Studies of Consumptive Use Of Water by Phreatophytes And Hydrophytes Near Yuma, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 486-F

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WATER RESOURCES OF LOWER COLORADO RIVER—SALTON SEA AREA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 486-F

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 35 cents (paper cover)

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STUDIES OF CONSUMPTIVE USE OF WATER BY PHREATOPHYTES AND HYDROPHYTES NEAR YUMA, ARIZONA

By Charles C. McDonald and Gilbert H. Hughes

ABSTRACT

Studies of transpiration by several species of flood-plain vegetation and evaporation from water surfaces and bare soil were carried out near Yuma, Ariz., during a 6-year period, 1961–66. Arrowweed, fourwing saltbush, quailbrush, and bermuda grass were grown under controlled conditions in large tanks about 1,000 square feet in area, and cattail was grown in tanks 100 square feet in area. The larger tanks were also used for studies of evaporation from bare soil. Evaporation from water surfaces was measured by two standard U.S. Weather Bureau Class "A" pans and by a ground-level tank which was 10 by 10 feet. Related meteorological observations were made near the sites, and those of nearby meteorological stations at Yuma Proving Ground and Yuma, Ariz., were used.

The sites were on the flood plain of the Colorado River below Imperial Dam. Although the immediate area had a moderately dense cover of preponderantly arrowweed, the environment was principally desert, with high temperatures, low humidity, and a long growing season. Rates of evaporation and transpiration for this area rank among the highest in the United States.

Annual consumptive use by the several species increased with the volume of vegetation, but the consumptive use per unit volume decreased as the plants approached maturity. Depth to the water table strongly influenced evaporation from bare soil; for water table depths of 2.0–4.0 feet, evaporation varied from 3 to 20 inches yearly. Water table depths moderately influenced transpiration by *Atriplex*, although the depth of the tanks did not permit the water table to be held at sufficient depth to create substantial moisture stress. Average yearly water use for the vegetation was as follows:

	Depth to water table in feet	*Average yearly water use, in inches*
Arrowweed (*Pluchea sericea*)	5. 5	96
Quailbrush (*Atriplex lentiformis*)	3. 5–5. 5	44
Fourwing saltbush (*Atriplex canescens*).	3. 5–5. 5	38
Bermuda (*Cynodon dactylon*)	3. 5	73

INTRODUCTION

Native flood-plain vegetation consumes a large amount of water along many river channels in the arid southwestern United States. The vegetation is preponderantly phreatophytes that obtain most of their moisture directly from ground water. They consume a significant part of the available water supply in the western States; nearly 25 million acre-feet (Robinson, 1952) may be consumed yearly by more than 16 million acres of phreatophytes growing mostly on river flood plains. In six States—Arizona, California, Colorado, Nevada, New Mexico, and Utah—the area of phreatophytes was estimated by the Select Committee of the U.S. Senate (1960) to be 7 million acres, with an estimated annual consumptive use of 10–12 million acre-feet of water. In the basins of the Colorado River and its tributaries below Hoover Dam, the annual consumptive use by phreatophytes was estimated by the Select Committee to be 1.2 million acre-feet. In the Colorado River valley between Davis Dam and and the international boundary, about 200 miles in length, preliminary estimates (U.S. Bureau of Reclamation, 1964) indicated that 167,000 acres of phreatophytes and hydrophytes consumed 570,000 acre-feet of water yearly.

Water consumed by phreatophytes, such as saltcedar, arrowweed, willow, mesquite, and *Atriplex*, generally produces benefits of lower economic value than would be produced if the water were used for agriculture and domestic purposes; thus salvage of water by eradication of such vegetation in certain areas has considerable appeal. Control measures have been carried out in several areas. An outstanding example is the extensive clearing of saltcedar in the flood plain of the Rio Grande River in southern New Mexico (U.S. Senate, 1960).

The quality of water available for salvage is the difference between the evapotranspiration from the area before modification of the vegetation and the evapotranspiration from the area after modification of the vegetation. Estimates of such losses, however, are subject to large errors. Rates of water use by vegetation vary greatly because the rates are influenced by many factors, including the types of vegetation, availability of water, wind movement, relative humidity, growth rates, solar radiation, and soil characteristics. Several species of plants of different size and growth patterns may intermingle, thus complicating the problem of determining the water use in a given area. Furthermore, eradication of the vegetation does not assure that the water loss by evapotranspiration will be stopped. For example a rise in the water levels resulting from the lack of vegetation may promote increased evaporation from wet soil and rapid regrowth of plants. Estimates of evapotranspiration from the area after modification of the vegetation requires an appraisal of the altered hydrologic regimen, including the efficiency of any works constructed to capture the salvaged water.

Preliminary estimates by the U.S. Bureau of Reclamation (1964) suggest that in the Colorado River valley below Davis Dam, consumptive use by phreatophytes may be reduced by more than 250,000 acre-feet yearly by clearing flood-plain vegetation and improving the river channel.

Measurement of consumptive use by native vegetation under natural growing conditions is not readily accomplished. Many different methods for deriving a suitable index for consumptive use have been devised and experimentation is still in progress (Robinson, 1964), but all methods used to date seem to be deficient in some way and none provide results that are directly applicable to the determination of consumptive use by large areas of heterogeneous native phreatophytes. The influence of such diverse factors as vegetation density, advected energy, and the availability of water on the rate of water use have not been reliably determined.

Evapotranspirometers are tanks in which vegetation is grown under controlled conditions in extensive stands of native vegetation. They permit precise measurement of water consumed by vegetation in the tanks and provide a reasonable approximation of the natural environment. These attributes have resulted in their frequent use in the past. In recent studies, tanks of large size, up to 1,000 square feet in area (Robinson and Bowser, 1959), have been utilized to study a more representative sample of the larger shrub-type plants. Still larger phreatophytes, such as mature mesquite and willow, cannot be readily grown in tanks. The diversity and range of factors affecting evapotranspiration in natural environments are so great and the relations between factors so complex that it is impracticable to try to completely reproduce all factors in tanks. Available tank data, therefore, usually represent only a fraction of the range of natural conditions affecting consumptive use even for the principal species. Nevertheless, the tank method was considered to have sufficient applicability to justify its use in studies of consumptive use in the lower Colorado River valley.

The first phase of the joint study by the Geological Survey and Bureau of Reclamation, as described in this report, was carried out during the years 1961–1966. Two groups of evapotranspiration tanks (one group near Imperial Camp, Calif., and one at Mittry Lake, Ariz., see fig. 1) were installed in the Colorado River flood plain, about 20 miles north of Yuma, Ariz. Operation of the tanks at the Mittry Lake site was discontinued on December 31, 1964, but operation of the tanks at Imperial Camp is expected to be continued until 1968 as a part of the second phase of the study.

Most of the area shown in figure 1, which is outlined approximately by Imperial and Laguna Dams, the All-American Canal and the Gila Gravity Main Canal, is occupied by the river channel, shallow lakes, and the flood plain. Phreatophytes occupy nearly all of the flood plain and hydrophytes grow in much of the shallow water. The largest body of open water in the area is Mittry Lake.

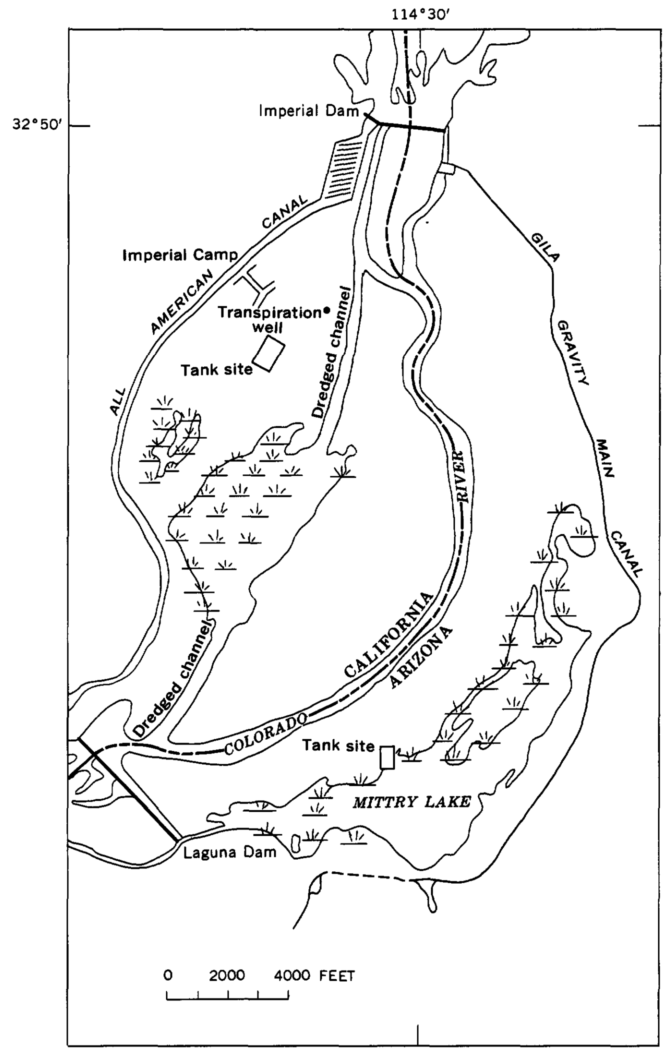


FIGURE 1.—Sites of evapotranspiration tanks near Imperial Dam, Calif. and Mitty Lake, Ariz., about 20 miles north of Yuma, Ariz.

The tanks were constructed by the Bureau of Reclamation, Yuma Projects Office, and were instrumented and operated by the Geological Survey. Mr. G. H. Hughes was in direct charge of operation of the tanks from April 1961 to July 1965; Mr. R. H. Westphal operated the tanks from August 1965 to July 1966, and Mr. O. M. Grosz from August to December 1966. The entire study was under the general supervision of C. C. McDonald, project hydrologist. Water and power for the operations were provided by the Imperial Irrigation District; their cooperation contributed greatly to the tank experiments.

IMPERIAL CAMP SITE

The Imperial Camp site is in an extensive area of vegetation, which is preponderantly arrowweed of moderately uniform height, density, and vigor. The environment is representative of much of the Colorado River flood plain where arrowweed and *Atriplex* are the dominant vegetation types. Some of the vegetation around the tanks was destroyed in the construction phase but was restored afterwards by transplantation so that a complete cover of similar vegetation surrounded each tank.

Three tanks were planted with arrowweed (*Pluchea sericea*), and three with *Atriplex* (*lentiformis* and *canescens*) in 1961. Three tanks were used to measure evaporation from bare soil during 1961–64 but were planted with bermuda grass (*Cynodon dactylon*) in 1965. Individual tanks were separated by about 60 feet of vegetation similar to that grown in the tanks, and each group of three tanks was separated from the other groups by about 300 feet (fig. 2).

The tanks at Imperial Camp were constructed by lining an excavation with a watertight plastic membrane in a manner similar to that described by Robinson and Bowser (1959). The sites were dug to the desired dimensions without shoring, the bottom was carefully smoothed, and all rocks and other obstructions that might puncture the membrane were removed. A sheet of polyvinylchloride 0.022-inch thick was then placed in the excavation, and the sides were brought to the ground surface as the soil was replaced, thus forming a flat-bottomed tank with vertical sides. The soil removed by excavation was replaced in the tanks without deliberate mixing or selection. The soil at the sites of the several tanks varied to some extent, but in general it consisted of fine sand, river silt, and minor amounts of clay.

The water-feed system, consisting of three parallel 2-inch perforated plastic pipes connected to a 4-inch riser, was placed in a 6-inch blanket of sand at the bottom of the tank. An observation well of 1¼-inch pipe, about 5 feet from the feed line, permitted readings of

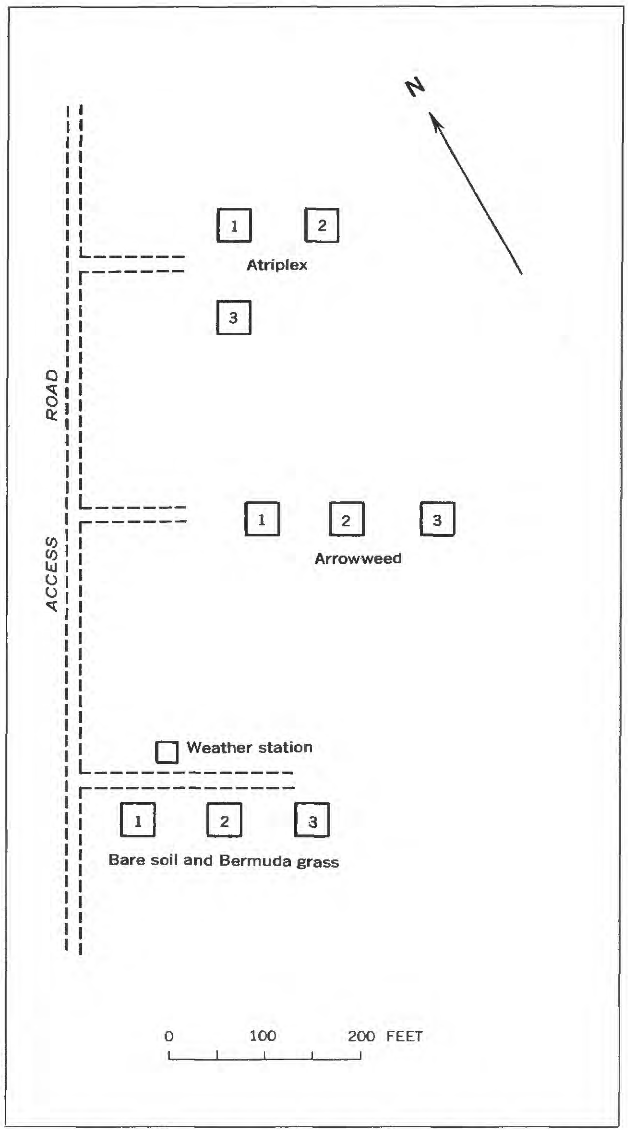


FIGURE 2.—Layout of evapotranspiration tanks at Imperial Camp, Calif.

the water level and provided access for the electrical contacts which activated the automatic water-feed controls. The quantity of water added to each tank was measured by a totalizing meter that had to be read at specified times. Changes in the moisture content of the soil above the water table were measured with a soil-moisture meter. The meter recorded the return of fast neutrons that were emitted by a 5 millicurie radium element and subsequently reflected by hydrogen atoms in the soil moisture. Access for the probe was provided by a thin-walled steel tube, 1.625 inches in diameter that was plugged at the bottom and that extended to a depth below the lowest expected water level in the tank. The moisture content of each tank was computed at least once each month from readings of the moisture content of the soil at 0.5-foot intervals as the probe was lowered into the access tube.

