channel profile. The differences in slope associated with age define the differences in erosional and depositional patterns in the stream channel. In the young reach erosion is dominant, although minor pockets of coarse depositional material may be present that will be removed during high flows. The velocity of flow is proportional to the slope of the channel. In the young reach velocities are higher relative to those in the mature reach. As a result of these factors, little opportunity exists for the development of alluvial areas or large stands of riparian vegetation in the young reaches. In contrast, the mature reach typically has a mild slope, a generally balanced erosional-depositional regimen, a lower flow velocity, a large ground-water storage area, and a wide flood plain—all factors that are conducive to the establishment and maintenance of riparian vegetation communities. In a mature reach the material is deposited in a particular manner. At the upstream end of the alluvial-fill areas, the average grain size of the deposits will be larger than that at the downstream end because the larger material will be dropped from suspension first as the water velocity slows.

Figure 5 shows the general hydrologic conditions in young and mature reaches. Based on observations made during this study, the general statement can be made that the shallowest ground water in the mature reach occurs at the downstream end, where flow frequently is perennial at the outlet of the basin. Thus, the density and size of the riparian vegetation will be greatest at the downstream end.

All the above factors are related to the estimates of consumptive use by riparian vegetation. Using these factors and field observations, two general guidelines can be established; minimal evapotranspiration losses occur in a young valley reach, and the largest evapotranspiration losses occur at the downstream end of a channel in a mature valley and decrease in the upstream direction.

## Acknowledgments

During this study, cooperation was received from many employees of the Arizona Game and Fish Department. The author is especially grateful for the assistance given by John Theobald in mapping riparian vegetation types and densities. Special thanks are due personnel of the Photogrammetry and Mapping Division of the Arizona Highway Department for the aerial photographs.

## METHODS OF ANALYSIS

Estimates of present evapotranspiration losses and possible future evapotranspiration losses were made using available data and several analytical techniques. The existing losses were estimated using the integration method (Chow, 1964, sec. 11, p. 25), base-flow method, and water-budget method. The possible future losses were estimated using the integration method and empirical potential evapotranspiration method, which was applied using the following techniques: (1) adjusted pan evaporation, (2) the Thornthwaite (1948) method, (3) the Blaney-Criddle (1950) method, and (4) lake evaporation.

In estimating present (1975) evapotranspiration losses the integration method is the only method that could be applied everywhere in the study area. The base-flow and water-budget methods are dependent on adequate streamflow records, and the water-budget method requires inflow and outflow data. Therefore, these two methods have limited application and were used where possible as a means of verifying the estimates obtained by the integration method.

The integration method also was used to estimate future losses assuming a greater flow regimen than exists at present (1975). In the future the factor that will have the greatest effect is shallower depth to water in the reaches that do not have perennial flow at the present time. Basically, the method uses the available data on consumptive use and depth to water to define a general relation for a specific vegetation type. A general relation was then developed for each of the different types of riparian vegetation mapped along the stream channels in the study area. The areas are all normalized with respect to areal density. The method includes evaporation losses from bare soil and open-water surfaces in the areas where this loss is significant. The total evapotranspiration for a given reach of stream was determined by summing the products of evapotranspiration for each vegetation type times its area, plus evaporation from bare soil times its area, plus open-water surface evaporation times its area.

The use of base-flow records was possible only at streamflow-gaging stations having sufficient record (fig. 4). The period of record used was of varying length but was at least 8 years long; the maximum length of record was 13 years—1961-73. The difference between the average winter and average summer base flow for the period of record provided an estimate of the possible consumptive use by water-loving riparian vegetation.

The budget analysis of evapotranspiration losses is the summation of all flow components into and out of the channel reach. The budget equation for the flow in a reach is

$$\sum_{i=1}^{8} S_i = O, \qquad (1)$$

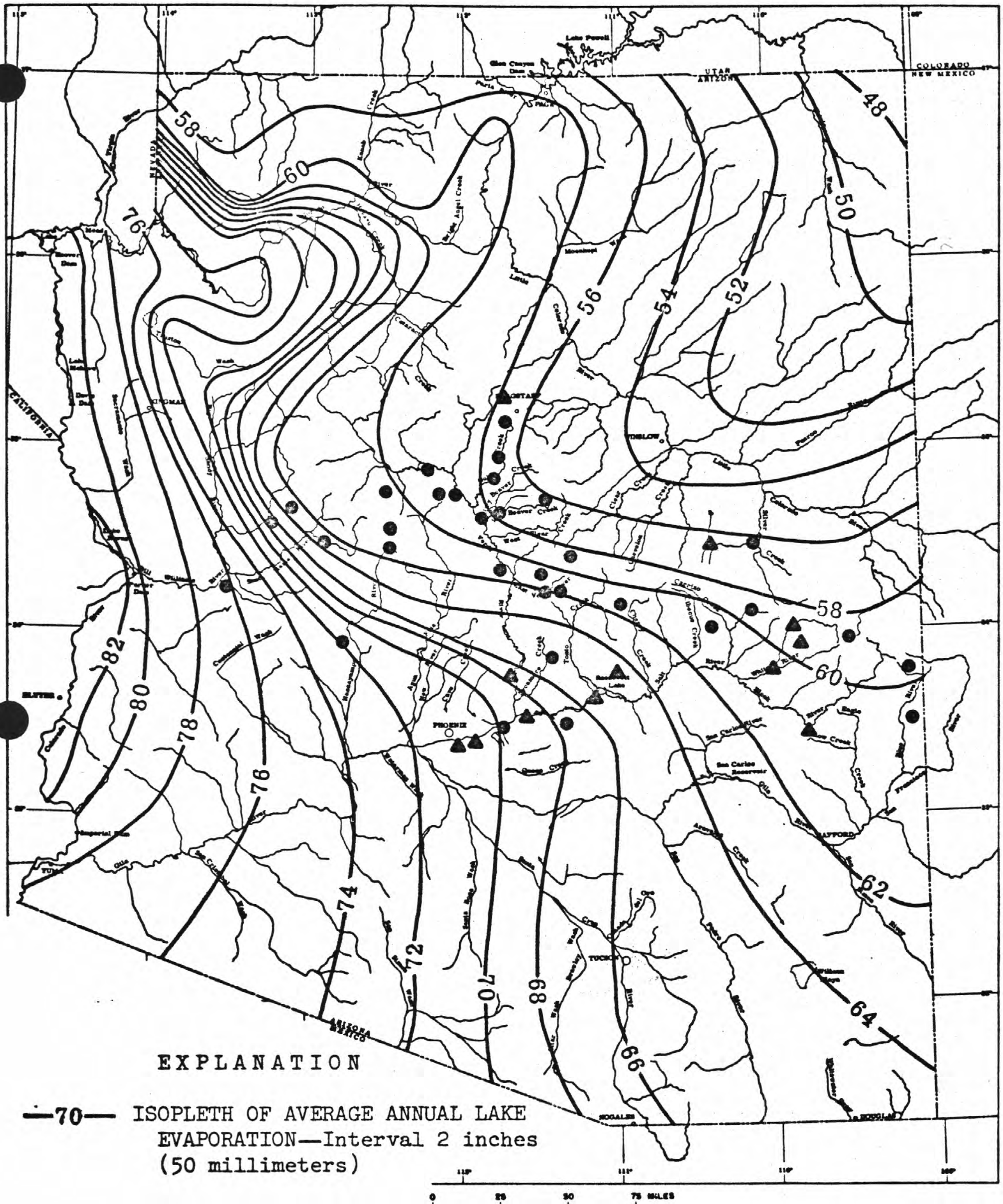
where $S_1, \ldots, S_8$ denote volumes of (1) surface-water inflow at the upstream end, (2) tributary inflow, (3) ground-water inflow, (4) precipitation on the flood plain, (5) losses to infiltration and seepage, (6) surface-water outflow at the downstream end, (7) changes in ground-water storage, and (8) evapotranspiration. Only the reaches in which surface-water inflow and outflow are monitored by streamflow-gaging stations were used, and daily flow data for the reaches were used only for the periods in which the system was in an approximate steady state. Periods of large precipitation or unusual tributary inflow to the budget reach were not included. Only the reaches in which no known diversions exist were used. Using these limitations and the assumption that flow to or from the ground-water system was constant throughout the year, it was possible to compare the average summer budget with the average winter budget for the period of available data since 1961 and to assume that the difference was equal to the evapotranspiration losses by riparian vegetation in the reach during the summer; this necessitated the assumption that evapotranspiration losses are virtually nonexistent in the winter.

The budget method is very similar to the base-flow method in that averages for the summer and winter periods are compared, and the difference is assumed to be attributable to evapotranspiration. The difference between the methods is in the area in which the evapotranspiration loss may occur. In the budget method the loss occurs in the reach between the inflow and outflow points; in the base-flow method the loss occurs throughout the watershed upstream from the gaging station and, therefore, necessarily includes the areas of upland vegetation.

Future evapotranspiration losses were estimated using the integration method. Two possible future conditions were assumed, and estimates for each condition were made. The possible future conditions are (1) near future, for which only the depth-to-water changes and increases in consumptive use would result from greater water availability via a shallower ground-water table; and (2) long-term future, for which the shallower water table is accompanied by an increase in density of the native riparian vegetation—the final density would fall in the dense category, which is explained later.

In addition, a third value for future losses was estimated based on the value of potential evapotranspiration. For this future condition it is assumed that the vegetation density will increase to an optimum value in the areas where vegetation now exists; no change is assumed for the area of bare soil. Potential evapotranspiration has been defined by Langbein and Iseri (1960, p. 15) as the "water loss that will occur if at no time there is a deficiency of water in the soil for use of vegetation." Many empirical methods are available by which the potential evapotranspiration may be estimated. In this study several methods are used including (1) adjusted pan evaporation, (2) the Thornthwaite (1948) method, (3) the Blaney-Criddle (1950) method, and (4) lake evaporation. The methods were used because of the availability of the types of data required. Most other methods are more difficult to apply because they require such data as net solar radiation, windspeed, and saturated water-vapor density, which are not readily available.

For this study, adjusted pan evaporation was determined as a function of altitude. Adjusted pan evaporation is considered to be different from lake evaporation in that it more accurately reflects the influence of altitude; a relation was derived using only data in or near the study area, whereas the lake-evaporation map (fig. 6) is from a generalized map of the United States. Adjusted pan evaporation was estimated by relating average annual pan evaporation to altitude and then adjusting that figure by use of an empirical regional coefficient.




EXPLANATION

—70— ISOPLETH OF AVERAGE ANNUAL LAKE EVAPORATION—Interval 2 inches (50 millimeters)

● TEMPERATURE STATION

▲ TEMPERATURE AND EVAPORATION STATION

Data from U.S. Weather Bureau (1959)

Figure 6.--Average annual lake evaporation and location of temperature and evaporation stations used in central Arizona.

The Thornthwaite method is an empirical relation derived from data for a humid climate. The relation is

$$e_T = 1.6(10T/I)^a, \tag{2}$$

where

$e_T$ = unadjusted potential evapotranspiration, in centimeters, for a 30-day month;

$T$ = mean monthly air temperature, in degrees Celsius;

$I$ = heat index; and

$a$ = cubic function of $I$ and $T$.

The Thornthwaite method is not applicable in the arid West and will be used for comparison purposes only. According to Cruff and Thompson (1967, p. 1) and the Technical Committee on Irrigation Water Requirements (1973, p. 146), results obtained using the Thornthwaite method are consistently low compared with results obtained using the adjusted pan evaporation method.

The Blaney-Criddle method relates mean monthly consumptive use to mean monthly temperature and percentage of total daytime hours. The relation is

$$U = K \sum \frac{T \times p}{100}, \tag{3}$$

where

U = consumptive use, in inches, during growth of the crop;

K = empirical consumptive-use coefficient that is dependent on the type and location of crop;

p = monthly percentage of total daytime hours in the year; and

T = mean monthly temperature, in degrees Fahrenheit.

The method assumes that ample moisture is available for use by vegetation. Cruff and Thompson (1967, p. 1) concluded that ". . . the Blaney-Criddle method . . . was the most practical . . . for estimating potential evapotranspiration."

Cruff and Thompson (1967, p. 2) assumed ". . . that lake evaporation may be used as a good average estimate of potential evapotranspiration." Strictly, this assumption does not apply in the area of this study because the riparian zone sometimes occurs as a stark ribbon of fairly dense vegetation in an otherwise slightly vegetated area—an oasis effect. Estimates of lake evaporation are obtained using pan evaporation adjusted by means of a regional coefficient.

## HYDROLOGIC DATA

The hydrologic data required for the application of the different methods of estimating evapotranspiration losses include rainfall, streamflow, temperature, and evaporation data. Ground-water levels also are desirable to document the depth to water along the streams.

Rainfall data are of primary importance in determining the suitability of an area for undergoing vegetation modification. As mentioned in the section entitled "Area-Selection Criteria," certain criteria must be met in regard to annual and seasonal precipitation. Rainfall is important in that it serves as a source of soil moisture during the growing season, and any moisture supplied by rainfall will not be derived from local ground water or streamflow.

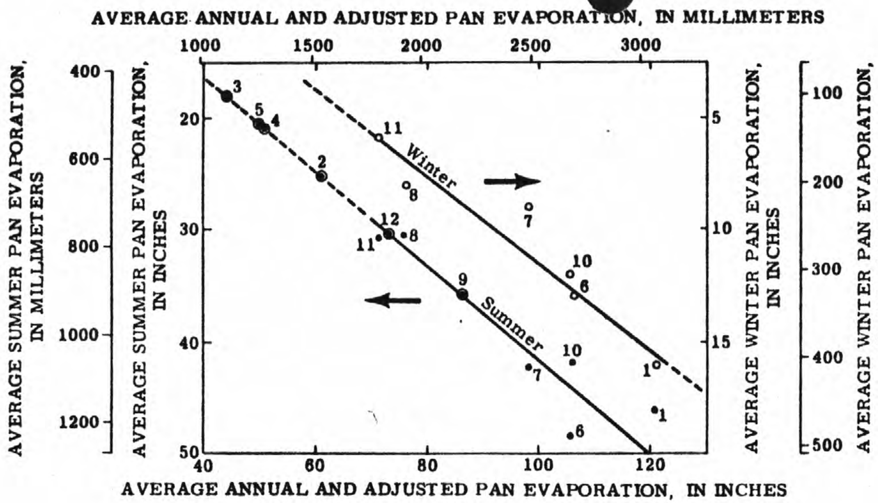
Streamflow data are important for use in the base-flow and water-budget methods of estimating evapotranspiration losses. Data from 17 streamflow-gaging stations were used in the study (fig. 4). All the gaging stations in the study area could not be used because of factors that affect the accuracy of the base-flow record—length of record, large runoff from snowmelt, or diversions. Only periods of steady base flow were used in estimating evapotranspiration losses. In the base-flow method the minimum daily flow for summer (June, July, and August) averaged over the period of available data since

1961 was compared to similar data for winter (December, January, and February), and the difference was attributed to consumptive use by riparian vegetation. In the water-budget method only the average daily discharge for periods of steady inflow and outflow were considered. The results of the budget analysis for the summer were compared with the results for the winter and the difference in inflow-outflow characteristics was attributed to the consumptive use by riparian vegetation in the budget reach.

