Water Use by Saltcedar and by Replacement Vegetation in the Pecos River Floodplain Between Acme and Artesia, New Mexico

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 491-G

Prepared in cooperation with the U.S. Bureau of Reclamation

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By EDWIN P. WEEKS, HAROLD L. WEAVER, GAYLON S. CAMPBELL, *and* BERT D. TANNER

STUDIES OF EVAPOTRANSPIRATION

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CONVERSION FACTORS

For readers who prefer to use inch-pound or other non-SI units, conversion factors for terms used in this report are listed below:

Multiply	*By*	*To obtain*
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
	Energy	
Joule (J)	9.4787×10^{-4}	British thermal unit (mean) (Btu)
	0.2388	calories (cal)
	Energy/Area	
Megajoule/square meter (MJm^{-2})	88.05	Btu/ft^2
	Energy/Area · Time	
watt/square meter (Wm^{-2})	5.2895×10^{-3}	Btu/ft^2 · minute
	1.434×10^{-3}	cal/centimeter^2 · minute (cal cm^{-2} min^{-1})
	Energy/Mass	
Joule/gram (Jg^{-1})	0.2390	cal/gram (cal g^{-1})
	0.4303	Btu/lbm
	Heat conductance	
watt/meter · Kelvin ($Wm^{-1}K^{-1}$)	9.629×10^{-3}	Btu/ft min degree Fahrenheit
	2.387×10^{-3}	cal/cm · second · Kelvin
	Length	
nanometer (nm)	0.3937×10^{-4}	mil
micrometer (μm)	$.397\times10^{-1}$	mil
millimeter (mm)	0.03937	inch (in)
centimeter (cm)	0.3937	in
meter (m)	3.281	foot (ft)
kilometer (km)	0.621	mile (mi)
	Mass	
gram (g)	2.205×10^{-3}	pounds mass (lbm)
	Mass flux	
gram/meter^2	17.71	pounds mass/ft^2/day
	Mass/Volume	
kilogram/meter^3 (kgm^{-3})	6.24×10^{-2}	pound mass/foot^3
	0.001	gram/cm^3 (gcm^{-3})
gram/meter^3 (gm^{-3})	6.24×10^{-5}	pound mass/foot^3
	10^{-6}	gcm^{-3}
	Power	
watt (W)	3.412	Btu/hour
	1.340×10^{-3}	horsepower
	0.2388	calories/second (cal s^{-1})
	Pressure	
kilopascal (kPa)	0.2953	inches of mercury (in Hg)
	0.1450	pound/inch^2 (psi)
	10	millibar (mb)
	Temperature	
degrees Celsius (°C)	1.8°C+32	degrees Fahrenheit (°F)
Kelvin (K)	(K−273.15)1.8+32°F	
	Velocity or Rate	
meter/second (ms^{-1})	2.237	mile/hour (mph)
	Volume	
cubic meter (m^3)	8.107×10^{-4}	acre-foot (acre-ft)
	Volume/Area	
cubic meter per hectare (m^3/ha)	3.281×10^{-4}	acre-ft/acre

WATER USE BY SALTCEDAR AND BY REPLACEMENT VEGETATION IN THE PECOS RIVER FLOODPLAIN BETWEEN ACME AND ARTESIA, NEW MEXICO

By EDWIN P. WEEKS, HAROLD L. WEAVER, GAYLON S. CAMPBELL,[1] and BERT D. TANNER[2]

ABSTRACT

Water-use estimates for saltcedar and for replacement plant communities following root plowing in the Pecos River floodplain between Acme and Artesia, New Mexico, were made by the eddy-correlation technique and a combined eddy-correlation energy-budget technique during 1980–82. Twenty-seven measurements of daily water use were obtained for various periods during the growing season—17 measurements from four saltcedar thickets and 10 from three stands of replacement vegetation. Large uncertainties exist in these estimates because of problems in extrapolating the data seasonally and areally, and because of discrepancies between the two methods. Nonetheless, the measurements indicate that annual water use by saltcedar probably is about 0.3 meters greater than that by the replacement vegetation. Such reductions in water use should have resulted in increased base flow of the Pecos River of $1.2–2.5\times10^{7}$ cubic meters per year (10,000 to 20,000 acre-feet per year). The fact that such gains have not been identified from streamgage records may arise from masking of short-term gains by variations in climate and in ground-water pumpage and from a continuing decline in the ground-water contribution to base flow from the shallow aquifer.

INTRODUCTION

Saltcedar was cleared, initially (1967) by bulldozing and mowing and later (1974) by root plowing, from 8,700 hectares (21,500 acres) of the floodplain of the Pecos River in the reach between Acme and Artesia, N. Mex., in anticipation that substantial quantities of water would be salvaged from evapotranspiration. An unpublished analysis of base flow in the reach (G.E. Welder, U.S. Geological Survey (USGS), written commun., 1978) indicated that no readily identifiable gains in base flow occurred following either mowing or root plowing, suggesting that the actual salvage of water by evapotranspiration was considerably less than anticipated.

PURPOSE AND SCOPE

The current study was begun in 1979 to determine evapotranspiration from representative plots of saltcedar and of replacement vegetation, in order to determine whether initial estimates of consumptive use by saltcedar were erroneously high and (or) whether estimates of use by replacement vegetation were erroneously low to the extent that actual salvage from evapotranspiration was quite small. This report contains a preliminary evaluation of the evapotranspiration measurements and of the suggested magnitude of ground-water salvage from evapotranspiration.