ARROWWEED

In May 1961, arrowweed was planted in three tanks, each of which was 32 by 32 by 7 feet; but because of hot weather and high soil salinity, survival was poor. Additional transplanting in January to March 1962 resulted in better survival but good growth and complete vegetal cover were not achieved until 1963, after the tanks had been leached to reduce the salinity of the soil. Leaching was accomplished by ponding water on the soil surface and pumping from the feed pipes.

By October 1963, all tanks had a vigorous stand of arrowweed about 6 feet in height, but less dense than most normal stands (fig. 3). Water levels were maintained about 3.5 feet below the land surface during 1962 to promote root development but were lowered to about 5 feet during 1963 and 5.5 feet during 1964–66.

Consumptive use by phreatophytes is known to be roughly related to the volume of transpiring foliage; moreover, the relations are much closer for plants of the same species growing in similar environments. Methods of measuring the areal density and volume of vegetation for large areas have been developed by the Phreatophyte Subcommittee of the Pacific Southwest Interagency Committee and have been described by Horton, Robinson, and McDonald (1959). These methods utilize transects to define indices of the thickness and the areal extent of the canopy and of height of the vegetation. To aid in the application of evapotranspirometer data to other areas, careful measurements of foliage volume were made at least once each year.

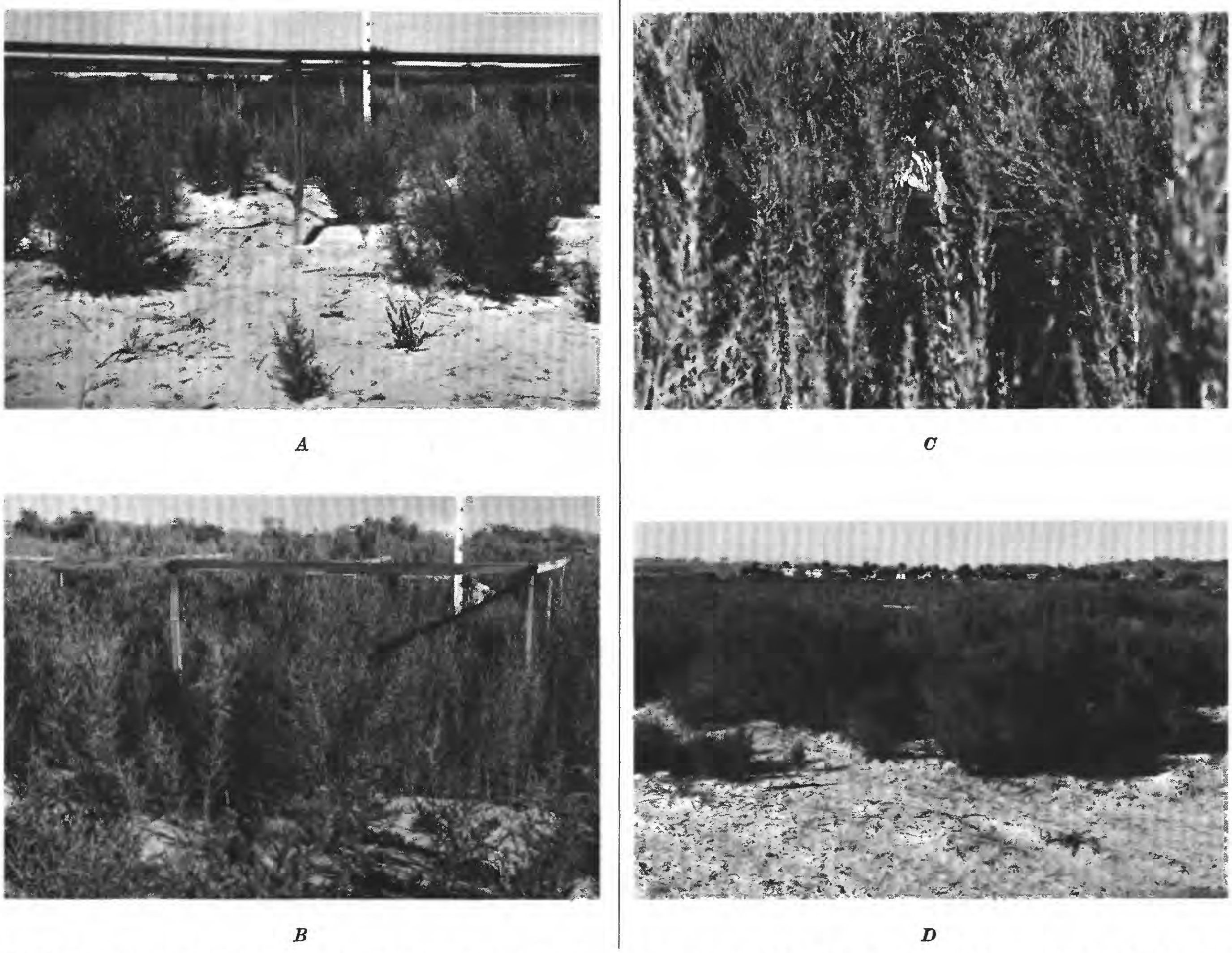


FIGURE 3.—Arrowweed (*Pluchea sericea*) growing in evapotranspiration tanks at Imperial Camp, Calif. *A*. Tank AW2 shows thin stand on Aug. 24, 1962. Framework outlines margins of tank; crossbars are 6 feet above ground. *B*. Tank AW1 on Oct. 25, 1963, following a period of vigorous growth. *C*. Detail of arrowweed in tank AW2, Sept. 18, 1964; maximum height is 11 feet. *D*. General view of arrowweed tanks toward northwest. Framework marks the location of tanks. Nov. 5, 1964.

Vegetation survey methods described by Horton, Robinson, and McDonald (1959) are commonly used for estimates of consumptive use. They employ an areal density factor to express the percentage of the area covered by the canopy, but they do not provide a measure of foliage density within the canopy. This factor may be important in evaluating the evapotranspiration by arrowweed. The authors believed some measure of foliage density within the canopy was desirable, though no completely satisfactory technique was found to measure it. The method used expressed as a percentage the relationship of the visual estimates of the density of segments of the foliage in the tanks to the usual density of the foliage of vigorous native stands of arrowweed. The areal extent of the canopy and the vegetation height were measured directly instead of by transects. The tanks were divided into segments varying in number from 10 to 100; the results for the segments were then weighted to arrive at a total for the tank. The same segments were used for the visual density estimates.

Results of the vegetation surveys are given in table 1. The area of the canopy was calculated as the sum of the areas covered by the outer limits of the foliage, without regard to density. The average height and relative density are weighted values for the total canopy area. The total volume of vegetation, without consideration of density of foliage, is the product of the area of the canopy and the average height, the equivalent volume is the product of the area of the canopy, the average height, and the relative density.

Prior to 1965, the depth of the canopy seemed to be about equivalent to the average height of the vegetation. The growth pattern of the arrowweed in the tanks and apparently also of the young native stands, was such that the foliage transpired throughout the height of the plant until the density of the foliage above was sufficient to provide nearly complete shading from sunlight. Where the foliage was thin, permitting moderate penetration of sunlight, new shoots and green leaves were commonly found. In 1966, however, following the addition of small quantities of fertilizer (commercial urea) to the feed water, the top foliage became so dense, especially in tanks AW1 and AW2, that the lower 3–3.5 feet of the vegetation produced essentially no transpiring foliage. This denudation and lessening of new growth near the ground began in all tanks during 1965, but the condition became more manifest in 1966.

Measurements of the vegetation, especially the density, are highly subjective. Differences in successive surveys should be expected, even though they were made by the same individual. Moreover, foliage density of arrowweed can increase rapidly during periods of vigorous growth or decline quickly as a result of dropping of leaves during periods of reduced vigor.

TABLE 1.—*Results of surveys of arrowweed in evapotranspiration tanks, Imperial Camp, Calif.*

[Tank area, in square feet, for AW1, 992; AW2, 999; and AW3, 1,000. Depth of canopy Sept. 15 1966, for tank AW1, 5.0 feet; AW2, 5.0 feet; and AW3, 4.5 feet]

Date of survey	Area of canopy (square feet)	Average height (feet)	Average relative density (percent)	Equivalent volume (cubic feet)
AW1				
Dec. 13, 1962	331	2.8	57	520
July 11, 1963	455	4.6	85	1,770
Oct. 8, 1963	675	6.1	77	3,080
Sept. 24, 1964	952	7.3	75	5,220
Aug. 6, 1965	1,010	8.1	75	6,110
Sept. 15, 1966	1,080	8.4	95	8,620
AW2				
Dec. 13, 1962	293	3.9	39	440
July 11, 1963	347	5.5	65	1,250
Oct. 8, 1963	486	5.9	72	2,090
Sept. 24, 1964	982	7.1	77	5,340
Aug. 6, 1965	1,020	8.2	67	5,580
Sept. 15, 1966	1,060	8.2	97	8,420
AW3				
Dec. 13, 1962	351	4.1	49	710
July 11, 1963	583	5.1	85	2,540
Oct. 8, 1963	617	6.1	78	2,940
Sept. 24, 1964	998	7.6	89	6,760
Aug. 6, 1965	1,060	8.1	68	5,880
Sept. 15, 1966	996	7.8	77	5,980

Some differences in the vigor and rate of growth of vegetation in the three tanks were observed, and these differences are reflected in the results of the density surveys. The best early growth during 1963 occurred in tank AW3, but between July 11 and October 8 tanks AW1 and AW2 gained much more volume than tank AW3. Nevertheless, by September 24, 1964, vegetation in tank AW3 was still larger and more vigorous than that in the other two tanks. During the spring of 1964, the arrowweed in tanks AW2 and AW3 appeared to lose vigor: the leaves had developed a noticeable silvery color, which disappeared by midsummer. The vegetation survey of August 6, 1965, showed a drop in equivalent volume of about 15 percent in tank AW3 and an average increase of about 10 percent in the other two tanks. Although part of these differences may be the result of inconsistencies in the surveys, the relative differences were confirmed by visual observations.