Pan-evaporation data were used to define a general relation between potential evapotranspiration and altitude, which was accomplished by relating available pan-evaporation data to altitude and in turn using an empirical coefficient to relate pan evaporation to potential evapotranspiration. The object of relating pan evaporation to potential evapotranspiration is to obtain a number that will represent a best estimate because it is based on pan-evaporation data obtained in and immediately adjacent to the study area.

The U.S. Weather Service operates 12 pan-evaporation stations in and near the study area (fig. 6). Evaporation and evapotranspiration are dependent mainly on atmospheric conditions. One factor that affects atmospheric conditions is altitude, and other factors—such as soil, water, and plant conditions—also affect the rate of evapotranspiration.

For most of the evaporation stations at higher altitudes, annual data are incomplete. Because some of the streams in the study area are at high altitudes and have incomplete annual pan-evaporation data, it was necessary to extrapolate the lower altitude pan-evaporation data to the higher altitudes. The average pan evaporation for the summer was compared to the average annual pan evaporation for six stations having complete annual data (fig. 7A). The stations also were used to correlate winter pan evaporation with annual pan evaporation (fig. 7A). The seasonal relations were then used to develop the relation of annual pan evaporation to the corresponding altitude of the pan-evaporation station (fig. 7B). The pan-evaporation data used to develop the relation are given in table 2. An average coefficient of 0.70 has been used to relate Class A pan evaporation to potential evapotranspiration (Linsley and others, 1958, p. 117); the adjusted value of pan evaporation is referred to as adjusted pan evaporation. The theoretical relation between adjusted pan evaporation—which is assumed to be synonymous with potential evapotranspiration—and altitude is shown in figure 7B. Direct use of this relation allows an estimate of potential evapotranspiration for each stream based on the actual altitude and local data.



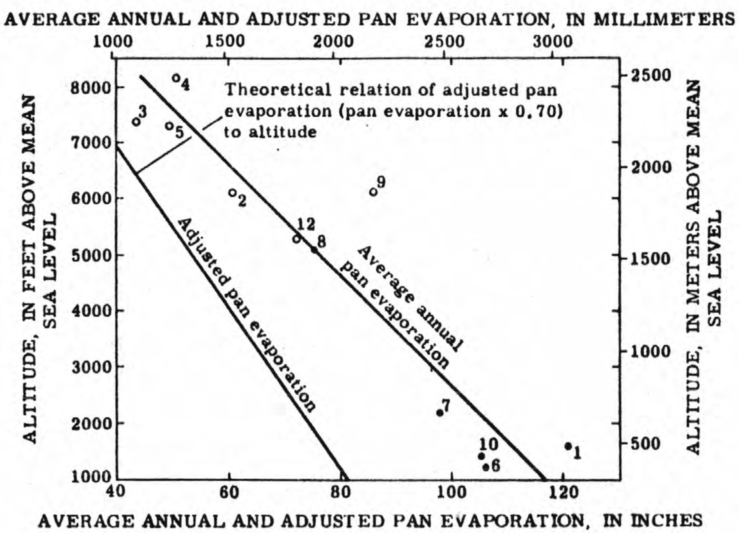

A. Relation between summer and winter pan evaporation and annual evaporation.

**EXPLANATION**

SUMMER PAN EVAPORATION—Number refers to station in table 2

WINTER PAN EVAPORATION—Number refers to station in table 2

ESTIMATE OF AVERAGE ANNUAL EVAPORATION—Based on summer pan evaporation. Number refers to station in table 2




B. Relation between pan and adjusted pan evaporation and altitude.

**EXPLANATION**

PAN EVAPORATION STATION FOR WHICH COMPLETE RECORD FOR YEAR IS AVAILABLE—Number refers to station in table 2

STATION WITH AVERAGE PAN EVAPORATION BASED ON RELATION IN FIGURE 7A—Estimated from summer data. Number refers to station in table 2

**Figure 7.--Relation between summer and winter pan evaporation and annual evaporation, and relation between pan and adjusted pan evaporation and altitude in the study area.**

Table 2.--Summer, winter, and annual pan evaporation at selected stations in central Arizona

[Data from Sellers and Hill, 1974, p. 39-45]

| Station | Altitude, in feet above mean sea level | Pan evaporation, in inches | | |
|---|---|---|---|---|
| | | Summer | Winter | Annual |
| (1) Bartlett Dam | 1,650 | 46.30 | 13.89 | 120.77 |
| (2) Black River Pumps | 6,040 | 25.33 | - | 1/ 60.3 |
| (3) Fort Valley | 7,347 | 18.27 | - | 1/ 43.5 |
| (4) Hawley Lake | 8,180 | 21.26 | - | 1/ 50.6 |
| (5) McNary | 7,320 | 20.94 | - | 1/ 49.9 |
| (6) Mesa Experiment Farm | 1,230 | 48.61 | 11.35 | 106.31 |
| (7) Roosevelt 1 WNW | 2,205 | 42.40 | 8.09 | 98.06 |
| (8) Sierra Ancha | 5,100 | 30.31 | 7.37 | 75.66 |
| (9) Snowflake 15W | 6,080 | 35.99 | - | 1/ 85.7 |
| (10) Stewart Mountain | 1,422 | 41.61 | 10.68 | 105.67 |
| (11) Tempe Citrus Experiment Station | 1,180 | 30.60 | 5.74 | 2/ 71.75 |
| (12) Whiteriver | 5,280 | 30.49 | - | 1/ 72.6 |

1/ Data estimated from relation in figure 7A.

2/ Data not plotted on altitude-evaporation relation.

The Thornthwaite (1948) method (eq 2) and the Blaney-Criddle (1950) method (eq 3) require mean monthly temperature values to estimate potential evapotranspiration. Therefore, a generalized relation of mean temperature versus altitude was defined for each month from temperature data at 44 stations in and near the study area (fig. 6). The relations are shown in figure 8, and the data used to determine the relations are given in table 3. The straight-line relations are a least squares best fit of the data. Data from the general relations for use in the empirical equations are summarized in table 4. The monthly percentage of total daytime hours in the year for use in the Blaney-Criddle equation is given in table 4. All the study area is between lat 33° and 35°N.; therefore, data for lat 34°N. were used.

The empirical consumptive-use coefficient, K, in the Blaney-Criddle equation depends on vegetal species, density of growth, and depth to ground water. A consumptive-use coefficient of 0.85 was used for the study area for the entire year. The value for K is not a precise quantity; Rantz (1968) indicated that with a depth to water of 8 ft (2.4 m) and dense growth, K for the growing season could range from 0.30 to 1.10, depending on vegetation type. Cruff and Thompson (1967, p. 16) recommended a K of 0.85 for the entire year for an arid or modified arid environment, such as that in the study area. A nomograph

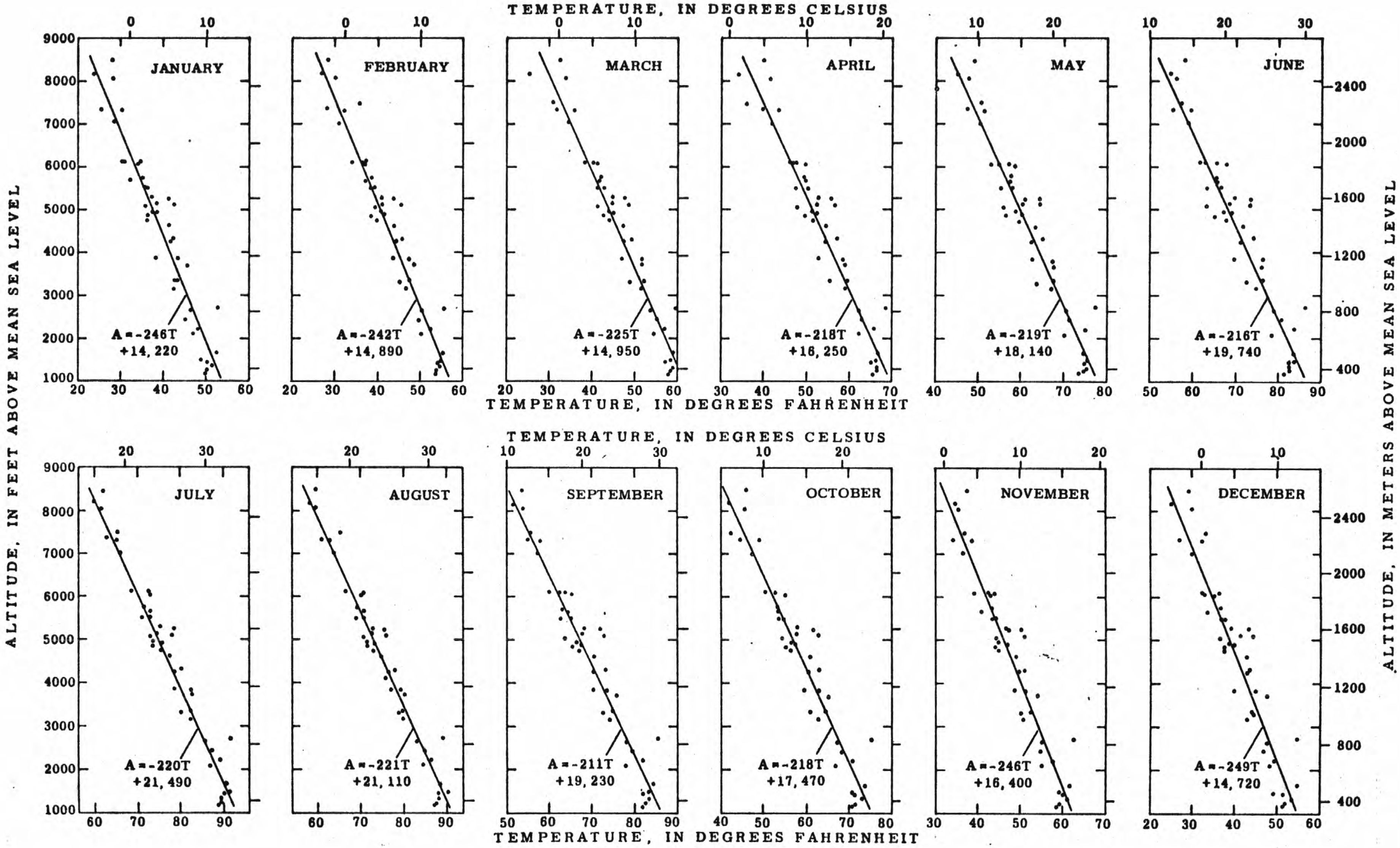



Figure 8.--Monthly relations between temperature and altitude in the study area.

Table 3.--Mean monthly temperature, in °F, for selected stations in central Arizona

[Data from Sellers and Hill, 1974]