Measurements of evapotranspiration were made periodically during the growing season in 1980–82 using an eddy-correlation approach. During 1980 and 1981, the measurements were made over three plots (fig. 1)—one with old-growth saltcedar, one with saltcedar regrowth following mowing, and one with replacement vegetation. In 1982, two other saltcedar sites and two other replacement vegetation sites were added to gain areal coverage.

Weather data, including solar radiation, air temperature, relative humidity, precipitation, windspeed, and soil temperatures were collected on a continuous basis during the growing season of each year from 1980 to 1982 at the New Mexico State Wildlife Refuge at Artesia. Other data, including stomatal resistances, plant-water potentials, soil-moisture contents, root densities, moisture-characteristic data, and other plant- and soil-related parameters, also were collected, in order to model the evapotranspiration process.

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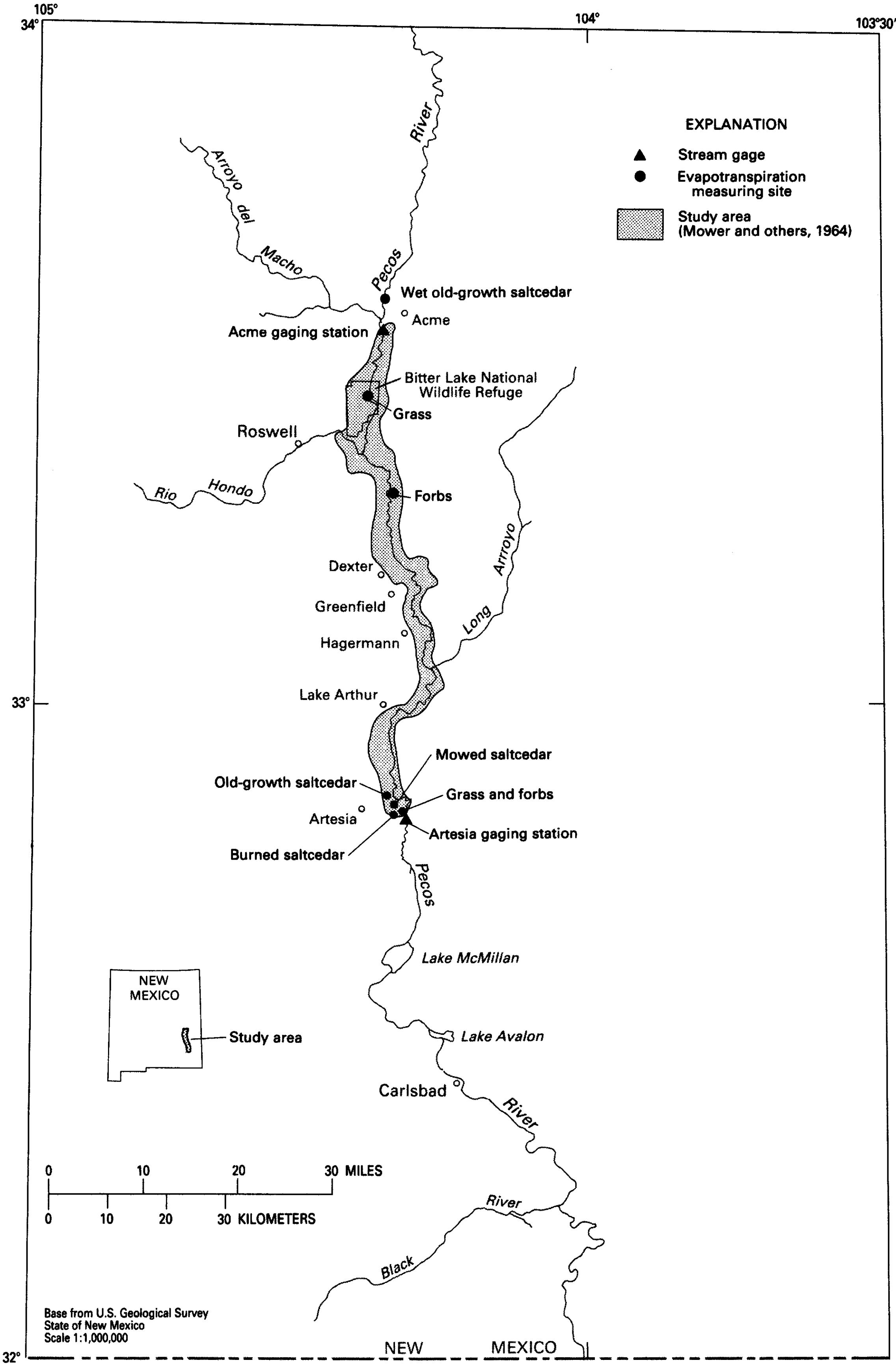

FIGURE 1.—Location of stream gages and evapotranspiration measurement sites used in this study.