Monthly water use by arrowweed is given in table 2, and the averages for the three tanks are plotted in figure 4. These figures represent water added to the tanks through the supply system and do not include water added by precipitation on the surface. The principal interest in these studies was the net consumption

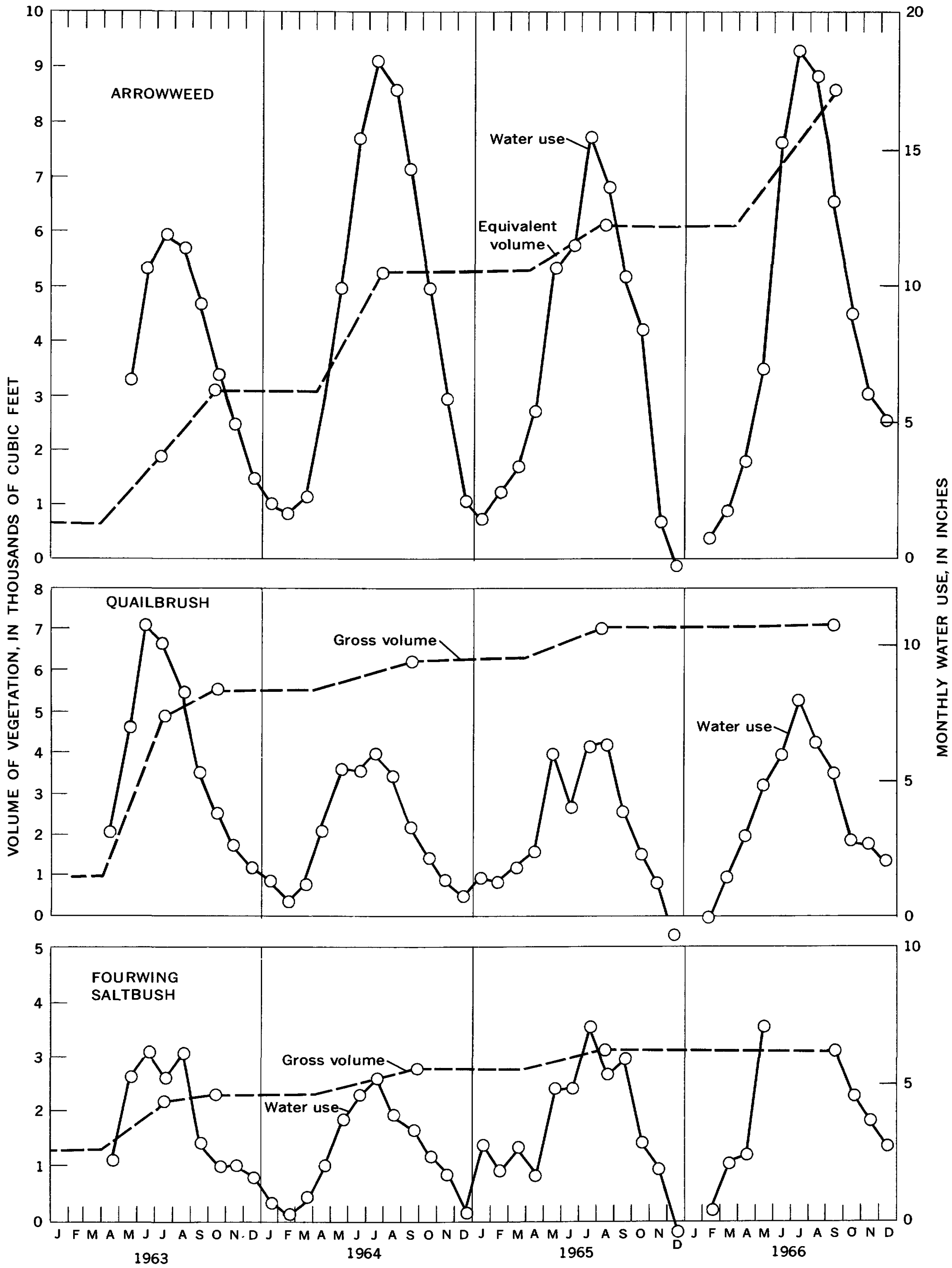


FIGURE 4.—Monthly water use and volume of vegetation grown in tanks at Imperial Camp, Calif. Dashed lines show approximate volume changes between vegetation surveys.

TABLE 2.—*Monthly water use by arrowweed in tanks, excluding rainfall, in inches, Imperial Camp*

[Negative values indicate that gain in soil moisture in tank exceeded water added through supply system]

	1962			1963			1964			1965			1966		
Tank	AW1	AW2	AW3	AW1	AW2	AW3	AW1	AW2	AW3	AW1	AW2	AW3	AW1	AW2	AW3
Depth to water feet	3.7	3.5	3.8	5.1	5.0	5.0	5.3	5.7	5.8	5.5	5.5	5.5	5.5	5.5	5.5
January							1.9	1.9	2.3	1.2	1.4	1.8		0.2	
February							1.9	1.2	2.0	2.3	2.7	2.5	1.0	.7	0.7
March							2.4	2.2	2.1	2.6	3.8	3.6	2.9	1.1	1.4
April							5.4	5.4	6.0	5.2	6.2	4.9	2.8	4.6	3.4
May				7.7	5.5	6.4	9.9	9.1	10.8	11.8	10.2	9.8	8.4	8.8	3.9
June				10.7	9.4	11.5	14.0	15.5	16.4	12.5	11.9	9.9	15.0	21.4	9.1
July				10.1	11.4	14.0	15.8	19.5	19.0	17.4	17.0	11.8	19.5	26.4	9.8
August				12.1	9.9	12.0	14.8	18.7	17.7	16.6	13.2	10.9	20.1	21.9	10.8
September		5.9	6.5	9.5	8.8	9.9	13.2	15.1	14.3	12.2	10.5	8.3	14.4	15.8	9.1
October	5.2	4.4	5.9	6.6	6.4	7.2	8.8	10.5	10.4	9.1	9.6	6.4	9.8	10.0	7.3
November	3.2	2.6	1.9	4.8	4.7	5.3	5.2	6.5	6.1	1.6	.2	2.0	6.2	6.8	5.2
December	2.2	1.9	2.1	3.0	2.6	3.4	1.8	2.2	2.3	.1	−.2	−.2	6.0	5.1	4.1
Total				64.5	58.7	69.7	95.1	107.8	109.4	92.8	86.6	71.6	106.1	122.8	64.8

of ground water by native vegetation, but adjustments for rainfall can be made if desired. Except for the rare storm rainfall, such as occurred during September and October 1963 and December 1965, precipitation did not add an appreciable amount of water to the water supply system. Figure 4 shows that water use tends to increase as the volume of foliage increases, but it also varies with other factors such as maturity of the foliage. These factors are discussed in the section on relation between volume of vegetation and water use.

ATRIPLEX

Two species of *Atriplex*, fourwing saltbush (*Atriplex canescens*) and quailbrush (*Atriplex lentiformis*), commonly grow on the lower Colorado River flood plain; however, both species cover less than 1 percent of the total area occupied by phreatophytes (U.S. Bureau of Reclamation, 1964).

Sometimes *Atriplex* is found in areas that have such a deep water table that the plants probably subsist on soil moisture derived from surface sources; however, it grows more vigorously and probably consumes more water in areas that have a shallow water table.

Three tanks, each approximately 1,000 square feet in area, and identical in design with those used for arrowweed, were planted with *Atriplex* in the late spring of 1961. Quailbrush, the larger of the two species, was grown in two tanks, A1 and A2, and fourwing saltbush was grown in tank A3. Young vigorous plants of both kinds were transplanted in the tanks and in a strip surrounding the tanks to obtain a uniform cover of similar vegetation within the tanks and in the surrounding area.

Transplanting the *Atriplex* in 1961 was not entirely successful, probably because of the late season and high soil salinity, which was described in the discussion of the arrowweed tanks. Following leaching of the tanks to reduce salinity early in 1962, retransplanting and seeding resulted in good cover both in the tanks and in the adjacent areas, but vigorous growth did not occur until after additional leaching during January and February 1963.

The quailbrush grew very rapidly in 1963, and most of the volume of vegetation looked as if it were actively transpiring. Changes in the seasonal appearance of the vegetation are noticeable in figure 5. Green leaves were present throughout the foliage during 1963, but in the years following only the outer 2–3 feet looked as if it were made up of actively transpiring leaves. By 1964 the plants had formed a complete outer dense canopy, with a skeletal maze of angular branching twigs lacking green foilage underneath—a structure that provides excellent cover for quail and other small wildlife. Quailbrush in the tanks and in the surrounding area seemed to become progressively less vigorous as it approached maturity during 1965 and 1966.

The vegetation in the *Atriplex* tanks was surveyed annually using methods similar to those used in surveying the arrowweed, except that the density of the *Atriplex* foliage was nearly normal each time, and no adjustment for relative density had to be made. In making the surveys, the tank areas were divided into sections, which varied in number according to the density of the vegetation; the dimensions of individual plants were taken to obtain the total volume. The results of these surveys are given in table 3.

TABLE 3.—*Volume, in cubic feet, of Atriplex in evapotranspiration tanks, at Imperial Camp*

Date of survey	Tank A1	A2	A3
Dec. 13, 1962	1,250	860	1,290
July 11, 1963	4,810	5,020	2,150
Oct. 8, 1963	5,600	5,700	2,290
Sept. 24, 1964	6,410	6,080	2,770
Aug. 6, 1965	7,210	6,840	3,080
Sept. 15, 1966	7,720	7,070	3,740

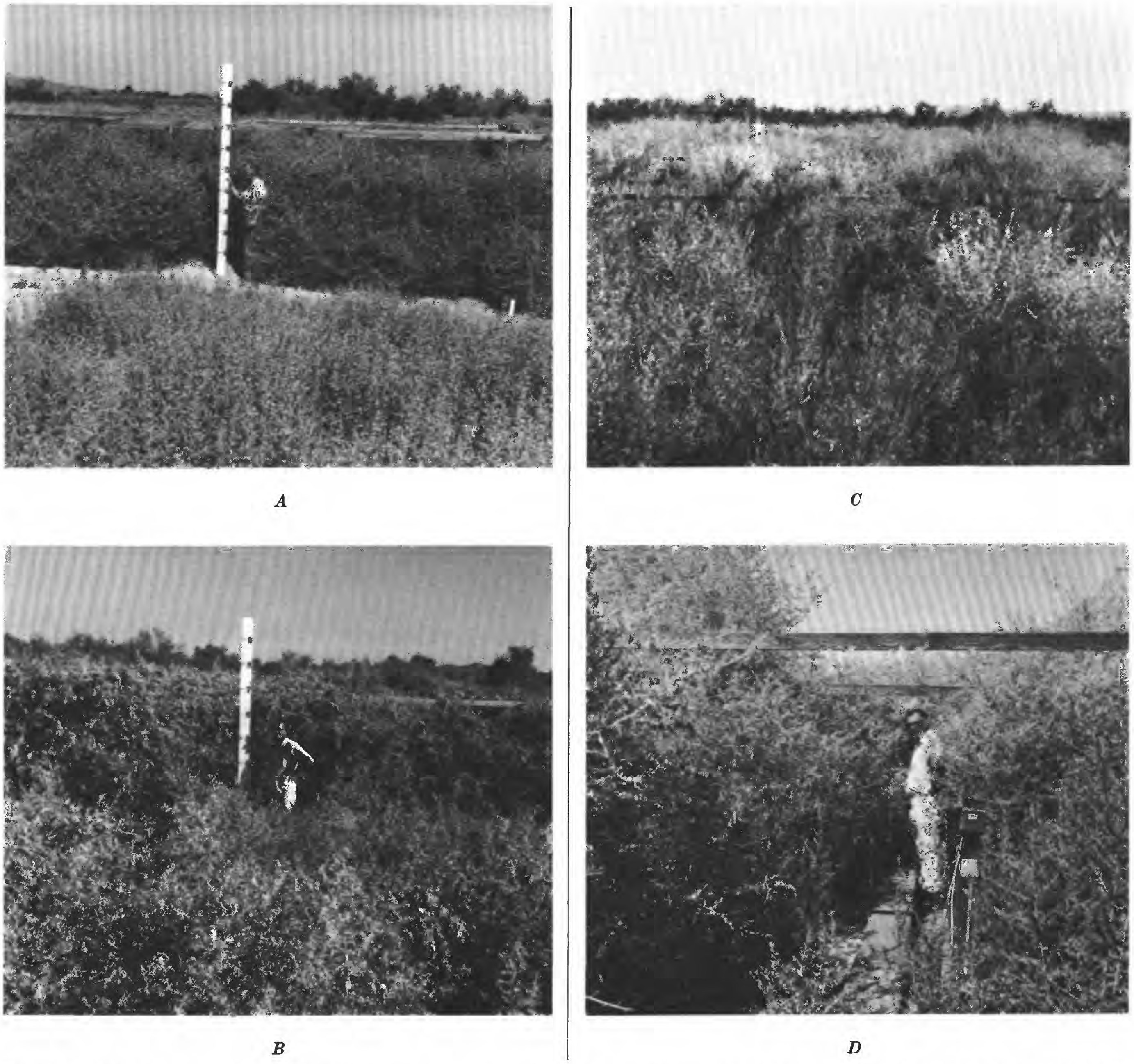


FIGURE 5.—Quailbrush (*Atriplex lentiformis*) in evapotranspiration tank A2, Imperial Camp, Calif. Framework at a height of 7 feet outlines tank. *A*. View from west, June 4, 1963, during vigorous growth period. *B*. In seed at end of growing season, Oct. 25, 1963. *C*. Mature vegetation, less vigorous than during previous year, with little seeding evident, Nov. 5, 1964. *D*. View of fill pipe, water-feed controls and soil moisture tube (at end of walkway), Sept. 18, 1964.

The water table in the quailbrush tanks, A1 and A2, was held at a depth of about 3.5 feet during 1962 to expedite root development; then it was lowered to 5.0 feet during 1963 and 5.5 feet during 1964. The lower depths were believed to be more representative of the natural environment of the plants. The quailbrush looked less vigorous in 1964 than it did in 1963, and the water use was significantly less. To determine whether growth and water use were influenced substantially by depth to the water table, the water level in tank A2 was raised to about 3.5 feet below the land surface during 1965. No change in the vegetation of A2 was apparent, either in relation to the other tank or to the previous year, but water use increased. During 1966 both quailbrush tanks, A1 and A2, were operated with the water table 5.5 feet below land surface. Monthly water use by quailbrush for the years 1962–66 is given in table 4 and plotted in figure 4.