| Station | Altitude, in feet above mean sea level | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alamo Dam 6 ESE | 1,480 | 48.8 | 54.7 | 58.5 | 66.1 | 75.8 | 83.7 | 91.3 | 90.1 | 82.9 | 70.8 | 59.0 | 49.1 | 69.2 |
| Alpine | 8,050 | 28.1 | 30.0 | 33.9 | 41.3 | 47.8 | 56.0 | 61.4 | 59.4 | 54.0 | 45.9 | 35.6 | 30.1 | 43.6 |
| Bagdad | 3,712 | 45.5 | 48.5 | 51.5 | 59.0 | 67.7 | 76.0 | 82.6 | 80.5 | 75.8 | 65.3 | 54.0 | 47.4 | 62.8 |
| Bagdad 8 NE | 4,240 | 41.7 | 44.2 | 47.2 | 54.3 | 62.2 | 71.0 | 78.4 | 76.5 | 70.5 | 60.6 | 49.5 | 42.8 | 58.2 |
| Bartlett Dam | 1,650 | 52.5 | 55.4 | 58.8 | 66.9 | 75.4 | 83.6 | 90.6 | 88.6 | 84.3 | 73.9 | 61.6 | 54.4 | 70.5 |
| Beaver Creek Ranger Station | 3,820 | 43.4 | 47.3 | 51.4 | 58.4 | 67.6 | 76.5 | 82.4 | 79.3 | 73.7 | 63.0 | 51.1 | 44.7 | 61.6 |
| Black River Pumps | 6,040 | 34.0 | 36.8 | 41.1 | 49.8 | 58.3 | 67.7 | 72.7 | 70.0 | 65.2 | 55.0 | 43.0 | 35.3 | 52.4 |
| Blue | 5,760 | 35.1 | 38.4 | 42.0 | 49.3 | 57.3 | 65.4 | 71.5 | 69.0 | 63.1 | 53.3 | 43.5 | 36.5 | 52.0 |
| Childs | 2,650 | 46.2 | 50.3 | 53.9 | 62.1 | 70.7 | 78.9 | 85.7 | 83.1 | 78.0 | 67.1 | 55.0 | 47.5 | 64.9 |
| Chino Valley | 4,750 | 36.2 | 39.8 | 44.0 | 51.5 | 59.2 | 67.7 | 75.1 | 72.9 | 67.1 | 56.4 | 44.8 | 37.4 | 54.3 |
| Cibecue | 4,950 | 37.4 | 40.7 | 44.0 | 51.3 | 58.5 | 66.9 | 73.6 | 71.5 | 66.5 | 56.3 | 44.8 | 38.6 | 54.2 |
| Cottonwood | 3,360 | 43.3 | 47.5 | 52.0 | 59.5 | 67.3 | 76.2 | 82.2 | 79.8 | 74.6 | 64.5 | 52.3 | 44.0 | 61.9 |
| Flagstaff WSO Airport | 7,006 | 28.4 | 30.8 | 34.4 | 42.0 | 50.1 | 58.7 | 65.9 | 63.7 | 57.3 | 47.4 | 36.5 | 30.0 | 45.4 |
| Forestdale | 6,100 | 30.8 | 34.0 | 38.2 | 46.2 | 53.1 | 61.7 | 68.5 | 66.3 | 60.2 | 50.6 | 39.4 | 32.4 | 48.5 |
| Fort Valley | 7,347 | 25.2 | 28.0 | 31.8 | 39.7 | 47.1 | 55.1 | 62.7 | 60.7 | 54.9 | 44.9 | 34.3 | 27.1 | 42.6 |
| Granite Reef Dam | 1,325 | 51.6 | 54.6 | 58.9 | 66.6 | 74.8 | 82.2 | 89.4 | 88.1 | 83.1 | 72.8 | 60.8 | 53.5 | 69.7 |
| Greer | 8,490 | 28.0 | 28.3 | 32.6 | 40.1 | 48.8 | 56.0 | 61.8 | 59.4 | 53.9 | 46.0 | 37.8 | 29.2 | 43.5 |
| Groom Creek | 6,100 | 34.2 | 37.2 | 40.1 | 46.9 | 54.5 | 62.6 | 68.7 | 66.5 | 62.5 | 53.0 | 42.6 | 36.2 | 50.4 |
| Happy Jack Ranger Station | 7,480 | ---- | 35.8 | 30.8 | 36.0 | 50.5 | 57.1 | 65.1 | 65.2 | 55.8 | 42.4 | 37.1 | 33.1 | 43.0 |
| Hawley Lake | 8,180 | 23.8 | 26.9 | 25.2 | 34.1 | 45.1 | 54.3 | 59.4 | 58.0 | 51.7 | 42.0 | 34.9 | 25.2 | 40.1 |
| Hillside 4 NNE | 3,320 | 42.9 | 45.3 | 48.9 | 55.5 | 63.7 | 72.4 | 80.1 | 78.7 | 72.3 | 61.0 | 50.1 | 44.1 | 59.6 |
| Jerome | 5,245 | 41.1 | 43.9 | 47.6 | 55.8 | 64.5 | 73.3 | 78.2 | 75.5 | 71.9 | 61.9 | 50.3 | 43.3 | 58.9 |
| Junipine | 5,124 | 38.5 | 40.8 | 44.6 | 52.6 | 60.5 | 68.5 | 74.4 | 72.5 | 67.7 | 57.7 | 47.6 | 41.2 | 55.6 |
| McNary | 7,320 | 30.2 | 32.1 | 35.9 | 43.8 | 51.4 | 59.4 | 64.8 | 62.8 | 58.0 | 49.1 | 38.5 | 32.4 | 46.5 |
| Mesa Experiment Farm | 1,230 | 50.3 | 53.9 | 58.3 | 66.3 | 74.5 | 82.6 | 89.2 | 87.4 | 82.2 | 71.4 | 59.1 | 51.9 | 68.9 |
| Montezuma Castle National Monument | 3,180 | 42.4 | 46.5 | 51.2 | 59.0 | 66.7 | 74.9 | 82.1 | 80.0 | 74.1 | 62.9 | 50.5 | 42.7 | 61.1 |
| Morman Flat | 2,715 | 52.9 | 55.7 | 59.8 | 68.6 | 77.4 | 86.1 | 91.5 | 89.1 | 85.4 | 75.0 | 62.5 | 54.6 | 71.6 |
| Natural Bridge | 4,607 | 41.1 | 43.7 | 47.2 | 54.5 | 63.1 | 71.7 | 77.2 | 74.7 | 70.6 | 61.1 | 49.2 | 42.7 | 58.1 |
| Payson | 4,913 | 38.4 | 41.5 | 44.9 | 52.4 | 60.1 | 69.0 | 75.5 | 73.1 | 67.5 | 57.8 | 46.9 | 39.9 | 55.6 |
| Payson 12 NNE | 5,500 | 36.2 | 38.3 | 41.0 | 47.3 | 54.9 | 63.2 | 70.8 | 68.7 | 62.6 | 53.7 | 44.2 | 37.8 | 51.6 |
| Payson Ranger Station | 4,848 | 36.2 | 38.6 | 42.5 | 49.5 | 56.6 | 65.4 | 73.6 | 71.4 | 65.5 | 55.2 | 44.0 | 37.6 | 53.0 |
| Perkinsville | 3,855 | 38.6 | 43.4 | 46.9 | 52.7 | 62.4 | 69.5 | 78.5 | 77.0 | 70.2 | 59.5 | 48.5 | 39.6 | 57.2 |
| Pleasant Valley Ranger Station | 5,050 | 35.8 | 39.2 | 41.4 | 47.9 | 56.0 | 63.1 | 72.7 | 70.4 | 63.7 | 54.3 | 44.4 | 36.3 | 52.1 |
| Prescott | 5,510 | 35.8 | 39.1 | 42.7 | 50.2 | 57.9 | 66.4 | 72.9 | 70.5 | 65.1 | 54.7 | 43.8 | 37.0 | 53.0 |
| Reno Ranger Station | 2,420 | 45.1 | 49.8 | 55.2 | 62.9 | 71.4 | 80.7 | 87.2 | 84.6 | 79.4 | 68.1 | 54.7 | 46.9 | 65.5 |
| Roosevelt 1 WNW | 2,205 | 48.0 | 52.3 | 57.0 | 65.9 | 75.0 | 83.8 | 89.0 | 86.5 | 81.8 | 70.8 | 57.7 | 49.4 | 68.1 |
| Sedona Ranger Station | 4,320 | 42.4 | 45.7 | 49.2 | 57.1 | 65.2 | 74.1 | 80.1 | 78.0 | 73.2 | 63.2 | 51.0 | 43.5 | 60.2 |
| Sierra Ancha | 5,100 | 42.6 | 45.3 | 48.5 | 56.4 | 64.4 | 73.3 | 77.9 | 75.9 | 72.7 | 62.7 | 51.3 | 44.2 | 59.6 |
| Snowflake | 5,642 | 32.2 | 37.0 | 41.7 | 49.9 | 57.5 | 65.9 | 72.7 | 70.6 | 64.3 | 53.5 | 40.8 | 33.3 | 51.6 |
| Snowflake 15 W | 6,080 | 30.3 | 36.2 | 41.4 | 47.7 | 57.5 | 65.5 | 72.7 | 70.5 | 63.9 | 52.9 | 44.0 | 32.7 | 51.3 |
| Stewart Mountain | 1,422 | 50.3 | 54.2 | 57.1 | 65.2 | 74.9 | 82.5 | 90.0 | 88.1 | 81.9 | 71.4 | 60.0 | 51.6 | 68.9 |
| Tempe University of Arizona Experiment Station | 1,180 | 49.9 | 53.5 | 57.9 | 65.7 | 73.5 | 81.4 | 88.5 | 86.9 | 81.8 | 70.8 | 58.3 | 51.3 | 68.3 |
| Whiteriver | 5,280 | 37.4 | 40.7 | 44.7 | 52.6 | 61.1 | 69.8 | 75.2 | 72.7 | 68.2 | 58.0 | 46.4 | 39.2 | 55.5 |
| Wickenburg | 2,095 | 46.7 | 50.1 | 54.3 | 62.1 | 70.0 | 78.5 | 86.7 | 84.5 | 77.9 | 66.8 | 54.9 | 48.1 | 65.1 |

Table 4.--Mean monthly temperature, in °F, for 1,000-foot-altitude intervals in central Arizona

[Based on regression analysis of data from 44 temperature stations in and near the study area]

| Month | Altitude, feet above mean sea level | | | | | | | | P[1/] |
|---|---|---|---|---|---|---|---|---|---|
| | 1,000 | 2,000 | 3,000 | 4,000 | 5,000 | 6,000 | 7,000 | 8,000 | |
| January | 53.7 | 49.7 | 45.6 | 41.5 | 37.5 | 33.4 | 29.3 | 25.3 | 7.10 |
| February | 57.4 | 53.3 | 49.1 | 45.0 | 40.9 | 36.7 | 32.6 | 28.5 | 6.91 |
| March | 62.0 | 57.6 | 53.1 | 48.7 | 44.2 | 39.8 | 35.3 | 30.9 | 8.36 |
| April | 70.0 | 65.4 | 60.8 | 56.2 | 51.6 | 47.0 | 42.4 | 37.8 | 8.80 |
| May | 78.3 | 73.7 | 69.1 | 64.6 | 60.0 | 55.4 | 50.9 | 46.3 | 9.72 |
| June | 86.8 | 82.1 | 77.5 | 72.9 | 68.2 | 63.6 | 59.0 | 54.4 | 9.70 |
| July | 93.1 | 88.6 | 84.0 | 79.5 | 75.0 | 70.4 | 65.9 | 61.3 | 9.88 |
| August | 91.0 | 86.5 | 81.9 | 77.4 | 72.9 | 68.4 | 63.8 | 59.3 | 9.33 |
| September | 86.4 | 81.7 | 76.9 | 72.2 | 67.4 | 62.7 | 58.0 | 53.2 | 8.36 |
| October | 75.5 | 71.0 | 66.4 | 61.8 | 57.2 | 52.6 | 48.0 | 43.4 | 7.90 |
| November | 62.6 | 58.5 | 54.5 | 50.4 | 46.3 | 42.3 | 38.2 | 34.1 | 7.02 |
| December | 55.1 | 51.1 | 47.1 | 43.1 | 39.0 | 35.0 | 31.0 | 27.0 | 6.92 |

1/ Monthly percentage of daytime hours of the year for lat 34° N. (Chow, 1964, sec. 21, p. 7).

(Cruff and Thompson, 1967, p. 8) was used to solve Thornthwaite's general equation (eq 2) for estimating potential evapotranspiration using the monthly heat-index values of Cruff and Thompson (1967, p. 9).

# RIPARIAN VEGETATION

In central Arizona the vegetation in the riparian zone—the areas along the stream channels or watercourses and in the flood plains—is a large source of water loss from streamflow. The loss occurs mainly by the consumptive use of water by the plants. An integral part of estimating the possible increased losses from surface water was the complete inventory of vegetation along the streams. The inventory included the identification of vegetation type and density. Although chaparral, juniper, pinyon, and pine are sometimes present at higher altitudes in the riparian zone, they were not included in the riparian vegetation inventory.

## Mapping of Vegetation Types and Densities

Aerial photographs were used to map the areal extent, areal density, and general type of vegetation. The photographs were taken between May 30 and June 18, 1973, using black and white modified infrared film. The film enabled easy identification and distinction of certain types of riparian vegetation because of the different infrared-reflectance characteristics of the different vegetation types. The vegetation was in full foliage at the time the aerial photographs were taken. The scale of the photographs is about 1:13, 000 or 1 in (25 mm) equals about 1, 100 ft (330 m).

Little ground-truth information was obtained, and the mapping was dependent entirely on proper interpretation of the aerial photographs; in terms of the overall objectives of the investigation, a large amount of ground-truth data was not warranted. Handheld, low-altitude, 35-mm color and color infrared transparencies were evaluated in conjunction with the aerial photographs for many sites along most streams. The first step in the use of the aerial photographs involved making a mosaic of the pictures and outlining the extent of the flood plain. The area of study was limited to the flood plain because of the probability of the riparian vegetation deriving its water from underground storage in the coarse alluvial material of the flood plain; the alluvium is recharged directly by streamflow. Generally, the depth to water is greater and the vegetation is much less dense and usually of an entirely different type outside the flood plain; the material outside the flood plain is much less permeable, possibly bedrock, and the occurrence of water may or may not be influenced by the water in the streams and in the flood-plain alluvium. Agricultural land and large areas covered with homes, trailer parks, lawns, or non-native vegetation were excluded from the flood-plain areas because they either do not support vegetative growth or are irrigated.

The riparian vegetation was mapped using six broad classifications:

1. Mixed broadleaf, including many miscellaneous types of deciduous trees, such as sycamore, alder, walnut, ash, oak, and maple.
2. Cottonwood-willow, including pure stands of either or a mixed stand of both.
3. Saltcedar.
4. Mesquite.
5. Saltcedar and mesquite mixed.
6. Riparian scrub, including low-lying brush-type vegetation and grasses.

The mosaicked aerial photographs, which include the outline of the flood plain, were used to delineate subareas of different vegetation types. Density of the native riparian vegetation was determined on the basis of the approximate percentage of canopy cover compared to the total flood-plain area. The classification zones are heavy density, medium density, and light density and generally corresponded to areal canopy covers of more than 2/3, 2/3 to 1/3, and less than 1/3, respectively. The densities were estimated from the aerial photographs, and one value was chosen for each subarea that was mapped on the basis of vegetation type. Thus, an area was not subdivided further on the basis of density unless the subarea was quite large. The areas as determined from the aerial photographs were then adjusted for density by multiplying by 0.3 for light density, 0.6 for medium density, or 1.0 for heavy density; this served to adjust all areas to an equivalent dense stand, and no further corrections for consumptive use were applied. Figure 9 gives an example of the vegetation mapping.

## Habitat

The type and density of vegetation in a particular area or stream reach are dependent on physical, hydrologic, and climatological characteristics. Altitude, soil type, permanence of flow, depth to water, or water quality can influence both the type and density of riparian vegetation.

Altitude is an important factor in determining vegetation type because it controls temperature and length of growing season. At higher altitudes, riparian vegetation is mainly a mixed broadleaf type. The mixed broadleaf vegetation is dominantly sycamore and ash at lower to intermediate altitudes and oak, maple, and alder at higher altitudes. Although soil type, permanence of flow, depth to water, and water quality influence the type of vegetation, they control the density and size of the vegetation. For example, in areas of fairly deep water mesquite thickets will not reach 100 percent density, and the plants generally are smaller than in an area of shallow ground water (Meinzer, 1927, fig. 14 and p. 53).

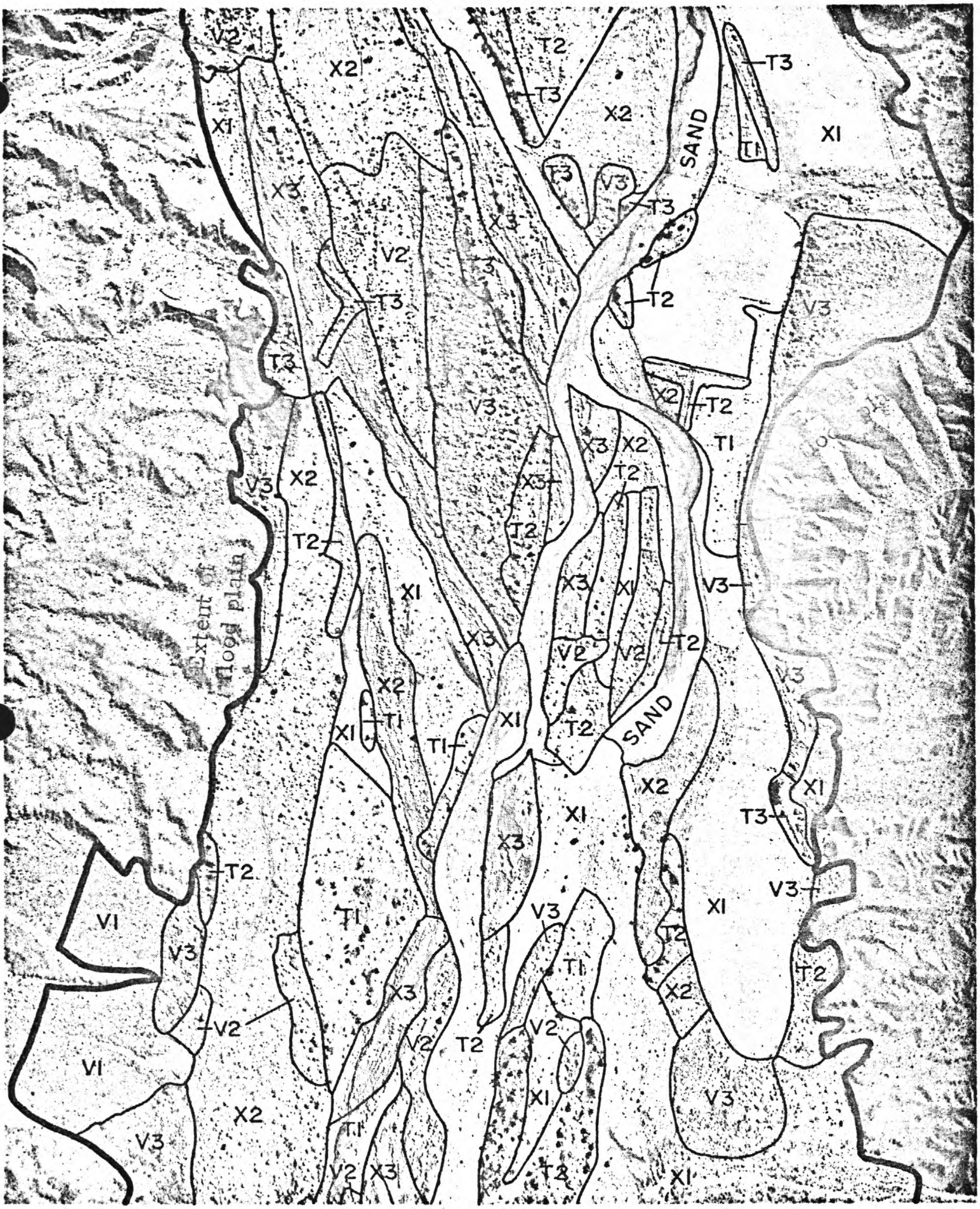



Figure 9.--Vegetation in the flood plain of the Bill Williams River upstream from the Alamo Reservoir.

