Water Use by Saltcedar as Measured by the Water Budget Method

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By T. E. A. van Hylckama

STUDIES OF EVAPOTRANSPIRATION

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WATER USE BY SALTCEDAR AS MEASURED BY THE WATER BUDGET METHOD

By T. E. A. van Hylckama

ABSTRACT

Water use by saltcedar (*Tamarix pentandra*) was studied from 1961 through 1967 near Buckeye, Ariz. The test site, in the flood plain of the Gila River, was surrounded by a kilometer-wide dense strip of saltcedar thickets. Areas to the north and south of the strip were mainly desert and a few cotton fields. The test site growing season lasts 8 to 9 months, the humidity is low, winds are strong, summer temperatures at the site often reach 50°C, and evapotranspiration rates are among the highest in the United States.

Evapotranspiration rates and quantities were observed in six plastic-lined evapotranspirometers (tanks) with 81-m^2 (square-meter) surfaces. Analyses were made on the effects of depth to ground water in the tanks, of salinity of soil moisture, and of vegetation density. Rates of water use from bare and vegetated soil were observed in five smaller tanks (36 m^2 each).

When the depth to ground water, or water table, was 1.5 m (meters) the average water use was about 215 cm/yr (centimeters per year); when the water table was 2.1 m, the use diminished to about 150 cm/yr; and when the water table was 2.7 m, the yearly water use was less than 100 cm/yr.

Water use varies greatly with salinity of the soil moisture. Salinity may be expressed in terms of specific conductance of the saturation extract (ECs) in mmho/cm (millimhos per centimeter) at 25°C. In tanks which measured ECs=20, the water use was 70 percent; in tanks which measured ECs=30, the water use was only half that in tanks with an ECs=10.

When the vegetation was cut twice a year from an original average height of 3 m. to a height of about 50 cm the water use decreased to about half that in tanks where the vegetation was not cut. However, when the vegetation was thinned to 50 percent of the original density the water use diminished by only 10 percent.

The maximum yearly water use (311 cm) was measured in 1965 in a tank with a high water table, a dense vegetation, and an ECs less than 10. Although in half of the 36 cases (6 tanks×6 years) the yearly water use was 150 cm or less, there were 11 tank-years with a water use of 200 cm and more—when the table was high, the salinity was comparatively low, and the stand density was medium to high.

The daily fluctuations in water use from bare soil showed that in summer the evaporation at midday diminishes because of the formation of a vapor barrier; but, evaporation continues from the soil underneath a dense vegetation.

Atmospheric pressure fluctuations which affect the water level in the plastic-lined tanks must be considered when such levels are used to determine water consumption quantitatively.

BACKGROUND OF THE BUCKEYE PROJECT

REDUCTION OF WATER LOSS

The increasing population of the arid and semiarid regions of the southwestern United States and the accompanying need for more water has continually focused the attention of hydrologists and water managers on ways and means to salvage water when and wherever possible.

Current studies reflect efforts to conserve water by: reducing water loss from lakes and ponds (and even plants) by covering the surfaces with chemicals that reduce evaporation; determining the most economical methods of irrigation; eradicating plant growth along arroyos and rivers; condensing moisture in the air to induce precipitation; and desalting saline water for industrial, domestic, and agricultural use. The southwestern United States and many other parts of the world will be able to support their present and future populations only if some or all of such studies eventually make more water available.

This paper discusses reduction of water loss by converting saltcedar jungles, vegetation which uses a lot of water, into less thirsty pasturelands or bare soil.

WATER USE BY SALTCEDAR

The Latin name for saltcedar *(Tamarix pentandra)*,[1] and the often used name "tamarisk", were derived from the name of a river in the Pyrenees. Maybe this led to the belief that saltcedar was imported into this country by early colonists from the Mediterranean regions. Later studies (Horton, 1964) raise doubt on this supposition. (There is, for instance, evidence that in 1823 saltcedar was imported simply as a garden plant, at least in New York.) Whatever happened, saltcedar was introduced and started to spread. No attention was paid to this until construction of reservoirs and excessive use of ground

[1]Dr. B. R. Baum (1967), botanist at the Hebrew University, Jerusalem, discovered that *T. pentandra* Pallas might be the wrong name for *T. chinensis* or *T. ramosissima*. However, J. S. Horton (written commun., June 1971) is of the opinion that most and perhaps all of the five-stamen tamarisk in North America are in either the *T. pentandra* or the *T. gallica* group of genotypes.

water began in many places to lower the water table along rivers. As a result, the native vegetation died, and saltcedar, with its deep rooting system and salt exudation, was left in sole command of the water-depleted areas. During the 1920's people began to realize that the plant might well be using copious amounts of ground water. Thus began the studies on saltcedar and many other phreatophytes.

Although saltcedar has some value for the control of soil erosion and for wildlife habitat, these beneficial features are offset by its lavish use of water. The sometimes remarkably deep rooting system developed by this species enables it to use ground water from depths as great as 10 m (meters) or more (30 ft (feet) or more) below the land surface, a feat equaled only by a few other species, usually known by the generic name of phreatophytes or "well plants" (Meinzer, 1927). Because of this deep rooting capacity, saltcedar may have free access to water and, therefore, may consume by evapotranspiration as much or more water than the amount that would (other things being equal) evaporate from a lake surface. For instance, the U.S. Bureau of Reclamation (1964) estimates that along the Colorado River 67,000 hectares (167,000 acres) of saltcedar and other water-loving plants[2] consume as much as 700 million m^3 (cubic meters) (568,000 acre-ft) of water per year. It is, therefore, not surprising that eradication of saltcedar has been undertaken over vast areas of the Southwest.

MEASUREMENT OF WATER LOSS

Water use by vegetation or evaporation losses from bare soil can be measured in several ways. There is a great demand for techniques that use portable or semiportable instrumentation with which one can measure the evapotranspiration indirectly. The advantages are obvious: the hardware can be moved from place to place, and, once proper correlation between direct and indirect methods is established, information can be obtained in a comparatively short time. Such methods have been successfully tested over open water (U.S. Geological Survey, 1954; Harbeck and others, 1958) and over low vegetation (Rider, 1956; Tanner, 1960) but rarely over such high stands as saltcedars. The Buckeye Project was equipped with instruments to observe the radiation balance as well as to collect data on mass transfer. These instruments and their functions will be explained and the data will be presented in another report in this series.

The most direct method of measuring water use is the water-budget method, in which an account is kept of the amounts of water applied to, and lost from, a particular container, area, or type of surface. Such a method is expensive and time consuming but generally gives the most accurate data, provided the physical surroundings are properly maintained and controlled. This paper discusses the water budget and presents data on water use as measured in evapotranspirometers.

This project was established as a joint effort by the Geological Survey and the Bureau of Reclamation. The author gratefully acknowledges the generous assistance given by the Bureau and its personnel, especially by Curtis W. Bowser. Also the assistance and advice of other individuals too numerous to mention is acknowledged with gratitude.

EVAPOTRANSPIROMETERS

DEFINITION

According to the "Glossary of Meteorology" (Huschke, 1959), evapotranspirometers are instruments which measure the rate of evapotranspiration, the loss of water from the soil both by evaporation and by transpiration from plants growing on that soil. Evapotransirometers consist of a vegetated soil tank designed so that all water added to the tank and all water remaining after evapotranspiration can be measured. Some are quite simple, such as oil drums filled with soil and inserted into the ground. Others are large elaborate structures attached to recorders which indicate gains and losses of weight due to gains and losses of moisture. Some have perforated bottoms and the water seeping through can be tapped off, weighed and chemically analyzed; they are called lysimeters, a word derived from the Greek "λυσειν" which means "to dissolve". Whereas a lysimeter can nearly always be used as an evapotranspirometer, the reverse is not true.

The size of evapotranspirometers is partly determined by the type of vegetation to be studied. Obviously, a small container might suffice for grasses, but instruments like those built in the Netherlands, which have an area of 625 m^2 (square meters) (6,725 ft^2 (square feet)) and are 5 or more meters deep (15 ft and over), may be needed for studying trees. The larger the size, the more difficult it becomes to detect malfunctioning such as leakage (Penman and Schofield, 1941) and to accurately maintain ground water at intended levels.

OASIS EFFECT

It is difficult to imitate natural conditions inside and outside the lysimeters or evapotranspirometers. Often the failure to maintain a representative test environment has resulted in grossly overestimated amounts of water used by similar plants in a natural environment (Mather, 1954). Figures 1 and 2 for example illustrate variations of plant density. The first photograph shows a saltcedar plant standing alone with the fronds (as the terminal branches with their scalelike leaves are called) all green down to the ground. Such plants have a large active surface and therefore are capable of transpiring more water than plants shown in figure 2. Owing to in-

[2] Some of these water-loving plants sharing saltcedar's notoriety have been extensively studied by McDonald and Hughes (1968).

FIGURE 1.—Saltcedar freely exposed. Rod is a standard stadia type (feet and tenths of feet).

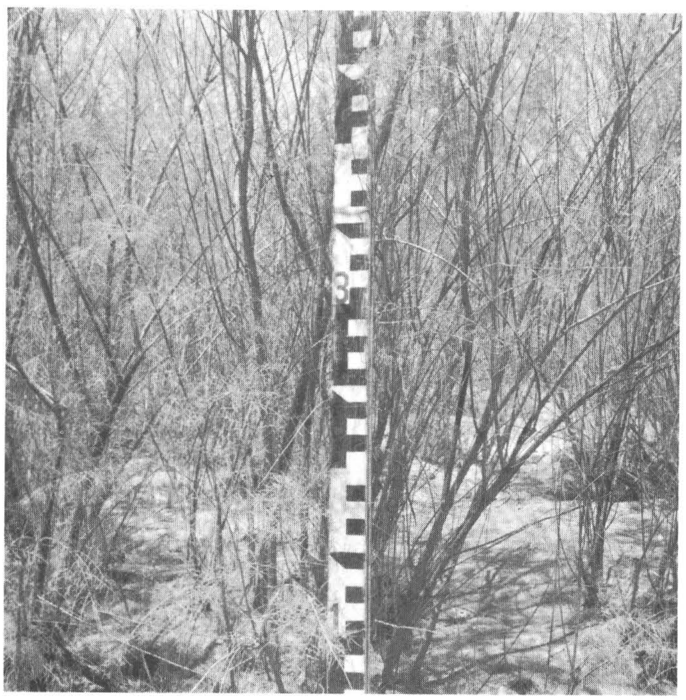

FIGURE 2.—Saltcedar as part of a thicket. Rod is a standard stadia type (feet and tenths of feet).

tolerance to shade and possibly to lack of moisture, these plants have shed many of their fronds. Each plant has much less active surface and consequently can transpire less, other things being equal, than a single plant standing as if in an oasis.

Clearly, if the use of water by a single plant such as shown in figure 1 is measured, it is not warranted to apply results on a per-plant basis to an acre, much less to thousands of acres of dense growth. To dispel the oasis effect, an evapotranspirometer must be surrounded by a buffer zone planted with the same vegetation as that of the tank, and all other conditions should be as similar as possible to those of the instrument. The size of such a buffer zone depends on climatic conditions. Thornthwaite and Mather (1955) point out: "In a moist climate such as Ireland a square 50 meters on a side should be sufficient, but in the desert probably a square 400 meters on a side would not be too large." In semiarid climates, however, the riparian vegetation is subject to some oasis effects anyway, especially when winds blow normal rather than parallel to the stream. The actual size of the buffer zone becomes relatively insignificant compared with the requirements that the vegetation is of equal height and density and that the surrounding soil is kept as moist as the soil in the tanks.

THE BUCKEYE TEST SITE

LOCATION

The test site is located in the southeast corner of section 11, R. 3 E. and T. 1 S. of the Gila and Salt river base line and meridian (33°21′ N. and 112°31′ W.), as indicated in figure 3, and its elevation is about 260 m (855 ft) above mean sea level. The area was inspected in the fall of 1958 by members of the U.S. Geological Survey and the U.S. Bureau of Reclamation. At that time, most of sections 11 and 12 as well as the land furthur up and downstream along the Gila River presented a nearly homogeneous stand of very dense saltcedar. For this reason, and because electric power lines were near, the site was considered ideal for the phreatophyte studies. The low-flow channel of the Gila River was remote enough to eliminate danger of flooding; but as the map (fig. 3) shows, the low-flow channel of the Waterman Wash curves very closely around the project site and minor flooding could be expected.

TEST ENVIRONMENT

CLIMATE

In general, the climate at the project site is typical of that of the Sonoran Desert, but it differs in detail considerably from the average climate. As mentioned before, the area lies in the flood plain of the Gila River. Five km (kilometers) (3 mi (miles)) to the south are the Buckeye Hills which rise to 270 m (900 ft) above the valley floor; 16 km (10 mi) to the north are the White Tank Mountains, rising slowly at first and then steeply to 600 m (2,000 ft); and to the east the Sierra Estrella towers 1,100 m (3,600 ft) above the project site. Daytime temperatures can be very high, indeed, compared with those observed at standard weather installations outside the area. But, as a result of the surrounding mountains, there is considerable cold-air drainage on quiet nights,

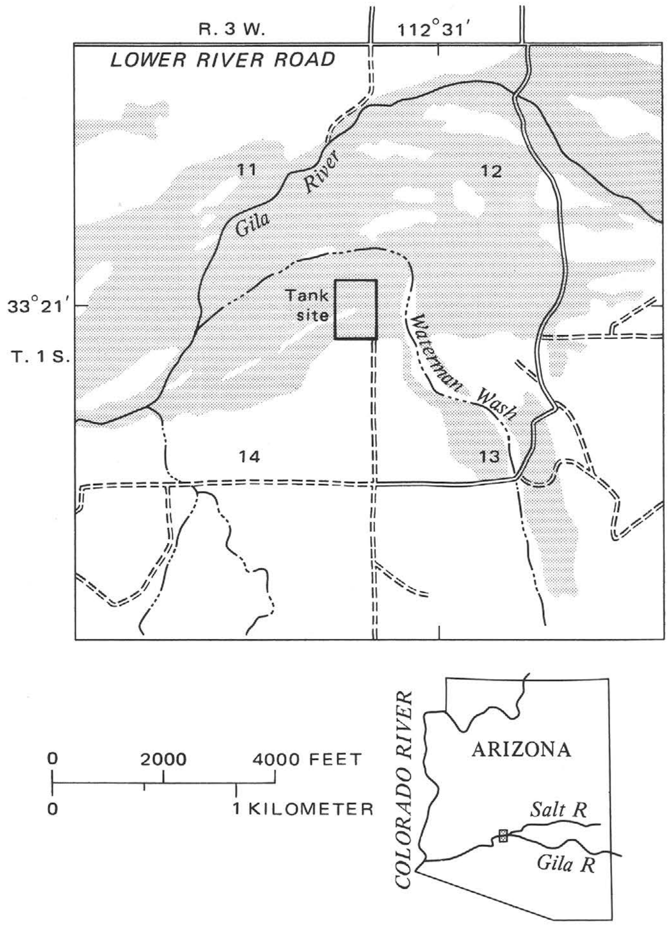

FIGURE 3.—Location of the Buckeye test site.

FIGURE 4.—Frost damage on saltcedar twigs.

and, even during the summer, nights are often cool.

Freezing in the dawn hours of the early spring sometimes damaged young fronds, as shown in figure 4. However, it is not likely that the frost affected evapotranspiration because the plants quickly outgrew the damage.

The dense vegetation and large irrigated areas north and south of the Gila River can create relatively high humidities. Table 1 presents monthly data on total precipitation, mean maximum and mean minimum temperatures and relative humidities, average wind speed, and average daily solar radiation. At first it was planned to install a U. S. Weather Bureau class A evaporation pan, but the dusty winds in the area together with dead leaves and other trash falling from surrounding saltcedars would make pan data practically worthless.

FLOODS

When the project site was chosen there was some concern about the frequency of flooding of the Waterman Wash. Based on information obtained here, it was decided that floodings were so rare that the risk of damage to the site would be small. However, during the second half of 1959 the project site was inundated nine times. When flood conditions such as shown in figure 5 again occurred repeatedly during 1960, it became necessary to construct levees capable of preventing small floods from upsetting the records.

All floodings between July 1959 and September 1967 and the times that levees had to be strengthened or repaired are listed in table 2.

On November 2, 1963, a severe storm with hail stones as large as 2.5 cm (centimeters) (about 1 in. (inch)) in diameter hit the project site. One pyrheliometer was smashed and anemometer cups were so severely dented that five sets had to be replaced.

The Gila River flooded a few times, usually only making access roads north of the project site impassable. But, in December, 1965, the Salt River Project was forced to release water from behind Roosevelt and other dams, and the usually dry bed of the Gila became a "mile-wide" river; however, water reached just the northern row of evapotranspirometers, causing some gullying which was easily repaired.

CICADAS

During the latter half of May and the beginning of June each year, thousands of cicadas crawled out of the ground (fig. 6) and invaded the saltcedar stands. Damage was done by the females who laid eggs on the young branches after making an incision in the bark for each egg. This often resulted in girdling of the branches; the parts above the girdling died as shown in figure 7. However, regrowth from the plant underneath the

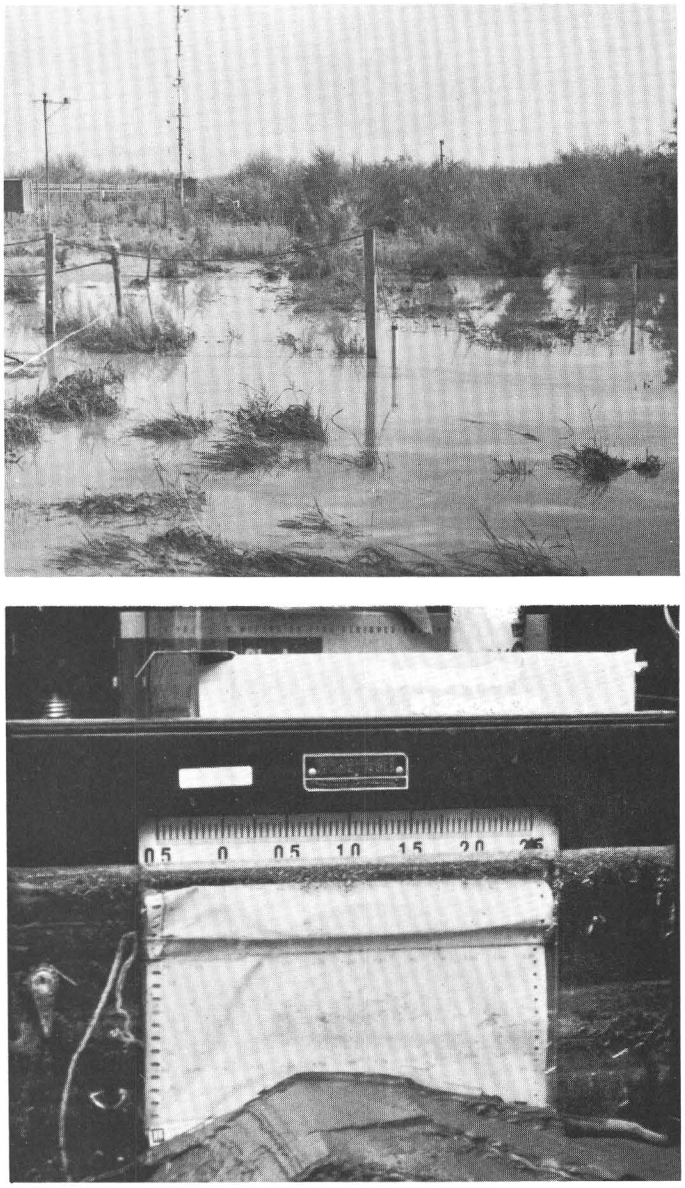

FIGURE 5.—Two results of typical floods. Top: December 1959; tank 5 in foreground has not been planted yet. Bottom: September 1966, mud deposited on and in one of the recorders; high water mark about 95 cm (3.5 ft) above ground level.