TABLE 4.—*Monthly water use by* Atriplex *in tanks, excluding rainfall, in inches, Imperial Camp*

[Negative values indicate that gain in soil moisture in tank exceeded water added]

	1962			1963			1964			1965			1966		
Tank	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3
Depth to water feet	3.3	3.8	3.7	4.9	5.0	5.2	5.8	5.3	5.8	5.5	3.5	3.5	5.5	3.5	5.5
January							1.6	1.0	0.6	0.5	2.5	2.8			
February							.4	.8	.2	.8	1.8	1.8	−0.2	0.3	0.3
March							1.5	1.0	.8	1.8	2.0	2.6	1.8	1.2	2.1
April				2.1	4.0	2.3	3.5	2.7	2.0	2.9	1.8	1.6	2.9	3.1	2.3
May				5.9	8.0	5.2	6.6	4.2	3.7	6.8	5.1	4.8	4.2	5.5	7.0
June				10.7	10.6	6.2	7.1	3.6	4.6	4.1	4.0	4.9	5.7	6.2	[1] 10.7
July				11.8	8.2	5.2	7.0	4.9	5.2	6.2	6.4	7.0	8.9	7.0	[1] 15.5
August				8.8	7.6	6.2	6.4	3.8	3.9	6.5	6.1	5.3	6.4	6.7	[1] 13.8
September	3.1	4.6	4.2	4.8	5.5	2.8	3.7	2.8	3.3	4.0	3.8	5.9	6.0	4.7	6.2
October	3.4	3.7	4.3	4.3	3.4	2.0	2.5	2.0	2.3	2.4	2.5	2.7	3.4	2.4	4.5
November	5.5	2.2	2.6	3.0	2.1	2.0	1.3	1.4	1.7	1.0	1.4	1.9	3.2	2.3	3.7
December	1.5	1.9	2.4	2.4	1.4	1.6	.8	.5	.2	−.6	−1.2	−.4	2.4	1.8	2.7
Total				53.8	50.8	33.5	42.4	28.7	28.5	36.5	36.2	41.0	44.7	41.2	[1] 68.8

[1] Records not representative because of growth of young arrowweed in tank.

Fourwing saltbush, which is smaller and slower growing than quailbrush, commonly grows in separate rounded clumps with bare areas between. Tank A3 and the area surrounding it were planted with fourwing saltbush in 1961. Because of poor survival, additional planting was necessary in 1962 and 1963. Full areal coverage was not achieved during the period of operation. Photographs in figure 6 show the vegetation in tank A3 in two stages of growth and a natural stand of fourwing saltbush on the Yuma Mesa during an infrequent seeding period.

The water table in A3 was held at a depth of 3.7 feet during 1962, then lowered to 5.2 and 5.8 feet during 1963 and 1964, respectively. In 1965, it was again raised to 3.5 feet below the land surface to test the effect of depth of the water table on water use. The vegetation was noticeably less vigorous during 1965 than in 1964, but the water use was greater. Raising the water levels probably was not the only cause for the poor condition of the vegetation in the tank, as similar vegetation outside the tank also lost vigor during 1965. In January 1966, the tank was leached and 10 pounds of nitrogen fertilizer was added to the feed water; the water level was held at 5.5 feet below the land surface. The vegetation showed renewed vigor during the year and made good growth, while similar vegetation adjacent to the tank showed little change from 1965.

Monthly water use by the fourwing saltbush in tank A3 for the period of record is shown in table 4 and plotted in figure 4. The high rate of water use during May to August 1966 was affected by an infestation of young volunteer arrowweed and baccharis, which was removed on August 20; therefore, the water use rates during these months are not representative of the fourwing saltbush alone. Comparison of the vigor and growth of the saltbush during 1965 and 1966 suggest that the rate of water use should be higher during 1966 than during 1965, but not so high as indicated in the table.

BARE SOIL

Evaporation from bare soil was measured in three tanks; they have the same features as the tanks previously described. Water was added from the bottom through feed pipes, and the surface was wet only by upward moving moisture except for rare occurrences of precipitation. The surface of the tanks was approximately level with the adjacent land surface, and an area at least 30 feet wide surrounding the tanks was maintained free of vegetation.

The soil in the tanks was fairly well mixed as a result of the method of construction. Generally, it consisted of sand and silt with a minor percentage of clay. The results of sieve analyses, as shown in table 5, indicate some differences in the soil of the three tanks. Tank BS1 has the greatest percentage of clay and silt, and BS3 has the greatest percentage of sand.

TABLE 5.—*Sieve analyses of soil in bare-soil tanks at Imperial Camp*

Type of soil	Particle size, in mm	Cumulative percent, by weight, of particles smaller than size indicated		
		BS1	BS2	BS3
Clay to silt	0.010	9	7	4
	.020	14	8	6
	.037	26	16	11
	.074	62	49	37
Sand	.140	99	97	95
	.590	100	100	100

Water levels in the bare-soil tanks were maintained at depths of 3.0 feet below the land surface in 1962. In 1963 and 1964 the level in BS1 was held at 2.0 feet, and in BS3 it was held at 4.0 feet to determine the effect of depth on evaporation rates. Prior to August 1963, the water levels were maintained within a narrow range

A *C*

B

FIGURE 6.—Fourwing saltbush (*Atriplex canescens*), in evapotranspiration tank at Imperial Camp, Calif. *A*. View of evapotranspiration tank A3 from northwest, July 12, 1962. *B*. Similar view of A3, Oct. 25, 1963. Vegetation in seed following good growth. *C*. Native stand on mesa near Yuma following good growing season, Oct. 25, 1963. The water table was about 50 feet below land surface.

by an automatic water feed, but after that date, the water levels fluctuated greatly because relatively larger quantities of water had to be added to the tanks by hand two or three times a week. As the depth to water was measured each time before water was added, the average water level after August 1963 was higher than indicated by the measurements. This effect was most pronounced for tank BS1, which had the highest water level and water use.

The surface of the soil in tank BS1 appeared moist except during periods of greatest evaporation. A crust of alkali that formed during 1963 was scraped off with a square-point shovel during the spring of 1964, but it re-formed within a few weeks. Pools of water sometimes formed briefly on the surface of the tank shortly after rapid manual filling; these were probably attributable to temporary hydrostatic pressure, which caused the water to move upward through the more permeable zones.

Some deposition of salts was apparent on the surface of tank BS2, but the soil surface of tank BS3 differed little in appearance from that of the surrounding area. Photographs shown in figure 7 depict the difference in surface conditions of the three tanks.

Precipitation has not been included in the data shown in table 6, because the purpose of the study was to determine the net draft on ground water by evaporation from bare soil. Precipitation during the months of August, September, and October 1963 and August 1964, as shown in table 12, was sufficient to affect the draft on ground water significantly during those months. In some other months, the rainfall was greater than the evaporation; this resulted in a net gain of water for those months. Beginning with April 1963, records of evaporation were adjusted for changes in soil moisture during the month. These changes were small, generally ranging from 0.1 to 0.3 inch. They hardly exceeded the range of probable error of determination.

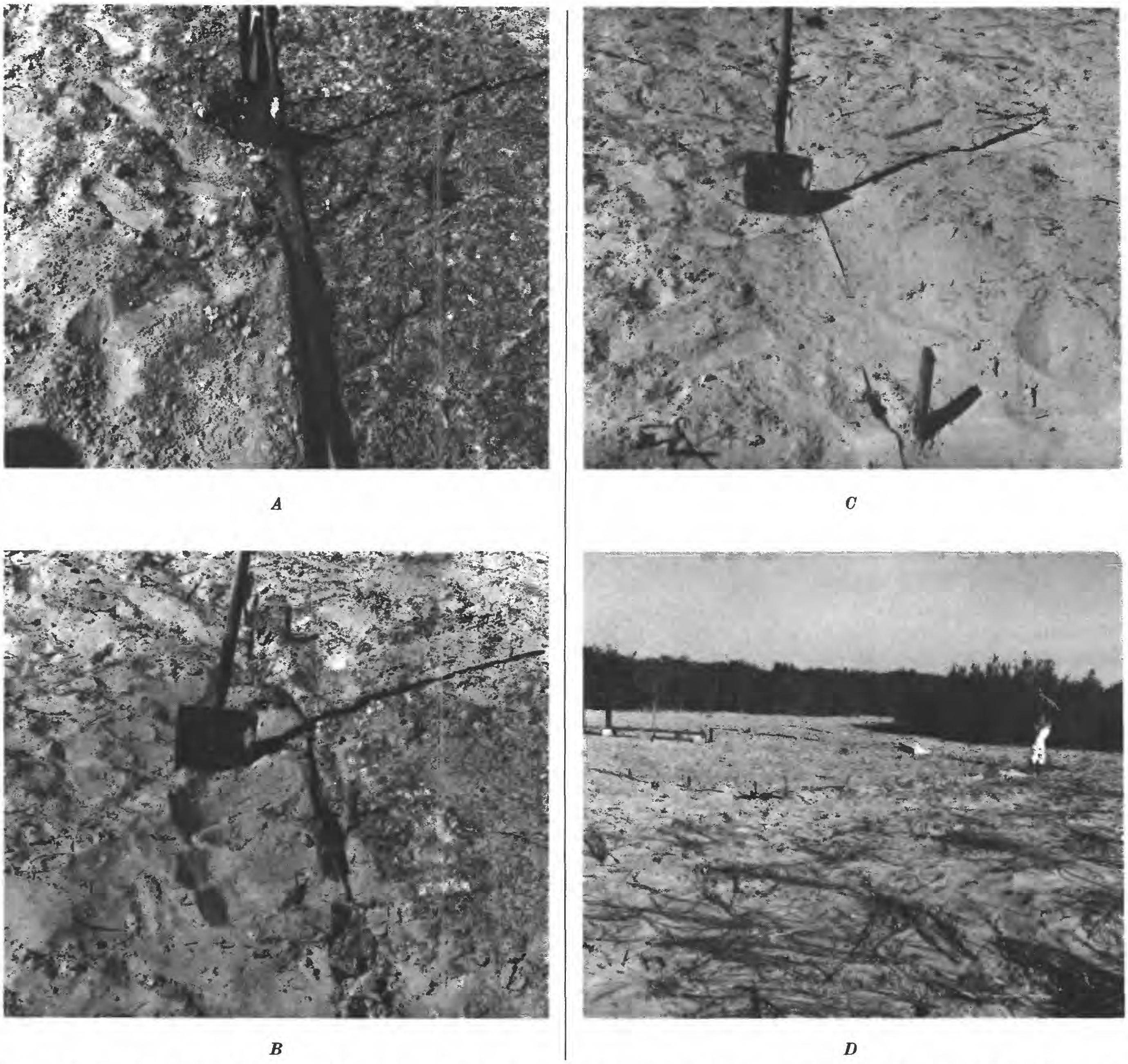


FIGURE 7.—Surface of bare-soil evaporation tanks, June 26, 1964, Imperial Camp, Calif. *A*. Detail of soil in tank BS1, right side of photograph Ground water about 2.0 feet below land surface. Note wet surface and salt crust, in contrast with surrounding soil. *B*. Tank BS2, right side of photograph. Ground water 3.0 feet below surface. Soil in tank usually appeared dry, but salt deposits are evident. *C*. Tank BS3, on right. No difference in soil appearance inside or outside the tank. Soil surface always appeared dry. Depth to water 4.0 ft. *D*. General view of tank BS2.

Deviation from any apparent seasonal trend of evaporation from tank BS3, and to a less extent from BS2, may be, in part, attributed to error inherent in taking the soil-moisture measurements.

Annual evaporation from the bare-soil tanks at water-table depths of 2 and 3 feet, estimated from data in table 6 to be 20.0 and 6.6 inches respectively, are within the range of previous experimental results. At a water-table depth of 4 feet, however, the indicated evaporation of 3.2 inches is less than that found in some other experiments.

Research hydrologist T. E. A. van Hylckama (written commun., 1965), U.S. Geological Survey, reports that near Buckeye, Ariz., net yearly evaporation from a silty clay soil was about 17 inches from depths of 4 feet in a 100-square-foot tank surrounded by vegetation and

TABLE 6.—*Monthly evaporation of ground water from bare-soil tanks, excluding precipitation, in inches, at Imperial Camp*

[Negative values indicate that gain in soil moisture is greater than feed water added]

	1962			1963			1964		
Tank	BS 1	BS 2	BS 3	BS 1	BS 2	BS 3	BS 1	BS 2	BS 3
Nominal depth to water ... feet	2.7	3.0	2.6	1.9	3.0	3.5	2.1	3.0	4.0
January				1.20	0.37	0.15	1.04	0.67	0.17
February				1.48	.32	.10	.94	.43	.17
March				1.45	.49	.11	1.23	.44	.04
April				1.46	.55	.13	1.57	.88	.04
May	0.80	0.68	0.59	1.27	.73	.40	2.31	1.17	.44
June		.58	.91	1.60	.52	.24	3.62	1.19	.28
July	.98	.64	1.03	1.61	1.05	.65	2.74	.96	.61
August	.88	.69	1.05	[1].94	[1].45	[1].18	2.37	[1].07	[1].27
September	.65	.58	.76		[1]−.11	[1]0	2.05	.56	1.01
October	.59	.51	.68		[1].42	[1]−.20	2.01	.27	.32
November	.40	.38	.51		.87	.42	1.86	.53	.40
December	.28	.27	.42	.78	.32	.30			
Total	4.58	4.33	5.95	11.79	5.89	2.48	21.74	7.17	3.75

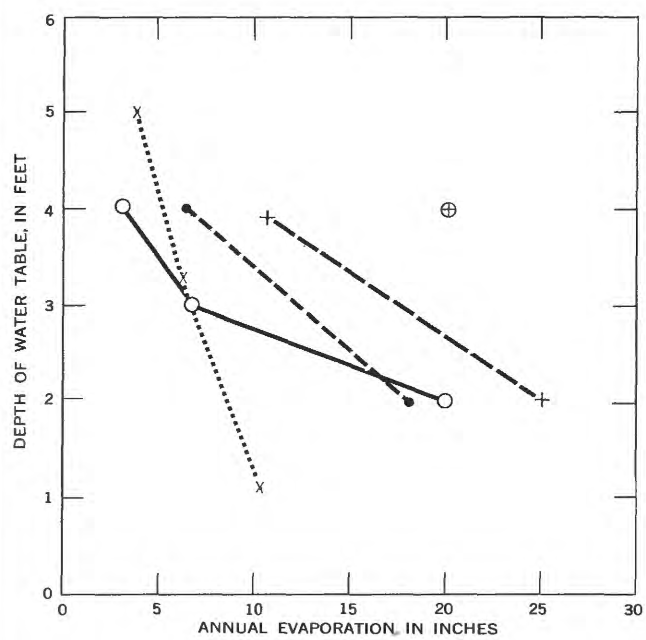
[1] Affected by precipitation.

about 23 inches from a similar tank in a cleared area. Precipitation at Buckeye is only slightly more than at Yuma. At Glenbar, Ariz., the U.S. Geological Survey measured evaporation from clay loam soil in metal tanks 4 feet in diameter in 1943–44. The records cover about a year but are incomplete. They showed evaporation of 11 inches for a depth to water of 3.9 feet and about 25 inches for a depth of water of 2.0 feet. Young (1933) found that for fine sandy loam soil at Santa Ana, Calif., the evaporation from tanks similar to those used at Glenbar, Ariz., was 18 inches for a depth to water of 2.0 feet in disturbed soil, and 6.5 inches for a depth to water of 4 feet in undisturbed soil. The Santa Ana tanks were shielded from rainfall.