ACKNOWLEDGMENTS

This study was partially financed by the U.S. Bureau of Reclamation (USBR). In addition, USBR personnel, including Leon Marcell, Kirby Lykins, and Joseph Odell, obtained landowner permission for the studies, made backhoe excavations for soil sampling, and provided materials and equipment. Personnel of the USGS New Mexico District office, including G.E. Welder, Paul Davis, and Doug McAda, provided logistical support and assisted at various times. Tinco van Hylckama (USGS) provided assistance by identifying the various vegetation species at the replacement vegetation site. Other USGS personnel who assisted in data collection at various times include Rita Carmen, Dwight Hoxie, Eric Lappala, David Redinger, and David Stannard. Keith Bristow of Washington State University also provided advice and assistance in making plant-water status and stomatal-resistance measurements.

HISTORICAL BACKGROUND

The Roswell basin, which basically includes the study reach of the Pecos River, has been extensively developed for irrigation. The first irrigation development, which started in the 1890's, involved the use of flowing wells that tapped the artesian aquifer that underlies the basin. Development of the shallow alluvial aquifer took place primarily during the period 1935–37. State law ended growth of irrigation development in both aquifers, and in 1967, flow meters were placed on all irrigation wells in the basin by order of the State Engineer's office. Since that time, pumpage from existing wells has been limited to a 1.1×10^4 m^3 per ha (3.5 acre-ft per acre) annual allocation, and no new wells have been permitted. These restrictions have resulted in stabilization of water levels in the artesian aquifer, but water levels in the shallow aquifer were still declining in 1975 (Welder, 1983, fig. 21).

Saltcedar (*Tamarix chinensis*) was first noted in the basin in about 1912 (Eakin and Brown, 1939); it rapidly became the dominant species in the Pecos River floodplain, occupying 11,200 ha (28,000 acres) of the 16,400-ha (41,000-acre) floodplain in 1958 (Mower and others, 1964). Saltcedar mainly replaced two phreatophytic grass species, saltgrass (*Distichlis stricta*) and alkali sacaton (*Sporobolus airoides*). Saltcedar has a substantial reputation as a plant that consumes large quantities of water (Robinson, 1965), and the observed declines in streamflow in the middle basin of the Pecos River (the reach from Alamagordo to Red Bluff Reservoirs) was attributed in part to the saltcedar invasion (Thomas, 1963).

Because of the concern that saltcedar could be a substantial agent in the depletion of the flow of the Pecos River, the New Mexico State Engineer requested in 1956 that the USGS investigate the use of water by "nonbeneficial vegetation" in the 80-km (48-mi) reach of the river from Acme (now a ghost town) to Artesia, N. Mex. This reach was chosen for study because long-term streamflow records were available. In that study (Mower and others, 1964), saltcedar was found to cover about 11,200 ha (28,000 acres) of the floodplain within the study reach, although only 7,200 ha (18,000 acres) supported an areal saltcedar density of more than 10 percent. Also, on the basis of the extrapolation of water-use data for saltcedar developed by Gatewood and others (1950) for the Safford Valley, Mower and others (1964) estimated that the eradication of saltcedar in the reach would result in a reduction in consumptive use in the floodplain of 3.5×10^7 m^3 (28,000 acre-ft) per year.

Blaney (1961) made a separate estimate of water salvage by saltcedar eradication in the reach of the Pecos River from Acme to Artesia. He estimated annual salvage of about 2.5×10^7 m^3 (20,000 acre-ft).

In 1967, the U.S. Bureau of Reclamation began a program to eradicate saltcedar from about 8,700 ha (21,500 acres) in the Acme-Artesia reach. Initially, the trees were felled by bulldozers and burned. Thereafter, an attempt was made to control saltcedar regrowth by mowing. This technique was not successful, because the mown saltcedar regrowth grew back with great vigor. Consequently, a program of root plowing saltcedar from the previously bulldozed and mowed areas was initiated in 1974, followed by a maintenance program. These clearing operations included nearly all the denser thickets of saltcedar except those in a 15-m-wide (50-ft-wide) strip along each bank of the river, which meanders for 132 river kilometers (82 mi) within the 80-km (48-mi) reach. Saltcedar thickets also were retained on the Artesia State Wildlife Refuge and on the Bitter Lakes National Wildlife Refuge. About 600 ha (1,500 acres) of dense to moderately dense saltcedar and about 2,000 ha (5,000 acres) of saltcedar with a density of less than 10 percent remain of the saltcedar plots mapped by Mower.

In 1971, G.E. Welder, of the USGS New Mexico District office, began a study of base flow of the Pecos River in the Acme-Artesia reach to determine whether the expected gains due to saltcedar eradication could be detected. His unpublished study indicated that the base-flow pickup in the reach declined from about 3.9×10^7 m^3 (32,000 acre-ft) in 1957 to about 1.8×10^7 m^3 (15,000 acre-ft) in 1964 (3 years before initial clearing) but then varied between 2.0×10^7 and 3.0×10^7 m^3 (16,000 and 25,000 acre-ft) per year without a particular time trend until the present time (1982). Lack of any apparent gain in base flow that could be attributed to saltcedar eradication, either following the period of mowing in 1967–69 or following root plowing in 1974–

76, raised concern that the amount of water that could be salvaged by saltcedar eradication had been substantially overestimated. This concern prompted the present study.