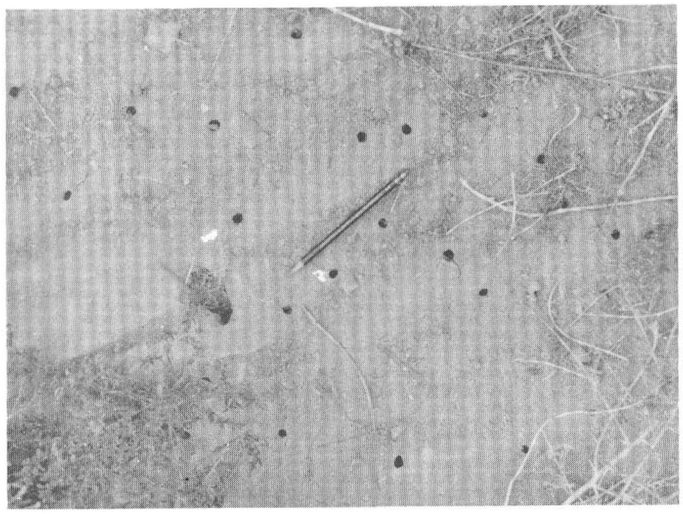

FIGURE 6.—Cicada egress holes; pencil is 15 cm (6 in.) long.

FIGURE 7.—Saltcedar twigs damaged by cicada egg laying.

girdled areas was so vigorous that the cicada damage could not possibly have affected water use significantly.

TANK CONSTRUCTION

In May 1959 construction started on the first of six tanks, 9×9 m (30×30 ft) in surface and about 4.25 m (14 ft) deep. To reduce cost and construction time, large sheets of plastic were used to line the evapotranspirometers, as suggested by Robinson and Bowser (1959). Robinson (1970) has described the construction and the plumbing in detail. It is necessary to mention here only that since the tanks were dug without shoring and the soil was fairly dry even at great depths it was not surprising that cave-ins occurred. As a result, the sides of the tanks were not straight walls, as suggested in figure 5 of Robinson's paper. The surface, too, deviated somewhat from the intended 9×9 m.

After each tank was finished, it was planted to saltcedar. Vigorously growing bushes were selected from the surrounding stands and carefully dug up. Branches and roots were pruned to about 60 cm (2 ft). Twenty-five crown cuttings were planted in each tank, and when the last one was finished in October 1959, the surroundings of the tanks were similarly planted. Figure 8 shows a newly planted tank.

In 1962, five small tanks were constructed north of the existing ones as shown in figure 9. These new tanks were 6 meters square (20×20 ft) and only a little more than 2 m (6 ft) deep. They were lined with heavy butyl rubber instead of plastic. Tanks 7 and 8 were planted to saltcedar in February, 1963, but the others were kept

Table 1.—*Meteorological data for project site near Buckeye, Ariz.*

Month	Precipitation (in.)	Precipitation (cm)	Mean temperature (°C) Max	(°C) Min	(°F) Max	(°F) Min	Relative humidity (percent) Max	(percent) Min	Wind speed at 4 meters (cm/sec)	Wind speed at 4 meters (mph)	Solar radiation Langleys/day
1961											
Jan	0.43	1.1	21.2	4.7	70.1	40.5	98.5	38.7	121	2.7	282
Feb	0.00	0.0	23.9	-0.9	75.1	30.3	82.7	23.1	...	...	421
Mar	0.24	0.6	27.5	2.2	81.5	35.9	68.5	21.0	130	2.9	514
Apr	0.00	0.0	31.9	4.2	89.5	39.6	46.0	17.0	103	2.3	682
May	0.00	0.0	38.6	9.3	101.5	48.7	59.5	19.5	80	1.8	717
June	0.00	0.0	44.4	14.5	111.9	58.1	83.4	23.8	94	2.1	698
July	0.67	1.7	44.5	22.3	112.1	72.1	87.0	26.0	121	2.7	648
Aug	0.55	1.4	42.7	22.3	108.9	72.1	86.0	25.2	125	2.8	567
Sept	0.08	0.2	39.2	15.2	102.5	59.4	84.5	24.4	119	2.6	529
Oct	0.20	0.5	33.1	6.9	91.5	44.5	74.0	22.0	139	3.1	429
Nov	0.00	0.0	23.8	1.1	74.8	33.9	87.0	26.0	89	2.0	305
Dec	1.65	4.2	18.8	-0.8	65.9	30.5	96.0	33.6	80	1.8	259
Total or mean	3.82	9.7	32.5	8.4	90.4	47.1	79.4	25.0	109	2.4	504
1962											
Jan	1.61	4.1	19.7	-1.2	67.4	29.8	93.6	28.0	85	1.9	307
Feb	0.75	1.9	23.2	3.1	73.7	37.5	92.0	30.0	119	2.6	369
Mar	0.63	1.6	24.8	0.5	76.6	32.9	81.0	23.3	119	2.6	505
Apr	0.00	0.0	34.7	6.4	94.4	43.6	78.0	22.6	139	3.1	630
May	0.00	0.0	36.0	8.3	96.8	47.0	60.4	21.6	94	2.1	696
June	0.20	0.5	42.3	12.4	108.1	54.4	67.5	21.0	67	1.5	654
July	0.24	0.6	45.1	19.1	113.1	66.3	51.5	18.0	134	3.0	679
Aug	0.08	0.2	46.1	19.4	114.9	66.9	62.1	18.4	148	3.3	623
Sept	1.50	3.8	41.3	17.4	106.4	63.3	82.6	30.3	94	2.1	488
Oct	0.00	0.0	35.3	7.5	95.6	45.5	84.7	21.6	67	1.5	450
Nov	0.16	0.4	28.4	3.3	83.1	38.0	83.7	25.6	76	1.7	321
Dec	0.35	0.9	22.6	0.3	72.7	32.6	87.0	28.7	...	...	268
Total or mean	5.52	14.0	33.3	8.0	91.9	46.5	77.0	24.1	104	2.3	499
1963											
Jan	0.16	0.4	19.3	-3.7	66.7	25.3	85.2	23.9	...	...	314
Feb	0.32	0.8	28.3	3.4	82.9	38.2	82.1	22.6	...	...	403
Mar	0.28	0.7	27.4	1.6	81.3	34.8	77.7	20.4	...	...	530
Apr	0.00	0.0	30.8	3.8	87.5	38.8	83.4	16.4	...	...	628
May	0.00	0.0	39.8	11.9	103.6	53.4	50.3	16.2	...	...	680
June	0.00	0.0	40.8	12.3	105.4	54.2	53.4	19.8	...	...	732
July	0.00	0.0	45.9	22.1	114.6	71.7	58.5	24.9	...	...	656
Aug	2.60	6.6	41.9	22.0	107.4	71.6	81.3	25.4	...	...	558
Sept	0.04	0.1	41.7	18.4	107.0	65.2	76.9	22.3	124	2.8	532
Oct	0.91	2.3	36.6	11.6	97.9	52.8	83.2	23.9	105	2.3	435
Nov	0.87	2.2	26.8	5.2	80.3	41.4	90.0	28.0	153	3.4	437
Dec	....	...	22.8	-3.7	73.1	25.4	87.7	21.8	...	...	319
Total or mean	5.18	13.1	33.5	8.7	92.3	47.7	74.1	22.1	127	2.8	519
1964											
Jan	0.28	0.7	19.4	-4.4	67.3	24.1	76.7	23.1	...	...	290
Feb	0.08	0.2	22.4	-4.3	72.3	24.3	65.4	19.1	...	...	407
Mar	0.87	2.2	24.4	1.5	76.0	34.7	79.4	19.6	...	...	521
Apr	0.00	0.0	32.0	5.9	89.6	42.7	66.5	21.0	...	...	598
May	0.00	0.0	36.8	9.6	98.2	49.2	53.4	17.3	152	3.4	683
June	0.00	0.0	41.3	14.6	106.4	58.3	53.8	21.4	120	2.7	685
July	0.87	2.2	44.5	22.6	112.1	72.5	63.0	22.6	129	2.9	632
Aug	2.60	6.6	41.2	21.6	106.1	70.8	84.0	26.7	129	2.9	517
Sept	1.54	3.9	36.1	16.7	97.0	62.1	85.9	24.2	118	2.6	478
Oct	0.35	0.9	33.6	10.6	92.5	51.1	83.0	22.2	80	1.8	409
Nov	0.43	1.1	22.1	0.5	71.8	32.9	90.3	26.1	...	...	320
Dec	0.71	1.8	20.2	-0.7	68.4	30.7	85.9	30.3	...	...	245
Total or mean	7.73	19.6	31.2	7.8	88.1	46.1	73.9	22.8	121	2.7	482

Table 1.—*Meteorological data for project site near Buckeye, Ariz*—Continued

Month	Precipitation (in.)	Precipitation (cm)	Mean temperature (°C) Max	Mean temperature (°C) Min	Mean temperature (°F) Max	Mean temperature (°F) Min	Relative humidity (percent) Max	Relative humidity (percent) Min	Wind speed at 4 meters (cm/sec)	Wind speed at 4 meters (mph)	Solar radiation Langleys/day
1965											
Jan	1.65	4.2	19.0	1.3	66.2	34.4	91.5	28.4	156	3.5	267
Feb	1.54	3.9	21.2	-0.6	70.2	31.0	88.6	23.4	163	3.6	367
Mar	0.79	2.0	23.1	2.0	73.6	35.6	86.4	22.7	162	3.6	433
Apr	1.54	3.9	28.6	6.1	83.5	42.9	85.1	19.6	190	4.2	518
May	0.43	1.1	34.1	7.6	93.4	45.6	71.5	18.1	220	4.9	592
June	0.08	0.2	37.4	9.7	99.4	49.4	59.5	18.4	162	3.6	639
July	0.35	0.9	42.3	20.3	108.2	68.5	66.1	21.1	171	3.8	577
Aug	0.08	0.2	41.7	18.8	107.1	65.8	70.4	20.7	181	4.0	582
Sept	0.35	0.9	40.9	12.6	105.7	54.6	78.3	21.5	149	3.3	465
Oct	0.00	0.0	35.2	7.1	95.3	44.7	71.8	22.0	150	3.4	432
Nov	0.67	1.7	26.6	3.8	79.8	38.8	83.2	29.2	113	2.5	260
Dec	3.78	9.6	19.9	2.9	67.8	37.2	96.5	46.7	117	2.6	194
Total or mean	10.83	28.6	30.8	7.6	87.5	45.7	79.1	24.3	161	3.6	444
1966											
Jan	0.55	1.4	17.8	-2.3	64.1	27.8	97.5	31.6	...	...	253
Feb	1.54	3.9	18.3	-1.1	64.9	30.1	97.6	28.3	151	3.4	360
Mar	0.16	0.4	27.1	3.9	80.8	39.0	92.7	21.0	170	3.8	440
Apr	0.00	0.0	32.2	5.4	89.9	41.8	81.5	29.9	258	5.8	575
May	trace	trace	38.1	10.8	100.6	51.4	76.8	24.4	172	3.8	649
June	0.00	0.0	41.6	14.3	106.8	57.7	71.7	23.9	139	3.1	677
July	0.83	2.1	43.3	20.8	109.9	69.5	80.1	28.0	166	3.7	576
Aug	0.51	1.3	39.6	22.2	103.2	72.0	83.8	24.8	186	4.2	527
Sept	4.49	11.4	37.8	16.6	100.0	61.8	89.2	26.1	131	2.9	457
Oct	0.28	0.7	31.2	8.1	88.1	46.6	93.8	23.7	...	...	378
Nov	0.43	1.1	26.7	4.0	80.0	39.2	93.4	25.5	...	...	270
Dec	0.00	0.0	21.2	-2.3	70.1	27.8	86.9	27.6	...	...	255
Total or mean	8.79	22.3	31.2	8.4	88.2	47.1	87.1	25.4	172	3.8	451
1967											
Jan	0.24	0.6	20.1	-3.7	68.1	25.3	79.6	23.2	281	6.3	285
Feb	0.00	0.0	24.8	-2.0	76.6	28.4	63.6	20.7	168	3.8	437
Mar	0.24	0.6	28.4	2.8	83.7	37.1	74.4	24.5	164	3.7	512
Apr	0.20	0.5	27.4	3.4	81.4	38.1	85.1	21.5	156	3.5	636
May	0.00	0.0	34.8	7.9	94.6	46.2	72.4	21.7	187	4.2	696
June	0.16	0.4	39.6	14.2	103.3	57.5	74.1	24.4	...	...	...
July	0.24	0.6	44.9	22.9	112.9	73.3	89.5	27.5	...	...	...
Aug	0.20	0.5	43.1	23.3	109.5	74.0	72.6	25.1	...	...	...
Total or mean	1.28	3.2	32.9	8.6	91.2	47.5	76.4	23.6	191	4.3	513

TABLE 2.—*Dates of flooding of the Waterman Wash*

Year	Dates[1]	Total
1959	July *18*, *30*; Aug. *2*, *6*, *11*; Oct. *29*; Dec. *13*, *25*, *31*	[2]9
1960	Mar. *1*; July *30*; Aug. *10*, *22*. Levees built in November	4
1961	July 3, 23; Aug. 18, 20, 23; Sept. 13	6
1962	Jan. 24; Feb. 21; Aug. 19; Sept. 22. Levees strengthened in October	4
1963	Aug. 6, 22, 26, 30; Sept. 18; Oct. 25; Nov. 7	7
1964	Jan. 23; Mar. 2; July 24, 31; Aug. 4, 12, *13*, 26; Sept. 13; *14*; Oct. *17*; Dec. 19. Levees repaired in November	12
1965	Feb. 7; Mar. 11; July 18, 29; Sept. 4, 18; Nov. 23; Dec. 23	8
1966	May 8; July 24; Aug. 9, 11; Sept. *16*[3]	5
1967	July 11; Sept. *4*[3]	[4]2
Total		57

[1]Dates on which the evapotranspirometer site was partly or totally inundated are italicized.
[2]After July 1 only.
[3]These were very large floods, of more than 3,000 m^3/sec (10,000 cfs).
[4]Before Sept. 5 only.

bare. Tank 11, however, was surrounded by a triple hedge of saltcedar about 3 m (10 ft) wide. The purpose was to determine whether an "oasis-in-reverse" situation would have any effect on evaporation from bare soil.

INSTRUMENTATION

FLOATLESS CONTROL SYSTEM

The water level in the tanks was regulated by a floatless control system in which a valve automatically opened as soon as the water level fell below the lowest of two electrical contact points. Water then entered the tank until the level reached the upper contact point, which was about 5 mm (millimeters) (0.2 in.) above the lower point. A pen on an event recorder indicated the time and duration that the valve was open, and the

FIGURE 8.—Man standing on surface of an evapotranspirometer newly planted to saltcedar; original vegetation in the background.

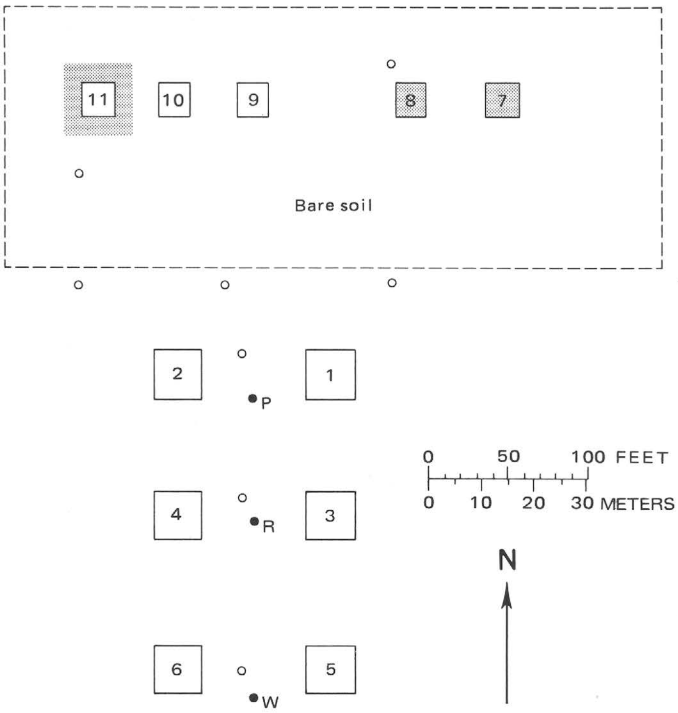

FIGURE 9.—Location of tanks and instruments. Tanks 1–6 are inside a dense stand of saltcedar; tanks 7–11 in an open area, 7 and 8 planted to saltcedar; tanks 9, 10 and 11 are bare but 11 is surrounded by a hedge of saltcedar. P, R, and W, solid dots, are instrument masts. Circles indicate locations of access tubes for determining soil moisture outside the tanks. Tanks 1, 2, 3, 4, and 6 were constructed in May and June of 1959, tank 5 in October, 1959, and tanks 7–11 in November and December of 1962.

quantity of water (to the nearest tenth of a gallon) that entered the tank could be read from a standard water meter. Routinely, the meters were read every morning from Monday through Friday, and frequently, on Saturdays and Sundays. Occasionally (quite often in 1966 and 1967) readings were taken at 2-hour intervals for periods of 72 hours or more. Figure 10 shows the instrumentation at one of the tanks. One pen on the recorder, a, indicates the temperature of the water; the other pen marks the time that the magnetic valve b is open and water via

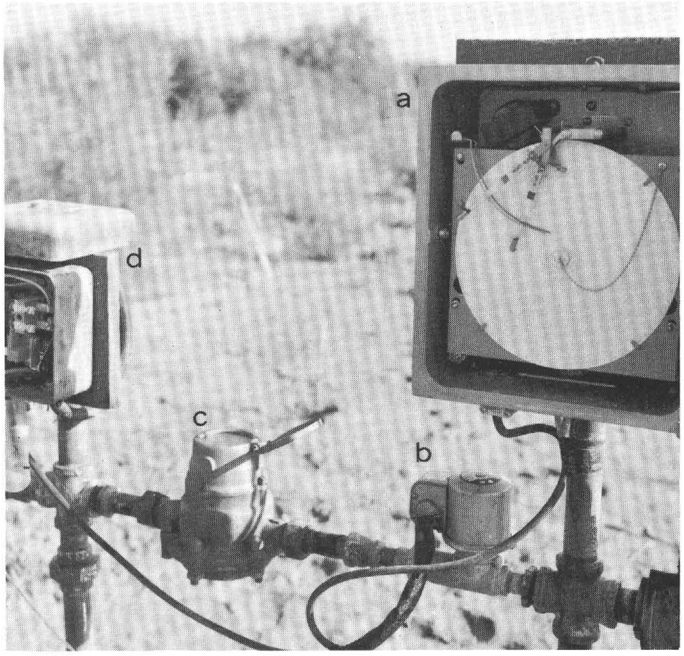

FIGURE 10.—Instrumentation for the water budget: a, on/off and water temperature recorder; b, magnetic valve; c, water meter; d, valve-control mechanism.

meter c enters the tank. The switching mechanism, d, opens and closes valve b.