## EXPLANATION

### DESIGNATION OF VEGETATION TYPE, T, AND DENSITY, 1

| | |
|---|---|
| T | Cottonwood-willow |
| V | Mesquite |
| X | Riparian scrub |
| 1 | Light density |
| 2 | Medium density |
| 3 | Heavy density |

# ESTIMATES OF EVAPOTRANSPIRATION LOSSES FROM RIPARIAN AREAS

The study area includes 1,287 mi (2,071 km) of stream channel that covers more than 42,000 acres (17,000 ha) of riparian vegetation and bare soil. The term "riparian water losses" includes all components of loss along the flood plain—transpiration by riparian vegetation, evaporation from the stream surface, and evaporation from bare-soil surfaces.

## Present Losses

The estimates of flow losses under present (1975) streamflow and vegetation conditions were made using an integration method in which the area of vegetative cover was determined; an empirical consumptive-use rate was applied to the area. The resultant estimate of total consumptive use was the evapotranspiration loss for the area. As a means of checking these estimates, a base-flow analysis and a water-budget analysis were used where sufficient data were available.

Integration method.--The data required to estimate the evapotranspiration losses using the integration method for a given reach are (1) areal extent of each type of vegetation, bare soil, and open-water surfaces, and (2) the consumptive-use rate for each type and density of vegetation. The consumptive-use rate applied to an area is dependent mainly on the type of vegetation, the density of the vegetation, and the depth to water. In addition, the annual use by a given species may be influenced by climate and ground-water quality (Robinson, 1958; van Hylckama, 1974). Few empirical relations exist that relate annual water use for a particular plant species to depth to water. Use of water by plants through evapotranspiration is greatest where the ground water is at shallow depth, and use decreases as the depth to water increases (Gatewood and others, 1950; Muckel, 1966; van Hylckama, 1970). (See fig. 10.) Insufficient data are available to produce an accurate relation for each vegetation type mapped; however, the curve for mesquite is fairly well defined (fig. 10), and the assumption is made that the general shape should be nearly the same for the other vegetation types. Few data are available for most other vegetation types in the environment found in the study area; therefore, available data were used as control points in conjunction with the general shape, as determined from the curve for mesquite (fig. 10), to develop a set of consumptive-use versus depth-to-water curves (fig. 11). The relations shown in figure 11 were used to estimate the consumptive use by riparian vegetation in the integration method.

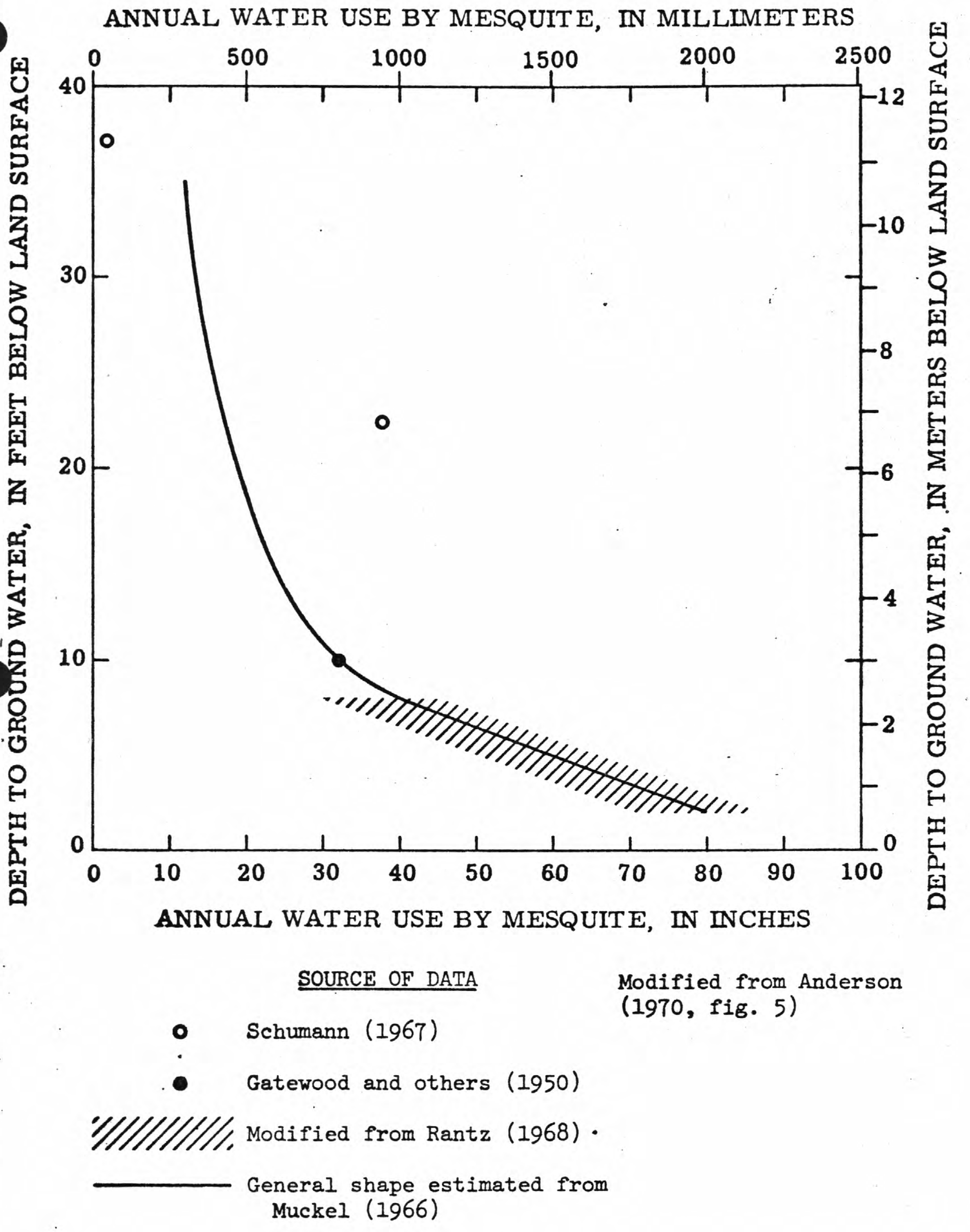
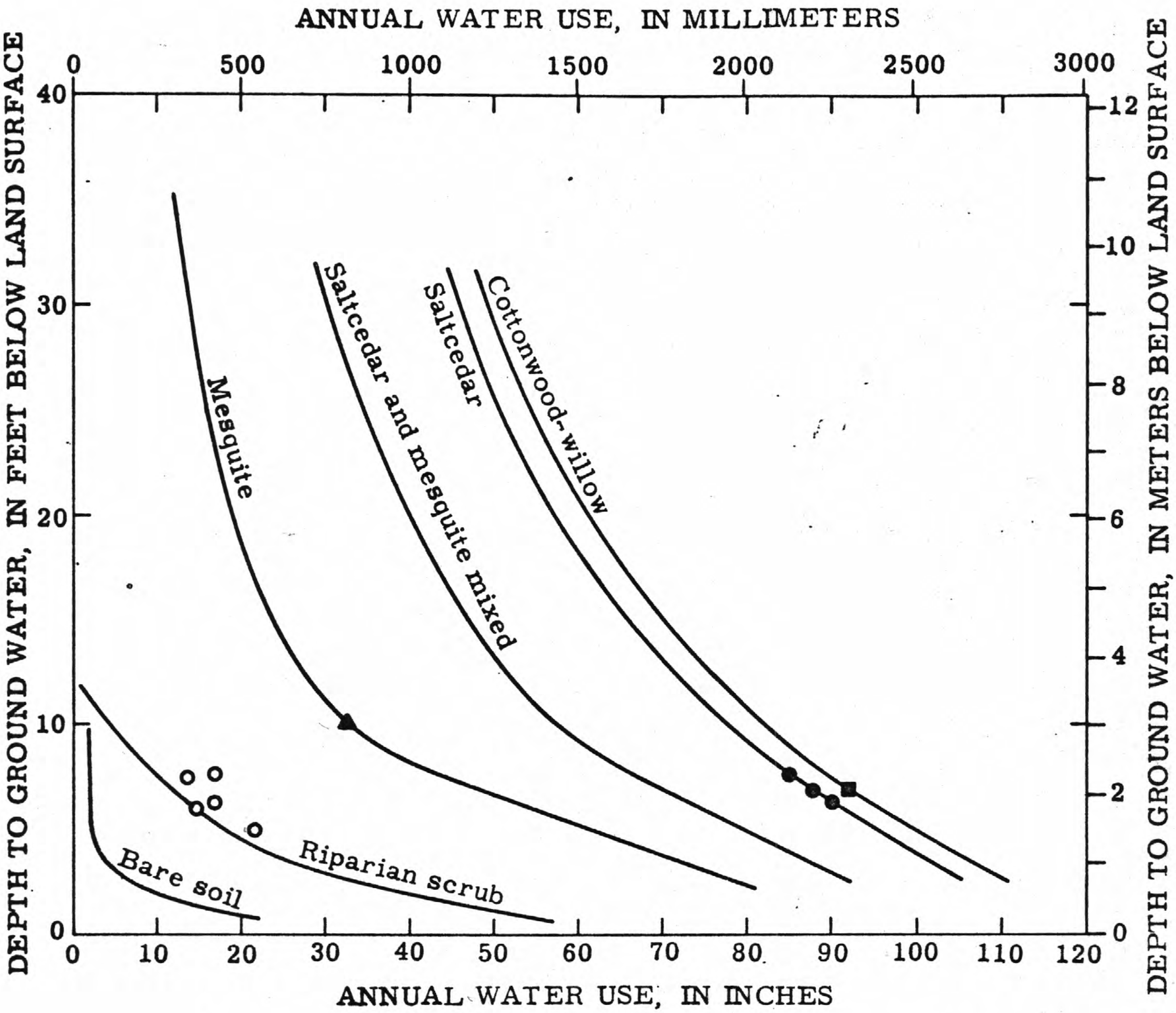



Figure 10.--Estimated relation between depth to ground water and annual water use by mesquite.




Bare-soil curve modified from Anderson (1970, fig. 6)

EXPLANATION

DATA FROM GATEWOOD AND OTHERS (1950, p. 138)

● Saltcedar

■ Cottonwood-willow

▲ Mesquite

DATA FROM ROBINSON (1970, p. 28)

○ Greasewood

Figure 11.--Estimated relation between depth to ground water and annual water use by different types of vegetation.

The relation for saltcedar and cottonwood-willow (fig. 11) is based on data from Gatewood and others (1950, p. 137-138) and on the general shape of the curve for mesquite (fig. 10). The relation for riparian scrub was estimated from data for grasses and greasewood (Robinson, 1970, p. 28). The maximum depth of the root zone for weeds and grasses was assumed to be 12 ft (3.7 m). The relation for saltcedar and mesquite mixed was arbitrarily placed midway between the curves for saltcedar and mesquite, assuming that the water use in a typical area covered by a mixed stand would be somewhere near the mean of the consumptive use of a pure stand of either of the vegetation types. Mixed broadleaf vegetation generally occurs in areas similar to those occupied by cottonwood-willow except that it occurs at higher altitudes. Therefore, for lack of better data, the consumptive-use versus depth-to-water relation for mixed broadleaf is assumed to be the same as that for cottonwood-willow. The main fact that allows the assumption is that most of the mixed broadleaf vegetation occurs only along reaches that contain perennial flow. Therefore, the depth to water probably is not more than 15 ft (4.6 m) in the area covered by vegetation, and the curve does not need to be estimated to the depths required for cottonwood, saltcedar, or mesquite.

Although depth-to-water data were not available in sufficient quantity, the assumption was made that the water level is at the same altitude as the stream surface during base flow in all perennial streams. The depth to water in the flood plains of the perennial streams was estimated on the basis of the average height of the terraces that compose the flood plain. The heights were obtained from previous studies and from estimates made from stereo photographs of the flood plains. For streams that do not contain perennial flow, a reasonably reliable estimate of depth to water was made using the type and density of vegetation and the general geomorphic setting. Vegetation type was used only as an indicator of the depth to water. Certain types of vegetation flourish only in areas having shallow depth to water. A lack of the vegetation, therefore, indicates that these conditions are exceeded, and the height and density of the vegetation is indicative of the availability of ground water.

The general geomorphic setting is important because the size and shape of the alluvial pockets along the streams are dependent on the slope control downstream, which probably is the point at which the stream has downcut to bedrock. The shallowest depth to water occurs in the alluvial pockets at the downstream end, and the greatest occurs in the pockets at the upstream end (fig. 5).

Base-flow method.--In an attempt to verify the evapotranspiration values estimated using the integration method, an analysis of base flow was made for selected streamflow-gaging stations. In the base-flow method the average minimum base-flow values for the 1961-73 water years—or a slightly shorter period—were used to evaluate the seasonal variation in base flow. The seasonal variation was attributed to the effects of evapotranspiration by riparian vegetation upstream from the gaged site. The method was not used at sites where there are large diversions from or to streamflow upstream from the gage, where a large snowmelt component is included in the winter and early spring runoff, or where the length of streamflow record is less than about 8 years. The data were used on a seasonal basis—winter is December, January, and February; spring is March, April, and May; summer is June, July, and August; and autumn is September, October, and November.

Several assumptions are necessary in order to equate the difference in base flow to riparian evapotranspiration losses. First, the water use by riparian vegetation during the winter is assumed to be zero, which is probably a safe assumption in most of the area. Secondly, the assumption is made that the reduction between base flow in the winter and that in the summer is from water used only by riparian vegetation and not by the upland vegetation in the watershed. Although the assumption is not completely true, it probably is safe enough to use the results as a check on the results from the integration method. The assumption is probably safe for the reaches used in this study; however, the nearer the headwaters the less valid the assumption becomes. The assumption also is made that the volume of ground water transpired by the upland vegetation, and not contributing to base flow, is generally small; this quantity is dependent largely on the geology of the area and on how quickly water on or near the land surface percolates downward beyond the root zone. The effect of this assumption should be minimized because the analysis is based on the average minimum flow for each month averaged over the period of record.