In order to select a micrometeorological technique to be used in the study, grants were made to Lloyd Gay of the University of Arizona and to Leo Fritschen of the University of Washington to demonstrate such techniques in the summer of 1979. Gay (1980) made measurements necessary to apply the Bowen-ratio method, and Fritschen and others (1980) made measurements necessary to apply the eddy-correlation technique. Both methods are described in the section on "Theory."

PREVIOUS WORK

CONSUMPTIVE USE BY SALTCEDAR

Perhaps the earliest measurements of water use by saltcedar were from tank experiments performed in 1940 at Carlsbad, N. Mex., by Blaney and others (1942). They reported water use of 1.67 m/yr (meters per year) from a tank with a 0.6-m depth to water and of 1.43 m/yr for a tank with a 1.2-m depth to water.

An extensive study of water use by saltcedar was made in the floodplain of the Gila River in the Safford Valley in 1943–44 by Gatewood and others (1950). They measured evapotranspiration by saltcedar in nine tanks, two of which were 3.05 m in diameter and seven of which were 1.8 m in diameter, with a range in depth to water of 1.2 to 2.1 m. However, these tanks were located in a natural clearing (Gatewood and others, 1950, p. 37) and were undoubtedly subject to "oasis effects" (explained in "Discussion of Previous Results"). Water use ranged from about 1.2 m/yr to about 3 m/yr. Gatewood and others also introduced the concept that consumptive use of water by saltcedar is proportional to its volume density. Based on this concept, their consumptive use adjusted for 100-percent volume density ranged from about 2.1 to 3 m/yr, excluding precipitation.

Gatewood and others (1950) also measured water use from 3,765 ha (9,300 acres) of the Gila River floodplain by a water-budget (inflow-outflow) method. These measurements indicated an annual water use of about 0.73 m over that area, about half of which had a cover of saltcedar and the remaining half a cover of seepwillow (*Baccharis*), cottonwood (*Populus fremontis*), mesquite (*Prosopis velutina*), undifferentiated brush, and bare ground (predominantly sandbars in the river channel).

The U.S. Bureau of Reclamation (1973) measured evapotranspiration by saltcedar at a site in the floodplain of the Rio Grande near Bernardo, N. Mex. Measurements were made in six large tanks 93 m^2 in area by 3.7 m deep that were planted with saltcedar in 1961 and 1962. The tanks were operated as constant-water-level evapotranspirometers from 1962 to 1968. In 1968, saltcedar in two tanks was replaced by Russian olive (*Elaeagnus augustifolia*). Salt was added at a rate of about 5,000 mg/L to the feed water for two other tanks. The water level in the remaining two tanks was dropped from about 0.90 m to about 2.75 m below land surface by cutting off the feed water or by pumping water from the tank. Water use by saltcedar in the various tanks showed substantial variation, ranging from 0.7 m to 1.4 m, including rainfall. Average water use during the period of operation with fresh water and constant water levels was 1.0 m (including precipitation), with water levels maintained 0.9 to 1.5 m below land surface. Lowering the water table from 0.9 to 2.7 m initially reduced annual consumptive use by 0.30–0.45 m, but usage nearly recovered in about 2 yr.

Hughes (1972) analyzed the U.S. Bureau of Reclamation (1973) data to show that evapotranspiration by saltcedar was not linearly related to volume density, but instead was almost as large for 50-percent volume density as for 100-percent volume density. He also demonstrated that water use by saltcedar was less than potential evapotranspiration as computed by the Penman (1956) equation, unless corrected downward by use of an empirical stomatal-resistance term.

Van Hylckama (1974) measured water use by saltcedar during the period 1962–67 in the floodplain of the Gila River near Buckeye, Ariz., using six large (9 m×9 m×4.25 m deep) tanks located within a saltcedar thicket and two smaller (6 m×6 m×2 m deep) tanks within a large bare area. In 1965 (the year during which vegetative cover and lysimeter operations were most representative of the natural environment), water use by saltcedar in three large tanks using fresh water ranged from 2.6 m/yr, with a depth to water of 2.7 m, to 3.4 m/yr, with a depth to water of 1.5 m. Water use in one small "oasis" tank previously flushed with fresh water was 3.6 m/yr, with the water table maintained at a depth of 1.2 m. Van Hylckama also performed experiments that indicated that a decrease in volume density of saltcedar from 100 percent to 50 percent reduced consumptive use by only about 10 percent.

Gay and Fritschen (1979) determined evapotranspiration from a saltcedar thicket at the Bernardo, N. Mex. lysimeter site during a 5-day (d) period in June 1977 using an energy-balance (Bowen-ratio) technique. They measured rates of evapotranspiration of 7.4 and 9.0 mm/d (millimeters per day) at two locations about 75 m apart, which compared favorably with measurements in four lysimeters that varied from 6.4 to 9.2 mm/d during the same period.

Fritschen and others (1980) measured evapotranspiration from two thickets of saltcedar in the Lake McMillan delta area of the Pecos River near Artesia, N. Mex., by the eddy-correlation method. One thicket constituted regrowth from a fairly recent burn, and the other constituted old-growth saltcedar. Water use during an 8.5-h (hour) period in July was 2.3 mm for the regrowth and 1.9 mm for the old growth. The day was cloudy, and hence the results probably are not representative of water use by saltcedar. Gay (1980) measured water use of 1.7 mm during an 8-h period on the same day by the same regrowth plot measured by Fritschen and others (1980), using a Bowen-ratio technique.