Figure 11 is a schematic cross section of a tank, showing contact points of the electrode rods at the water table and other features.

ADVERSE CONDITIONS

It is not surprising that the rigors of the climate often adversely affected the contol system. Temperatures as high as 50°C (122°F) combined with high humidity were not infrequent. Dust storms interfered with the electrical

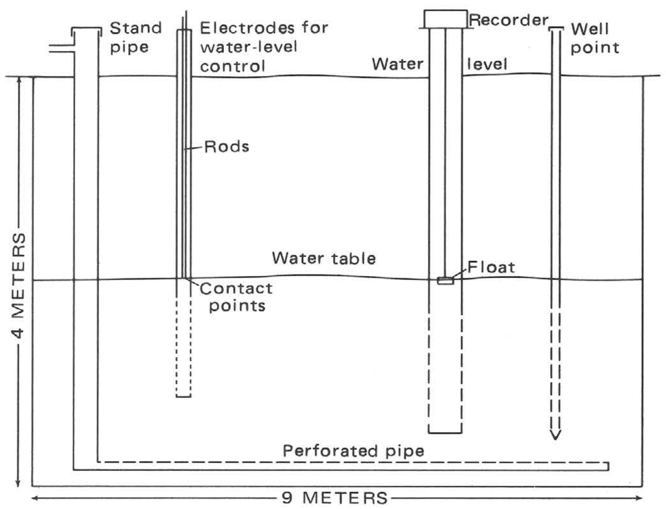

FIGURE 11.—Schematic cross section of an evapotranspirometer. Access tubes for soil moisture determination, tensionmeters and thermocouples not shown. (Instruments and plumbing not to scale.)

contacts. During the colder seasons, frost damage occurred in the plumbing, even though heat bands were installed to protect the pipes from bursting. The well water often contained a large amount of sand, and, owing to the comparatively high content of dissolved solids, the metal pipes and aluminum tubes and rods corroded easily. As a result, valves stuck, water meters did not turn, and contacts failed. Various quantities of water which entered the tanks were sometimes unaccounted for, but the amount of water was always in excess of that used during such periods through evapotranspiration alone. The method which was devised to correct for these undesirable effects is discussed in the following section.

WATER LEVEL

In order to have a certain amount of control on malfunctioning which might escape attention, 1½-in. (about 4-cm) well points were installed about 3 m (9 ft) from the stand pipe (fig. 11). Depth to water in the well points was measured whenever the water meters were read. Corrections for apparent excessive use could reasonably be made by plotting the actual water-level fluctuations and assuming a 40-percent porosity of the subsoil in the tanks. Effects of unintentional flooding were also corrected sometimes by pumping water out of the tanks until the intended depth to water table was reached again.

Similar corrective measures were taken each time one or more of the evapotranspirometers was inundated by flooding of the Waterman Wash. In 1964 flooding occurred so frequently (see table 2) that only water-use data for short periods of controlled conditions could be considered reliable.

SOIL MOISTURE AND TEMPERATURE

The tanks were equipped with aluminum access tubes, each with 2-in. (about 5-cm) outside diameters and 1¾-in. (about 4.5-cm) inside diameters, for measuring soil moisture by the neutron scattering method. (These tubes are not shown in fig. 11.)

Most of the tanks had 8-inch (about 20-cm) plastic pipes which extended down to the water table. At times, water-level recorders were placed on these pipes. Batteries and tensiometers were installed in a few tanks in 1963 and in all tanks in 1965. The batteries made it possible to estimate moisture stress in the soil at different levels and also to estimate directions of soil-moisture flow towards or away from the land surface.

Tanks 1 and 6 were equipped with heat-flow plates to determine the incoming and outgoing sensible heat; also, several sets of thermocouples were installed inside and outside these and other tanks to measure soil temperature at two or more levels. Finally, most of the tanks were equipped with a small rain gage to measure throughfall.

VEGETATION

TANK PLANTING

Usually, phreatophytic vegetation along streambeds or around reservoirs and lakes is mapped by a set of standard survey procedures (Horton and others, 1964). These methods are very useful and effective in providing data which can be subjected to statistical and other analyses; they are unsatisfactory, however, for a small area such as an evapotranspirometer. The standard methods are not sensitive enough to elicit the possibly small differences that may exist between two tanks. In this experiment, the size of the tanks allowed detailed observation of the vegetation to be made conveniently by the procedures described below.

The surface of each tank was divided into twenty-five squares. Each square supposedly contained: one originally planted crown cutting, growth resulting from the sprouting of pieces of stem and root (buried during the construction of the tanks), and growth from seeds that were blown or washed in after construction. Growths of the latter two types sometimes reached the top of the vegetation, especially in the few areas where the crown cuttings did not succeed in dominating the surroundings. The leaf area completely shading the ground was estimated by percentage of each square, and the area of the canopy for each bush or clump was similarly estimated and then converted into square meters.

TRANSPIRATION VOLUME

It has often been assumed that consumptive water use by phreatophytes is more or less related to the volume of transpiring foliage. A method was therefore sought that would give a measure of volume of transpiring foliage. The total volume of the vegetation taken as the product of the area of the canopy times the average height, sometimes corrected for crown depth, has been used as a parameter (Gatewood and others, 1950).

This method has, at least for saltcedar, a decided disadvantage. The plants are considered to be a set of cylinders, and as a result, the actual transpiring volume is greatly over-estimated. Nonetheless, such data can be used to compare one area with another. A more natural geometric configuration is obtained, however, if one assumes the transpiring volume of the bush to be the upper half of an oblate spheroidal shell. In the tanks at the Buckeye Project, such a shell is about 50 cm (about 20 in.) thick. The horizontal radius is that of the mean radius of the more-or-less circular area shading the ground, and the vertical radius is about one-third of the total height of clump or bush. The volume of half an oblate spheroid is $(2\pi/3)\ a^2b$ in which a is the longer, in this case horizontal, radius, and b is the vertical or shorter radius. The volume of the shell is then $(2\pi/3)\ a^2b-(2\pi/3)[(a-50)^2(b-50)]$, and represents a transpiring volume based on a more realistic shape than that of cylinders. Volumes for 1965 computed by the method of Gatewood and others (1950) were between 150 and 250 percent larger than those obtained by the spheroidal shell method.

The average height, the mean coverage in percent of the total area, and the total transpiring volume of the canopy are shown in table 3 for each tank surveyed in the fall of the years 1962–66. As can be seen, equilibrium seemed to have been reached by 1964. It appears that although there were differences in rate of growth (to be discussed later), these differences were offset in each tank by the dying of parts that were no longer exposed to sufficient sunlight. In addition to being a phreatophyte, saltcedar is obviously a heliophyte.

TABLE 3.—*Results of surveys of saltcedar, taken in the fall of each year, in the evapotranspirometers*

Date of survey	Mean height (m)[1]	Mean cover density (percent)	Total spheroidal volume (m^3)
Tank 1			
1962	2.40	80	74.0
1963	2.70	90	90.8
1964	3.15	100	98.7
1965	3.30	100	100.8
1966	3.25	99	99.5
Tank 2			
1962	2.50	80	81.2
1963	2.90	80	88.3
1964	2.90	90	96.4
1965	3.25	100	98.7
1966	3.30	95	96.9
Tank 3			
1962	2.40	80	78.4
1963	2.75	80	92.4
1964	3.00	100	110.3
1965	3.15	95	108.2
1966	3.05	100	113.1
Tank 4			
1962	2.30	75	75.4
1963	2.80	90	94.3
1964	3.05	105	104.8
1965	3.20	100	110.5
1966	3.15	105	112.8
Tank 5			
1962	2.50	70	82.3
1963	2.95	80	90.2
1964	3.20	100	107.6
1965	3.15	100	108.0
1966	3.15	100	111.0
Tank 6			
1962	2.40	75	79.7
1963	2.80	75	93.8
1964	3.00	105	101.2
1965	3.00	95	105.2
1966	3.10	100	100.5

[1]To nearest 5 cm.

Finally, table 3 shows that there are considerable differences between the observed variables in the tanks (actually more than 10 percent), but they are not statistically significant. No attempt, therefore, has been made to relate water use to these variables. Moreover, the relationship between transpiring volume and water use, for example, is not so simple as is often assumed. This will be discussed under "Vegetation Growth and Development".

WATER USE, LARGE TANKS

1961-63: DEPTH TO WATER

During 1961, 1962, and 1963, the water levels in tanks 3 and 5 were maintained at 1.5 m (5 ft) below the land surface; in tanks 4 and 1, at 2.1 m (7 ft); and in tanks 2 and 6, at 2.7 m (9 ft). The water use by months is given in table 4. These 3 years are tabulated separately because the treatment did not change during this time; after 1964, some of the tanks were flushed to reduce the salinity of the ground water, and in 1966 other changes were made as explained below.

Table 5 summarizes the total use per tank per year for 1961, 1962, and 1963 and includes the results of an analysis of variance (Fisher, 1944; Fisher and Yates, 1943). (See "Appendix: Analysis of Variance" for explanation of least significant difference.) The analysis of variance, as can be seen from the table, shows a significant effect of interaction between years and depth to water. The table gives an F-value which is significant at the 1-percent level for effects of depth to water. Although some tanks show an increase in water use between 1961 and 1963, such increases are not statistically significant and are completely overshadowed by the depth-to-water effect. Data from tanks 2 and 6 show a gradual decrease in water use probably due to an increase in salinity of the ground water.

Unfortunately only a few measurements of specific conductance were made prior to 1963, but it may be assumed that the conductance in all the tanks was the same. Table 6 shows that the conductance of the ground water in tanks 2 and 6 had increased much more than in the other tanks. The low water use in tanks 2 and 6 may have been caused by high salinity of the ground water rather than depth to ground water. The difference, however, in water use between tanks 3 and 5, with a water table depth at 1.5 m (5 ft), and 1 and 4, with a water table depth at 2.1 m (7 ft), must have been caused by the deeper water table in tanks 1 and 4 because the specific conductance of the ground water in all four was practically the same. Further evidence of the effect of salinity of soil moisture will be discussed in "1965: Salinity."

TABLE 4.—*Monthly water use in evapotranspirometers by saltcedar, excluding rainfall*

Tank No. . . .	3		5		4		1		2		6	
Depth to water (cm). . .	150		150		210		210		270		270	
Date	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.
1961												
Jan	2.0	0.79	2.1	0.83	1.5	0.59	1.2	0.47	0.4	0.16	0.4	0.16
Feb	3.6	1.42	4.1	1.61	3.6	1.42	1.8	0.71	1.8	0.71	1.8	0.71
Mar	5.6	2.20	6.0	2.36	2.8	1.10	5.0	1.97	3.8	1.50	1.4	0.55
Apr	16.8	6.61	16.4	6.46	7.7	3.03	8.2	3.22	6.3	2.48	7.6	2.99
May	26.0	10.23	22.8	8.98	14.9	5.86	21.6	8.50	16.2	6.38	15.8	6.22
June	33.4	13.15	27.3	10.75	21.6	8.50	27.1	10.67	18.1	7.12	21.2	8.35
July	37.3	14.68	39.5	15.55	27.8	10.94	30.3	11.93	27.2	10.71	27.2	10.71
Aug	30.6	12.05	33.9	13.35	21.1	8.31	17.8	7.01	19.3	7.60	21.3	8.38
Sept	22.5	8.86	21.5	8.46	18.5	7.28	16.8	6.61	8.7	3.42	6.8	2.68
Oct	12.4	4.88	10.2	4.01	12.3	4.84	11.0	4.33	2.9	1.14	4.5	1.77
Nov	5.8	2.28	9.4	3.70	7.9	3.11	3.7	1.46	0.0	0.00	0.0	0.00
Dec	2.9	1.14	6.3	2.48	1.4	0.55	0.9	0.35	0.0	0.00	0.0	0.00
Total	198.9	78.29	199.5	78.54	141.1	55.53	145.4	57.23	104.7	41.22	108.0	42.52
1962												
Jan	1.7	0.67	2.9	1.14	0.8	0.31	0.0	0.00	0.0	0.00	0.0	0.00
Feb	2.6	1.02	2.6	1.02	1.1	0.43	1.1	0.43	1.1	0.43	1.1	0.43
Mar	5.4	2.12	4.1	1.61	2.5	0.98	2.5	0.98	3.4	1.34	3.4	1.34
Apr	23.3	9.17	22.0	8.66	11.2	4.41	12.0	4.72	9.0	3.54	9.0	3.54
May	40.0	15.75	40.4	15.90	25.9	10.20	29.5	11.57	19.1	7.52	15.2	5.98
June	42.3	16.65	45.0	17.71	33.1	13.03	34.2	13.46	20.5	8.07	21.7	8.54
July	24.3	9.57	25.6	10.08	16.7	6.57	17.2	6.77	10.6	4.17	10.1	3.98
Aug	22.0	8.66	22.4	8.82	12.7	5.00	15.3	6.02	7.8	3.07	8.2	3.23
Sept	20.6	8.11	20.7	8.15	11.7	4.61	12.7	5.00	7.9	3.11	8.8	3.46
Oct	16.0	6.30	17.9	7.05	10.5	4.13	11.4	4.49	7.4	2.91	8.1	3.19
Nov	14.3	5.63	14.2	5.59	7.3	2.87	9.9	3.90	4.7	1.85	5.8	2.28
Dec	5.8	2.28	3.9	1.53	3.5	1.38	4.5	1.77	2.3	0.90	2.8	1.10
Total	218.3	85.93	221.7	87.26	137.0	53.92	150.3	59.11	93.8	36.91	94.2	37.07
1963												
Jan	0.8	0.31	3.7	1.46	1.0	0.39	1.0	0.39	0.0	0.00	0.8	0.31
Feb	3.5	1.38	4.2	1.65	1.4	0.55	1.2	0.47	0.9	0.35	1.8	0.71
Mar	5.0	1.97	5.7	2.24	2.1	0.82	2.7	1.06	2.6	1.02	2.7	1.06
Apr	16.4	6.46	16.8	6.61	7.9	3.11	9.8	3.86	5.3	2.09	6.1	2.40
May	37.3	14.68	36.8	14.49	24.9	9.80	27.4	10.79	13.5	5.31	14.8	5.83
June	42.5	16.73	43.2	17.01	36.2	14.25	35.8	14.09	16.9	6.65	16.9	6.65
July	41.8	16.46	36.5	14.37	28.2	11.10	32.3	12.71	13.6	5.35	12.7	5.00
Aug	24.4	9.61	23.9	9.41	16.4	6.46	16.3	6.42	8.6	3.38	7.6	2.99
Sept	27.3	10.75	25.3	9.96	17.9	7.05	17.9	7.05	9.5	3.74	10.3	4.05
Oct	19.1	7.52	20.8	8.19	14.5	5.71	11.5	4.53	9.1	3.58	10.8	4.25
Nov	7.5	2.95	10.6	4.17	6.1	2.40	5.0	1.97	4.1	1.61	5.5	2.16
Dec	0.9	0.35	1.2	0.47	2.9	1.14	2.4	0.94	2.4	0.94	2.4	0.94
Total	226.5	89.17	228.7	90.03	159.5	62.78	163.3	64.28	86.5	34.02	92.4	36.35

1964: FLOODS

Obviously something had to be done to improve the quality of the ground water, and in January and February of 1964 all tanks were flushed. Therefore, the water-level controls were disconnected and water was forced through the stand pipe and the laterals at the bottom of the tank, thus driving water from the bottom to the top of the tank. Specific conductance (mmho cm^{-1} at 25°C) of the effluent was measured daily, and backwashing was continued for 5 to 10 days until the conductance was about equal to that of the well water. This treatment had two secondary effects which were foreseen but about which little could be done. First, the water content of the soil above the ground-water level was greatly increased, and it was expected that it would take considerable time before the water content in the soil would return to the 1963 levels, even though excess water was pumped out. The second effect, a result of the frequent flooding prior to the building of the levees, was that additional soil had been dumped on the evapotranspirometer site, and in many places the soil was higher than the plastic lining. As long as the top

TABLE 5.—*Yearly water use in evapotranspirometers, exluding rainfall*

Depth to ground water . . m. . / . . ft. .	1.5 / 5		2.1 / 7		2.7 / 9		Mean of all tanks
Tank No	3	5	4	1	2	6	
1961:							
Cm	198.9	199.5	141.1	145.4	104.7	108.0	149.6
In	78.29	78.54	55.53	57.23	41.22	42.52	58.89
1962:							
Cm	218.3	221.7	137.0	150.3	93.8	94.2	152.6
In	85.93	87.26	53.92	59.11	36.91	37.07	60.03
1963:							
Cm	226.5	228.7	159.5	163.3	86.5	92.4	159.5
In	89.17	90.03	62.78	64.28	34.02	36.35	62.77
Mean of 3 years:							
Cm	213.6	216.6	145.9	153.0	95.0	98.2	153.9
In	83.36	85.28	57.41	60.21	37.40	38.65	60.38

Analysis of variance

Source of variance	Sum of squares	Degrees of freedom	Mean square	F [1]
Years	308.91	2	154.5	9.6
Depth to water .	42,660.78	2	21,330.4	**1,324.9
Interaction	1,282.81	4	320.7	*19.9
Error	144.79	9	16.1	. . . .
Total	44,397.29	17	. . . .	. . . .

[1] *F* values: significant differences indicated by * at 5-percent level, ** at 1-percent level. Least significant difference at 1-percent level is 25.0 cm.