A definite seasonal variation in base flow occurs at all sites included in the analysis (fig. 12), and the variation is quite similar in appearance to the consumptive-use curves for different vegetation types (fig. 13). For the purpose of this study, the two are assumed to be complimentary; that is, a decrease in base flow is assumed to result from increased consumptive use by upstream riparian vegetation. The two curves are definitely in phase; the maximum base flow occurs at a time of zero or minimum consumptive use, and the minimum base

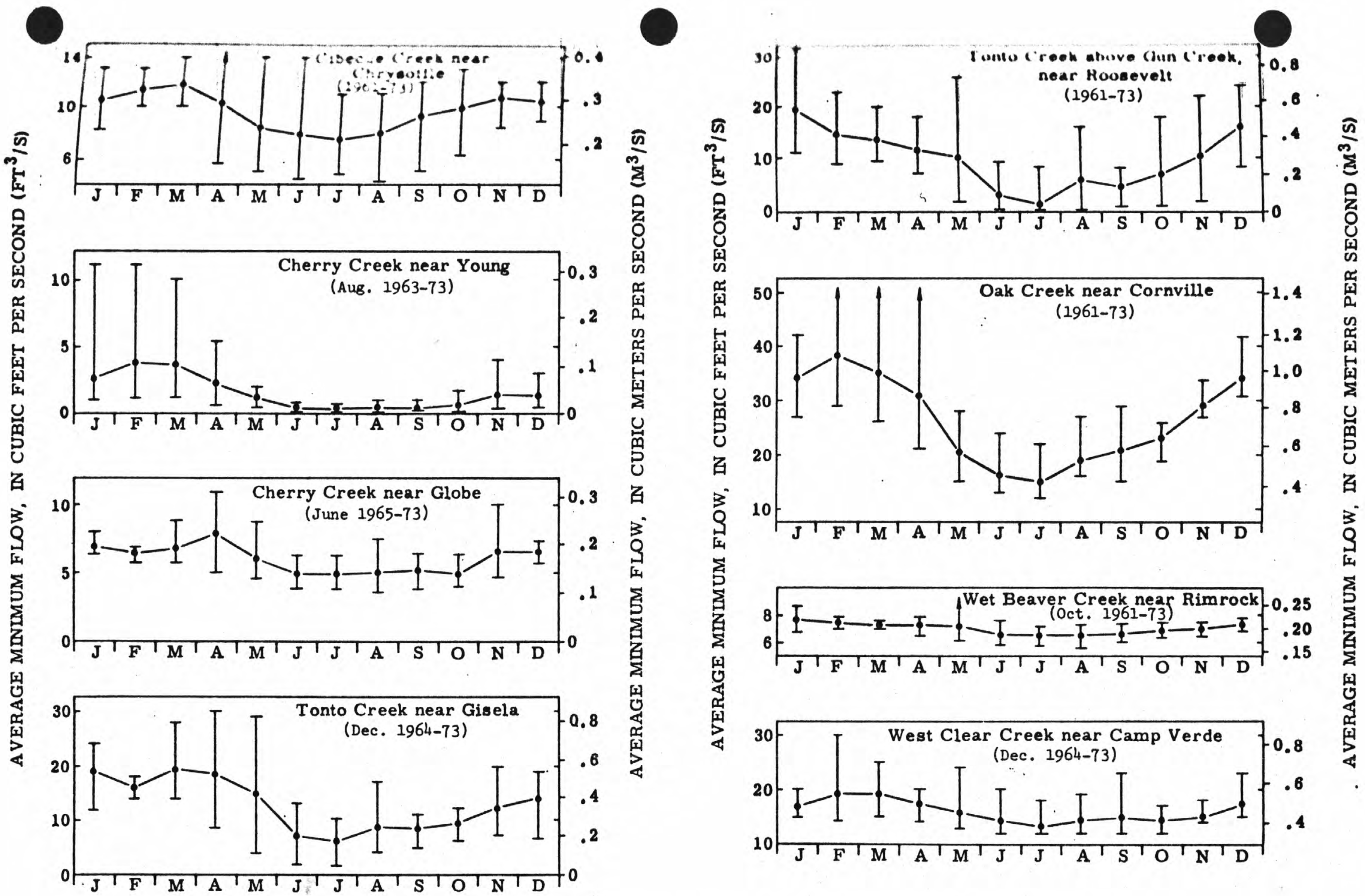



Figure 12.--Average monthly minimum flow at selected gaging stations.

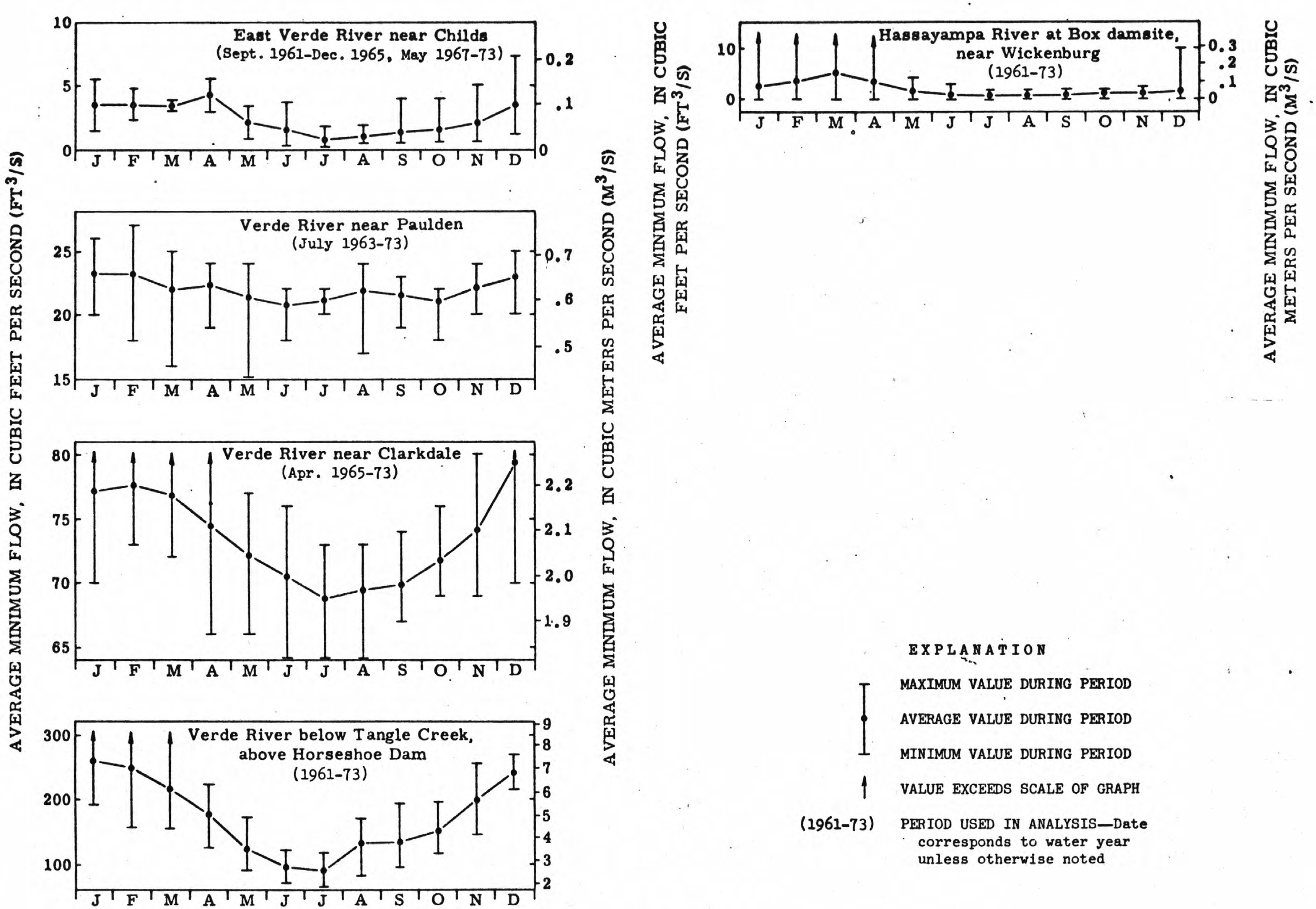
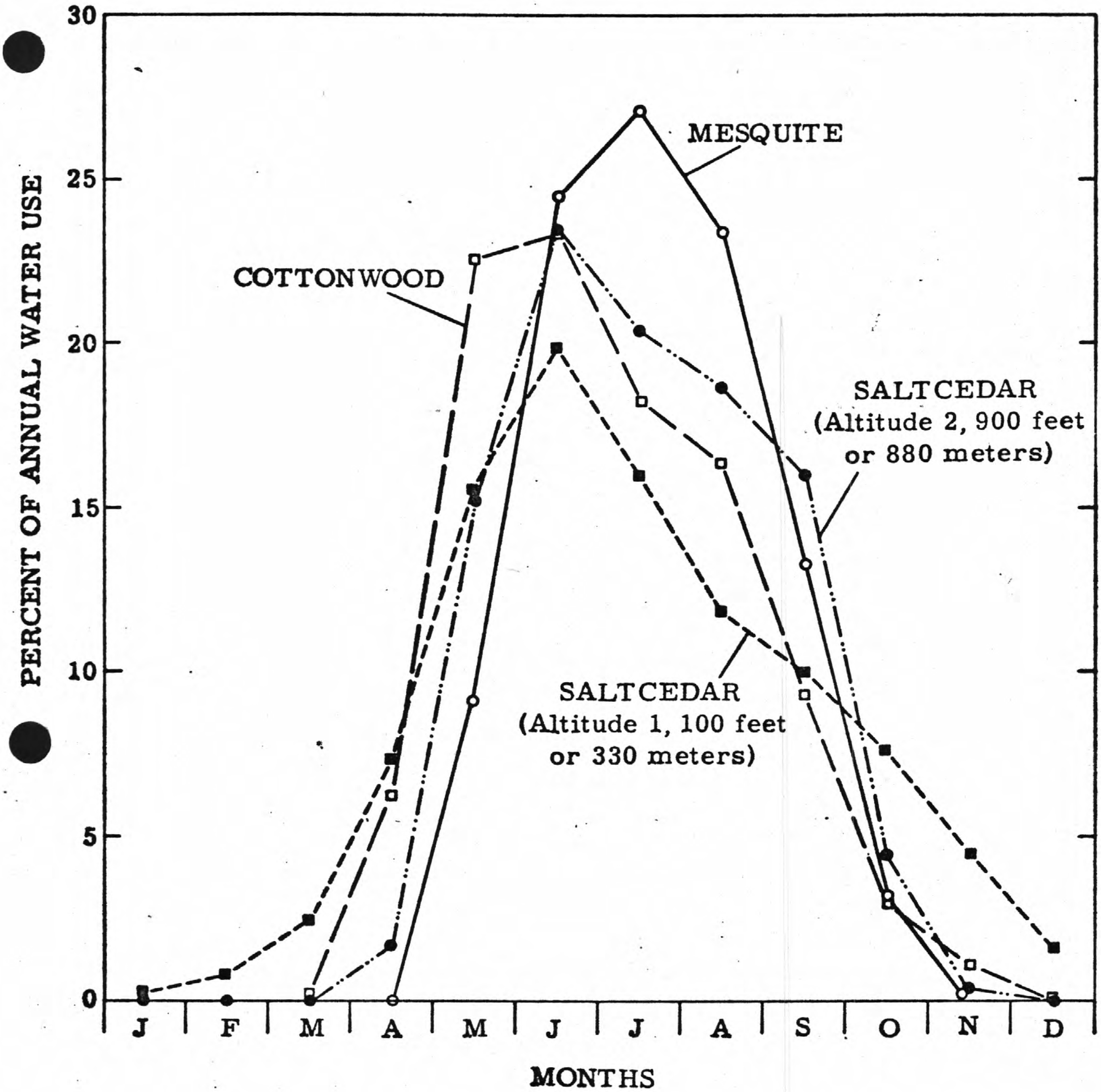



Figure 12.--Continued




Data from Gatewood and others (1950, table 3) and van Hylckama (1974, p. 11)

Figure 13.--Monthly use of water by different types of riparian vegetation.

flow occurs at the time of maximum consumptive use. Table 5 shows the annual consumptive use upstream from the gaging stations, the riparian area from which the loss is assumed to occur, and the computed unit consumptive-use rate if this value is deemed meaningful. In certain instances the consumptive-use rate was not computed because upstream withdrawals from surface flow were known to be large and, therefore, the calculation of the consumptive-use rate would be meaningless.

The annual consumptive use derived by the base-flow method should be larger than that obtained by the integration method because the riparian vegetation along small tributaries was not included in the integration-method data. In some instances the difference is markedly larger owing to the seasonal demands—upland vegetation use, agricultural use, domestic use, or a combination of these—in the area upstream from the gaging stations, which results in a lower summer base flow than may occur under natural conditions. Overall, the base-flow method appears to be poor for estimating riparian water losses owing to the influence of other demands; the results compare well with the results obtained from the integration method at only 4 of the 13 sites used in the analysis. The difference between the average winter flow and the average summer flow at the four sites ranged from 9 to 33 percent of the average winter flow and averaged about 16 percent;

Table 5.--Annual consumptive use as determined by the base-flow and integration methods for riparian areas upstream from gaging stations

| Station name | Annual consumptive use upstream from gage using base-flow data, in acre-feet[1] | Area of riparian vegetation included in inventory upstream from gage, in acres | Average consumptive-use rate, in acre-feet/acre | Annual consumptive use upstream from gage using integration method, in acre-feet | Remarks |
|---|---|---|---|---|---|
| Cibecue Creek near Chrysotile, Ariz. | 775 | 711 | 1.1 | 4,300 | Cause of poor agreement of results unknown. |
| Cherry Creek near Young, Ariz. | 825[2] | 156 | 5.3 | 500 | (3) |
| Cherry Creek near Globe, Ariz. | 491 | 354 | 1.4 | 1,000 | Base-flow figure probably affected by spring flow. |
| Tonto Creek near Gisela, Ariz. | 2,713[2] | <50 | -- | <100 | (3) |
| Tonto Creek above Gun Creek, near Roosevelt, Ariz. | 4,980[2] | 1,034[4] | -- | 1,600 | Consumptive-use values cannot be compared because of upstream seasonal demands.[3] |
| Verde River near Paulden, Ariz. | 850 | 384[4] | 2.2 | 600 | (3) |
| Verde River near Clarkdale, Ariz. | 3,285 | 1,283[4] | 2.6 | 2,800 | |
| Oak Creek near Cornville, Ariz. | 6,498[2] | 902[4] | -- | 3,500 | |
| Wet Beaver Creek near Rimrock, Ariz. | 336 | 50 | 6.7 | 300-400 | |
| West Clear Creek near Camp Verde, Ariz. | 1,250 | 112[4] | -- | 500 | (3) |
| East Verde River near Childs, Ariz. | 802 | 319 | 2.5 | 500 | (3) |
| Verde River below Tangle Creek, above Horseshoe Dam, Ariz. | 54,983[2] | -- | -- | 38,000 | |
| Hassayampa River at Box damsite, near Wickenburg, Ariz. | 2,160 | 1,877 | 1.2 | 2,300 | Base-flow data computed on monthly basis rather than seasonal. |

1/ Figure is exactly as computed, not rounded; an accuracy to three significant figures cannot be expected.
2/ Figure includes seasonal irrigation or domestic demands.
3/ Difference in two results may indicate that consumptive use by upland vegetation is large.
4/ Large area of riparian vegetation on tributary or upstream from mapped reach is not included.

at the stations not resulting in a good match, the ratio ranged from 28 to 81 percent and averaged 54 percent. The method should be applied only in areas where domestic and agricultural uses are near zero and where the possible upland vegetation use is small.