Van Hylckama (1980) made micrometeorological measurements at the Buckeye site in Arizona. The measurements were made during 3-d periods about one month apart from May to September in 1966 and in March and May 1967. The measurements included dry-bulb and wet-bulb temperature measurements and windspeed at five levels, net radiation, and soil-heat flux. These measurements should be adequate to estimate evapotranspiration by the energy-budget (Bowen-ratio) method. However, Bowen ratios computed using various pairs of wet- and dry-bulb temperature sensors indicated significant scatter in the computed Bowen ratio. These variations, and the fact that bias among the various sensors was not eliminated, as is generally recommended for Bowen-ratio studies (Suomi and Tanner, 1958, for example), caused van Hylckama to reject the energy-budget approach.

Our examination of van Hylckama's data suggests that the results are better than he allowed, particularly when examined in the context of the results of the study by Culler and others (1982) and of our study. For example, a cursory examination of the hourly average temperature and humidity data at various heights above land surface tabulated by van Hylckama (1980, p. F62–F69) indicate that, for the measurements at 4–5-m and 5–7-m heights, the Bowen ratio is typically near zero during the hours of peak radiation. Based on the net-radiation and soil-heat-flux measurements made by van Hylckama (1980, p. F70–F73), evapotranspiration would have been about 8 mm/d, compared with values of as much as 20 mm/d measured from van Hylckama's tanks. The Bowen-ratio estimates are in relatively good agreement with ours, and with those of Culler and others (1982) described below, whereas the evapotranspiration-tank data are not.

Leppanen (1981) applied the Bowen-ratio method to the measurement of evapotranspiration from rapidly growing young saltcedar near the upstream end of San Carlos Reservoir on the Gila River in Arizona. His measurements covered a 48-d period extending from August 17 to October 3, 1971. Evapotranspiration averaged 5.8 mm/d during this period, and 7.0 mm/d during the last 15 days of August. Depth to water at the site varied greatly because of reservoir-level fluctuations, but soil water content was high throughout the period of measurement.

Culler and others (1982) measured evapotranspiration by the water-budget method from a floodplain area of 2,190 ha along the Gila River between the town of Bylas and the backwater of San Carlos Reservoir in Arizona. The dominant riparian vegetation is saltcedar (1,540 ha) and mesquite (600 ha), with about 40 ha mapped as not having phreatophyte cover. Before clearing, consumptive use (excluding precipitation) from this area averaged about 0.83 m annually. Water use from reach 3, which had a cover of about 97 percent saltcedar, was about 1.0 m/yr.

CONSUMPTIVE USE BY REPLACEMENT VEGETATION

Water use by the various plant communities that have replaced saltcedar in the Pecos River floodplain has been less intensively studied than water use by saltcedar. Nonetheless, some studies are available.

The most comparable data were collected by Culler and others (1982). They measured evapotranspiration from vegetation that replaced saltcedar following root plowing in the floodplain of the Gila River. The saltcedar in the floodplains of some reaches was cleared by root plowing in 1967, and other reaches were cleared during 1968–71. Water-use data on replacement vegetation were collected from 1968 to 1971. These measurements indicate that evapotranspiration from the patches of bermuda grass, annual weeds, and bare ground that replaced the saltcedar averaged 0.64 m/yr, including 0.28 m of annual precipitation.

Patches of bare soil remain in some of the cleared areas of the Pecos River floodplain, and a possible water-management scheme is to maintain the soil bare over large areas of the floodplain. Thus, an estimate of bare-soil evaporation would be desirable.

Evaporation from bare soil underlain by a shallow water table has been studied extensively, using theory, laboratory columns, and field evapotranspirometer tanks. Only the evaporation from bare soil measurements derived from evapotranspirometer studies will be reviewed here. Blaney and others (1930) and Blaney (1933) determined evaporation at Santa Ana, Calif., from nine 0.60-m-diameter tanks, three containing repacked Hanford fine sandy loam and six containing "undisturbed" soil of the same composition. Results of their studies, as summarized by Blaney (1933), in