TABLE 6.—*Quality of ground water in evapotranspirometers*

[In 1960 only three tanks were sampled; in 1963 all tanks were sampled but in three tanks samples were taken from two locations: a) where water enters the tanks, and b) where the ground water is more or less stagnant and less diluted with incoming water. Agency making analysis: U.S. Geological Survey Quality of Water Laboratory, Albuquerque, N. Mex.]

Tank No.	Specific conductance (mmho cm⁻¹ at 25°C)			Sodium plus potassium (mg/l)			Chlorine (mg/l)		
	May 11, 1960	May 6, 1963		May 11, 1960	May 6, 1963		May 11, 1960	May 6, 1963	
		a	b		a	b		a	b
1	. . . .	. . . .	7.2	. . . .	. . . .	1,190	. . . . . .	. . . .	2,140
2	5.9	7.4	12.6	730	1,120	1,820	1,580	1,950	3,980
3	. . . .	. . . .	7.3	. . . .	. . . .	1,130	. . . . . .	. . . .	1,990
4	. . . .	. . . .	7.6	. . . .	. . . .	1,200	. . . . . .	. . . .	2,110
5	6.5	7.4	7.0	750	1,130	1,190	1,710	1,960	1,960
6	6.2	7.7	31.0	740	1,150	5,180	1,640	2,040	10,800

layers of the soil were dry, this did not matter. However, when tops of the tanks and also the surroundings were saturated, root growth from trees inside the tanks could be expected to reach over the tank boundaries. Also, roots from surrounding trees might penetrate the tanks. In March 1964, trenches were dug to the plastic lining wherever necessary to prevent the roots from overreaching.

As expected, water use increased enormously in 1964, not only due to the lowering of the salinity but also because of the high evaporation rate from the soil surfaces of the saturated tanks. In addition, the area suffered three floods (see table 2) which not only partially refilled the trenches, but also kept the topsoils of the tanks saturated with large quantities of freshwater. The water-use data for short periods could be used for comparison between tanks and for correlation studies with climatological phenomena. However, the monthly and yearly totals were so heavily influenced by these catastrophes that any attempt to compensate for them was thought to be futile and would result in completely unreliable data. For these reasons, data from 1964 are not tabulated in this report.

1965: SALINITY

After a sturdy dike was built in November 1964 to keep the Waterman Wash floods out of the study area, attention was once more focused on the water use by saltcedar. As was pointed out, by the end of 1963 it became apparent that the decrease in water use in tanks 2 and 6 might have been due to deterioration of the ground-water quality in those tanks. The vigorous growth and the tremendous increase in water use following the flushing in 1964 provided more evidence.

To make comparisons, one of each of the pairs of tanks with equal depth to water was flushed and the other was not. In 1964, when the flushing was finished, the excess water was simply pumped out until the water level had reached the original depth; whereas in 1965 the water table was lowered as far as the pump could draw it down. The soil moisture was then allowed to drain and the tank was again pumped out. This was repeated until no more water collected in the stand pipe. This procedure reduced the soil moisture above the capillary fringe, and the water content became more comparable with that in the untreated tanks. After this drying process, ground water was allowed to rise to its intended level.

Effectiveness of this treatment is shown in figure 12, where the percentages of soil moisture are plotted against depth for each of the six tanks. While the higher moisture content resulting from a higher water table is quite evident, there is no significant difference of moisture content between flushed and unflushed tanks. It seems, therefore, reasonable to assume that the differences in water use so clearly shown in table 7 are due to differences in salinity and depth to ground water and do not result from differences in soil moisture above the capillary fringe. Figure 13 summarizes the data from table 7 (third section). It is obvious that the differences between flushed and unflushed tanks significantly overshadow the influence of depth to ground water on the rate of water use.

Another study provided corroborative material. As mentioned previously, two of the small tanks were planted to saltcedar in 1963. About the same time, a cotton farmer to the south of the project area drilled a new well in the vicinity of the Waterman Wash. Results of the chemical analysis of samples from this well water and of the project water are presented in table 8. Clearly,

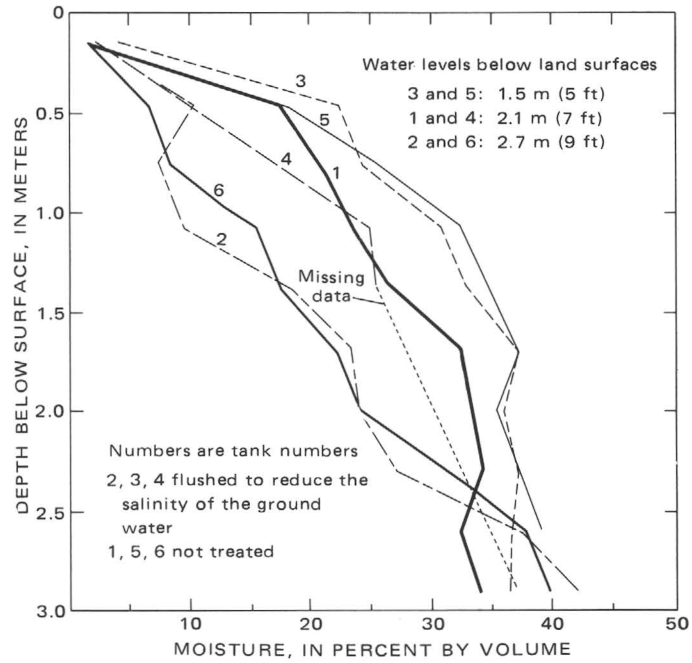

FIGURE 12.—Soil moisture by volume in the six large tanks on a typical summer day in 1965.

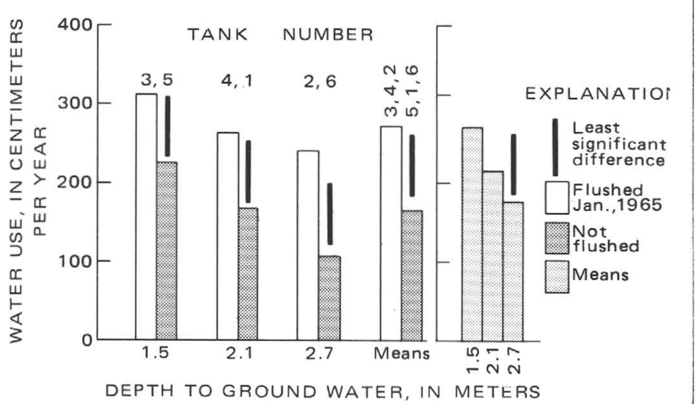

FIGURE 13.—Total water use during 1965 in six evapotranspirometers (tanks) showing the effect of depth to water and flushing of saline ground water. The bar denotes the least significant difference at the 5 percent level. Tanks 3, 4, and 2 were flushed in January 1965. The three columns to the right show the mean water use as a function of depth to ground water.

FIGURE 14.—Evapotranspirometer 7, top, received better quality water between June 1963 and February 1964 (when photograph was taken). The plants in tank 8, bottom, grew on project water.

water from the farmer's well is of far better quality than the water obtained at the project site. A (3,750-l (liter)) (1,000-gal (gallon)) container was installed near tank 7 so that water from the new well could be stored and delivered either to tank 7 or to tank 8 or both. From June 1963 through March 1964, tank 7 was provided with water from the new well while tank 8 was fed with project water.

Figure 14 shows that during this time, the saltcedar grew much more vigorously in tank 7 than in tank 8. It is not surprising that water use was also higher in tank 7. During the period mentioned, tank 7 used 264 cm (104 in.) in contrast to 170 cm (67 in.) for tank 8. It should be noted that the vegetation in these two tanks stood isolated, and actual water use obviously cannot be compared with that of the other tanks. Nonetheless, because such isolated clumps do occur in nature, some further results are discussed under "Water Use, Small Tanks."

1966: DENSITY OF STAND

Gatewood and others (1950) developed a method to compute estimated water use based on the assumption that water loss is directly proportional to the volume of green vegetative material growing on the area. The method implies that the denser the vegetation, the more voluminous is the water loss. Although objections

TABLE 7.—*Water use, excluding rainfall, in evapotranspirometers during 1965*

Tank No	3		5		4		1		2		6	
Depth to water... m	1.5		1.5		2.1		2.1		2.7		2.7	
ft	5		5		7		7		9		9	
Flushed	Yes		No		Yes		No		Yes		No	
Month	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.
Jan	0	0	0	0	0	0	0	0	0	0	0	0
Feb	1.0	.39	.4	.16	.4	.16	0	0	0	0	0	0
Mar	9.6	3.78	4.4	1.73	4.1	1.61	2.7	1.06	0	0	2.7	1.06
Apr	27.1	10.67	16.8	6.61	21.3	8.39	6.9	2.72	18.9	7.44	3.7	1.46
May	52.1	20.51	32.0	12.60	48.0	18.90	27.3	10.75	43.0	16.93	16.4	6.46
June	63.6	25.04	42.9	16.89	60.7	23.90	36.8	14.49	52.6	20.71	21.2	8.35
July	45.8	18.03	33.0	12.99	37.1	14.61	28.6	11.26	34.1	13.43	16.2	6.38
Aug	37.5	14.76	30.6	12.05	29.9	11.77	20.2	7.95	29.2	11.50	14.4	5.67
Sept	30.5	12.01	26.8	10.55	24.9	9.80	18.6	7.32	24.2	9.53	12.4	4.88
Oct	27.4	10.79	25.1	9.88	21.7	8.54	17.7	6.97	24.4	9.61	10.6	4.17
Nov	15.0	5.91	12.6	4.96	10.4	4.09	7.8	3.07	9.7	3.82	5.8	2.28
Dec	1.3	.51	1.1	.43	1.4	.55	.9	.35	1.7	.67	2.1	.83
Total	310.8	122.36	225.8	88.90	259.8	102.28	167.5	65.94	238.0	93.70	105.6	41.57

Mean of tanks Nos	3 and 5		4 and 1		2 and 6		3, 4, and 2		5, 1, and 6	
Depth to water (m)	1.5		2.1		2.7		Flushed		Not flushed	
Month	Cm	In.	Cm	In.	Cm.	In.	Cm	In.	Cm	In.
Jan	0	0	0	0	0	0	0	0	0	0
Feb	.7	.28	.2	.08	0	0	.5	.20	.2	.08
Mar	7.0	2.76	3.4	1.34	1.4	.55	4.6	1.81	3.3	1.30
Apr	22.0	8.66	14.1	5.55	11.3	4.45	22.4	8.82	9.1	3.58
May	42.0	16.54	37.6	14.80	29.7	11.69	47.7	18.78	25.2	9.92
June	53.3	20.98	48.7	19.17	36.9	14.53	59.0	23.23	33.6	13.23
July	39.4	15.51	32.9	12.96	25.1	9.88	39.0	15.35	25.9	10.20
Aug	34.0	13.39	25.1	9.88	21.8	8.58	32.2	12.68	21.8	8.58
Sept	28.7	11.30	21.7	8.54	18.3	7.20	26.5	10.43	19.3	7.60
Oct	26.2	10.31	19.7	7.76	17.5	6.89	24.5	9.65	17.8	7.01
Nov	13.8	5.43	9.1	3.58	7.7	3.03	11.7	4.61	8.7	3.43
Dec	1.2	.47	1.1	.43	1.9	.75	1.4	.55	1.4	.55
Total	268.3	105.63	213.7	84.13	171.8	67.64	269.6	106.14	166.3	65.47

Depth to water (m)	1.5		2.1		2.7		Mean	
Flushing	Cm	In.	Cm	In.	Cm	In.	Cm	In.
Flushed	310.8	122.36	259.8	102.28	238.0	93.70	269.6	106.11
Not flushed	225.8	88.90	167.5	65.94	105.6	41.57	166.3	65.47
Mean	268.3	105.63	213.7	84.11	171.8	67.64	......	......

Analysis of variance[1]

Source of variance	Sum of squares	Degrees of freedom	Mean square	[2]F
Depth to water	9,366.86	2	4,683.43	14.38
Flushed vs. not flushed	15,985.68	1	15,985.68	*49.08
Error	651.35	2	325.68	
Total	26,003.89	5	....	......

[1]The analysis of variance indicates that no interaction between depth to water and flushing could be taken into account because of lack of replication
[2]*F* value: *indicates significant difference at the 5-percent level.

against this method have been cited (Coleman, 1953), Horton, Robinson, and McDonald (1964) stated, "No better method is yet known."

The Buckeye Project provided opportunity to shed some qualitative light on the relationship between density of stand and water use. It is, after all, reasonable to assume that in fairly open stands wind can penetrate deeper into the vegetation, and, at least on favorable occasions, the wind may take away moisture, thus allowing "space" for additional evaporation and transpiration. For this reason the following experiment was conducted in 1966.

After tanks 2, 3, and 4 had again been flushed, the water level in all tanks was brought to 2.1 m (7 ft) and in

TABLE 8.—*Analysis of project water and better-quality water from a new well south of the project site.*

[Agency making analysis: U.S. Geological Survey Quality of Water Laboratory, Albuquerque, N. Mex., May 1963. Data in mg/l except when otherwise designated]

Analysis factors	Project water	Better quality water
Residue at 180°C	4,760	2,280
Hardness as $CaCO_3$	1,490	650
Percent Na	63	63
Sodium adsorption ratio	13	8.8
pH	6.8	7.3
Specific conductance (mmho cm^{-1} at 25° C)	7.57	3.64
SiO_2	31	32
Ca	396	182
Mg	122	48
Na+K	1,150	515
HCO_3	405	234
SO_4	836	256
Cl	1,980	915
F	1.3	2.5
NO_3	1.0	17

March of 1966 the vegetation in tanks 1 and 4 was thinned out to approximately 50 percent of the original density. This was accomplished by simply cutting half of the branches in each clump, taking the diameter of the branches into consideration. All vegetation in tanks 3 and 5 was shorn off at knee height. Figure 15 illustrates the general appearance of three of the six tanks, and figure 16 shows the combined results of the two treatments.

As expected, the tanks that had been flushed (2, 3, and 4) used more water than those that were not treated. The water use in the shorn tanks was much less than in the vegetated tanks, but within two months, use increased sharply with regrowth of the vegetation. The shorn stumps, still having their root systems, sprouted very fast, especially in tank 3. In mid-July tanks 3 and 5 were again shorn and water use dropped for the second time.

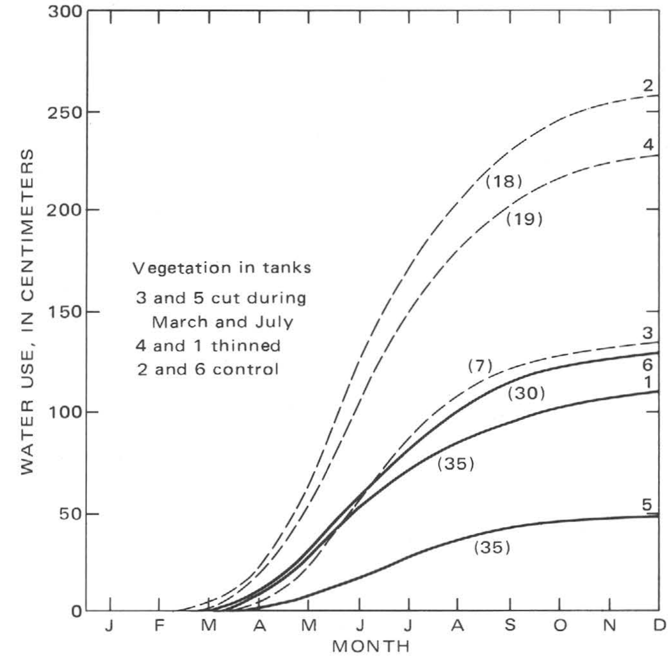

FIGURE 16.—Accumulated water use in six evapotranspirometers (numbers shown at right on curves) during 1966 showing the effects of density of stand and salinity of artificially maintained ground water. Dashed curves represent tanks flushed in Jan. 1966; solid curves represent tanks not flushed. Numbers in parentheses give the specific conductance (mmho cm^{-1} at 25°C) of the soil moisture extract in the root zones as determined from samples taken in August.

Figure 16 also shows the comparatively small difference between the quantity of the water used by the thinned-out vegetation and that used in the control tanks. Of course, the vegetation in the thinned-out tanks did not remain at the original 50 percent density. Nonetheless, even in September the thinned-out stands were still much more open than the controls. The numbers in parentheses in figure 16 are the specific conductances of the soil moisture saturation extract taken in August and explain the differences in water use due to salinity. Conductance in tank 3 remains much lower than in tanks 2 and 4, probably because much less water

FIGURE 15.—Three of the six evapotranspirometers after treatment of vegetation in March 1966. Tank 3 (left), all vegetation above knee height removed; tank 1 (center) thinned out 50 percent of its original density; tank 2 (right), no treatment.

was used and, therefore, much less salt could accumulate in that tank.

Table 9 presents the water use data for the period of most vigorous growth. It can be seen that thinning did not produce significant increases in water use but flushing resulted in great differences between shorn, thinned-out, and control tanks.

TABLE 9.—*Water use in six evapotranspirometers between April 1 and September 1, 1966*

[Least significant difference between values at the 5-percent level is 48.7 cm (19.17 in.)]

Vegetation treatment	Tank No.	Flushed Cm	Flushed In.	Tank No.	Not Flushed Cm	Not Flushed In.	Mean Cm	Mean In.
Shorn	3	108.0	42.52	5	35.6	14.01	71.8	28.27
Thinned	4	180.4	71.02	1	85.3	33.58	132.9	52.30
Control	2	206.2	81.18	6	101.4	35.92	153.8	60.55
Mean		164.9	64.92	..	74.1	29.17	....	....

1967: FINALE

No further manipulation of the tanks, either in terms of flushing or cutting and thinning, took place in 1967. The vegetation was allowed to grow and the inevitable salt accumulation took place, as will be shown. Table 10 presents the total water use during 1967. A comparison with table 9 shows that an equalizing effect has taken place. The analysis of variance gives a least significant difference larger than all of the differences in water use. As during 1966, all six tanks had the water level at the same depth and there remained only slight differences in salinity due to previous flushings and possibly due to slight differences in density of stand.

TABLE 10.—*Water use in six evapotranspirometers between April 1 and September 1, 1967*

[Least significant difference between values at the 5-percent level is 36.0 cm (14.17 in.)]

Vegetation treatment of 1966	Tank No.	Flushed in 1965 and 1966 Cm	Flushed in 1965 and 1966 In.	Tank No.	Not flushed in 1965 and 1966 Cm	Not flushed in 1965 and 1966 In.	Mean Cm	Mean In.
Shorn	3	96.0	37.80	5	60.4	23.78	78.2	30.79
Thinned	4	112.6	44.33	1	76.2	30.00	94.4	37.17
Control	2	109.3	43.03	6	93.8	36.93	101.6	39.98
Mean		106.0	41.73	......	76.8	30.24	....	.....