Water-budget method.--The water-budget method was used as another means of checking the data obtained using the integration method. The main limitation on the water-budget method is the requirement for tandem gaging stations—a station at the inflow point and one at the outflow point of a reach. This requirement and the requirements of a common length of record and a knowledge of tributary inflow limited the applicability of the water-budget method to three reaches—the Verde River between Bartlett Dam and the gaging station near Scottsdale, Tonto Creek between the stations near Gisela and above Gun Creek near Roosevelt, and Salt River between the stations near Chrysotile and near Roosevelt (fig. 6).

Only streamflow data for daily periods of steady flow were analyzed. The criteria of less than 10-percent variation in mean daily flow at a station and no major precipitation in the immediate area were established to qualify the data for inclusion in the analysis. The data were sorted by computer, and a regression analysis was run to determine the inflow-outflow relation. A comparison between winter and summer inflow and outflow was made, and any difference between winter inflow and outflow was attributed to some continuing demand or some hydrologic or geologic influence. The difference may be caused by pumping, a loss through seepage, a gain from spring flow, steady tributary inflow, or underflow and was assumed to be constant throughout the year. The inflow-outflow relation was determined for the summer, and the difference between the summer and winter relations was assumed to equal the consumptive use by riparian vegetation.

## Future Losses

In order to estimate the magnitude of possible future losses it is necessary to assume that additional water will be introduced into the stream channel at some upstream point and that the water will be of sufficient quantity to alter the flow regimen. The assumption is made that the maximum loss condition will be created—that is, all reaches will contain perennial flow, and soil moisture will always be sufficient to satisfy plant-use demand.

Several factors can cause an increase in evapotranspiration losses from the riparian zones. The first factor is an increase in water-surface area and a resultant increase in evaporation losses.

The second factor is a rise in the ground-water table and a resultant increase in consumptive use through plant transpiration (figs. 10 and 11); a truly shallow water table also results in greater evaporation from bare soil. The third factor is an increase in vegetation density as a result of more water being available for plant use; the vegetation will spread to the optimum density for the soil, climate, and changed water conditions in the area. An increase in vegetation density will occur only along the streams that are not perennial under natural conditions. The assumption is made that the density of vegetation along perennial streams was at an optimum in 1975, and no further increase will take place. A time element is involved in the increased losses as a result of increased vegetation density in that several years will be required before the vegetation will reach its optimum density. Therefore, two possible future loss conditions are considered in table 6—near future, which is the added loss that will be caused by an increased open-water surface and a shallower ground-water table, and long-term future, which is the evapotranspiration loss that will occur after the flow regimen has increased to the point that available moisture is not a limiting factor and vegetation has reached an optimum density throughout the present area of growth. A third value of possible future losses was estimated based on potential

Table 6.--Stream characteristics and present, fut[illegible] potential annual evapotranspiration losses along streams in central Arizona

[Present, future, and potential an[illegible] evapotranspiration losses rounded to two significant figures]

Flow regimen: P, perennial; I, intermittent; U, unknown.

Geomorphic age: Y, youthful; M, mature.

Predominant riparian vegetation type and density: S, mixed broadleaf; T, cottonwood-willow; V, mesquite; X, riparian scrub; 1, light; 2, medium; 3, heavy.
Possible increase in evapotranspiration losses, in acre-feet per year: N, negligible.

| (1) Stream | (2) Vegetation and bare soil, in acres 1/ | (3) Altitude of mid-point of reach, in feet above mean sea level | (4) Approximate length of stream channel, in miles | (5) Flow regimen | (6) Geomorphic age | (7) Predominant riparian vegetation type and density | (8) Flood-plain width, in feet: Estimated range | (8) Flood-plain width, in feet: Estimated average | Estimated potential evapotranspiration values, in inches: (9) Thornthwaite method | (10) Blaney-Criddle method | (11) Lake-evaporation method | (12) Adjusted pan-evaporation method | (13) Average potential evapotranspiration Average of columns (10), (11), and (12) | (14) Present (1975) evapotranspiration losses, in acre-feet per year | (15) Near-future evapotranspiration losses, in acre-feet per year | (16) Long-term future evapotranspiration losses, in acre-feet per year | (17) Possible increase in evapotranspiration losses, in acre-feet per year Column (16) minus column (14) | (18) Estimated potential evapotranspiration losses, in acre-feet per year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blue River | 710 | 5,500 | 49 | P | Y | S, 1 | 50-1,000 | 300+ | 25 | 44 | 60 | 50 | 51 | 1,300 | 1,300 | 1,300 | N | 1,500 |
| San Francisco River | 908 | 3,600 | 43 | P | Y | V, 2 | 100- 800 | 300+ | 33 | 52 | 61 | 62 | 58 | 1,400 | 1,400 | 1,400 | N | 2,300 |
| Black River | 542 | 5,600 | 111 | P | Y | V, 2 | 50- 400 | 200+ | 25 | 44 | 60 | 48 | 51 | 1,500 | 1,500 | 1,500 | N | 2,300 |
| Big Bonita Creek | 5 | 6,200 | 26 | P | Y | S, 1 | 30- 300 | 100+ | 25 | 44 | 60 | 45 | 50 | <100 | <100 | <100 | N | <100 |
| White River | 880 | 5,100 | 57 | P | Y | S, 2 | 30- 400 | 200 | 28 | 48 | 60 | 53 | 54 | 3,500 | 3,500 | 3,500 | N | 4,000 |
| Salt River | 1,764 | 3,100 | 87 | P | Y | V, 2 | 100-2,600 | 300 | 38 | 56 | 63 | 66 | 62 | 4,500 | 4,500 | 4,500 | N | 8,400 |
| Carrizo Creek | 1,339 | 5,000 | 56 | P | Y | X, 2 | 100-1,400 | 200+ | 28 | 48 | 60 | 53 | 54 | 2,900 | 2,900 | 2,900 | N | 5,300 |
| Corduroy Creek | 201 | 5,600 | 22 | P | Y | S, 3 | 50- 500 | 200- | 26 | 46 | 60 | 49 | 52 | 1,000 | 1,000 | 1,000 | N | 700 |
| Cedar Creek | 922 | 4,800 | 22 | I | Y | V, 1 | 50-1,000 | 400+ | 29 | 49 | 60 | 54 | 54 | 800 | 1,200 | 3,500 | 2,700 | 3,400 |
| Cibecue Creek | 711 | 4,800 | 43 | P | Y | T, 3 | 50-1,400 | 200+ | 29 | 49 | 61 | 54 | 55 | 4,300 | 4,300 | 4,300 | N | 3,200 |
| Canyon Creek | 162 | 4,700 | 46 | P | Y | S, 2 | 30- 400 | 100+ | 29 | 49 | 61 | 55 | 55 | 700 | 700 | 700 | N | 800 |
| Cherry Creek | 1,241 | 3,900 | 44 | 2/ | Y | V, 2 | 50-1,500 | 200+ | 34 | 52 | 62 | 61 | 58 | 1,600 | 2,600 | 4,000 | 2,400 | 5,100 |
| Salome Creek | 389 | 2,900 | 12 | 2/ | Y | V, 2 | 50-1,300 | 100+ | 39 | 56 | 64 | 68 | 63 | 300 | 800 | 1,400 | 1,100 | 2,000 |
| Tonto Creek | 4,907 | 2,900 | 59 | 2/ | 3/ | V, 2 | 100-2,600 | 800+ | 39 | 56 | 64 | 68 | 63 | 8,700 | 12,000 | 18,000 | 9,300 | 22,000 |
| Haigler Creek | 43 | 5,200 | 19 | P | Y | S, 1 | 20- 400 | 100 | 28 | 47 | 60 | 52 | 53 | 200 | 200 | 200 | N | 200 |
| Spring Creek | 188 | 4,100 | 17 | U | Y | S, 1 | 20- 300 | 100- | 32 | 51 | 62 | 59 | 57 | 600 | 700 | 1,500 | 900 | 900 |
| Verde River | 6,649 | 4/ | 159 | P | 3/ | V, 3 | 100-5,000 | 2,200 | 4/ | 4/ | 4/ | 4/ | 4/ | 48,000 | 48,000 | 48,000 | N | 77,000 |
| East Verde River | 319 | 3,700 | 40 | P | Y | S, 1 | 100-1,000 | 300+ | 34 | 53 | 62 | 62 | 59 | 500 | 500 | 500 | N | 1,400 |
| Pine Creek | 46 | 4,100 | 13 | P | Y | S, 1 | 50- 900 | 200 | 32 | 51 | 61 | 60 | 57 | 100 | 100 | 100 | N | 200 |
| Fossil Creek | 100 | 3,900 | 20 | 5/ | Y | V, 2 | 20- 300 | 100 | 33 | 52 | 60 | 61 | 58 | 400 | 400 | 400 | N | 500 |
| West Clear Creek | 948 | 4,200 | 32 | P | Y | T, 1 | 100-2,500 | 300 | 32 | 51 | 58 | 59 | 56 | 2,400 | 2,400 | 2,400 | N | 4,400 |
| Wet Beaver Creek | 955 | 3,600 | 27 | P | 3/ | S, 2 | 30-1,000 | 200+ | 35 | 53 | 58 | 63 | 58 | 3,500 | 3,500 | 3,500 | N | 4,600 |
| Dry Beaver Creek | 498 | 3,400 | 32 | I | Y | V, 2 | 100- 600 | 200 | 36 | 54 | 58 | 64 | 59 | 600 | 1,100 | 2,000 | 1,400 | 2,100 |
| Oak Creek | 1,354 | 3,800 | 47 | P | 3/ | S, 3 | 30-1,000 | 200+ | 34 | 53 | 58 | 62 | 58 | 4,700 | 4,700 | 4,700 | N | 6,500 |
| Agua Fria River | 2,890 | 2,100 | 44 | 2/ | Y | V, 2 | 50-1,000 | 200+ | 43 | 59 | 65 | 73 | 66 | 5,500 | 8,400 | 8,900 | 3,400 | 9,800 |
| Hassayampa River | 2,768 | 3,000 | 47 | 2/ | 3/ | V, 2 | 30-2,200 | 400+ | 38 | 56 | 68 | 67 | 64 | 3,000 | 4,800 | 8,500 | 5,500 | 13,000 |
| Bill Williams River | 2,101 | 1,100 | 5 | I | M | X, 1 | 2,000-5,000 | 3,800 | 48 | 63 | 76 | 80 | 73 | 3,400 | 5,000 | 9,600 | 6,200 | 12,000 |
| Santa Maria River | 6,405 | 1,900 | 49 | 2/ | 3/ | X, 2 | 100-4,500 | 500 | 44 | 60 | 70 | 74 | 68 | 11,000 | 16,000 | 18,000 | 7,000 | 32,000 |
| Kirkland Creek | 1,702 | 3,900 | 37 | I | Y | V, 3 | 30-4,000 | 200 | 33 | 52 | 63 | 61 | 59 | 5,000 | 7,300 | 9,500 | 4,500 | 8,000 |
| Skull Valley Wash | 694 | 4,500 | 22 | I | Y | V, 2 | 30-2,000 | 100+ | 31 | 50 | 62 | 57 | 56 | 1,000 | 1,700 | 4,000 | 3,000 | 3,000 |
| TOTAL | 42,339 | ----- | 1,287 | -- | -- | ---- | ----------- | ----- | -- | -- | -- | -- | -- | ----- | ----- | ----- | ----- | ----- |

1/ Does not include open-water and bedrock areas.
2/ Part of the reach is perennial and part is intermittent.
3/ Part of the reach is mature in geomorphic age; most of the reach is youthful.
4/ The Verde River is divided into subreaches, and a value for each subreach was used to estimate the potential evapotranspiration loss.
5/ Affected by diversion for powerplant.

evapotranspiration; the estimate was made using an average of the values determined from the empirical relations—the Blaney-Criddle method (eq 3), the lake-evaporation map (fig. 6), and the adjusted pan evaporation-altitude relation (fig. 7). The Thornthwaite method (eq 2) was not used in computing the average because the results were consistently low. The altitude at the midpoint of the reach was used to determine the average monthly temperature (fig. 8) and adjusted pan evaporation (fig. 7). (See table 6.)

The possibility of a change in the dominant riparian vegetation as a result of a change in the surface-water flow regimen is one factor that was not considered in this study; the factor should be recognized as a possibility but was beyond the scope of this study. For example, saltcedar may invade and become dominant in what is presently a mesquite community.

## Losses From Selected Streams

The following discussions include the estimates of present (1975), near-future, and long-term future evapotranspiration losses from the flood plains along selected streams in central Arizona. Only the streams for which other methods were used in addition to the integration method are discussed. The loss figures for most streams in central Arizona are given in table 6.

Salt River.--The perennial reach of the Salt River included in the vegetation mapping is 87.3 mi (140.5 km) long and extends from Roosevelt Lake upstream to the confluence of the Black and White Rivers. The geomorphology indicates that the reach is youthful in age. The flood plain is narrow and probably averages less than 300 ft (90 m) wide; upstream from Roosevelt Lake, the flood plain is about 0.5 mi (0.8 km) wide. Vegetation is sparse in most of the flood plain and is generally composed of mesquite and riparian scrub. The largest stand of riparian vegetation is upstream from Roosevelt Lake, where the flood plain is widest and ground-water levels are shallowest. In this area saltcedar is the dominant riparian vegetation.

The reach of the Salt River used in the budget analysis is from the gaging station near Chrysotile downstream to the station near Roosevelt—a distance of about 48 mi (77 km). The reach terminates about 5 mi (8 km) upstream from Roosevelt Lake. The relations for the winter and summer budget are nearly linear and indicate that although there are larger losses in the summer than in the winter, the difference increases as the flow increases—probably owing to increased wetted area in the reach—and remains about 10 percent of the inflow at all times. Using an approximate average loss rate of 8 $ft^3/s$ (0.23 $m^3/s$), the annual consumption by riparian vegetation is estimated to be between

2, 000 and 2, 500 acre-ft (2.5 and 3.1 $hm^3$) under present (1975) conditions. For the same reach, data from the integration method indicate a loss of about 1, 900 acre-ft (2.3 $hm^3$) per year.

The Salt River was divided into three subreaches for use in the integration calculations—from Roosevelt Lake at a lake elevation of about 2, 120 ft (650 m) above mean sea level to the gaging station near Roosevelt, a distance of 4.9 mi (7.9 km); between the gaging stations near Roosevelt and near Chrysotile, a distance of 48.4 mi (77.9 km); and upstream from the gaging station near Chrysotile to the head, a distance of 38.9 mi (62.6 km). Under present (1975) conditions, the evapotranspiration losses are estimated to be 4, 500 acre-ft (5.5 $hm^3$) per year for the entire reach and 2, 300, 1, 900, and 300 acre-ft (2.8, 2.3, and 0.4 $hm^3$) per year for the subreaches in upstream order. The near-future and long-term future evapotranspiration losses probably will not change. The potential evapotranspiration losses are estimated to be about 8, 400 acre-ft (10.4 $hm^3$) per year.