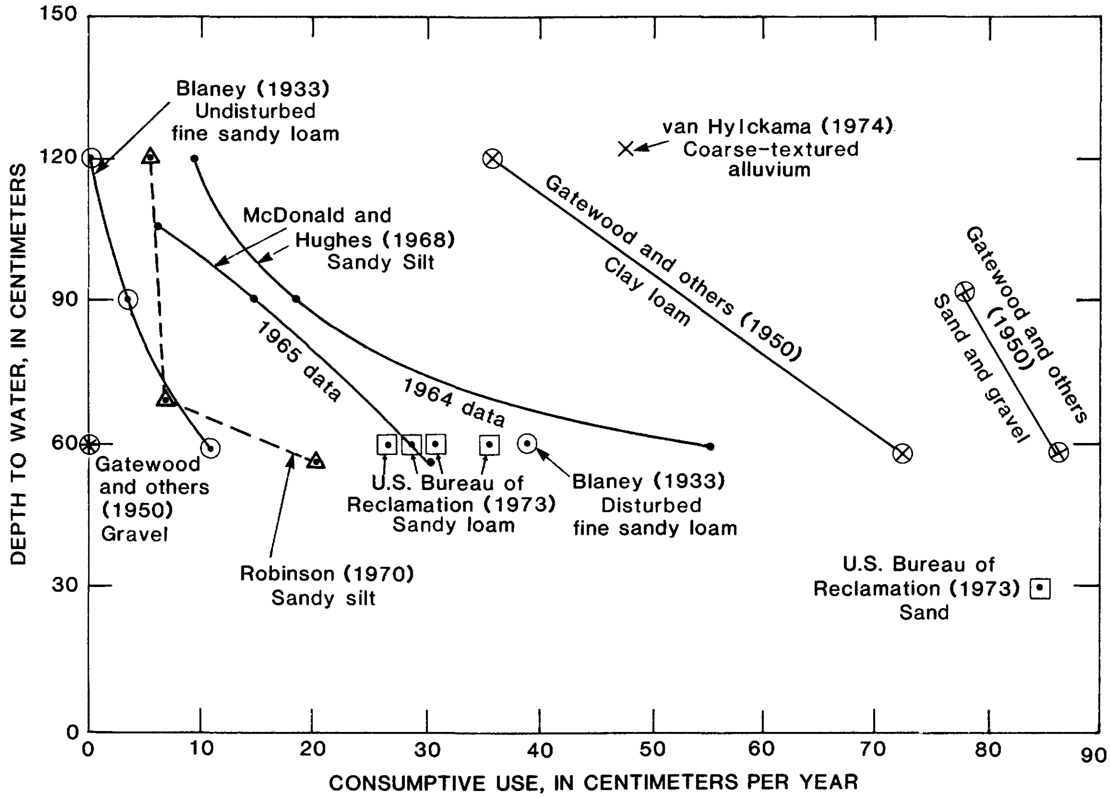

FIGURE 2.—Annual rates of bare-soil evaporation of ground water versus depth to water for various evapotranspirometer experiments.

terms of annual water use versus depth to water, are shown in figure 2. Gatewood and others (1950) conducted experiments on 12 tanks, each 1.2 m in diameter, to determine evaporation from bare soil in the Safford Valley near Glendale, Ariz. Six of the tanks were filled with sand and gravel, two with gravel, and four with clay loam. Results for those tanks for which full-year data are available are shown in figure 2. Large (3×3 to 12×12 m) plastic-lined tanks have been used near Yuma, Ariz. (McDonald and Hughes, 1968), near Buckeye, Ariz. (van Hylckama, 1974), near Winnemucca, Nev. (Robinson, 1970), and near Bernardo, N. Mex. (U.S. Bureau of Reclamation, 1973), to measure evaporation from bare soil underlain by a constant shallow water table. The tanks near Yuma and Winnemucca were filled with sandy silt, while those near Buckeye contained a coarse-textured alluvial soil but with more clay and silt than the Yuma soil (van Hylckama, 1974). Three tanks at Bernardo were filled with sand and silt with clay lenses of various thickness, and one was filled with sand. The results are summarized in figure 2. Veihmeyer and Brooks (1954) measured evaporation from 1935 to 1939 from bare soil near Davis, Calif., in 38 tanks—13 tanks 0.64 m in diameter filled with Yolo fine sandy loam and 25 tanks 0.7 m in diameter filled with Yolo silt loam. They show an average monthly water use in August of about 2.5 cm.

The Pecos River has developed a natural levee, and the depth to water landward of the levee is about 1.5 to 3 m, with an average depth to water of about 2 m. The materials above the water table are typically sandy loam to clay loam in texture. None of the tank experiments involved depth to water greater than 1.2 m, but the data shown in figure 2 suggest that evaporation discharge of ground water should be no more than about 0.1–0.2 m/yr from bare soil in the Pecos River floodplain.

Young and Blaney (1942) cite measurements of water use by various species of weeds grown in tanks having a shallow water table. Of the weeds grown, only Russian thistle (*Salsola kali*) was common to the Pecos River floodplain. The Russian thistle used about 0.60–0.65 m of water during the period May 3 to September 17, 1932, with a depth to water of 0.30–0.45 m.

Blaney and Hanson (1965) quote water use for alkali sacaton, a species prevalent in the Pecos River flood-

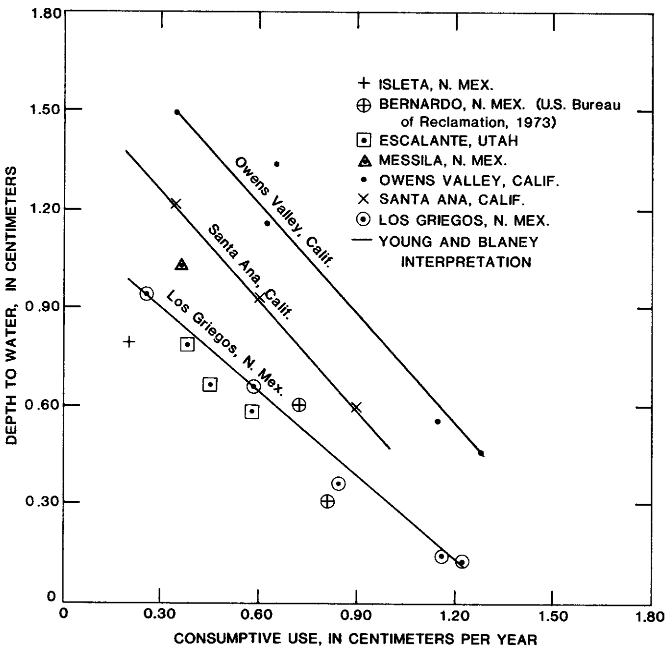

FIGURE 3.—Relationship of evapotranspiration by saltgrass versus depth to water for various evapotranspirometer studies (modified from Young and Blaney, 1942).

plain, that was grown in tanks at Carlsbad, N. Mex. Annual water use by sacaton was 1.2 m with a 0.60-m depth to water, and 1.05 m with a 1.2-m depth to water. Average daily use by sacaton in the tank with the 1.2-m depth to water was 5.6 mm in June and 6.6 mm in August 1940.