As will be shown later, growth and development of the vegetation in the thinned or shorn tanks was much greater than in the control tanks, and this accounts for a distinct trend to equalization of the stands. In figure 17, the accumulated water-use data for the six tanks are plotted, but only for the growing season up to September when the project was terminated. Conductances *(ECs)* observed in August 1967 are shown in parentheses. Comparison with the data of figure 16 shows that salinity increased very fast, especially in the tanks that used the greatest amount of water in 1966 and 1967. The rapid increase of water use in tanks 3 and 5 (shorn twice in 1966) is also worthy of notice.

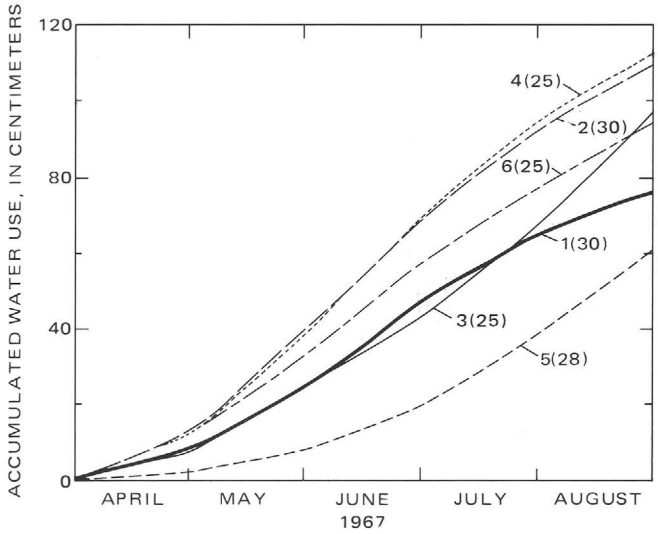

FIGURE 17.—Accumulated water use in tanks 1 to 6 between April 1 and September 1, 1967. Dashed curves represent tanks flushed in Jan. 1966; solid curves represent tanks not flushed. See figure 16 for tank treatments. Tank numbers indicated on curves; numbers in parentheses indicate conductance of soil moisture in August 1967 (mmho cm^{-1} at 25°C).

The last flood of the project history occurred on September 4, which made it virtually impossible to work in the project area during the rest of the month. In October dismantling of the equipment began, and in November some of the tanks were partially excavated to determine the condition of the linings. It appeared that the plastic and the rubber had endured well, except that occasionally small holes made by gophers or mice were encountered in the top 30 cm (12 in.). However, since these holes were well above the water table and in the dry region of the soil blocks, effects on water use were suspected to be negligible.

Below the level of the water table a fine network of roots clung to the outside of the plastic lining. The insides of the tanks below and slightly above the water table were considerably cooler than the dry soil at the same level outside the plastic. Even though the soil outside the tank was very dry at these depths there was enough vapor to condense on the lining. Thus, roots coming in contact with this water developed into the fine network.

SOIL MOISTURE AND SOIL-MOISTURE FLUCTUATIONS

METHOD OF MEASUREMENT

In reports on water use by vegetation in lysimeters or evapotranspirometers, the increase or decrease of water during a period is often taken into account (for instance, Gatewood and others, 1950). If from one month to the next, there is a rise in the water table, the increase in content is subtracted from the amount of water measured in the tank, and the actual water use by the vegetation is obtained. The water levels in the project tanks varied little, usually less than 1.5 cm (0.05 ft) from one month to the next, and there was not a discernible seasonal fluctuation. This is not surprising in view of the mechanism by which the water levels were controlled. (The daily fluctuations, to be discussed later, have no measurable effect on the monthly water use.)

It was surprising that at times soil moisture contents above the water level varied considerably. Fairly large differences in water content from month to month occurred or, as explained below, seemed to have occurred in some of the tanks. It appears, however, that these changes may have been due to causes other than water use or lack of use by the vegetation, since the increases and decreases were not consistent. Table 11 shows examples of changes in soil moisture content expressed as centimeter depth of water and as the percentages of measured water use during the indicated period. For instance, from May 16 to June 24, 1963, there is an increase in water content of 4.5 percent in tank 4, but in tanks 1, 2, and 6, a decrease is measured. From May 3 to June 13, 1966, there is a decrease in tanks 2 and 3 whereas there is an increase in tanks 1 and 4.

TABLE 11.—*Change in soil moisture content*

[Δ=change expressed as centimeter depth of water, and percent=change expressed as percentage of measured use of water during indicated periods; minus symbol indicates a decrease]

Tank No. . . .	1		2		3		4		5		6	
	Δ	Percent	Δ	Percent	Δ	Percent	Δ	Percent	Δ	Percent	Δ	Percent
1963												
May 16–June 24	−1.0	2.2	−2.8	13.5	No data .		1.9	4.5	No data .		−0.8	3.8
1965												
July 21–Aug 20	1.4	4.3	1.4	3.3	5.2	9.4	0.9	2.0	0.4	1.1	2.6	7.0
1966												
May 3–June 13	2.5	9.1	−3.9	5.4	−2.2	7.3	0.7	1.1	3.9	[1]50.0	14.0	[1]48.0

[1]This increase resulted when a sprinkler hose burst between tanks 5 and 6 in early June.

These soil-moisture measurements were made by the neutron scattering method with instruments calibrated at the project (Task Force, 1964). Figure 18 shows the instrument calibration data. The correlation coefficient is, as the figure shows, highly significant, yet a considerable scattering is possible. A good example of what can happen is given in figure 19 where a few soil-moisture measurements by the neutron scattering method are plotted against depth.

Soil-moisture readings obtained in August and October of 1963 were 3-5 percent higher than readings taken in May and June, but the greatest differences were in readings about 0.5 m (1.6 ft) above and below the water

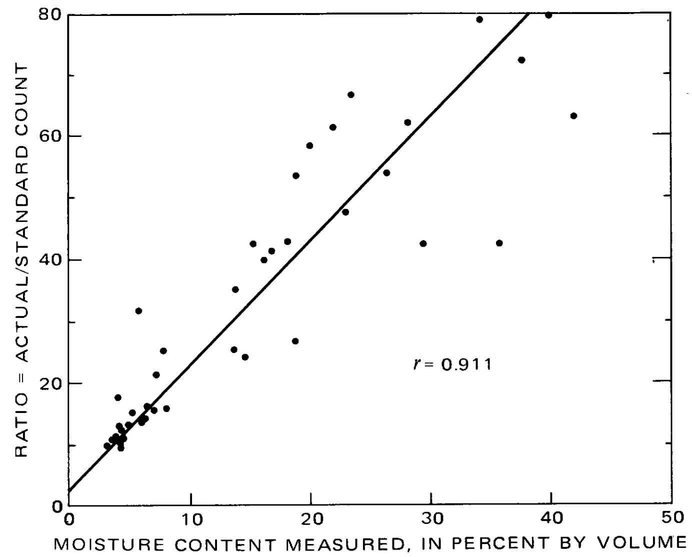

FIGURE 18.—Calibration curve of soil moisture measurements by the neutron method; individual readings indicated by dots. The correlation coefficient (*r*) is 0.911 and is highly significant.

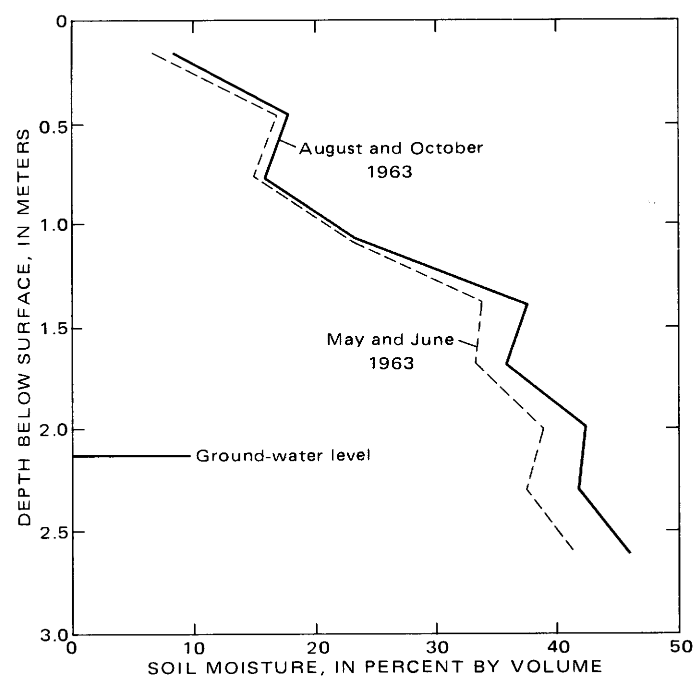

FIGURE 19.—Soil moisture in one tank showing the typically small variations.

table, where the soil is saturated and such large variations are not likely to occur.

AMBIENT AIR TEMPERATURE

During two of the special observation series undertaken in 1966, soil-moisture readings were taken at 3- to 4-hour intervals over a period of 3 days. Data for one tank are plotted in figure 20. While the water-level fluctuations are negligible, there seems at first sight to be a considerable fluctuation in soil moisture, but these fluc-

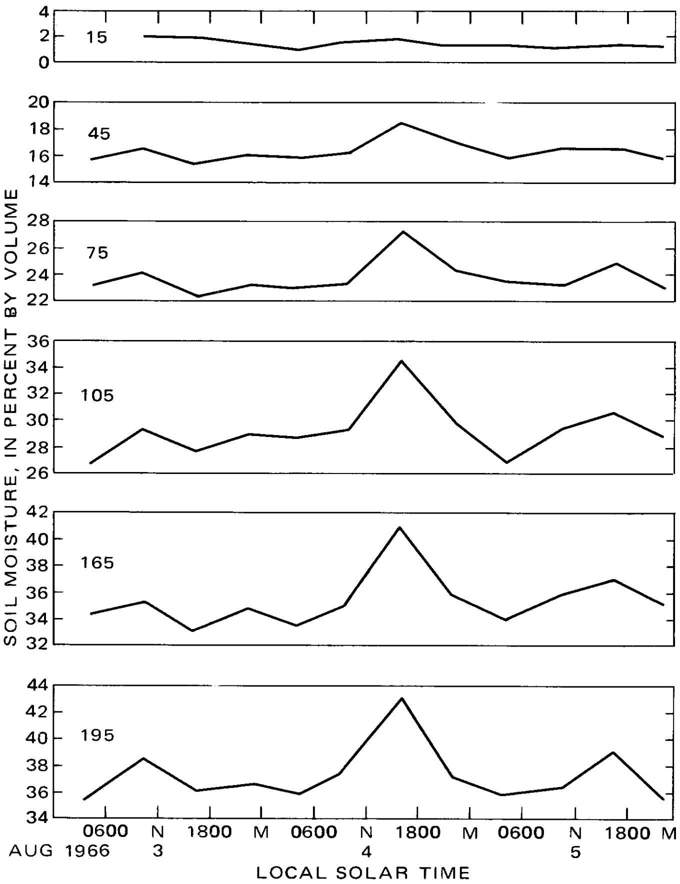

FIGURE 20.—Apparent fluctuations in soil moisture during a 3-day period in one evapotranspirometer; true solar time, N=1200 and M=2400. Variations may be due to temperature sensitivity of the counting apparatus, the probe and the standard. Numbers at the left end of curves indicate depth of sampling, in centimeters, below soil surface.

tuations are inconsistent. For instance, on August 3 soil moisture at all levels decreased between 1030 and 1600 hours, but between the same times on the next day the moisture increased. Temperature of the ambient air near neutron loggers can have a profound influence on the readings (Task Force, 1964), and this probably accounts for the apparent anomalies. Usually though, soil-moisture readings were taken in the early mornings and the effect of temperature differences could safely be ignored.

SALINITY

Another source of possible misreadings was the salinity of the soil moisture. It is known (Benz and others, 1965) that a high chloride content of the soil can affect the readings because chloride atoms are capable of absorbing neutrons. The result is that, with increasing chloride content, the count ratio goes down. In order to measure this, several batches of rock salt and water were mixed and neutron readings were taken at different concentrations. The batches were then analyzed for chloride content. In figure 21, counting ratios of the neutron logger are plotted against the chloride contents of the

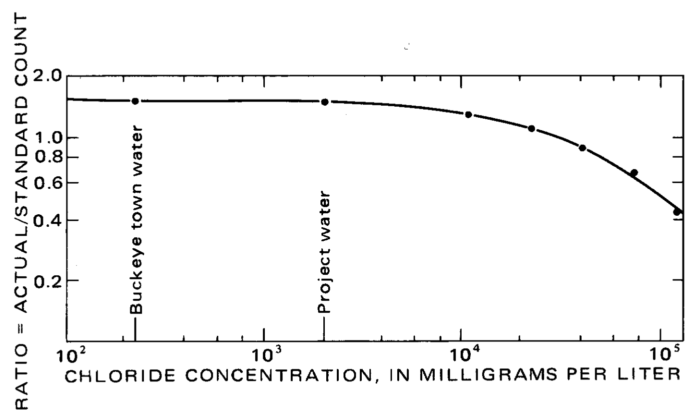

FIGURE 21.—Effect of chloride concentrations on the counting ratios of a neutron logger.

batches and also against chloride contents of the project water and of the town-of-Buckeye water. The counting rates diminished very little between nearly pure water and that containing 2,000 mg/l (milligrams per liter) chloride.

CHLORIDE CONTENT

The maximum chloride content determined in the saturation extracts at the project site was 11,000 mg/l. According to the curve of figure 21, this would bring a count down by about 0.2 on the ratio scale, equivalent to about 2 percent of soil moisture by volume. Obviously, such high chloride contents may affect the readings significantly. On the other hand, the chloride content in the saturation extracts was rarely more than 7,000 mg/l. Nonetheless, one could expect higher meter readings for a given moisture content. An example is given in figure 22. Moisture contents of the saturated soil between 25 cm above and 50 cm below the water table are plotted against depth below the land surface. When the salinity was high ($ECs \simeq 30$ mmho) as in May of 1963 and 1967,

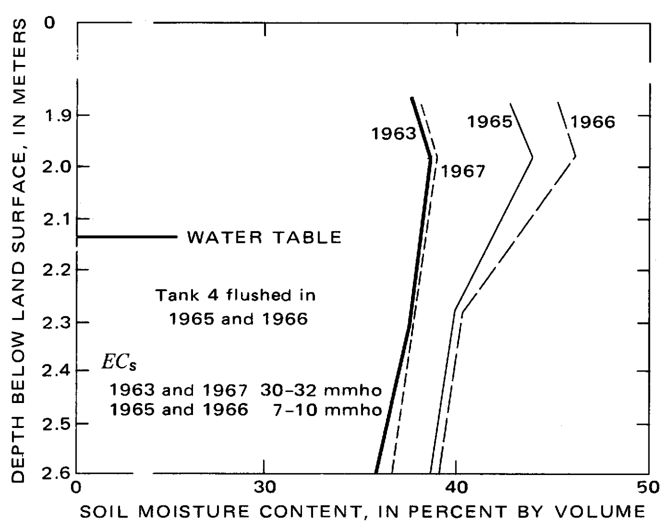

FIGURE 22.—Soil moisture near the water table in tank 4 in May of 1963, 1965, 1966 and 1967.

neutron logger readings were lower than in May of 1965 and 1966, when flushing had reduced the salinity to about 10 mmho or less.

VEGETATION GROWTH AND DEVELOPMENT

TRANSPIRATION RATE

In many studies of the use of water by plants it is assumed that the transpiration rate is controlled only by the ambient conditions at the test site. For this to be true at all, it must further be assumed that the vegetation is of uniform height and forms a closed stand completely shading the ground (Penman, 1955). When this happens and water is freely available to the plant, the amount of water transpired per unit time is said to be the potential transpiration (Thornthwaite, 1948; Penman, 1948).

The vegetation on evapotranspirometers 1 through 6 blended with the surrounding vegetation, creating an evenly growing homogeneous stand of saltcedar. Since the water in the tanks is near the surface, the plants can draw on it freely and one might expect transpiration to take place at the potential rate.

The controversy on the subject of the effect of soil moisture availability on water use is still raging. Some maintain that transpiration continues at a potential rate so long as the moisture content in the root zone is above the wilting percentage, while others say that a decrease in soil moisture necessitates a decrease in water use. An intermediate position is taken by Penman (1955), who considers that limited supplies can come from the soil below the root zone. A good survey is given by Chang (1968).

Penman points out that the evidence cited one way or another is often irrelevant because it deals wit growth rate rather than water use, and growth rate may decline before there is a decline in the rate of water use. It is often assumed that for maximum growth it is necessary for the plant to maintain a maximum rate of transpiration. It does not seem that this "axiom", as Penman calls it, has ever been proved, certainly not as a general rule. But what about the opposite: Does a plant having optimum access to water ever stop growing at the maximum rate permitted by weather conditions; and if the plant for any reason (other than weather or water conditions) stops growing at the maximum or optimum rate, does that coincide with a decline in water use?

In the spring and early summer of several years, young shoots inside and outside the evapotranspirometers were tagged and the increase in their lengths was measured at intervals varying from 5 to 10 days. In some years, the number of side shoots developing was also counted. If either the growth rate, as expressed by the increase in length, or the development, as expressed by the number of side shoots, would correlate with a change in rate of water use, one could conclude that plants begin to use less water when they stop growing or developing, even if at the same time the environmental conditions would indicate a higher potential water use.

WATER USE

Studies undertaken in 1961 and 1962 suggested a relationship between growth and water use (van Hylckama, 1963). In the quoted article, the salinity of the ground water in the tanks was considered to be of no influence on the growth or development rate, or on water use. The data quite clearly showed that a decrease in growth and development paralleled a diminishing use of water, even though this water seemed to be freely available. These results were, qualitatively at least, similar to those reported by Arkley (1963), who specifically excluded evaporation and only studied the relationships between plant growth and transpiration, a distinction not made by van Hylckama. However, the latter compared water use during periods when differences in water use could assuredly be assigned to differences in transpiration only.

SUNLIGHT, SALINITY, STAND DENSITY

Between April and June 1966, 10 trees inside each tank were again marked with numbered labels, and 10 controls were chosen outside the tanks, 5 trees on dry land and 5 on ground in the vicinity of the tanks (where sprinklers were used).

The results of the 1966 observations are tabulated in table 12 where the total increase in length for each twig during the observation period is listed. There exist very large variations among individuals, but differences between treatments are nonetheless very convincing. In tank 3, with soil moisture of low conductance, the mean daily increase in twig lengths was no less than 25 mm, and on individual branches increases of more than 50 mm/day were observed. The combined effect of better water, a well-developed root system, and full sunlight resulted in this fantastic growth.