In Escalante Valley, Utah, White (1932) measured the evaporation from a clay loam soil in metal tanks during 1926 and 1927 for periods approximating the growing season, April to October. For soil tanks having a water-table depth of 5 feet, evaporation from May to October averaged 3.7 inches; for a depth of 3.3 feet, the evaporation from May to October was 6.3 inches (partly estimated); and for a depth of 1.1 feet, from June to October, 10.1 inches.

In all previous experiments, except those at Santa Ana, Calif., the tanks received natural rainfall that was not included as evaporated water. These records, therefore, represent evaporation of ground water from the soil surfaces. Data on evaporation from soil surfaces referred to above are plotted in figure 8.

The type of soil and degree of compaction probably have an important effect upon rates of evaporation. Certainly when the capillary fringe reaches the surface of the soil, the transfer of vapor to the atmosphere is expedited and evaporation rates are substantially greater than if the upper limit of the capillary fringe is a foot or more below the surface. The tanks near Yuma and those near Buckeye were not compacted after filling except by rare foot traffic, by adding water through the feed pipes, and by rainfall. The sandy soil on the surface of tanks BS2 and BS3 remained loose throughout the tests; however, by 1962 the soil in the tanks was believed to be comparable to that of similar soil in the natural flood plain.



EXPLANATION

O Yuma, Arizona	Silty-loam soil
⊕ Buckeye, Arizona	Silty-clay soil
+ Glenbar, Arizona	Clay-loam soil
• Santa Ana, California	Fine sandy-loam soil
x Escalante Valley, Utah	Clay-loam soil

FIGURE 8.—Relations of annual evaporation of ground water from bare soil to depth of water table below land surface, Ariz., Calif., Utah.

BERMUDA GRASS

The three large tanks previously used for bare-soil evaporation studies were seeded to bermuda grass (*Cynodon dactylon*) during the early spring of 1965. Sprinkling was necessary until early May when the grass roots had developed sufficiently to maintain growth by subirrigation. The depth to the water table in all tanks was held at about 3.5 feet during 1965 and 1966, and throughout this time the grass did not seem to suffer from lack of water. A strip 20 feet wide surrounding these tanks had been maintained bare for the soil evaporation studies and was kept bare for the bermuda grass studies.

During the 1965 season, growth was only fair: areal density was estimated to be 95 percent, and the average height was about 4 inches. The amount of foliage represented probably less than 50 percent of the foliage grown commercially for seed in the Yuma area. Two light applications of nitrogen fertilizer proved to be inadequate to promote good growth. The tanks were leached during January 1966, and heavy applications of nitrogen fertilizer (commercial urea) were applied to each tank as follows: 25 pounds on March 14, and 10 pounds on April 4, 22, May 23, and July 11. The bermuda grass responded quickly and grew vigorously during the year. The areal density in tank BG1 was about 90 percent, and the other two tanks were completely covered. The grass reached a height of about 12–15 inches in June and remained at this height until November. A compact mat of vegetation about 4 inches deep was formed by the stems as they reclined while continuing to grow in length during the season. The grass in tank BG2, harvested on November 9, 1966, produced a dry weight of hay equivalent to 10.0 tons per acre.

The monthly water use, shown in table 7, was calculated on the basis of the net area enclosed by the redwood frame placed just inside the plastic tank liner to protect the liner from damage by roots. During 1966 the average water use by the three tanks was about 68.5 inches during the growing season, April to November. This figure does not include 2.94 inches of precipitation.

TABLE 7.—*Monthly water use by bermuda grass in tanks, excluding rainfall, in inches, Imperial Camp*

[Negative values indicate that gain in soil moisture is greater than feed water added]

	1965			1966		
Tank	BG 1	BG 2	BG 3	BG 1	BG 2	BG 3
January						
February				1. 3	0. 7	0. 1
March				2. 0	2. 7	2. 6
April				5. 3	6. 4	7. 7
May				7. 5	11. 0	9. 2
June	6. 0	6. 5	6. 4	10. 2	11. 1	11. 0
July	6. 1	8. 9	9. 0	13. 4	14. 5	14. 8
August	5. 6	8. 4	7. 2	12. 1	12. 3	10. 6
September	4. 7	5. 3	6. 6	8. 0	8. 0	8. 2
October	3. 8	4. 2	4. 0	3. 0	4. 1	[1] 2. 0
November	[3] 0	[3] 0. 6	[3] 0. 8	2. 4	[2] 1. 9	2. 5
December	[3] −0. 5	[3] −0. 8	[3] −1. 0	. 9	1. 6	. 3
Total	25. 7	33. 1	33. 0	66. 2	74. 3	69. 0

[1] Estimated, tank flooded.
[2] Grass cut Nov. 10.
[3] Affected by precipitation.

RELATION BETWEEN VOLUME OF VEGETATION AND WATER USE

The records of vegetation volume and water use of the tanks at Imperial Camp indicate, in general, a decrease in rate of water use per unit volume during the years 1963–66, as shown in figure 9. In this graph, the volume of arrowweed for 1963 used in computing the plotting position was the average equivalent volume for the two surveys given in table 1, July 11 and October 8. The volume of *Atriplex* (fourwing saltbush and quailbrush) was calculated in a similar manner from table 3 by using the total measured volumes. Monthly water use is given in tables 2 and 4. The short periods of missing record were estimated so that yearly totals could be calculated.

The relation between the volume of vegetation and the consumptive use (see fig. 9) is influenced by the methods of measuring volume, which were too crude to provide an accurate measure of actual transpiring foliage or to define changes within the growing season. The amount of nontranspiring vegetation included in the volumes used to define the relations tended to increase with time and tended to reduce the computed unit rate of water use. As previously mentioned, during and after 1964, the average height of the quailbrush in tanks A1 and A2 was 6–7 feet, but only the upper 2 to 3 feet was actively transpiring. If the estimated volume of transpiring foliage is used to compute a rate of consumptive use per unit volume, there is no reduction with time.

The unit rate of water use by arrowweed is also influenced by nontranspiring foliage, although to a lesser extent than quailbrush. During the survey of vegetation volume on September 15, 1966, the lower margin of the transpiring foliage was estimated to be about 3.3 feet above ground level (table 1). Even during the 2 previous years, the amount of transpiring vegetation near the ground decreased. The downward trend of the curve for arrowweed in figure 9 is undoubtedly influenced by the relative increase in the nontranspiring volume, but by an undertermined amount.

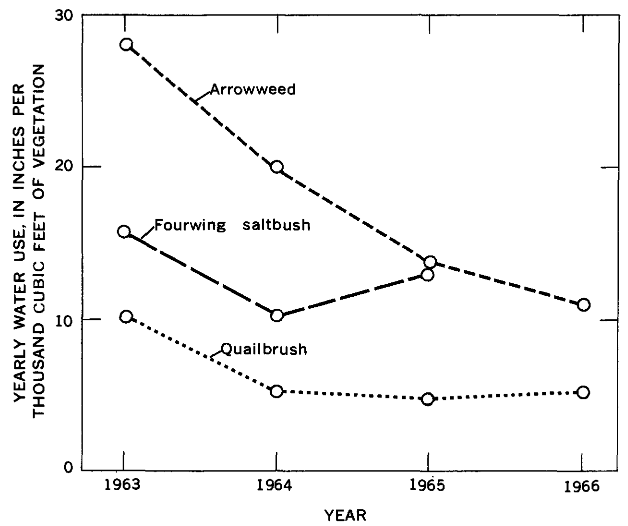


FIGURE 9.—Yearly water use of vegetation in tanks at Imperial Camp, Calif., 1963–66.

EFFECTS OF SALINITY

The Imperial Camp area is fairly typical of much of the phreatophyte-infested flood plain of the lower Colorado River. Although the bare soil in some small tracts was very saline, the soil at the tank sites was less saline and seemed to be representative of most of the soils in which the native arrowweed was growing. Because most of the native phreatophytes are relatively tolerant of salts, the soil excavated for construction of the tanks was considered satisfactory for growing the plant species to be studied. Any natural stratification of salts that may have existed in the undisturbed soils was destroyed when the soil was disturbed by the excavating and the refilling of the tanks. Leaching was necessary to establish a good stand of vegetation in the tanks. These experiments were not designed to determine the effects of salinity on water use, but the authors believe the effects may be significant.

The feed water was obtained from a deep well that supplied Imperial Camp and was similar in quality to Colorado River water. Chemical analyses of samples taken from the feed pipe and from Colorado River on April 21, 1961, showed the following results:

	Feed water	*Colorado River*
Specific conductance at 25°C micromhos	1, 160	1, 190
Ca+Mg ppm	115	126
HCO_3 ppm	174	172
SO_4 ppm	297	307
Cl ppm	108	111

Soil samples were collected in 1963 and 1966 to determine the concentration of salts in the soil of the tanks and in the areas of native vegetation nearby. Figure 10 shows the standard specific conductance (electrical conductivity of water at 25°C) of water extracted from

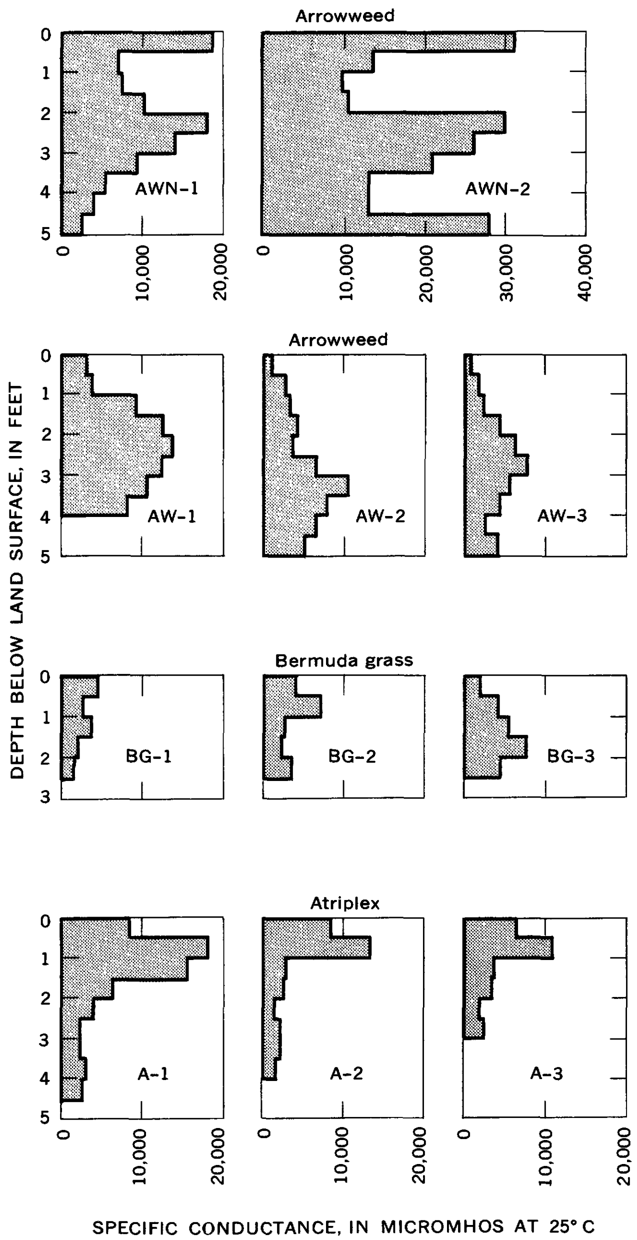


FIGURE 10.—Specific conductance of water extracted from saturated soil samples at various depths at Imperial Camp, Calif., January 1966.

saturated soil samples taken at various depths in January 1966. The specific conductance is related to the salinity of the water sample, and the dissolved solids in parts per million may be obtained by multiplying the specific conductance in micromhos by a factor of 0.6. Samples designated AWN1 and AWN2 in figure 10 were obtained from native arrowweed areas near the tanks. Other samples were from arrowweed and atriplex tanks that were leached during January to February 1963 and from bermuda grass tanks that were leached in January 1965.