Cibecue Creek.--Cibecue Creek is a generally south-flowing tributary to the Salt River in east-central Arizona (fig. 4). The reach included in the vegetation mapping is 42.9 mi (69.0 km) long. The stream is probably perennial throughout most of the reach; however, flow may be intermittent near Cibecue, where the flood-plain width is at a maximum and the seasonal ground-water pumping may deplete streamflow during parts of dry years. The flood plain ranges from less than 50 ft (15 m) to more than 0.2 mi (0.4 km) wide. The lower 17 mi (27 km) of the reach has virtually no flood plain, and the channel occupies a V-shaped canyon that has a bedrock bottom. The dominant vegetation types are cottonwood, willow, and mixed broadleaf. Most of the vegetation is at and upstream from Cibecue.

Under present (1975) conditions, the evapotranspiration losses are estimated to be about 4,300 acre-ft (5.3 $hm^3$) per year; the losses probably will not change if the streamflow is increased in the near future or in the long-term future. The potential evapotranspiration losses are estimated to be 3,200 acre-ft (3.9 $hm^3$) per year. This value is lower than that for the present estimated losses because no correction was applied for the vegetation type; the consumptive use by dense stands of cottonwood and willow is much greater than the uncorrected potential evapotranspiration figure obtained by the different methods. The results obtained by the base-flow method applied to the data obtained at the Cibecue Creek near Chrysotile gaging station indicate that the net loss upstream from the station is less than 800 acre-ft (1.0 $hm^3$) per year. This value is less than 20 percent of the amount determined by the integration method and 25 percent of the amount indicated by the average potential evapotranspiration data.

Although the cause for the large difference is not known, the base-flow determination is assumed to be the least reliable.

Cherry Creek.--Cherry Creek is a south-flowing tributary to the Salt River and joins the Salt about 18 mi (29 km) upstream from Roosevelt Lake. The reach included in the vegetation mapping is 44.5 mi (71.6 km) long and extends from the mouth upstream to the bridge on Arizona Highway 288 northeast of Young. The reach is divided into three subreaches; the Cherry Creek near Young gaging station divides the upper subreach from the middle subreach, and the Cherry Creek near Globe gaging station divides the middle subreach from the lower subreach. Flow is not perennial in the upper subreach above the Cherry Creek near Young gaging station; however, the no-flow period is short, and the depth to ground water during times of no flow probably is shallow. The flood plain in the upper subreach is as much as 1,000 ft (300 m) wide, and vegetation is entirely of the mixed broadleaf type. Flow is perennial in the middle subreach. The flood plain is narrow, averages about 200 ft (60 m) wide, and in places is on bedrock in a V-shaped canyon. Vegetation is sparse and of the mixed broadleaf type; the vegetation is present only in the few alluvial pockets along the stream. Flow in the lower subreach is intermittent. The subreach is characterized by a broad sandy flood plain covered by mesquite and riparian scrub in light- to medium-density stands. The depth to ground water is too great to sustain a dense stand of mesquite throughout the subreach.

The estimated annual evapotranspiration losses for the upper and middle subreaches are 500 acre-ft (0.6 $hm^3$) for the present (1975), near-future, and long-term future conditions. Present (1975), near-future, and long-term future losses are estimated to be 600, 1,600, and 3,000 acre-ft (0.7, 2.0, and 3.7 $hm^3$), respectively, for the lower subreach. Data from the base-flow analysis indicate a loss of about 800 acre-ft (1.0 $hm^3$) per year in the upper subreach, which includes the effects of local diversions and ground-water withdrawals in the summer. The base-flow data for the lower gaging station indicate a possible loss of only about 500 acre-ft (0.6 $hm^3$) per year for the middle and upper subreaches. The seasonal fluctuation in base flow is less at the downstream site than at the upstream site, probably because of large tributary spring flow in the middle subreach. The potential evapotranspiration loss for the entire reach is estimated to be about 5,100 acre-ft (6.3 $hm^3$) per year.

Tonto Creek.--Tonto Creek drains a large area south of the Mogollon Rim (fig. 4) and flows into Roosevelt Lake. The reach included in the vegetation mapping is 59.3 mi (95.4 km) long and extends from Roosevelt Lake upstream to the bridge on Arizona Highway 260 at Kohls Ranch.

For the purposes of discussion and in order to match the reaches used in the budget and base-flow analyses, Tonto Creek is divided into three subreaches—the lower, middle, and upper subreaches. The lower subreach extends from Roosevelt Lake to the Tonto Creek above Gun Creek near Roosevelt gaging station and is 17.1 mi (27.5 km) long; the middle subreach extends upstream to the Tonto Creek near Gisela gaging station and is 13.6 mi (21.9 km) long; and the upper subreach extends upstream to the end of the study reach and is 28.6 mi (46.0 km) long. The upper subreach is perennial, and riparian vegetation was practically nonexistent in 1975; the lack of riparian vegetation probably is the result of the flood of September 1970, which scoured all the vegetation and alluvial deposits in the channel. The upper subreach is youthful in geomorphic age, is generally on bedrock, and occupies a narrow V-shaped canyon. The flow in the middle subreach is perennial, and the flood plain ranges from less than 100 ft (30 m) to more than 0.5 mi (0.8 km) wide; the reach is mature in geomorphic age. Vegetation is mainly mesquite and some riparian scrub; the density of the vegetation is generally medium to light, which may be the result of the 1970 flood. Flow in the lower subreach is ephemeral, and the flood plain averages about

2,000 ft (600 m) wide. The lower subreach is classified as mature in geomorphic age. Vegetation is dominantly mesquite and includes small amounts of cottonwood and riparian scrub.

Under present (1975) conditions, the evapotranspiration losses in the upper subreach are estimated to be less than 100 acre-ft (0.1 $hm^3$) per year and probably will not increase for either future condition. The base-flow analysis for the Tonto Creek near Gisela gaging station at the end of the upper subreach indicates a loss of about 2,700 acre-ft (3.3 $hm^3$) per year. (See table 5.) This figure probably is affected by seasonal diversions and (or) pumping at the summer resort area near the upstream end of the reach.

As computed by the integration method, the present (1975) losses are estimated to be 1,500 acre-ft (1.8 $hm^3$) per year in the middle subreach; budget-method results for the middle subreach give a more conservative estimate of about 800 acre-ft (1.0 $hm^3$) per year. After correcting for tributary inflow from Rye Creek, data for the budget reach indicate an average loss of 3 $ft^3/s$ (0.085 $m^3/s$) in the 13.6 mi (21.9 km) between the Tonto Creek near Gisela and the Tonto Creek above Gun Creek near Roosevelt gaging stations. The base-flow analysis indicates a loss of about 2,300 acre-ft (2.8 $hm^3$) per year between the gaging stations; however, this value is undoubtedly too high owing to the large stands of riparian vegetation along the tributaries in the subreach. Based on the average of the integration and budget methods, the reasonable value for evapotranspiration losses in the middle subreach may be 1,100 acre-ft (1.4 $hm^3$) per year; however, for consistency in methods, the value shown in table 6 is that obtained by the integration method. The near-future and long-term future losses probably will not be greater because of the availability of more surface water.

In the lower subreach present (1975) evapotranspiration losses are estimated to be about 7,100 acre-ft (8.8 $hm^3$) per year; the value compares fairly well with the results obtained by Schumann and Thomsen (1972). Schumann and Thomsen (1972, p. 32) indicated a total consumptive use by plants of 13,000 acre-ft (16.0 $hm^3$), of which about 5,000 acre-ft (6.2 $hm^3$) was attributed to agricultural consumptive use, which is not included in this report. The estimated near-future losses probably will increase to slightly more than 10,000 acre-ft (12.3 $hm^3$) per year, and the estimated long-term future losses probably will increase to slightly more than 16,000 acre-ft (20 $hm^3$) per year.

In summary, the present (1975), near-future, and long-term future losses for the entire reach of Tonto Creek are estimated to be 8,700, 12,000, and 18,000 acre-ft (10.7, 14.8, and 22.2 $hm^3$) per year, respectively. The average consumptive use rate is estimated to be

63 in (1,600 mm); Schumann and Thomsen (1972, p. 31) obtained an annual potential evapotranspiration rate of 66.6 in (1,690 mm). The potential evapotranspiration losses for the entire reach of Tonto Creek probably will be between 21,000 and 23,000 acre-ft (26 and 28 $hm^3$) per year.

Verde River.--The Verde River is the major drainage in central Arizona, and the general direction of flow is from north to south. The flow of the Verde River is collected in the reservoir system near Phoenix and is used for irrigation, public-supply, and recreational purposes. The reach included in the vegetation mapping is 158.6 mi (255.2 km) long and includes the areas from the mouth, which is at the confluence with the Salt River, upstream to Bartlett Dam and from above Horseshoe Reservoir upstream to the head at Sullivan Lake, excluding the reach between Bartlett and Horseshoe Reservoirs.

For ease in discussion and in order to refer to the same reaches used in the budget and base-flow analyses, the above-described reach of the Verde was divided into six subreaches. The first subreach extends from the mouth to the Verde River near Scottsdale gaging station and is 2.7 mi (4.3 km) long. The second subreach extends upstream to Bartlett Dam and is 20.4 mi (32.8 km) long. The third subreach starts above Horseshoe Reservoir and extends to below

Camp Verde and is 50.4 mi (81.1 km) long. The subreach flows through canyons having flood plains that generally are less than 1,200 ft (370 m) wide. The vegetation is dominantly mesquite and riparian scrub and some scattered cottonwood-willow; bare soil is uncommon. The fourth subreach extends 47.1 mi (75.8 km) upstream to the Verde River near Clarkdale gaging station and includes a large area of agricultural land. The flood plain is as much as 1 mi (1.6 km) wide, and the vegetation is dominantly cottonwood and scattered mesquite and riparian scrub. The fifth subreach extends 28.2 mi (45.4 km) upstream to the Verde River near Paulden gaging station. The flood plain averages about 400 ft (120 m) wide and generally is in a V-shaped canyon. Vegetation is mainly mesquite and mixed broadleaf, cottonwood, and riparian scrub. The sixth reach extends 9.8 mi (15.8 km) upstream to Sullivan Lake at the head of the Verde River. The flood plain is narrow, and the vegetation is mainly riparian scrub and cottonwood, mesquite, and mixed broadleaf. Under present (1975) conditions, the evapotranspiration losses estimated using the integration method in the six subreaches are 3,600, 17,400, 6,000, 18,000, 2,200, and 600 acre-ft (4.4, 21.5, 7.4, 22.2, 2.7, and 0.7 $hm^3$) per year in upstream order.

Results of the budget method for a 20.4-mi (32.8-km) reach of the Verde River show the difference in inflow and outflow in the winter and summer (fig. 14). In this reach about 5,800 acres (2,300 ha) of flood plain is subject to evapotranspiration. The data indicate that losses occur in summer and winter but that the losses are considerably larger in the summer. Winter losses can be attributed to seepage to the underlying ground-water reservoir; the seepage replaces water pumped by Phoenix. The winter losses vary with the varying discharge but reach a maximum of 20 $ft^3/s$ (0.57 $m^3/s$) at inflow rates of more than 80 $ft^3/s$ (2.27 $m^3/s$). In the summer losses of between 40 and 45 $ft^3/s$ (1.1 and 1.3 $m^3/s$) occur at inflow rates of between 60 and 100 $ft^3/s$ (1.7 and 2.8 $m^3/s$); most of the inflow of less than 60 $ft^3/s$ (1.7 $m^3/s$) is lost. The values include seepage that replaces water withdrawn by the Phoenix well field along the river. For inflow rates of more than 100 $ft^3/s$ (2.8 $m^3/s$), the evapotranspiration losses appear to decrease, probably owing to the overall accuracy of the data and the fact that the loss becomes a small percentage of the discharge. The conclusion is that the loss in the summer is about 25 $ft^3/s$ (0.71 $m^3/s$) more than the loss in the winter. About 50 percent of the annual losses occur in June, July, and August (<u>see</u> fig. 13). Converting the percentage to an annual

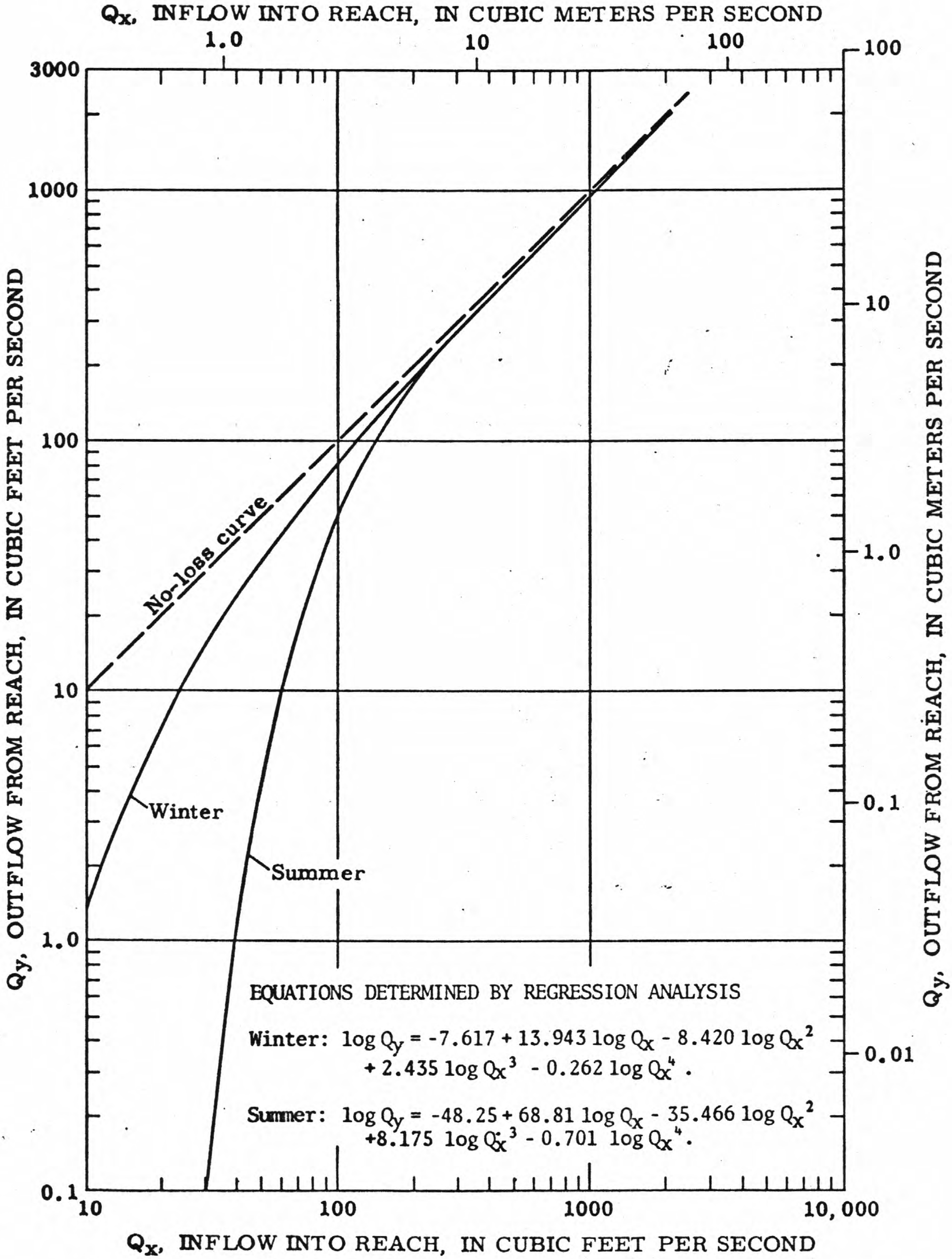



Figure 14.--Relation between summer and winter evapotranspiration losses using the budget method, Verde River from Bartlett Dam to the gaging station near Scottsdale.

volume gives about 9, 400 acre-ft (11.6 $hm^3$) of consumptive water use by riparian vegetation along the 20.4-mi (32.8-km) reach of the Verde River. Using the integration method for the same area gives an average annual loss of about 17, 400 acre-ft (21.5 $hm^3$).