In tanks where the vegetation was thinned out, the combined effects of water low in dissolved solids and of light are also discernible. Where the salinity of the water was high, as in tank 1, the growth was hardly faster than in tank 6, which also was not flushed, but which had a density of stand twice that of tank 1. It is also worthy of note that on irrigated lands outside the tanks no detrimental salt accumulation took place and growth rate equaled that in a flushed-out tank with full density of stand, such as tank 2.

Evidently, at least some of the results reported for 1961 and 1962 may have been affected by an increase in salinity during 1962.

It is obvious from the foregoing discussion that effects of exposure to light and of quality of soil moisture or ground water may mask any correlation that might exist

TABLE 12.—*Increase in twig length of saltcedar inside and outside evapotranspirometers between April 5 and June 22, 1966.*

Treatment . . .	None		Thinned		Shorn		[1]Controls	
Tank No. . . .	2	6	4	1	3	5	A	B
Flushed	Yes	No	Yes	No	Yes	No	.....	.....
Twig length .. (mm)	387	108	741	325	1,998	943	76	597
	524	282	810	253	1,742	945	123	594
	534	300	508	282	2,410	902	68	270
	463	151	475	236	1,800	1,246	69	553
	343	182	626	431	1,865	575	145	264
	430	97	765	148	1,785	833	185	586
	428	332	743	255	2,396	553	178	774
	445	226	989	432	2,522	738	49	212
	555	325	863	403	1,345	620	120	374
	533	590	1,396	123	1,805	647	240	253
Mean ..	464	259	792	289	1,967	800	125	448
Mean per day.	5.9	3.3	10.1	3.7	25.2	10.2	1.6	5.7

Analysis of variance

Source of variance	Sum of squares	Degrees of freedom	Mean square	[2]F
Density of stand	158,217.47	4	39,554.37	**91.50
Salinity of ground water	60,318.64	1	60,318.64	**139.53
Interaction	22,559.65	4	5,639.91	**13.05
Error	29,829.25	70	432.31	....
Total	270,925.01	79	....	....

[1]Controls outside tanks: A, on nonirrigated area; B, on sprinkler-irrigated grounds.
[2]F value: significant differences indicated by ** at the 1-percent level; least significant difference at 1-percent level is 174 mm.

between water use and growth rate of the vegetation. Neither do the present data allow for a growth rate versus salinity analysis, although there is a clear tendency toward less growth as salinity increases. (see "Discussion").

PLANT VARIATIONS

It was mentioned that a large variation exists among individual plants, at least along the Gila River near the project site. Figure 23 shows an example. Here are four branches taken from four plants of equal height and volume and of equal exposure. Such variations may be genetic or they may be due to chemical characteristics of soil moisture. In the first case we would have genotypes and, therefore, real subspecies or variations; in the second case the variations are phenotypical. Added to the illustrated differences, there are also plants with various shades of green foliage and flower colors which vary from near-white to pink to deep red. All this might well be the cause of what Douglas (1967) calls "confusion among saltcedars."

WATER USE, SMALL TANKS

The original plan required that the vegetation from the large tanks (1 through 6) would be removed after sufficient data on water use had been gathered. Observations would then continue on the water loss from bare soil. It was feared, however, that this would delay completion of the study by at least 2 years. Moreover, it would have been impossible to remove the roots without destroying the plastic lining of the tanks. Therefore, the U.S. Bureau of Reclamation in 1962 installed the five smaller tanks previously mentioned in "The Buckeye Test Site." Figure 24 presents a view of the small-tank area shortly after construction. The vegetation was not surrounded by an equal stand as was that in the large tanks. The water use, therefore, cannot be compared with that of tanks 1 through 6 because of possible oasis effects as discussed in "Evapotranspirometers." A synopsis of water use in the small tanks is presented at the end of this chapter.

HARMONIC ANALYSIS

During the summer of 1963, when saltcedar became established in tanks 7 and 8, detailed observations were made on the water use (van Hylckama, 1966). The water was maintained at a nearly constant level of 1.20 m (4 ft) below the surface in the manner discussed in "Instrumentation." When the tanks filled frequently, it was possible to compute the water use by 1- or 2-hour periods. Figure 25 shows a 1-week record of fillings in tank 7. It can be seen that during the day this tank filled more frequently than during the night. For computing short time rates it was necessary to assume that equal quantities of water were used per tank for each filling period; however, this did not actually happen because the rate of inflow was influenced by the pressure in the storage reservoir that delivered water to the evapotranspirometers. It was also necessary to assume a constant rate of water use between one filling and the next. With these assumptions, 2-hour points were obtained, centered on the uneven hour, and expressed as liters per hour for 5-day periods. A curve was drawn through these sets of points; thus, irregularities were smoothed out and one set of diurnal fluctuations could be compared with another. The data from the curves formed the basis for harmonic analyses.

For those not familiar with this method the following discussion may be useful. If we plot, for example, daily mean temperatures from moderate climates for each day of a year, a curve is obtained that reaches a maximum in summer and a minimum in winter. Such a curve, however, will rarely be smooth because of small day-to-day differences.

Mathematical analysis of periodic fluctuations makes it possible to separate a complicated curve into two or

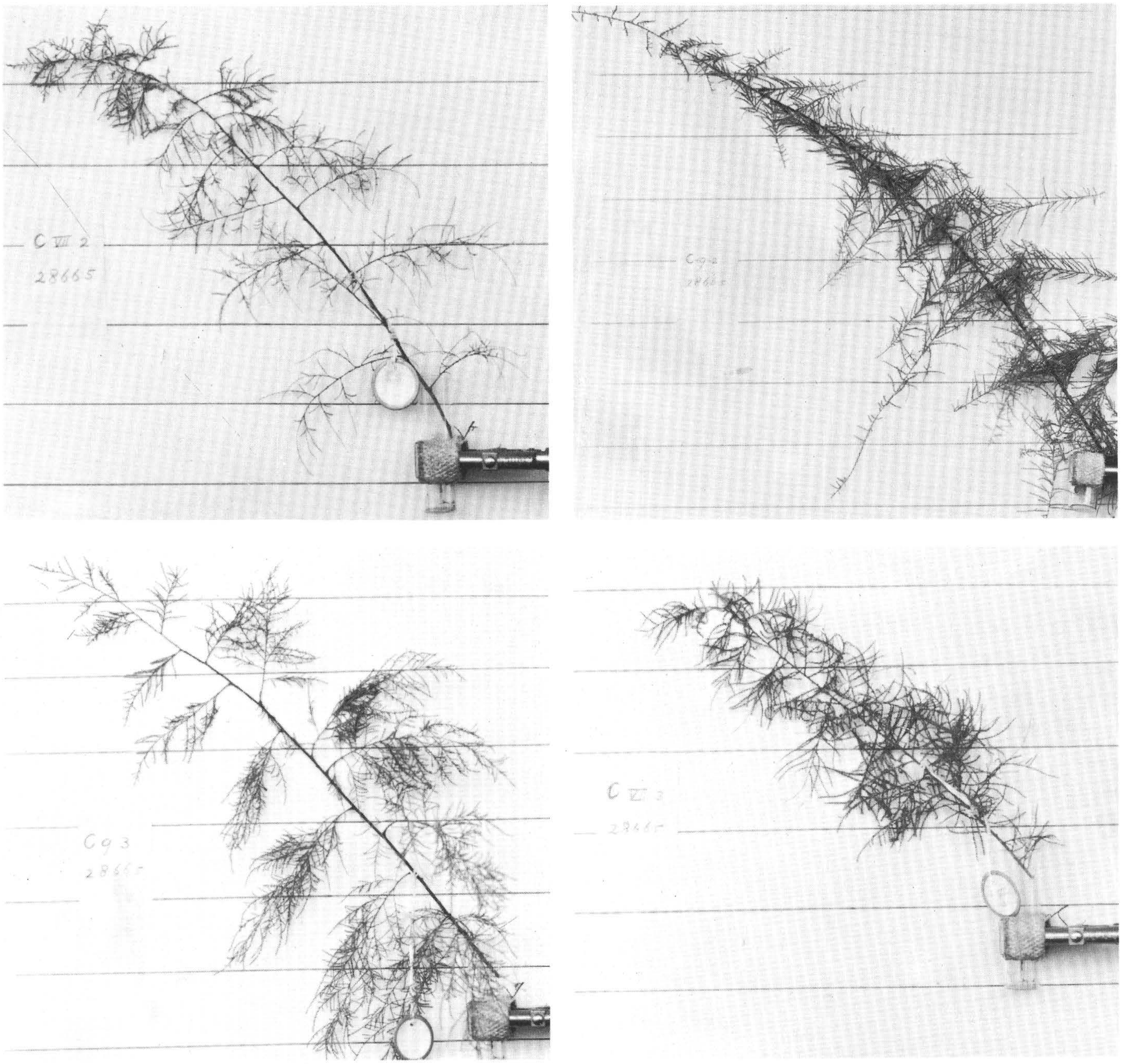

FIGURE 23.—Two- to three-month-old branches of saltcedar from the Buckeye Project site along the Gila River in Arizona showing the large variability in appearance of the species *Tamarix* that grows in this area.

more simple ones having a variety of amplitudes and frequencies. We may have a simple wave, peaking once a day, a second wave with two peaks per day, and a third wave peaking every 6 hours, or four times a day, and so on. These waves are called harmonics and the difference between the maximum and the mean values is called amplitude. In the present study Fourier series were employed using a method described by Brooks and Carruthers (1953). Analysis showed that nearly always 95 percent or more of the daily variations could be attributed to the first and second harmonics. Additional harmonics seemed to be due to random noise, such as irregularity of fillings, fluctuations in water level (see "Soil Moisture and Soil Moisture Fluctuations"), and other variables.

How well two harmonics describe the observations is illustrated in figure 26. The top curves in each graph present the average hourly fluctuations for tank 7 during

FIGURE 24.—Small-tank area at the Buckeye Project, March 1963. The new plants in tanks 7 and 8 are visible in the background, as is the better-quality-water reservoir (arrows) near tank 7. The man stands near tank 10.

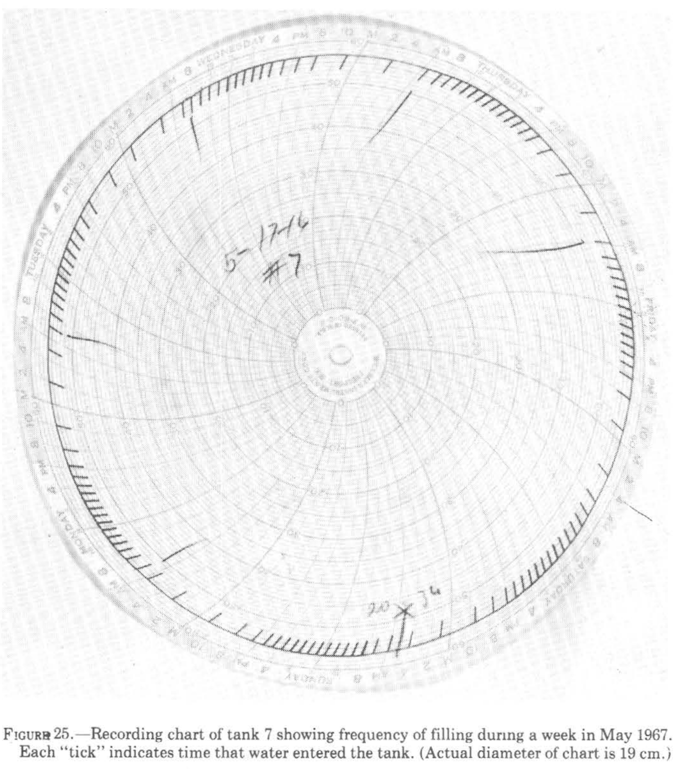

FIGURE 25.—Recording chart of tank 7 showing frequency of filling during a week in May 1967. Each "tick" indicates time that water entered the tank. (Actual diameter of chart is 19 cm.)

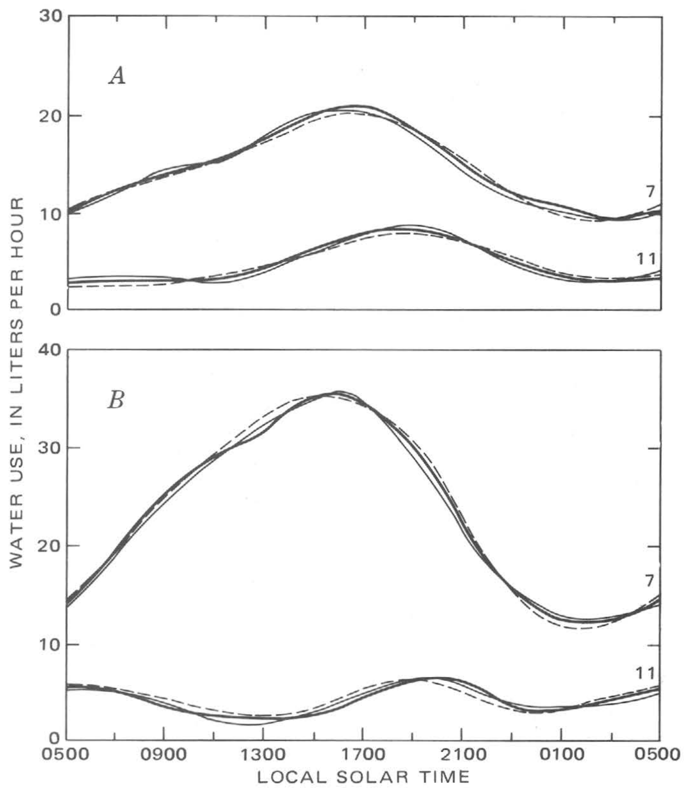

FIGURE 26.—Water use in evapotranspirometers 7, planted to saltcedar, and 11, bare. *A*, average hourly fluctuations for June 9–13; *B*, average hourly fluctuations for June 25–30. Heavy solid line represents measured water use for a mean of five days; light solid line, harmonic analysis using three harmonics; dashed line, harmonic analysis using two harmonics.

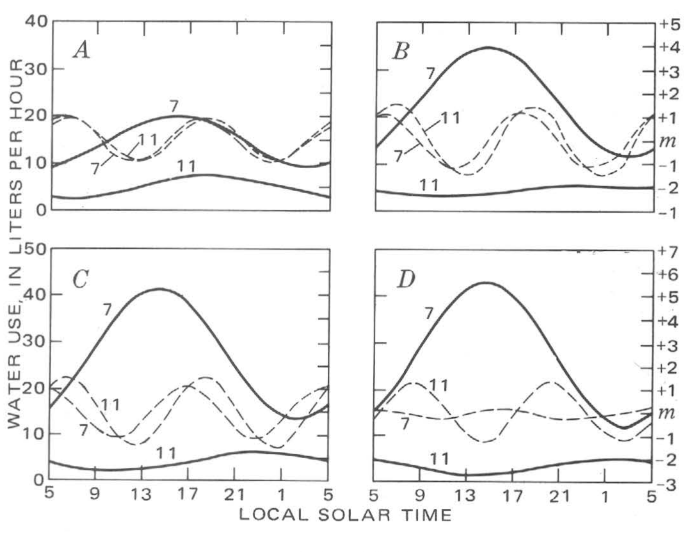

FIGURE 27.—First (solid line) and second (dashed line) harmonics of the analyses of average hourly water use for the periods June 9–13, *A*, June 25–29, *B*, July 3–7, *C*, and July 9–13, *D*, 1963, in evapotranspirometers 7, planted to saltcedar, and 11, bare. Second harmonics are plotted around a common mean (*m*).

two 5-day periods. This tank was planted to saltcedar and both the increase in foliage and a higher radiation input resulted in a larger amplitude during June 25–30 than during June 9–13. The curves for tank 11 show less water use because the tank was kept bare.

Figure 27 shows the first and second harmonics for the separate curves of figure 26, and also gives two more sets of average hourly fluctuations for later periods.

In figure 27, a first harmonic represents the rate of water use due to the daily fluctuations of radiation and temperature. There is only one maximum, shortly after noon, and one minimum, after midnight. The second harmonic has two peaks and two lows; it appears that this represents the rate of evaporation from the soil. Toward the middle of the day the top soil dries out and the vapor shield prevents further evaporation. When the soil cools off condensation occurs and the soil moisture at the surface is again in contact with the ground water. The capillary rise can follow the demand for water due to radiation, air temperature, winds, and so on. At night, of course, the evaporation from the soil diminishes just as does the transpiration.

Note that the second harmonics are drawn on an enlarged scale (the same for both tanks) and centered around a common mean. The similarity of the second harmonics is quite striking, although there is an apparent phase shift of about 2 hours in the harmonics of figures 27*B* and 27*C*. Whether this is due to the technique of averaging the values, or to the effects of shading, or to noise, cannot be determined with certainty. There appears to be no mathematical method by which the significance of differences in phase angles can be determined. It seems safe to conclude that the differences are probably not significant.

Figure 27*D* shows that the second harmonic for tank 7 virtually disappeared while the one of tank 11 remained as before. These curves were drawn from data taken in July 1963. At that time tank 7 was well overgrown, the soil was shaded, and the second harmonic accounts for only 1 percent of the total variation. In tank 11, however, 35 percent of the variation is due to fluctuations of the second harmonic.

Table 13 summarizes the means and amplitudes for the two tanks during the periods discussed above, and it also gives data from analyses of observations made in 1966 and 1967. Some anomalies in this table beg for an explanation. The water use in tank 7 during the first part of 1966 seems to have been about equal to that of comparable periods in previous years, but use decreased after July 1966. The last time tank 7 was flushed was in the early spring of 1965, and it is quite likely that the salt build-up resulted in the decrease in water use in the late summer of 1966.

By contrast, the mean use in tank 11 was considerably higher in 1966 than in 1963. Tank 11 was flooded by the Gila River in 1965 (see "Test Environment") and the water level did not fall to its proper level until the beginning of April. The soil-moisture content above the water table remained much higher throughout 1966 than it was in 1963. (A similar phenomenon was discussed in "1964: Floods.")

Statistics on the second harmonic (table 13) show the effect of a dry layer of top soil on the rate of evaporation from bare soil, except early in the year (May 1966 and 1967). The drying effects become visible in June, remain so throughout the summer, but diminish in September. Figure 28 enables us to compare the second harmonics for the observation periods of 1966 and 1967 and shows the remarkable regularity with which the wetting and drying of the top soil controls the evaporation rates.