Evapotranspiration by saltgrass has also been measured at several locations using tanks. Results of most of these studies have been summarized by Young and Blaney (1942). In addition, the U.S. Bureau of Reclamation (1973) has measured water use by saltgrass at Bernardo, N. Mex. The results (fig. 3) show substantial scatter, and annual consumptive use ranged from about 0.25 m to 1.20 m. However, for water-table depths of a meter or more, the range in water use by saltgrass was 0.3 to 0.8 m, with climate a major factor.

Although the authors observed little saltgrass in the study area, Mower and others (1964) report that saltgrass was the dominant species in about half of the Pecos River floodplain prior to the saltcedar infestation. Hence, saltgrass may again become prevalent in the floodplain as a regrowth species as time progresses.

Fritschen and others (1980) measured water use by kochia (*Kochia scoparia*) at the forbs site described below in July 1979, by an eddy-correlation technique. (The listed common name for *Kochia scoparia* is summer-cypress, but the weed is locally known as "kochia" in the Roswell basin area and kochia will be used as its common name in this report.) Gay (1980) made simultaneous measurements of water use by the same stand at an adjacent site using a Bowen-ratio technique. Both methods indicated water use of about 3 mm/d.

DISCUSSION OF PREVIOUS RESULTS

Most rates of evapotranspiration from saltcedar have been made in the arid Southwest in areas having relatively similar climates. Nonetheless, the measured values vary by a factor of about six, with summertime latent heat flux, defined as the evapotranspiration rate, E, multiplied by the latent heat of vaporization of water, λ, or λE, ranging from about 0.7 times to more than 4 times the energy available from solar and thermal radiation, R_n. Conditions that produce values of $\lambda E/R_n$ greater than unity are commonly called "oasis effects" and indicate a locally greater supply of water compared with closely adjacent areas. The most extreme values of $\lambda E/R_n$ have been obtained from evapotranspirometer tanks, suggesting that these tanks were strongly influenced by oasis effects. The tanks used by Gatewood and others (1950) were located at the edge of a saltcedar thicket, and the potential for an oasis effect at that site is apparent. The six large tanks used by van Hylckama (1974) were located within a saltcedar thicket, however, and the occurrence of very localized oasis conditions is less easily inferred. The temperature profile data collected by van Hylckama (1980) indicate that oasis conditions did not generally prevail for the thicket as a whole, so that local oasis effects must have occurred within the vegetation in the tanks. Possibly the shallow water table in the tanks and the greater vigor of the relatively newly planted saltcedar combined to allow those saltcedar to use water more freely and to thus create oases within the thicket. In fact, the saltcedar outside the tanks appears to have been deprived of a significant source of water by a dike constructed in November 1964 to divert floods in Waterman Wash from the area. Following construction of the dike, saltcedar in the vicinity of the tanks began to die during periods of prolonged drought (van Hylckama, 1974, p. E29), indicating that the saltcedar underwent substantial moisture stress when deprived of soil moisture.

The occurrence of localized oases is also suggested by the work of Gay and Fritschen (1979). One of their Bowen-ratio towers demonstrated the occurrence of a significant oasis effect, while the other, 75 m distant, did not. However, the saltcedar cover in that study area reportedly is relatively homogeneous. Thus the indicated oasis effect is not readily explainable.

Results of the other cited studies, including the tank studies at Bernardo (U.S. Bureau of Reclamation, 1973) as well as our own results, indicate that water use by saltcedar is approximately equal to or less than net radiation, suggesting that oasis conditions generally do not prevail over large saltcedar thickets or within the floodplain environment as a whole. Thus, extrapolation of the tank experiment data on water use to natural floodplain environments may lead to erroneous conclusions concerning water use in the natural environment.

Historically, tank-derived evapotranspiration values have been extrapolated using the volume-density technique developed by Gatewood and others (1950). This method relies on the assumption that evapotranspiration is proportional to the volume density of plant foliage, an assumption that probably is valid when strongly oasitic conditions prevail. However, when such conditions do not prevail, water use may be relatively constant for a variety of situations, from full areal vegetative cover down to some fraction of full cover, as noted, for example, by Hughes (1972, fig. 1) and by van Hylckama (1974, p. E13–E16).

Culler and others (1982) developed an empirical relationship indicating that evapotranspiration from plots with less than 100-percent volume density was proportional to the fractional volume density raised to the 0.75 power. This relationship is more linear than that determined by Hughes (1972) or van Hylckama (1974). However, the average volume densities of their reaches 1, 2, 2a, and 3 were 0.41, 0.54, 0.43, and 0.81, respectively (Culler and others, 1982, table 10). Data from reach 3, the only one showing substantially different cover, were obtained for only two periods in the summer of 1965. During those periods, water use per unit area from this reach was about the same as that from reach 2 but was significantly larger than that from reach 1. It is possible that the differences in water use among reaches were due to saltcedar vigor or other factors rather than to volume density.