In general, the highest concentration of salts in the soil occurs in a zone just above the capillary fringe; this zone also seems to be the zone of greatest concentration of roots. Roots of arrowweed, for example, were found most frequently in soil samples taken at depths of about 3 feet, both in the tanks and outside; the zone of highest salinity was also at this depth. Roots of *Atriplex* were noticeably shallower. The distribution of the roots of bermuda grass seemed to be related to the type of soil. For example, the roots in tank BG1 were found mostly in the sample taken from the top 0.5 foot, whereas in BG3 many roots were found in the sample taken from 1.5 to 2.0 feet in depth. The difference in depths apparently reflects the difference in the relative amounts of sand and clay present in the two tanks. Rainfall during December 1965 may have leached the top few inches of soil in tanks AW2 and AW3, as the salinity profile for these tanks show lower concentrations than those indicated by the feed water.

Although the salinity profiles were defined by samples from only one site in each tank, the results are believed to be reasonably representative of the salinity of the tanks. Computations of the amount of soluble salts added by the feed water since the tanks were last leached agree approximately with the increase in total salts estimated from the profiles of May 1963 (not shown) and January 1966.

The concentration of salts in the soil in the area containing native vegetation was much greater than in the soil in the tanks because of the past leaching of the tanks. Sample AWN2 (fig. 10) had the highest salt concentration of all the samples. The site of this sample was about half a mile from the tanks in an area of native vegetation. The old arrowweed was about 4 feet high (with about 20 percent deadwood) and had slightly less than average vigor. Moderate deposits of salts were visible on the ground surface. Sample AWN1 was from an area surrounding a tank where the vegetation had been cleared and the soil surface disturbed during preparation of the tanks, and the vegetation had been restored by transplanting and natural regrowth. No surface deposits of salts were apparent here. Arrowweed at this site was 9–10 feet in height, vigorous and leafy, and without deadwood. The ground-water level at site AWN1 was about 5 feet below land surface, and at AWN2, about 6 feet.

Considering the vigor of the arrowweed near the site of sample AWN1, there is no reason to believe that the accumulation of salts in the arrowweed tanks limited either the growth or the water use during the period 1963–65. *Atriplex* seems to be at least as tolerant of salinity as arrowweed, and the concentration of salts in the tanks seems to have been well within the tolerance range.

MITTRY LAKE SITE

A group of evapotranspiration tanks and meteorological instruments were operated during the period July 1961 to December 31, 1964, at Mittry Lake, at a site about 3 miles southeast of the Imperial Camp site (fig. 1). Cattail (*Typha latifolia*) and carrizo (*Phragmites communis*) were planted each in three tanks. The tanks were 10 by 10 by 4 feet and similar in design to those at the Imperial Camp site.

The evapotranspiration tanks at Mittry Lake were dug in the swampy margin of the lake and were surrounded by cattail growing in shallow standing water. Toward the shore the native cattail became less dense and less vigorous, giving way to saltcedar within 150 and 200 feet from the water. Because cattail grows best in shallow water, the water level in the tanks was maintained at a depth of about 0.3 of a foot.

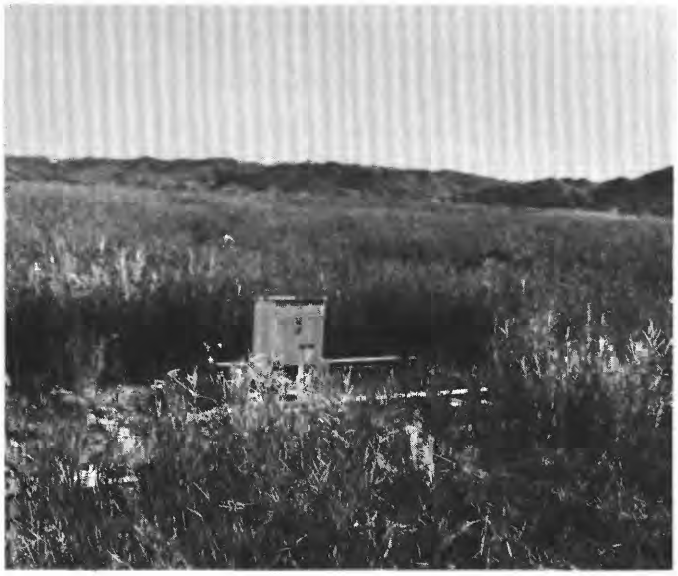
Water was pumped from Mittry Lake and applied directly to the surface of the tanks. The soil was predominately clay and silt deposited by the river after the construction of Laguna Dam in 1907. The carrizo did not thrive in the tanks; so this species was abandoned, and one of the tanks was converted to the measurement of evaporation from open water.

CATTAIL

Cattail stalks grow to maturity and die each season. In the Yuma area, growth begins in March and ends in July; the foliage begins to die in October and usually is dry by December. The cattail transplanted in the tanks in June 1961 survived but grew very little during the remainder of the year. During 1962 and the following years, the plants grew normally and attained an average height of 6–7 feet each year. The cattail in the tanks blended well with that of the surrounding area and attained comparable size and vigor, as can be seen in the photographs (fig. 11).

Volume of cattail was calculated from measurements of canopy area and average height. The cattail were planted in the tanks in the same pattern that the native cattails grow with about the same amount of space between each plant. The density varied little during the 3 years of growth. The height, and consequently the volume, tended to increase as shown in table 8.

Water in the tanks was maintained 0.2–0.3 foot above mean land surface, by reference to a fixed point. To prevent the concentration of dissolved salts, the water was changed at least once a week by pumping it through the reversible water-feed system. When the cattail top



A

C

B

FIGURE 11.—Mittry Lake, Ariz., evapotranspiration tanks showing cattail. *A*. General view of area, Oct. 12, 1963. Open-water evaporation tank to right and beyond instrument shelter. U.S. Weather Bureau Class A pan to left. Man standing at cattail Tank C1 beyond shelter. *B*. Tank C1 lies between rod and post to right of man. There is a plank walkway over standing water at left. Nov. 5, 1964. *C*. View showing detail of cattail in tank C1 and feed pipes, Apr. 6, 1964. Old vegetation had been removed in December.

growth was completely dead, about January 1 of each year, the tanks and about a 10-foot-wide area surrounding them were cleared by cutting the stalks just above water level. This was primarily a fire protection measure; the area nearby burned twice during the 3 years of operation.

TABLE 8.—*Volume, in cubic feet, of cattail in evapotranspiration tanks at Mittry Lake, Ariz.*

Date of survey	Tank			Average volume
	C1	C2	C3	
Dec. 28, 1962	524	569	558	550
July 12, 1963	618	600	618	612
Oct. 4, 1963	587	600	605	597
Sept. 24, 1964	612	676	800	696

Consumptive use from tank C1 showed no progressive increase or decrease during the 3 years, as indicated by table 9 and figure 12. Unlike the data collected at the Imperial Camp site, the water use data for this site included precipitation in addition to the water supplied by pumping. As the tank surfaces were covered with water at all times, precipitation contributed directly to the water supply.

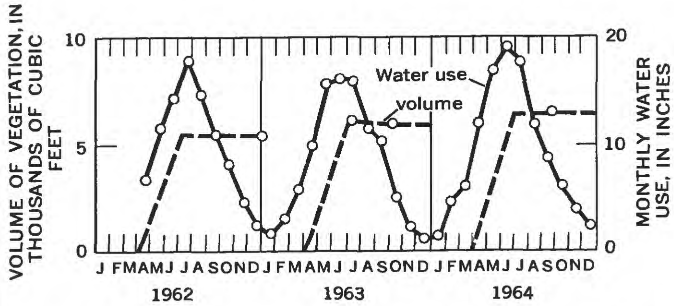


FIGURE 12.—Monthly water use and volume of cattail in tanks at Mittry Lake, Ariz. Dashed lines indicate approximate changes in volume of vegetation in the tanks. The vegetation was cut and removed during January of each year.

The color of the vegetation was about the same each year. The vegetation in tank C2 noticeably improved in vigor during 1964 compared with previous years, and the increased water use by this tank during that year is associated with this change. The improved vigor is believed to have resulted from the greater depth of water maintained in this tank during 1964, when the operating water level was raised 0.12 of a foot.

TABLE 9.—*Monthly water use, including rainfall, in inches, by cattail in tanks, Mittry Lake*

	1962			1963			1964		
Tank	C1	C2	C3	C1	C2	C3	C1	C2	C3
January				1.6	1.6	1.5	1.4	1.2	
February				3.0	3.1	2.9	4.7	4.4	
March				5.7	5.5	5.8	5.8	6.2	
April	7.3	6.3	6.6	10.3	9.1	10.2	11.3	12.3	
May	12.2	10.6	12.0	16.9	14.0	15.9	16.7	16.7	17.0
June	15.0	13.1	14.6	17.2	14.5	16.4	19.0	19.0	25.0
July	20.5	16.2	16.6	17.6	14.2		17.4	17.9	29.1
August	16.4	13.1	14.4	12.6	10.3		11.7	12.1	21.8
September	12.1	9.8	10.7	11.2	9.2		8.1	9.3	18.5
October	8.8	7.5	8.0	5.6	4.3		4.6	7.2	13.3
November	5.3	4.4	4.2	2.7	1.8		2.4	5.0	7.6
December	2.5	2.4	2.2	1.3	1.0		1.3	3.2	2.6
Total	100.1	83.4	89.3	105.7	88.6	52.7	104.4	114.5	134.9

Records from tank C3 are incomplete during 1963 and 1964 because of recurring leakage. After the tank was repaired in 1964, the depth of water in the tank was arbitrarily increased by about 0.25 of a foot, thereby raising the water level in this tank to an appreciably higher level than in the other two tanks. This condition apparently promoted the growth of the cattail, because at the end of the 1964 season, the plants were 2–3 feet higher than the cattail in the surrounding area and in the other two tanks. There is a possibility that not all the leaks in the tank were repaired, and if so, this would have affected the apparent rate of water use; however, no leakage was observed.

EFFECTS OF SALINITY

Cattail and other hydrophytes are affected by the concentration of salts dissolved in the water, but the concentration beyond which evapotranspiration and growth would be retarded was not determined by the tank experiments. Precautions were taken to assure that the water remained sufficiently fresh to insure good growth by using the water from Mittry Lake, which was supporting a good growth of cattails, and by frequently flushing the tanks. Tests of the water in Mittry Lake before construction showed an increase in saline concentration in a shoreward direction; the specific conductance was 5,000 micromhos for the open water at the margin of the vegetation in the lake and was 16,000 micromhos for the water about 2 inches deep and 200 feet from the open water. The height of the cattail decreased shoreward, but this may be attributable to the decreasing depth of water and to the occasional drying out of the lake bottom at low lake levels, as well as to the increased concentration of salts.

Analyses of sample water taken from the feed pipe and from the tanks during April 1962 indicate the quality of the water supply and the buildup of salts in the tanks. The water was changed in the tanks on March 30, 1962, and tests were made on April 4 and 12. The results were as follows:

Source	Date [April 1962]	Specific conductance, in micromhos, at 25° C.	Concentration of chloride (ppm)
Feed pipe	4	5,000	802
Tank C1	4	9,190	2,120
	12	12,500	
Tank C2	4	9,040	2,020
	12	12,200	
Tank C3	4	7,930	1,740
	12	10,800	

Rarely during the period of operation did the specific conductance exceed 10,000 micromhos, and the vegetation in the tanks at all times seemed to be about as healthy as the surrounding native vegetation.

FLUCTUATIONS OF THE WATER TABLE

A continuous record of water-level fluctuations was obtained for the years 1962–65 at a site on the flood plain in a stand of arrowweed. The well site was at Imperial Camp, about one-fourth of a mile northeast of the transpiration tanks and about 1,500 feet from the river; it was in a fairly uniform stand of arrowweed that had slightly less than average density.

The common pattern of diurnal fluctuations occurred in the well (see figs. 13, 14) at all times except during infrequent periods of extremely low temperature or of precipitation. According to White (1932, p. 59–61), the fluctuations result from diurnal variations in transpiration rates of the vegetation. Irregularities in the usual normal diurnal cycles of temperature and humidity are reflected in the shape of the diurnal fluctuation of water

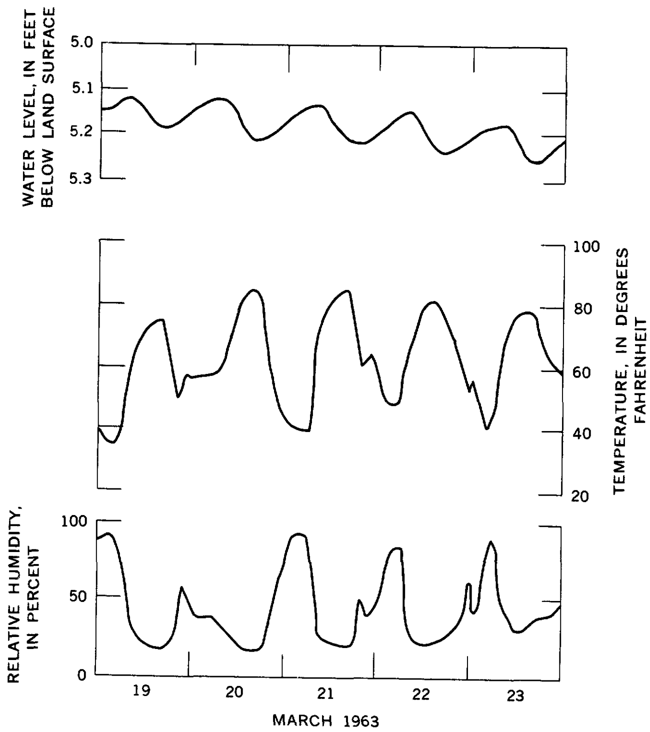


Figure 13.—Diurnal fluctuations in ground-water levels, air temperature, and relative humidity, Imperial Camp, Calif., March, 1963.