TABLE 13.—*Mean and amplitudes of the harmonic analysis of water use in tanks 7 and 11 (l/hr)*

[Numbers in parentheses are percentages of effect of amplitude on total variance (minus sign = less than 1 percent). Tank 7 was planted to saltcedar and tank 11 was bare soil]

Starting date of 5-day period	Mean		Amplitudes			
	Tank 7	Tank 11	First harmonic		Second harmonic	
			Tank 7	Tank 11	Tank 7	Tank 11
1963						
June 9	14.7	5.1	5.2 (95)	2.3 (87)	1.0 (3)	0.9 (12)
July 9	28.0	3.4	15.4 (99)	1.6 (56)	0.1 (1)	1.3 (35)
Aug. 12	28.2	4.0	10.6 (98)	4.1 (76)	1.2 (1)	2.0 (19)
Sept. 23	27.6		15.2 (98)		2.3 (2)	
1964						
Aug. 10	25.6	4.8	10.3 (98)	0.6 (50)	1.0 (1)	0.5 (39)
1966						
May 4	14.8	4.0	5.6 (89)	2.1 (86)	0.9 (2)	0.4 (4)
June 2	19.6	6.0	7.0 (86)	1.9 (48)	1.7 (5)	1.7 (39)
July 6	27.8	9.0	10.2 (91)	2.2 (41)	0.3 (-)	2.3 (44)
Aug. 3	17.3	7.4	5.5 (89)	2.6 (37)	0.3 (-)	2.9 (47)
Sept. 7	18.6	6.5	11.7 (89)	2.0 (52)	1.9 (2)	1.5 (30)
1967						
May 10	18.3	7.3	13.8 (91)	3.1 (90)	0.4 (-)	0.2 (1)

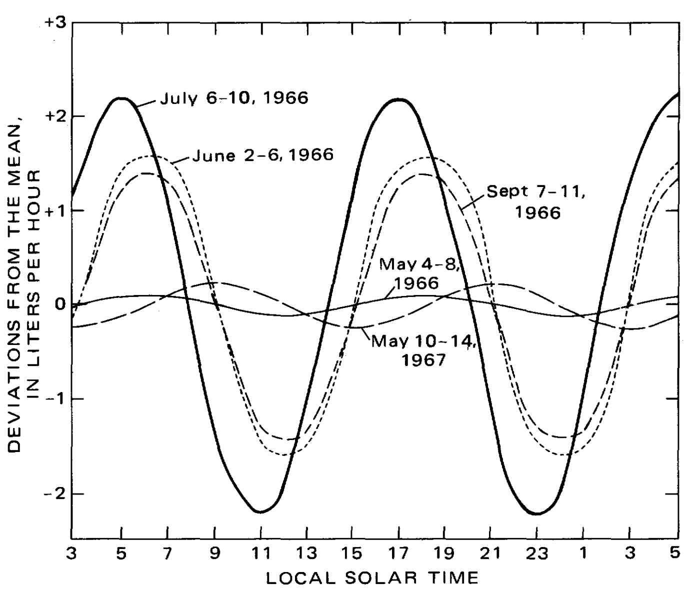

FIGURE 28.—Second harmonics of water-use fluctuations of bare-soil tank 11, computed from hourly means of 5-day periods.

OASIS TANKS

Monthly water-use data from oasis tanks 7 and 8 are given in table 14, and the results are graphically presented in figure 29. During 1963, tank 7, supplied

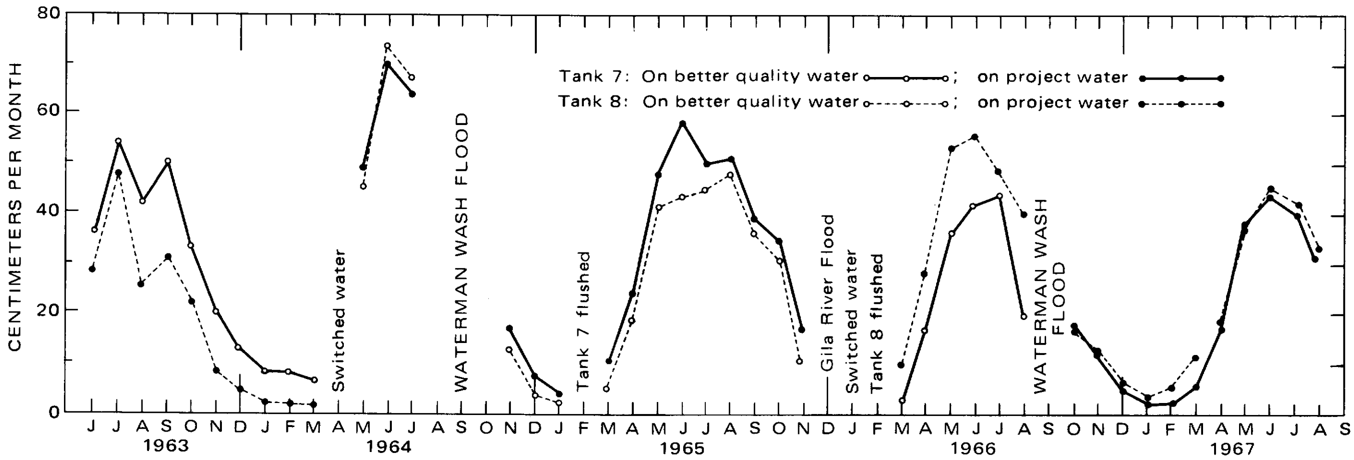

FIGURE 29.—Water use in tanks 7 and 8, planted to saltcedar, surrounded by bare soil (oasis tanks.)

TABLE 14.—*Water use in oasis tanks 7 and 8*

Year......	1963				1964				1965			
Tank No....	7		8		7		8		7		8	
Month	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.
Jan	.....	......	....	.....	7.9	3.11	1.6	0.63	2.8	1.10	0.8	0.31
Feb	.....	......	....	.....	7.9	3.11	1.6	0.63	([2])	([2])	([1])	([1])
Mar	.....	......	....	.....	6.2	2.44	0.7	0.27	9.8	3.85	4.3	1.69
Apr	.....	......	....	.....	([4])	([4])	([3])	([3])	23.8	9.37	18.0	7.09
May	([3])	([3])	([4])	([4])	48.1	18.94	45.0	17.72	47.6	18.74	40.5	15.94
June	36.0	14.17	28.4	11.18	68.8	27.09	73.1	28.78	57.5	22.64	42.8	16.85
July	54.4	21.42	47.4	18.66	63.8	25.12	66.9	26.34	49.2	19.37	43.8	17.24
Aug	41.1	16.18	25.0	9.84	([5])	([5])	([5])	([5])	50.1	19.72	47.0	18.50
Sept	50.5	19.88	31.2	12.28	([6])	([6])	([6])	([6])	37.8	14.88	35.4	13.94
Oct	32.8	12.91	21.6	8.50	([6])	([6])	([6])	([6])	33.7	13.27	30.00	11.81
Nov.	20.0	7.87	8.1	3.19	16.5	6.49	12.5	4.92	15.2	5.98	9.8	3.85
Dec	12.6	4.96	4.8	1.89	6.7	2.74	2.9	1.14	([7])	([7])	([7])	([7])

Year	1966				1967			
Tank No....	7		8		7		8	
	Cm	In.	Cm	In.	Cm	In.	Cm	In.
Jan	([1])	([1])	([1])	([1])	0.5	0.20	0.5	0.20
Feb	([3])	([3])	([2])	([2])	0.9	0.35	3.5	1.38
Mar	1.3	0.51	8.1	3.19	4.1	1.61	3.2	1.26
Apr	16.1	6.34	27.1	10.67	15.8	6.22	16.2	6.38
May	35.1	13.82	52.4	20.63	36.4	14.33	35.3	13.90
June	41.1	16.18	54.2	21.34	42.0	16.53	43.2	17.01
July	42.4	16.69	47.3	18.62	39.1	15.39	40.5	15.94
Aug	18.3	7.20	38.2	15.04	28.9	11.38	31.3	12.32
Sept	([4])	([5])	([5])	([4])	.....	.....	.....	.....
Oct	16.2	3.38	15.3	6.02	.....	.....	.....	.....
Nov	10.7	4.21	11.4	4.48	.....	.....	.....	.....
Dec	4.5	1.77	3.9	1.53	.....	.....	.....	.....

[1]Not connected
[2]Ground water in tanks flushed out with project water.
[3]Tank was fed better quality water (see analysis in table 8).
[4]Tank was fed project water (see analysis in table 8).
[5]Floods
[6]No data
[7]Gila River floods

with better quality water, used more water than did tank 8 on project water.

After the water qualities of the two tanks were switched in 1964 tank 8 began to use more water than did tank 7, but the differences were comparatively small. In 1965, tank 8 remained on better quality water, and was not flushed whereas tank 7 remained on project water but was flushed. Tank 7 measured higher water use than tank 8; although tank 8 was using better water, the salt accumulation resulted in a lower use. In 1966 tank 8 was flushed and fed project water, while tank 7 was not flushed but was switched to better water. Clearly, flushing increased the rate of water use significantly more than the feeding of better quality water without flushing. After the flood of September 1966, both tanks were fed project water and the differences in water use disappeared, as can be seen by the data of 1967.

BARE-SOIL TANKS

Bare-soil tank 9 was used for a variety of purposes, making it impossible to derive meaningful data on monthly water use. At times the water supply to this tank was shut off and the rate of change in the declining water table was used in connection with energy budget analysis. For the same purpose, the tank was shaded occasionally to study the different effects of drying of the top soil on the rate of water loss. Some of the results are discussed under "Water Table Fluctuations"; other results will be discussed in a paper dealing with the energy budget and mass-transfer methods for determining evapotranspiration.

Data from tanks 10 and 11 are summarized in table 15. Here, as in the vegetated tanks 1 through 6, the effect of change in water level on water losses is quite apparent. Compare, for instance, the data for tank 10 with those of tank 11 between June 1964 and December 1965. Before June 1964 the water level in both tanks was the same and tank 10 seemed to use more water, which might be due to the fact that tank 10 did not have the protective belt which surrounded tank 11. However, in 1966, tank 11 used more water than tank 10. It is possible that the previous high water level in tank 10 resulted in a considerable salt accumulation in the top layers of the tank which, in turn, may have affected the monthly water use. It is interesting to compare the water use recorded for these tanks with data published earlier on water use in similar tanks near Yuma, Ariz. (McDonald and

TABLE 15.—*Evaporation from bare soil in tanks 10 and 11*

Date	Tank 10				Tank 11			
	Nominal depth to water		Water use		Nominal depth to water		Water use	
	Cm	Ft	Cm	In.	Cm	Ft	Cm	In.
1963								
July	125	4.1	([1])	([1])	125	4.1	5.2	2.05
Aug	125	4.1	[2]2.1	[2]0.82	125	4.1	[2]3.6	[2]1.42
Sept	125	4.1	9.5	3.74	125	4.1	6.0	2.36
Oct	125	4.1	[2]5.8	[2]2.28	125	4.1	[2]4.5	[2]1.77
Nov	125	4.1	3.5	1.38	125	4.1	2.1	0.82
1964								
Jan	125	4.1	2.2	0.87	125	4.1	1.4	0.55
Feb	125	4.1	2.9	1.14	125	4.1	1.9	0.75
Mar	125	4.1	3.7	1.45	125	4.1	2.3	0.90
Apr	125	4.1	4.2	1.65	125	4.1	3.7	1.46
May	125	4.1	([3])	([3])	125	4.1	4.3	1.69
June	100	3.3	10.0	3.94	125	4.1	7.5	2.95
July	100	3.3	[2]9.4	[2]3.70	125	4.1	[2]7.3	[2]2.87
Aug	100	3.3	[2]9.0	[2]3.54	125	4.1	[2]5.3	[2]2.08
Sept	100	3.3	[2]5.7	[2]2.24	125	4.1	[2]4.2	[2]1.65
Oct	100	3.3	5.7	2.24	125	4.1	4.4	1.73
Nov	100	3.3	5.1	2.12	125	4.1	([1])	([1])
Dec	100	3.3	4.2	1.65	125	4.1	([1])	([1])
1965								
Apr	100	3.3	[2]7.4	[2]2.91	125	4.1	[2]5.6	[2]2.20
May	100	3.3	11.6	4.56	125	4.1	9.6	3.78
June	100	3.3	12.1	4.76	125	4.1	10.5	4.13
July	100	3.3	11.4	4.49	125	4.1	8.0	3.15
Aug	100	3.3	12.5	4.92	125	4.1	10.3	4.06
Sept	100	3.3	9.4	3.70	125	4.1	6.0	2.36
Oct	100	3.3	6.0	2.36	125	4.1	5.1	2.01
Nov	100	3.3	4.7	1.85	125	4.1	3.4	1.34
Dec	100	3.3	([1])	([1])	125	4.1	1.4	0.55
1966								
Apr	150	4.9	([1])	([1])	150	4.9	5.2	2.05
May	150	4.9	2.6	1.02	150	4.9	n.d.	n.d.
June	150	4.9	4.0	1.57	150	4.9	6.3	2.48
July	150	4.9	[2]3.3	[2]1.30	150	4.9	[2]5.0	[2]1.98
Aug	100	4.9	[2]4.7	[2]1.85	150	4.9	[2]6.2	[2]2.44
1967								
Apr	100	3.3	2.2	0.87	100	3.3	([4])	([4])
May	100	3.3	5.4	2.12	100	3.3	([4])	([4])
June	100	3.3	7.3	2.87	100	3.3	([4])	([4])
July	100	3.3	10.0	3.94	100	3.3	([4])	([4])
Aug	100	3.3	12.2	4.80	100	3.3	([4])	([4])

[1]Insufficient data to compute monthly use.
[2]Water use affected by rainfall.
[3]Chane of water level.
[4]Data suspect, excessive use probably due to leaks.

Hughes, 1968) and in the Humboldt River Valley in Nevada (Robinson, 1970).

The Humboldt River Valley report mentions water use by year but does not give data on temperatures and radiation. The growing season is undoubtedly shorter, radiation is less, and monthly temperatures are lower than those in either Yuma or Buckeye. It is therefore not surprising that the use is much less than that reported for the Yuma area.

A comparison of the weather data in Yuma and Buckeye shows clearly that the situations are quite similar, yet the water use near Buckeye is very much higher. Table 16 allows comparison of the water use in three tanks near Yuma with the use in two tanks near Buckeye during the later part of 1963 and for 1964. Some of the differences in water use might be explained by the differences in the soil. McDonald and Hughes (1968) present sieve analysis of the soils in the bare tanks at Imperial Camp. The percentage of particles less than 0.02 mm for the three Yuma tanks are 14, 8, and 6. The average percentage of particles for the soil in the bare tanks at the Buckeye Project is 28 for the top cm and 25 for the top 50 cm, with respectively 6.5 and 5.8 percent clay (particles less than 0.002 mm). Obviously, the soil at the Buckeye site is much finer and, although this may slow down the upward movement of water, it also accounts for finer capillaries and assures a more continuous supply of water for evaporation.

WATER TABLE FLUCTUATIONS

White (1932) and also Gatewood and others (1950) describe how one can make an estimate of evapotranspiration by analyzing the diurnal fluctuations of the water table. The fluctuations are partly caused by evaporation from the soil, but they are mainly caused by a pumping action as plants draw water from the water table or from the soil moisture above it. For this to be true, there should be a fall in water level during the day and a rise during the night. Although the phenomenon has been observed under natural conditions, the fluctuations of the water table in the evapotranspirometers showed the opposite: a rise during the day and a decline during the night.

A typical example of fluctuation in water table for a bare tank with the water controls shut off is given in figure 30. There is a gradual decline in the water table, but contrary to what is expected, there is a rise in the water table in the afternoon. Afternoon rises, however, coincide with lowering of the barometric pressure. To make the comparison easier to follow, the barometer readings have been reversed and the scale adjusted. The distance between "low" and "high" represents 5-cm water pressure and is 40 percent of the distance between 1.50 and 1.55 on the left scale. This percentage is called the barometric efficiency (Ferris, 1959).

Figure 31 shows a similar situation for a tank planted to saltcedar. The plants were dormant and the average

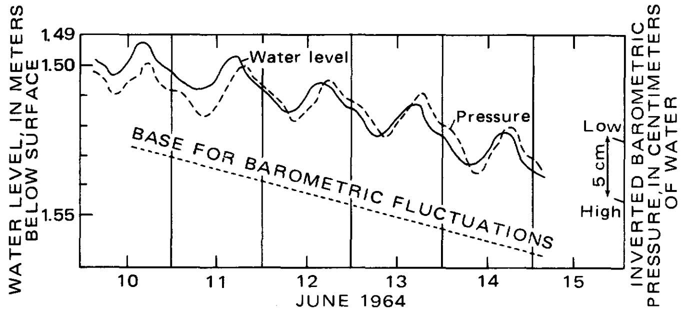

FIGURE 30.—Water levels in evapotranspirometer 9 and inverted barometric pressure. No vegetation; water controls off; June 10–14, 1964.

TABLE 16.—*Monthly evaporation, excluding rainfall, from ground water in bare-soil tanks at Imperial Camp and near Buckeye, Ariz.*

	Imperial Camp[1]						Buckeye			
Tank No....	BS1		BS2		BS3		10		11	
Nominal depth to water in 1963...cm, ft...	60	1.9	90	3.0	105	3.5	125	4.1	125	4.1
Month	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.
July.....	4.1	1.61	2.7	1.05	1.6	0.65	...	...	5.2	2.05
Aug.....	[2]2.4	[2]0.94	[2]1.3	[2]0.45	[2]0.4	[2]0.18	[2]2.1	[2]0.82	[2]3.6	[2]1.42
Sept....	...	...	...	...	...	...	9.5	3.74	6.0	2.36
Oct.....	...	...	[2]1.1	[2]0.42	...	...	[2]5.8	[2]2.28	[2]4.5	[2]1.77
Nov.....	...	...	2.2	0.87	1.1	0.42	3.5	1.38	2.1	0.82
Nominal depth to water in 1964...cm, ft.	65	2.1	90	3.0	120	4.0	125[3]	4.1[3]	125	4.1
Month	Cm	In.	Cm	In.	Cm	In.	Cm	In.	Cm	In.
Jan.....	2.6	1.04	1.7	0.67	0.4	0.17	2.2	0.87	1.4	0.55
Feb.....	2.4	0.94	1.0	0.43	0.4	0.17	2.9	1.14	1.9	0.75
Mar.....	3.1	1.23	1.1	0.44	0.1	0.04	3.7	1.45	2.3	0.90
Apr.....	4.0	1.57	2.2	0.88	0.1	0.04	4.2	1.65	3.7	1.46
May....	5.9	2.31	3.0	1.17	1.1	0.44	(4)	(4)	4.3	1.69
June....	9.2	3.62	3.0	1.19	0.7	0.28	10.0	3.94	7.5	2.95
July.....	7.0	2.74	2.4	0.96	1.5	0.61	[2]9.4	[2]3.70	[2]7.3	[2]2.87
Aug.....	6.0	2.37	[2]0.2	[2]0.07	[2]0.7	[2]0.27	[2]9.0	[2]3.54	[2]5.3	[2]2.08
Sept....	5.2	2.05	1.4	0.56	2.6	1.01	[2]5.7	[2]2.24	[2]4.2	[2]1.65
Oct.....	5.1	2.01	0.7	0.27	0.8	0.32	5.7	2.24	4.4	1.73

[1]Adapted from McDonald and Hughes (1968, table 6).
[2]Water use affected by rainfall.
[3]Depth to ground water was 100 cm (3.3 ft) after May 1964.
[4]Change in water level.