As computed by the base-flow method, the losses upstream from Horseshoe Reservoir are estimated to be 55, 000 acre-ft (67.8 $hm^3$) per year (table 5), which includes all evapotranspiration losses in the watershed above Horseshoe Reservoir and other seasonal demands. In summing all the losses obtained by the integration method for the Verde River and the tributaries above Horseshoe Reservoir that were included in this study, the evapotranspiration losses should be at least 38, 000 acre-ft (46.8 $hm^3$) per year. The losses in the many small tributaries and the seasonal agricultural demands were not included and can easily make up the difference between 55, 000 and 38, 000 acre-ft (67.8 and 46.8 $hm^3$). Applying the base-flow method to the fifth subreach indicates that evapotranspiration losses are about 2, 400 acre-ft (3.0 $hm^3$) per year compared with losses of 2, 200 acre-ft (2.7 $hm^3$) per year using the integration method. In the sixth subreach the losses using the base-flow method are estimated to be between 800 and 900 acre-ft (1.0 to 1.1 $hm^3$) per year compared with 600 acre-ft (0.7 $hm^3$) per year using the integration method. The difference probably is caused by the unaccountable losses in the Sullivan Lake area. The overall comparison among the evapotranspiration estimates obtained using the several methods is good considering the assumptions that were made and the limitations of each method.

Under present (1975) conditions, the evapotranspiration losses for the entire reach are estimated to be 47,800 acre-ft (58.9 $hm^3$) per year and probably will not increase for the near-future or long-term future conditions; however, for consistency with the data in table 6 the value should be rounded to two significant figures—48,000 acre-ft (59 $hm^3$) per year. The potential evapotranspiration losses are estimated to be 77,000 acre-ft (95 $hm^3$) per year.

East Verde River.--The East Verde River heads at the base of the Mogollon Rim, flows southwesterly, and is tributary to the Verde River. The reach included in the vegetation mapping is 40.1 mi (64.5 km) long. The East Verde River is perennial and receives some intermittent transbasin diversion from East Clear Creek. The river is youthful in geomorphic age and generally flows on bedrock in a narrow canyon having small scattered pockets of alluvium. The vegetation is generally sparse, but scattered stands of mixed broadleaf, mesquite, and some riparian scrub occur in places.

Under present (1975) conditions, the evapotranspiration losses are estimated to be slightly more than 500 acre-ft (0.6 $hm^3$) per year. The near-future and long-term future losses probably will not be any larger because sufficient water is always available to satisfy the demand of vegetation, and the vegetation density should not change. The losses as determined by the base-flow method are 800 acre-ft (1.0 $hm^3$) per year, which was computed using all the flow from the tributary drainages above the gaging station—such as Pine Creek—and some minor diversions; therefore, the losses should be larger than the 500 acre-ft (0.6 $hm^3$) per year that was determined for the East Verde River alone. The potential evapotranspiration is estimated to be 1,400 acre-ft (1.7 $hm^3$) per year.

West Clear Creek.--West Clear Creek is a westerly flowing tributary of the Verde River (fig. 4). The reach included in the vegetation mapping is 32.5 mi (52.3 km) long. Streamflow records from the West Clear Creek near Camp Verde gaging station indicate that the creek is perennial at the station, which is 9 mi (14 km) above the mouth (U.S. Geological Survey, 1964-75). The 23 mi (37 km) of the reach upstream from the gaging station is contained in a narrow channel in the bottom of a steep-sided V-shaped canyon. The stream is youthful in geomorphic age, the flood plain is generally narrow, and vegetation is sparse. Mixed broadleaf vegetation is scattered in the few pockets of alluvium in the reach. From the gaging station downstream to the mouth, the flood plain generally widens and is at a maximum of about 0.5 mi (0.8 km) wide near the mouth. The vegetation is dominantly cottonwood and willow and some mixed broadleaf, mesquite, and riparian scrub.

The evapotranspiration losses are estimated to be about 2,400 acre-ft (3.0 $hm^3$) per year for the entire reach under present (1975), near-future, and long-term future conditions. Using the integration method, the losses are estimated to be 500 acre-ft (0.6 $hm^3$) per year upstream from the gaging station. The base-flow analysis indicates losses of about 1,200 acre-ft (1.5 $hm^3$) per year for the area upstream from the gage (table 5). The comparison is not good, but the difference might be attributed to additional riparian use in the tributary drainages. The potential evapotranspiration losses are estimated to be about 4,400 acre-ft (5.4 $hm^3$) per year.

Wet Beaver Creek.--Wet Beaver Creek is a southwesterly flowing spring-fed tributary of the Verde River (fig. 4). The reach included in the vegetation mapping is 27.4 mi (44.1 km) long and extends from the confluence with the Verde River upstream to the springs at the head of the perennial-flow reach. The stream is perennial throughout the study reach except for the lower 1 to 2 mi (1.6 to 3.2 km) just upstream from the mouth and generally flows on bedrock. The upstream half of the reach is youthful in geomorphic age, and the downstream half is mature. The flood plain ranges from about 30 ft (9 m) wide near the upstream end to about 1,000 ft (300 m) wide near the mouth. The vegetation on the flood plain is dominantly cottonwood, willow, and mixed broadleaf and some mesquite and riparian scrub.

Under present (1975) conditions, the evapotranspiration losses for the entire reach are estimated to be 3,500 acre-ft (4.3 $hm^3$) per year, and the near-future and long-term future losses probably will not change. In the reach upstream from the gaging station about 20 mi (32 km) above the mouth the evapotranspiration losses are estimated to be between 300 and 400 acre-ft (0.4 and 0.5 $hm^3$) per year, as computed by the integration method. Using the base-flow method, the losses for the same reach are estimated to be 336 acre-ft (0.41 $hm^3$) per year (table 5). The potential evapotranspiration is estimated to be 4,600 acre-ft (5.7 $hm^3$) per year for the entire reach.

Oak Creek.--Oak Creek is a tributary of the Verde River and is perennial throughout its reach. The reach included in the vegetation mapping is 46.9 mi (75.5 km) long and extends from the mouth upstream to Sterling Springs at the headwaters. The flood plain ranges from 30 ft (9 m) wide at the head to more than 1, 000 ft (300 m) wide near the mouth. The vegetation is primarily mixed broadleaf in the upper two-thirds of the reach, and alder and sycamore are the dominant types. In the lower one-third of the reach the vegetation is typically cottonwood and some mesquite and riparian scrub. In the lower half of the study reach a large part of the flood plain has been converted from native vegetation to cropland.

Under present (1975) conditions, the evapotranspiration losses for the entire reach are estimated to be 4, 700 acre-ft (5.8 $hm^3$) per year. Upstream from the Oak Creek near Cornville gaging station, the losses are estimated to be 3, 500 acre-ft (4.3 $hm^3$) per year using the integration method, and 6, 500 acre-ft (80 $hm^3$) per year using the base-flow method. The large disparity between the results of the base-flow method and those of the integration method is caused by the large streamflow diversions for irrigation use. The evapotranspiration losses probably will not change in the near future or long-term future if an increase in streamflow occurs. The potential evapotranspiration losses are estimated to be about 6, 500 acre-ft (8.0 $hm^3$) per year for the entire reach.

Agua Fria River.--The evapotranspiration losses along the Agua Fria River are discussed in a report by Anderson (1970) and are summarized below. The reach discussed in the report is 44.2 mi (71.1 km) long and extends from Lake Pleasant upstream to the gaging station at Sycamore damsite. The Agua Fria River generally flows from north to south, and part of the reach is perennial but most is intermittent. The flood plain ranges from 50 ft (15 m) to more than 1,000 ft (300 m) wide, and the channel is youthful in geomorphic age. The dominant riparian vegetation is mesquite.

According to Anderson (1970), the evapotranspiration losses for the entire reach are estimated to be 5,500 acre-ft (6.8 $hm^3$) per year. The near-future and long-term future losses are estimated to be 8,400 and 8,900 acre-ft (10.4 and 11.0 $hm^3$) per year. The average value of potential evapotranspiration based on Blaney-Criddle, lake evaporation, and adjusted pan evaporation is 66 in (1,680 mm); the potential evapotranspiration from the flood-plain area is estimated to be 9,800 acre-ft (12 $hm^3$) per year.

Hassayampa River.--The Hassayampa River is a south-flowing stream that drains the west slopes of the Bradshaw Mountains southeast of Prescott. The reach included in the vegetation mapping is 46.9 mi (75.5 km) long and extends from the bridge on U.S.

Highway 60 at Wickenburg upstream to near the head of the river about 7 mi (11 km) south of Prescott. The Hassayampa River is perennial only along the few short reaches where the volume of alluvium is not sufficient to carry the normal downvalley flow. The perennial reaches are associated with canyons in which the channel and flood plain are narrow—between 30 and 50 ft (10 and 15 m) wide. In most areas the flood plain is between 400 and 500 ft (120 and 150 m) wide, but it is as much as 2, 200 ft (670 m) wide in places. The dominant vegetation in the upstream half of the reach is cottonwood-willow, and the dominant type in the downstream half is mesquite. Bare soil and scattered riparian scrub occur throughout the reach.

Under present (1975) conditions, the evapotranspiration losses for the entire reach are estimated to be 3, 000 acre-ft (3.7 $hm^3$) per year. In the reach upstream from the Hassayampa River at Box damsite near Wickenburg gaging station the evapotranspiration losses are estimated to be 2, 300 acre-ft (2.8 $hm^3$) per year, as computed by the integration method. Using the base-flow method, the losses for the same reach are estimated to be 2, 200 acre-ft (2.7 $hm^3$) per year. The base-flow data for most gaging stations were analyzed on a seasonal basis, but the data for the Box damsite near Wickenburg station were analyzed on a monthly basis owing to the longer growing season in this area. The near-future evapotranspiration losses are estimated to be 4,800 acre-ft (5.9 $hm^3$) per year, and the long-term future losses are estimated to be 8,500 acre-ft (10.5 $hm^3$) per year. The possible increases of 1,800 and 5,500 acre-ft (2.2 and 6.8 $hm^3$) per year in consumptive use by riparian vegetation would result from shallower ground-water levels in the flood plain and an increase in vegetation density. The potential evapotranspiration losses are estimated to be 13,000 acre-ft (16.0 $hm^3$) per year.

## ACCURACY AND LIMITATIONS OF METHODS AND RESULTS

Although the accuracy of the evapotranspiration losses estimated by the integration method is unknown, it is almost entirely dependent on the accuracy of the relation between depth to water and consumptive use (fig. 11). Unfortunately, the relation is poorly defined; by selecting the data to be included in defining the curve, it is possible to obtain any shape for the relation between depth to water and consumptive use. In order to establish an accuracy criterion it would be desirable to define envelope curves for different levels of confidence and accuracy for the relation because the relation constitutes the major source of possible error. Because of the nonuniformity of empirical data, it is not possible to develop statistical levels of confidence for the relation. By examining the relation (fig. 11) and drawing different envelope curves, it appears that all the empirical data for depth to water and consumptive use—notwithstanding location, altitude, or chemical characteristics of the water—are included in the ± 50-percent-error category and may be considerably better. The maximum possible error that might occur would be where a large water-level rise and a resultant large increase in evapotranspiration losses occur. The empirical data used in this study were obtained mainly for sites in Arizona where the water quality and other factors are comparable to those in the study area; therefore, the accuracy should be better than ± 50 percent. The accuracy of the water-budget and base-flow methods is unknown but may be ± 100 percent or more; however, no data exist to prove or disprove this assumption. Many factors can affect the data used in these analyses; where the influence of these factors is small, the results may be good, and where the influence is large, the results may be poor.

The effect of altitude was not considered in the integration method, although it is a potential source of error. The consumptive-use values were not adjusted for altitude because the magnitude of the required adjustment is not known. The data used to develop the curves showing the relation between consumptive use and depth to water were generally for an altitude of about 3,000 ft (900 m). The midpoint altitudes of the different streams ranged from 1,100 to 6,200 ft (300 to 1,900 m). For streams having midpoint altitudes of less than 3,000 ft (900 m), the estimated losses may be too conservative; whereas, for streams having midpoint altitudes of more than 3,000 ft (900 m), the estimated losses may be too large.

A factor that may affect the estimate of future losses is the assumption that perennial flow will be present in reaches where it does not presently occur. Along several of the intermittent streams the alluvial material that makes up the ground-water reservoir may be too coarse and the slope of the channel may be too steep for perennial flow. In this instance the actual increase in evapotranspiration losses would be less than the original estimates. In addition, the most probable result of vegetation modification would be slightly longer periods of base flow and higher peak flows and not the instigation of perennial flow. Increases in runoff would occur in the spring when evapotranspiration losses are at a minimum, and the actual losses would be less than the original estimates.

# SUMMARY

The purpose of this investigation was to estimate the possible increase in transitory water losses that may occur as a result of an increase in the availability of water at the upstream end of selected streams. The present and future evapotranspiration losses were estimated for most of the streams that drain central Arizona. The consumptive use by riparian vegetation will increase if ground-water levels rise and (or) vegetation densities increase.

The integration method was used to estimate the possible increase in evapotranspiration losses and was based on the relation between water use by different types of vegetation and the depth to ground water. In addition, several other methods were used to estimate evapotranspiration for the purpose of checking the results obtained by the integration method.

The study area includes 1, 287 mi (2, 071 km) of stream channel that covers more than 42, 000 acres (17, 000 ha) of riparian vegetation and bare soil. Near-future or long-term future increases in evapotranspiration losses were not estimated for many of the streams because the streams contain perennial flow at the present time (1975), and the addition of water to the streams would cause a negligible increase in losses. The streams for which large increases

in evapotranspiration losses are predicted generally are in a desert to semidesert environment in the west-central part of the State. The general geomorphic setting of a stream is indicative of the general loss characteristics along the stream.

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