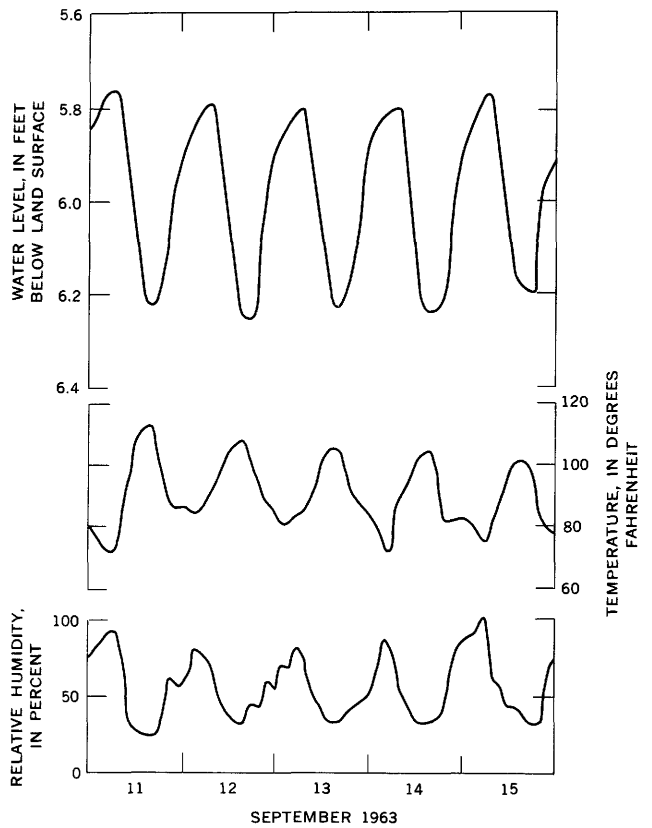


Figure 14.—Diurnal fluctuations in ground-water levels, air temperature, and relative humidity, Imperial Camp, Calif., September 1963.

levels. For example, the rapid drop in temperature and associated rise in relative humidity during late afternoon of September 14 (fig. 14) caused the water level in the well to rise faster than usual; these changes illustrate the close correlation of these variables.

As expected, the amplitude of the fluctuations was greater in summer than in winter, and the changes from rising to falling stages were closely related to air temperature and humidity. The water levels reacted quickly to the increased transpiration at sunrise during the summer months; the reversal from rising stage to falling stage was observed to occur less than 15 minutes after the first rays of sun reached the area.

The depth of the water table in the well was related to the amplitude of the water-level fluctuations, as shown in figure 15. The seasonal pattern of water levels in the well is the result of seasonal variations in water use by the vegetation and of the water level in the Colorado River. The amplitude of the diurnal fluctuations of water levels roughly correlates with the daily water use rate, and thus the diurnal fluctuations create a seasonal pattern similar to that of the water use rate during the years 1962–64. A new channel for the river was dredged nearer the well in 1965, and the river level dropped several feet, with a corresponding drop of more than 3 feet in the well. Apparently the lowering of the ground-water levels greatly reduced the withdrawal of ground water by arrowweed, as the amplitude of the diurnal fluctuations dropped drastically in June and July 1965 and the fluctuations stopped entirely in September when the water levels were more than 9 feet below land surface. It is presumed that at 9 feet, the water level was below the reach of the arrowweed roots at this location. Diurnal fluctuations resumed in November when water levels rose to 8 feet below the land surface.

The difference in phase of the seasonal pattern of depth of the water table and amplitude of diurnal fluctuations, shown in figure 15, cannot be readily explained. Normally, the greatest amplitude of fluctuations and the lowest ground-water levels would be expected to occur simultaneously. Note, however, that the lowest water levels occur in late July or early August, whereas the greatest amplitude of daily fluctuations occurs in September and October. During September and October, when nighttime relative humidity is at its highest, it is possible that transpiration is stopped for several hours during the night because a heavy dew forms on the vegetation; for this reason, the recovery of drawdown may be greater during these 2 months than it is during the drier months.

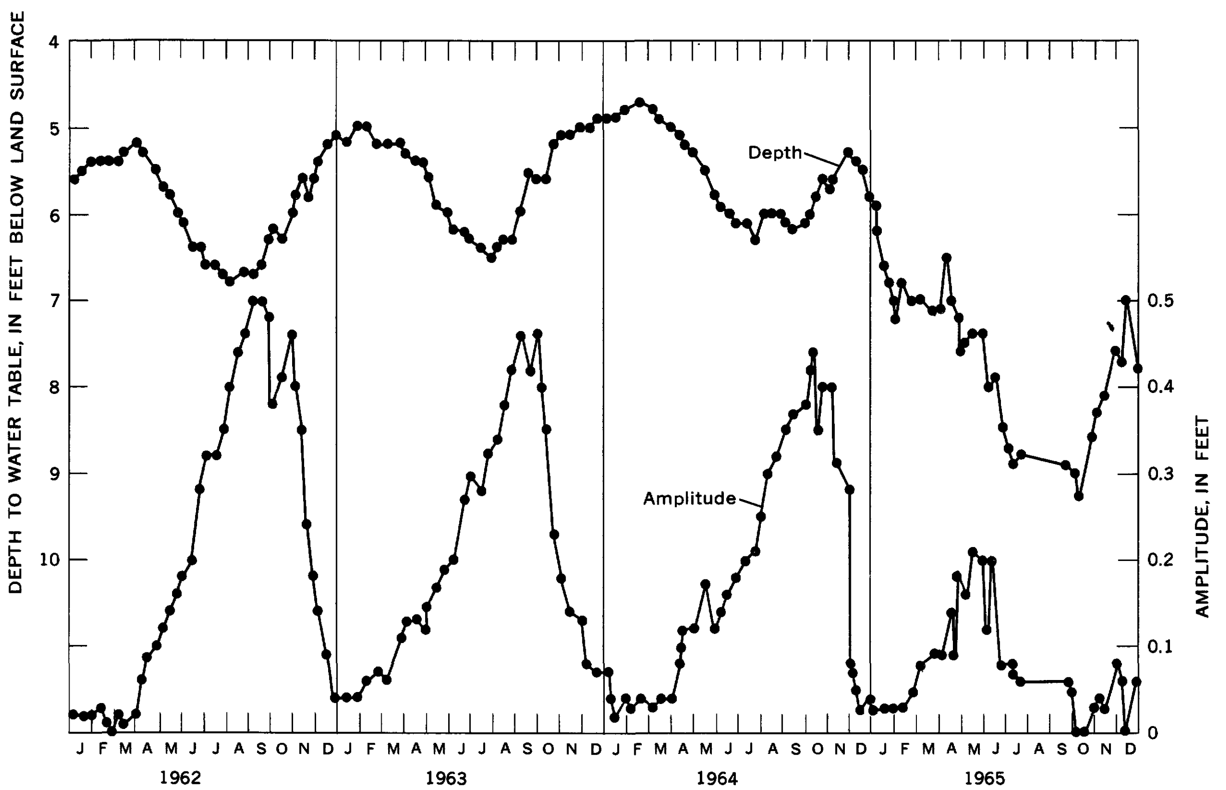


FIGURE 15.—Depth of water below land surface and amplitude of diurnal fluctuations in an area of arrowweed near Imperial Camp, Calif.

Figure 16 shows differences in phase during 1964 of several hydrologic variables, which are reduced to common units, as follows: Amplitude of fluctuations, water use by arrowweed in the tanks, evaporation from a U.S. Weather Bureau Class A pan, and solar radiation. Relatively, pan evaporation and solar radiation accelerate first, they lead the other variables by 2 or 3 months from January through April and peak together in June. Depth to water and evapotranspiration by arrowweed in the tanks are about the same relative magnitude in most months and both peak in July, a month later than evaporation and radiation. This lag of evapotranspiration by about a month might be expected, owing to storage of heat in the soil. The amplitude of water-level fluctuations begins to lag after all the other variables in June and peaks last of all in October, 2 to 3 months after the peak of evapotranspiration in the tanks. This lag was repeated during each of the 3 years of study, 1962–64 (fig. 17).

METEOROLOGICAL DATA

Transposition of water-use data from one area to another requires an adequate understanding of the environmental variables as well as of the characteristics of the plant species. Such understanding is still incomplete, especially for the flood plain of a river in a climate as arid as that of the area along the lower Colorado River. In the present study, consideration of environmental factors was limited principally to assembling and to analyzing conventional meteorological records.

Meteorological data were collected at Mittry Lake during 1963–64 and at Imperial Camp during 1963–66. Equipment at each site included a standard "Class A" evaporation pan with associated anemometer and maximum and minimum thermometers (in the water), a manual rain gage, and a hygrothermograph. At Mittry Lake, water-surface evaporation was measured in a special sunken ground pan that was 10 by 10 feet square and 1 foot deep. Both the ground pan and the Class A pan were at the edge of Mittry Lake. When the lake was at high levels, the pans were partly surrounded by water and cattail grew shoreward of the pans. When the lake was at low levels, generally in mid-summer, the shoreline was 10–15 feet from the pans, but the dry cattail shoreward of the pans still partly shielded the pans from winds overhead.

Other meteorological observations were made during the period of study by the U.S. Army at Yuma Proving Grounds about 3 miles east of Imperial Camp, by the U.S. Weather Bureau at Yuma International Airport, and by the University of Arizona Extension Service at the Yuma Citrus Station, which is about 6 miles south of Yuma.

At these places significant local differences were observed in air temperature, relative humidity, wind movement, and evaporation. These differences reflect the influence of the local environment. Meteorological data are given for Mittry Lake in table 10, for Yuma Proving Ground in table 11, and for Imperial Camp in table 12. Records for Yuma Airport and Yuma Citrus Station are published in U.S. Weather Bureau reports and are not reproduced here.

The Yuma Airport and Yuma Proving Ground stations are in desert areas with little vegetation in the immediate vicinity, although both are within 2 miles of a flood plain or irrigated lands. In contrast, the meteorologic station near Imperial Camp is surrounded by vegetation and the station at Mittry Lake is adjacent to open water. Conditions at the later site differ from those at the proving ground site, for example, the average daily minimum temperature is nearly 10°F less at the lake site; the average maximum relative humidity is higher, owing to the same influence that results in lower night-time temperatures; and the average wind speed is less than 25 percent of that at Yuma Proving Ground, owing to the nearby vegetation and the unlike heights of the anemometers above the land surface, 0.5 meter at the lake and 2 meters at Yuma Proving Ground.

Pan evaporation was about 25 percent greater at Imperial Camp than at Mittry Lake. The evaporation station at Imperial Camp was in a moderately large unobstructed area adjacent to the bare soil tanks; at Mittry Lake the station was in a small unobstructed area nearly surrounded by cattail. Humidity was expected to be higher at the Mittry Lake station than at the Imperial Camp station, but the hygrothermograph records did not bear this out. Studies by Hughes and McDonald (1966) indicate that differences in wind movement and air temperatures at the several sites account for most of the differences in measured evaporation.

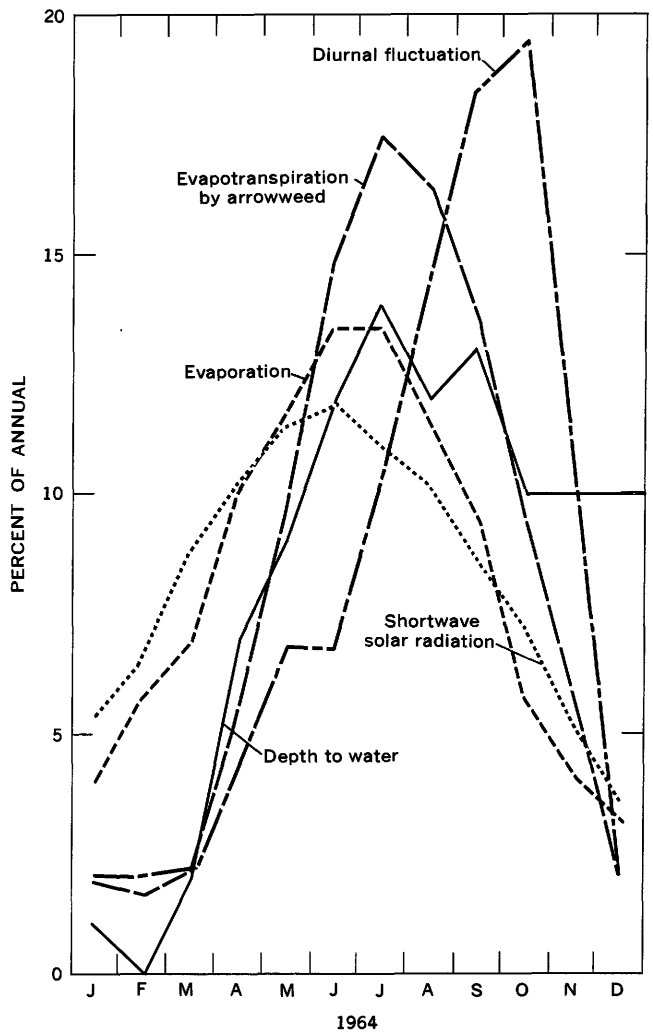


FIGURE 16.—Relative monthly magnitude of certain hydrologic variables near Imperial Dam, Ariz.–Calif.