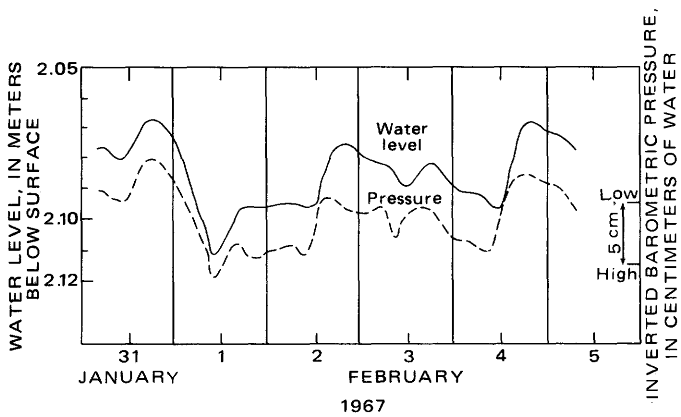

FIGURE 31.—Water levels in evapotranspirometer 1 and barometric pressure. Tank planted to saltcedar but plants leafless and dormant; January 31–February 5, 1967.

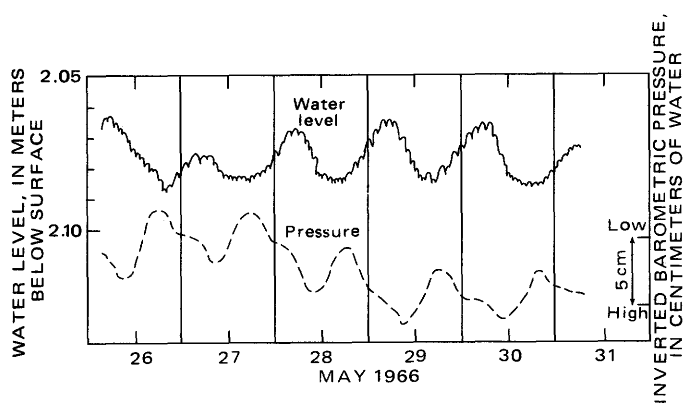

FIGURE 32.—Water levels in evapotranspirometer 2 and barometric pressure. Tank planted to saltcedar; May 26–31, 1966.

water level remained stationary, but the fluctuations followed the barometric ups and downs as before. The efficiency is again about 40 percent.

On vegetated tanks where saltcedar is transpiring, the barometric fluctuations and those of the water level are out of phase as shown in figure 32. The little wiggles were produced by the water-stage recorder in response to filling and occur at exactly the same time that the recorders indicate filling by the system illustrated in figure 25. Obviously the water level in the control pipes which contain the contact points (see "Instrumentation") did not respond to the atmospheric fluctuations. The water-level control pipes probably had a finer screen than the recorder pipes; also, the control pipes were installed shortly after the tanks had been constructed and a considerable amount of clogging could be expected. The reaction to falling and rising water levels in the control pipes was therefore sluggish compared to that in the water-level recorder tubes which were installed in 1964.

It is now possible to construct a hypothetical water level by adjusting the actual one for the atmospheric pressure changes, assuming a 40 percent barometric efficiency throughout. Under high atmospheric-pressure conditions the water level would have been shallower had the pressure been lowered to the mean pressure; under low atmospheric-pressure conditions the water level would have been deeper if the atmospheric pressure were increased to the mean. Figure 33 shows the results of such a manipulation of data for a 5-day average of the changes in evapotranspirometer 6. The line representing the adjusted water level and the points showing observed hourly rates of water use are clearly in phase.

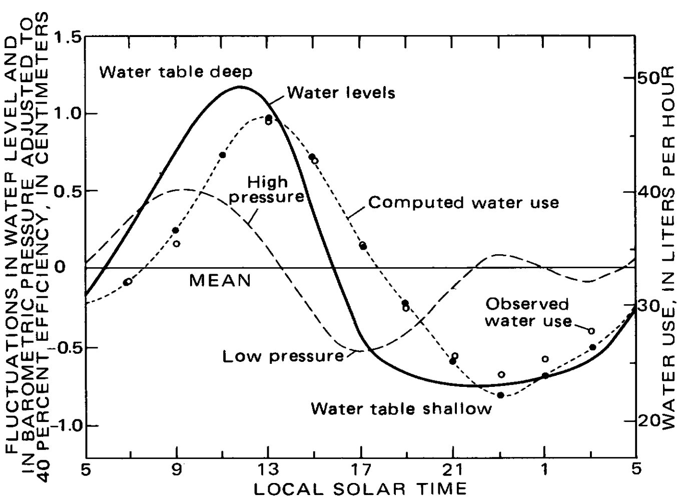

FIGURE 33.—Average water levels, average barometric pressures, and average observed and computed water use in tank 6, planted to saltcedar, for June 30–July 4, 1966.

The picture gets more complicated when there appear to be effects of salinity of the soil moisture. When the conductivity of soil moisture is low the plants seem to use that water first, and the ground-water levels are not affected until 2 to 4 hours after the transpiration has started. The result is a phase shift between the water-level curve adjusted for barometric effects and the curve drawn through measured points (van Hylckama, 1968).

It is clear that diurnal atmospheric-pressure effects can be masked, and yet they may have influenced the water level in transpiration wells. Also it is possible that there was selective water uptake by the vegetation; without that the analysis of transpiration-well data could lead to wrong estimates, if not of the daily amount of water transpired, at least of the time of consumption.

DISCUSSION

In the foregoing pages two things seem to stand out rather clearly: (1) water use by saltcedar varies with many factors, and (2) plastic-lined evapotranspirometers may be capricious instruments yielding data that should be considered with caution. Both statements, while true, are not very useful and should be reinforced with some further analytical studies.

VARYING FACTORS OF WATER USE

First of all, some of the data show that the water use by saltcedar can be enormous. Table 17 is a summary of all water-use data in rounded numbers, by years. The table shows that in 1965, tank 3 used a little more than 310 cm (122 in.) of water. This is nearly equal to the highest pan evaporation observed in the Lake Mead studies (Harbeck and others, 1958). A similar value was obtained by extrapolating data for tank 2 in 1966. Both tanks were flushed out in the spring of each year, and part of the high water use may be attributed to a high soil-moisture content, at least in the early part of the year. The next highest user for two consecutive years was tank 4 with 260 cm (102 in.) in 1965 and, again by extrapolation, 268 cm (106 in.) in 1966. This tank also was flushed out both years. The other high uses of 200 or more centimeters occured from tanks 3 and 5 in the years 1961, 1962, 1963, and 1965, and are comparable to the use rates observed by Gatewood and others (1950). The 1965 total use from tank 2 was also high (238 cm or 94 in.). However, in 50 percent of the tanks the water use was less than 150 cm (59 in.).

TABLE 17.—*Summary by years of water use in and treatment of six evapotranspirometers*

Tank No.	3	5	4	1	2	6
Depth to water...m	1.5	1.5	2.1	2.1	2.7	2.7
Vegetation treatment	None	None	None	None	None	None
Flushed	No	No	No	No	No	No
1961...cm	199	200	141	145	105	108
...in	78	79	56	57	41	43
1962...cm	218	222	137	150	94	94
...in	86	87	54	59	37	37
1963...cm	226	229	160	163	86	92
...in	89	90	63	64	34	36
Depth to water...m	1.5	1.5	2.1	2.1	2.7	2.7
Vegetation treatment	None	None	None	None	None	None
Flushed	Yes	No	Yes	No	Yes	No
1965...cm	311	226	260	168	238	106
...in	122	89	102	66	94	42
Depth to water...m	2.1	2.1	2.1	2.1	2.1	2.1
Vegetation treatment	(1)	(1)	(2)	(2)	None	None
Flushed	Yes	No	Yes	No	Yes	No
1966[3]...cm	154	51	268	122	294	145
...in	61	20	106	48	116	57
Depth to water...m	2.1	2.1	2.1	2.1	2.1	2.1
Vegetation treatment	None	None	None	None	None	None
Flushed	No	No	No	No	No	No
1967[3]...cm	137	86	161	109	156	134
...in	54	34	63	43	61	53

[1]Cut to 50 cm.
[2]Thinned 50 percent.
[3]Data extrapolated: 100/70×measured use, Mar. through Aug.

Figure 34, a graph of the data from table 4, clearly demonstrates how the water use diminished with in-

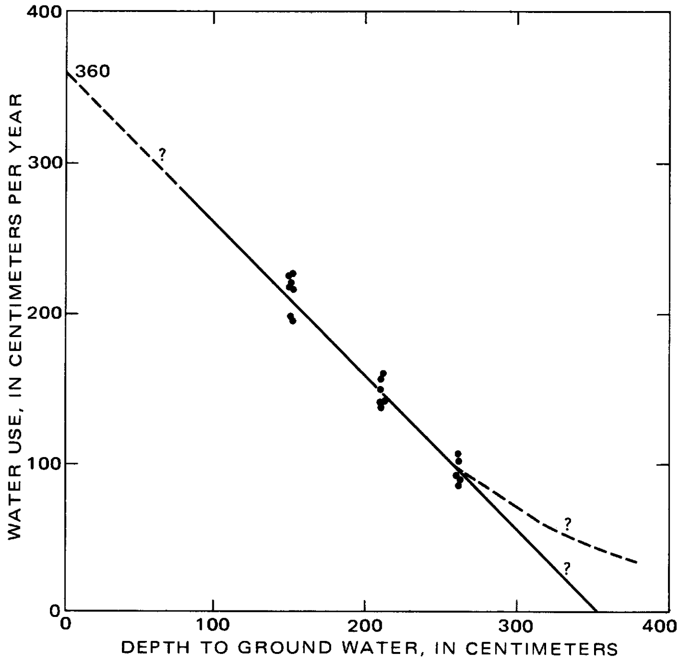

FIGURE 34.—Yearly water use (1961-63) versus depth to ground water in six evapotranspirometers at the Buckeye Project.

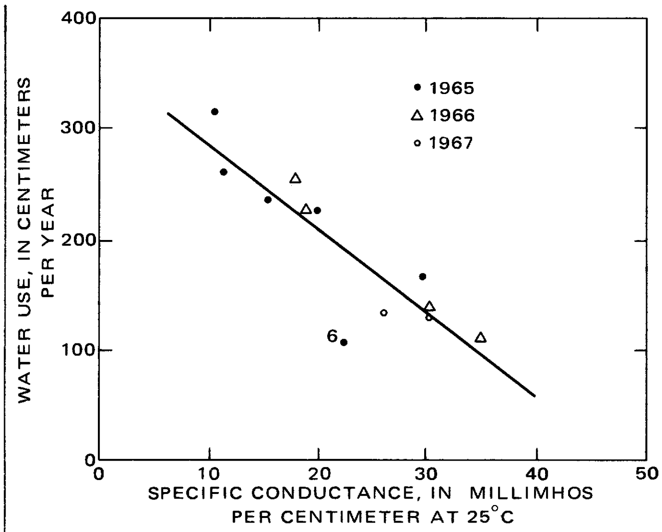

FIGURE 35.—Total water use per year in six evapotranspirometers versus specific conductance of the saturation extract of soil samples taken from the root zones in July or August of each year. The number 6 refers to an anomalous datum for tank 6 in 1965.

creasing depth to ground water. The straight line drawn by eye through the points leads to two interesting intersections with the y- and x-axes. Extrapolation to the zero water level would indicate a water use of about 360 cm (142 in.), which just about equals the 1952–53 pan evaporation for Boulder Island, mentioned in table 19 of the Lake Mead studies (Harbeck and others, 1958). Extrapolation in the other direction leads to the absurdity that the saltcedar would stop using water with a water table at 360 cm (12 ft) below the land surface. It seems altogether reasonable, though, that the water use would continued to diminish with a declining water level, but more in character with the curved line in figure 34.

The effects of salinity of the ground water and soil moisture can be illustrated in a similar manner (see fig. 35). Extrapolating the line to the left leads to an estimated water use of about 360 cm (142 in.) for pure water, which again checks with the Lake Mead data. Extrapolating to the right end would lead one to expect a zero water use at a conductance of about 50 mmho cm^{-1}; this is in the range of conductance of saturation extracts taken from the top soil. At such concentrations no seed, not even saltcedar seed, will germinate. Existing vegetation would stop growing too, as implied in "Vegetation Growth and Development."

The effects of stand density on water use in this study cannot be separated completely from the effects of salinity, but the interaction could be mathematically analyzed, as was done in table 9 with results shown in figure 16.

The section "1966: Density of Stand" refers to the practice of using a volume-density correction factor in estimating maximum water use by phreatophytes. For instance, if the volume density at time of measurement was 50 percent, it was assumed that the water use under 100 percent conditions would be twice as much. Under the circumstances of the experiments described in the previous sections, this is not necessarily so. Tanks deprived of 50 percent of their transpiring surfaces used only 10 to 15 percent less water than a control tank. Obviously, one has to consider these possibilities when estimating water use under natural conditions. On one hand, the investigator knows the amount of water lost from a 100 percent volume density stand, and he divides this amount in half to estimate water use in an area with only 50 percent volume density. His estimates of actual water losses will then be too low. On the other hand, if a certain water use by a stand of 50 percent volume density is measured, a prediction as to what might happen when this stand develops to 100 percent volume density will lead to conclusions which may be grossly overestimated.

Although a volume density correction factor is no longer used in current phreatophyte research (for example, McDonald and Hughes, 1968; Robinson, 1970), a search is still needed for a satisfactory way of expressing water use in relation to stand density on a quantitative basis. It would be pleasant to be able to estimate water use by simply measuring the vegetation (and maybe a few other factors, such as climatological and meteorological, which will be discussed in another report in this series).

The evapotranspirometers deserve some further discussion. Gatewood and others (1950) quote a list of sources of error in performing experiments with plants growing in tanks. Most of these deal with improper conditions of plant and soil compared with the natural environment. The number of tanks, their size, and the duration of the project eliminated most of these sources of error, but others occurred that were not mentioned.

Of these sources of error, the salinity build-up was probably the most serious. High salinity, however, does occur under natural conditions, and, although the situation in the tanks may have been exaggerated compared to what happens under natural conditions, this source of error actually led to a better understanding of soil-, plant-, water-relationships. Also the water-level fluctuations due to variations in atmospheric pressure could and would have affected the water use in the tanks if the fluctuations had occurred in the water level control pipes. Another possible source of error was the choice of the location of the experimental site in the flood plain of the Waterman Wash. Flooding was part of the natural environment of the vegetation, and when levees were built the saltcedar that was not sprinkle-irrigated began to die during periods of prolonged drought. Flooding as a source of error was eliminated by interpolating observed water use from periods in which tank sites were not adversely affected by floods.

METHODS OF EVALUATING WATER USE

Properly built evapotranspirometers should have provisions for draining the soil column, but this makes them expensive—even more so when they have to be large enough for the study of tall vegetation. Whether the apparatus used is of the plastic lining type or of more sophisticated construction, studies of water use by the evapotranspirometer method is time consuming, especially for such vegetation as saltcedar, mesquite, and other trees.

If only a water budget method is used, the results can actually be applied only to areas quite similar in ecology. Studies to date on the effects of environment (radiation, temperature, winds, and so forth) on rate and quantity of water use have been encouraging and may eventually lead to a better method of evaluating water use by phreatophytes. Portable equipment could be set up in places where a knowledge of water use is required. Observations made during comparatively short periods of a few weeks or months would likely yield results which could be reliably extrapolated to yearly quantities. As a control, the water losses from the soil should be measured and the fluctuations of the ground-water levels should be observed. It is along these lines that further research in water use by phreatophytes (and other plant covers) would be desirable and possible.

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APPENDIX: ANALYSIS OF VARIANCE WITH MULTIPLE CLASSIFICATION

If an investigator subjects units of his experiments to a variety of treatments it is possible by statistical analysis (provided the experiment is properly designed) to separate the effects of each treatment from random, or so-called error, effects. If the error effects due to unexpected influences are large, it becomes impossible to draw reliable conclusions about the significance of intentional treatments.

For example, in this paper units are tanks or saltcedar twigs, treatments are depth to water, salinity of soil moisture, and so on. The random or error effects result from possible differences in exposure to wind or sunlight, from differences in the functioning of the plumbing apparatus, from mistakes in chemical analysis or measurements, and from other differences between plants or tanks.[1]

Since there were only six large tanks the number of prescribed treatments was limited to two; otherwise we would have lost too many degrees of freedom and an analysis of variance would have been impossible. Our mathematical model thus becomes a relatively simple one. We might say that the magnitude of a particular observation is comprised of the following components: (1) the value of a mean that all observations in a particular experiment have in common, (2) one or more components arising from particular treatments, and (3) a component resulting from errors and random effects.

[1]A lucid discussion is given by Fisher (1944). We must assume here that the reader is familiar with such terms as: mean, standard deviation, variance, and degree of freedom.

For instance if we have two treatments, differences in depth to ground water and flushing versus non flushing, we may write:

$$T_{ij}=m+d_i+f_j+e_{ij}, \quad (1)$$

where m is the overall effect or mean, d_i is the effect of depth to water on water use, f_j is the effect of flushing or nonflushing, e_{ij} is the error, and T_{ij} is the water use value in a tank treated with a depth to water value, i, and a flushing treatment, j. Applying the method of least-squares we can arrive at an equation of the type:

$$\text{Water use per year}=C_1+C_2d+C_3f \quad (2)$$

in which the C's are constants. Thus, one obtains a set of actual and theoretical results to which a test of linearity can be applied. Then, a t-test to the partial regression coefficients would show that, for instance in table 5, the depth to water was the overriding influence on the quantities of water used and that the effect of years was only very small. This method, however, is slow and the error sum of squares is much more quickly computed by a technique known as the analysis of variance. In the method of least-squares each observation is represented as the sum of two or more components according to the mathematical model; in the analysis of variance the sum of such squares of the observation is partitioned according to components. This is illustrated in the analyses of variance given in tables 5, 7, and 12. The F-test is then applied, and the value obtained is compared with those in an F table. It is customary to mark F's that indicate significant differences at the 1-percent level with a double asterisk, those at the 5 percent level with a single variation and interaction that has been computed. Thus one has an estimate of those treatments which had significant effects on water use and those which did not.

The final step is to compute the least significant difference, which is done by making use of the so-called t-table. The distribution of t is used to test the significance of a deviation when its standard error is estimated from the data. Thus, t is the deviation divided by its estimated standard error. Then the least significant difference is computed by multiplying the appropriate t-value by the root of the mean square for error. This is the yardstick by which we can judge the significance of the differences due to treatment. See tables 5, 7, 9, 10 and 12.

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