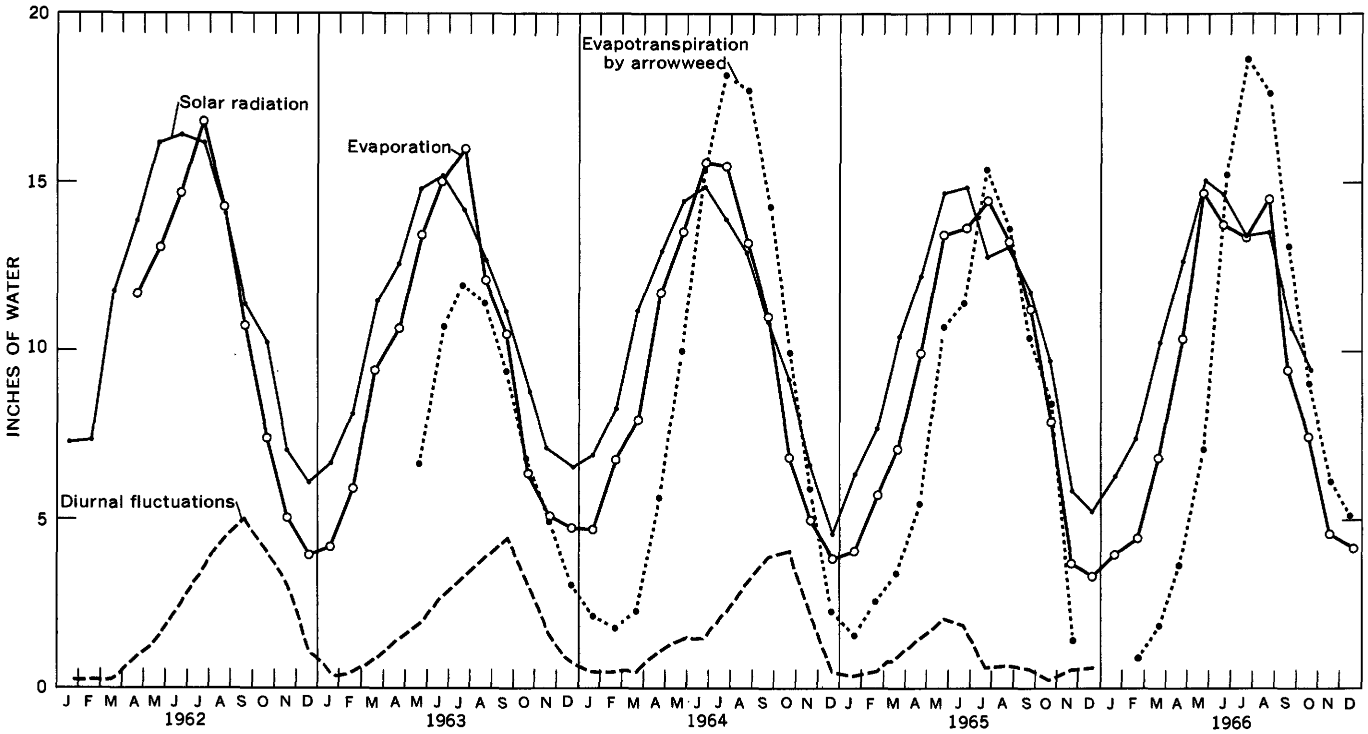


FIGURE 17.—Monthly evaporation from water surface, evapotranspiration by arrowweed, magnitude of diurnal fluctuations of ground-water levels, and evaporation-equivalent of short-wave solar radiation near Imperial Dam, Ariz.–Calif.

TABLE 10.—*Meteorological data for Mittry Lake site, Arizona*

[Records by U.S. Geological Survey]

Month	Precipitation (in.)	Air temperature (° F)		Relative humidity (percent)		Water temperature (° F)		Pan wind speed (mph)	USWB Class A pan evaporation (in.)	10- by 10-ft tank evaporation (in.)
		Max	Min	Max	Min	Max	Min			
1963										
Jan	---	---	---	---	---	---	---	---	---	2.35
Feb	---	---	---	---	---	---	---	---	---	3.00
Mar	---	---	---	---	---	---	---	---	---	4.62
Apr	0	81	49	94	20	84	48	1.7	7.99	5.79
May	0	93	58	92	20	93	62	1.1	10.06	6.96
June	0	95	62	89	24	99	65	1.4	11.18	7.78
July	0	103	72	91	27	104	73	1.4	12.99	8.43
Aug	.19	102	76	85	31	103	76	1.2	10.77	7.31
Sept	2.21	102	71	85	23	104	74	0.8	9.61	---
Oct	.95	90	59	90	28	90	64	0.5	5.10	---
Nov	.12	76	47	86	28	76	51	0.5	3.58	2.20
Dec	0	69	34	92	18	66	39	0.8	3.06	1.73
Total	3.47	90	59	89	24	91	61	9.4	74.34	50.17
1964										
Jan	0	65	31	93	18	65	36	1.3	3.44	2.15
Feb	.03	68	34	88	16	69	36	2.0	5.45	3.36
Mar	0	74	40	85	17	78	44	2.1	6.82	4.52
Apr	.02	82	47	80	18	86	50	2.2	9.86	6.73
May	.02	89	52	80	17	92	57	1.6	10.38	7.71
June	0	98	59	82	17	96	64	1.5	12.03	9.41
July	---	104	72	78	25	103	74	1.5	12.58	9.55
Aug	.96	101	72	87	28	102	74	1.5	10.14	7.90
Sept	0	97	63	90	22	98	67	1.0	8.44	6.13
Oct	.10	92	58	88	26	92	64	0.7	5.51	4.26
Nov	.26	71	40	91	26	72	45	1.0	3.55	2.62
Dec	.11	68	38	88	25	66	40	1.0	2.86	2.03
Total	1.50	84.1	50.5	85.8	21.2	84.8	54.2	1.47	91.06	66.37

TABLE 11.—*Meteorological data for Yuma Proving Ground, Ariz.*

[Records by Meteorology Dept., U.S. Army, Fort Huachuca, Ariz., lat 32°50′ N., long 114°24′ W., 3 miles east of Imperial Camp, Calif., alt 321 ft]

Month	Precipitation (in.)	Air temperature (° F)		Relative humidity (percent)		Wind speed at 2 meters (mph)	Solar radiation Langleys/day (Vertical Eppley)	Total radiation
		Max	Min	Max	Min			
1963								
Jan	0.48	64	39	62	21	4	31	894
Feb	.12	79	52	53	16	3	431	993
Mar	.22	77	49	49	13	3	553	1,090
Apr	.05	81	54	44	11	4	627	1,201
May	0	95	67	35	9	4	717	1,356
June	0	97	70	42	12	5	757	1,469
July	0	106	81	44	14	6	689	1,432
Aug	.13	102	81	58	25	5	608	1,422
Sept	2.06	102	77	57	18	4	555	1,361
Oct	1.17	90	66	66	24	3	422	1,202
Nov	.10	76	52	69	25	4	340	979
Dec	0	70	41	46	15	5	312	708
Total	4.33	87	61	52	17	4	528	1,176
1964								
Jan	0	65	37	46	14	6	328	686
Feb	.14	68	42	38	10	8	423	1,002
Mar	.04	74	47	46	12	8	537	1,139
Apr	.03	82	55	42	13	8	646	1,281
May	0	91	63	37	11	8	699	1,372
June	0	99	71	34	10	8	740	1,472
July	.04	106	82	45	17	8	671	1,548
Aug	.07	103	81	59	23	8	620	1,450
Sept	.01	98	73	52	16	6	541	1,369
Oct	.12	93	67	60	21	4	437	1,194
Nov	.26	71	47	62	23	5	332	964
Dec	.10	67	44	61	25	5	217	888
Total	0.81	85	59	49	16	7	516	1,190
1965								
Jan	0.66	68	45	66	25	4	304	923
Feb	.52	71	46	54	15	5	408	1,004
Mar	.09	74	49	56	18	5	500	1,133
Apr	1.91	83	58	56	18	5	606	1,276
May	0	90	63	41	11	7	710	1,414
June	0	95	67	38	10	6	739	1,388
July	.11	105	80	47	16	5	618	1,431
Aug	.03	104	81	56	19	5	630	1,422
Sept	0	96	71	47	15	5	579	1,290
Oct	0	95	62	35	10	3	468	805
Nov	.99	76	54	37	19	3	289	945
Dec	2.11	64	45	84	42	4	253	858
Total	6.42	85	60	51	18	5	509	1,157

TABLE 12.—*Meteorological data for Imperial Camp, Calif.*

[Records of U.S. Geological Survey]

Month	Precipitation (in.)	Air temperature (°F)		Relative humidity (percent)		Water temperature (°F)		Pan wind speed (mph)	USWB Class A pan evaporation (in.)
		Max	Min	Max	Min	Max	Min		
1963									
Jan	0.52	65	35	86	28	64	37	2.3	4.09
Feb	.21	81	45	81	23	77	48	2.1	5.89
Mar	.25	79	41	85	21	81	45	2.9	9.35
Apr	0	82	45	80	19	83	47	2.8	10.58
May	0	94	54	84	22	93	61	2.4	13.42
June	0	96	58	87	24	95	62	2.9	14.95
July	0	105	69	86	28	99	70	2.4	15.94
Aug	.75	102	73	89	36	100	74	2.0	11.95
Sept	2.25	101	66	77	22	97	70	1.05	10.37
Oct	1.07	90	56	93	29	87	63	1.2	6.24
Nov	.16	80	49	87	29	76	50	2.1	5.00
Dec	0	71	33	79	22	66	39	2.0	4.71
Total	5.21	87.2	51.9	84.5	25.2	84.9	55.6	2.21	112.87
1964									
Jan	0	67	30	72	22	64	34	2.1	4.59
Feb	.07	69	33	72	20	66	35	2.9	6.68
Mar	.03	75	39	78	20	77	41	2.5	7.84
April	0	83	47	77	22	85	48	2.9	11.64
May	.03	92	52	78	20	90	54	2.6	13.47
June	0	98	59	81	22	93	62	2.7	15.46
July	0	105	74	82	31	99	73	2.6	15.36
Aug	.81	102	72	85	31	100	74	2.3	13.16
Sept	0	100	61	89	25	95	65	1.7	10.94
Oct	.17	95	57	85	29	89	62	1.2	6.77
Nov	.27	73	41	83	27	71	43	1.9	4.85
Dec	.11	69	38	84	28	68	40	1.8	3.76
Total	1.44	85.6	50.3	80.5	24.8	83.0	52.7	2.27	114.52
1965									
Jan	0.73	70	39	79	26	65	38	1.7	3.98
Feb	.48	73	39	76	17	75	36	2.2	5.70
Mar	.16	75	40	82	20	81	43	2.0	6.00
Apr	1.51	83	48	83	21	88	53	2.1	9.92
May	0	90	52	79	17	91	56	2.3	13.34
June	0	94	53	79	18	94	58	2.1	13.60
July	.22	104	70	74	23	99	68	2.0	14.43
Aug	.02	104	71	86	26	102	71	1.8	13.13
Sept	0	--	--	--	--	96	62	2.0	11.19
Oct	0	--	--	--	--	88	55	1.0	7.83
Nov	.70	77	47	--	--	79	68	1.0	3.42
Dec	2.84	65	43	--	--	82	41	1.4	3.26
Total	6.66	--	--	--	--	86.7	54.1	1.80	106.79
1966									
Jan	0.58	64	36	--	--	64	36	1.9	3.79
Feb	.32	69	36	--	--	70	36	1.7	4.50
Mar	.23	83	42	--	--	82	45	1.4	8.07
Apr	0	88	54	--	--	89	52	1.9	10.63
May	0	97	55	82	17	97	58	1.7	14.65
June	0	102	61	67	14	97	62	1.7	13.68
July	.17	105	72	69	21	102	74	1.5	13.31
Aug	.32	106	74	84	28	104	76	1.6	14.50
Sept	.92	101	65	94	25	101	69	1.1	9.36
Oct	.85	89	53	91	22	85	57	1.3	7.41
Nov	.13	80	43	85	26	80	48	1.1	4.60
Dec	.12	70	39	84	28	69	38	1.7	4.13
Total	3.54	87.9	52.5	--	--	86.8	54.2	1.55	108.63

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U. S. GOVERNMENT PRINTING OFFICE : 1968 O - 287-538