The above data suggest that, under conditions of varying cover, net radiation will be the main energy source for evapotranspiration, with local advection of energy from areas between plants increasing evapotranspiration by individual plants in less dense stands. Thus, the volume-density approach may result in an underestimate of evapotranspiration under conditions of less than full cover. However, estimates of floodplain water use based on too-high water-use rates with overcompensating plant-density-effect estimates may result in overall projections that are nearly correct for an entire floodplain area. Nonetheless, grossly erroneous estimates would result from the volume-density technique for individual thickets, and use of these values to estimate total water consumption resulting from increases in saltcedar density in recently colonized areas would also be overemphasized.

THEORY

Several micrometeorological techniques have been developed to determine evapotranspiration from meteorological measurements made in the turbulent boundary layer above a plant canopy or other surface. Of these, the Bowen-ratio technique has been widely applied to measure evapotranspiration from floodplain vegetation in previous studies, and the eddy-correlation technique was applied in this study. The theory of both techniques is briefly described below, following a discussion of boundary-layer limitations that are applicable to both methods.

BOUNDARY-LAYER LIMITATIONS

Application of both the Bowen-ratio and eddy-correlation methods is based on the assumption that horizontal gradients in the vertical fluxes of heat, vapor, and momentum are zero. However, as air moves horizontally from a surface of a given roughness, wetness, and temperature to another surface having significantly different properties, the air-velocity, vapor-density, and air-temperature profiles (and the associated fluxes) must be in equilibrium with the new surface. This adjustment is completed within a boundary layer over the new surface that grows in thickness with distance from the upwind edge of the surface. A rule of thumb, based on review of wind-tunnel data and on various theoretical studies, indicates that the micrometeorological measurements should be made at a height above the canopy of no more than 0.01 times the "fetch," or distance from the upwind edge of the canopy (Tanner, 1967, p. 547).

Local inhomogeneities in the canopy surface also may cause horizontal gradients in the vertical fluxes. Effects of such local inhomogeneities can be minimized by increasing the height of the instruments above the canopy. However, the use of this approach is limited by the above requirement that the instruments be at a height no greater than 0.01 times the fetch.

THE BOWEN-RATIO METHOD

The Bowen-ratio method (Tanner, 1967) relies on the measurement of the energy budget (net radiation and soil-heat flux) and of temperature and vapor density or vapor pressure at two or more heights above an evapotranspiring surface. Heat and vapor are assumed to be transported by an eddy-diffusion process, and the eddy diffusivities are assumed to be equal for heat and vapor. Under these assumptions, the ratio of sensible to latent heat flux is given by the Bowen ratio:

$$\beta = H/\lambda E = \gamma \frac{\Delta T}{\Delta \rho} \ , \qquad (1)$$

where

β=Bowen ratio, dimensionless;
H=sensible heat flux, Wm^{-2};
λ=latent heat of vaporization, Jg^{-1};
E=evapotranspiration rate or vapor flux, $gm^{-2}s^{-1}$;
γ=psychrometer constant, $gm^{-3}{}^{\circ}C^{-1}$;
ΔT=difference in temperature at two vertically displaced measuring points; °C; and
$\Delta\rho$=vapor-density difference measured across the same vertical interval, gm^{-3}.

Evapotranspiration is then computed by the equation

$$E = (R_n - G)/\lambda(1+\beta) \ , \qquad (2)$$

where

R_n=net radiation, Wm^{-2}; and
G=soil-heat flux, Wm^{-2}.

Both R_n and G are readily measured using commercially available instrumentation, as described by Fritschen and Gay (1979). This method also requires the measurement of temperature and of vapor pressure or vapor density at two heights above the canopy or exchange surface. Because of the instrument height-to-fetch requirement and the need to make measurements far enough above the exchange surface to avoid the effects of surface heterogeneities, the temperature and vapor sensors in the Bowen-ratio setup must be quite closely spaced, commonly about 1 m apart. Under these conditions, the temperature and vapor differences are quite small, and slight biases in the temperature and humidity sensors, easily tolerated for most point measurements, can cause a significant error in the measured Bowen ratio. One common approach to avoiding this bias is to switch sensor positions periodically, so that each sensor is in the upper position half the time and in the lower position the other half. Bowen ratios are calculated for intervals including a full sequencing of sensor positions. This method was used by Gay (1980) and by Gay and Fritschen (1979). Switching sensor positions is a practical and proven method for avoiding bias-type errors in sensors if data are collected at only two heights. However, the Bowen-ratio technique can be made more reliable by collecting data at three or more heights. A ploy used in these circumstances to avoid bias in sensor readings is to sequentially bring air from different levels past the same sensor and then to average several readings to avoid the effects of not having simultaneous readings. Lepp nen (1981) used this approach.

THE EDDY-CORRELATION METHOD

The eddy-correlation method for measuring the flux of heat and water vapor from a surface is based on the concept (van Hylckama, 1980, p. F13) that a moving parcel of air carries with it, on its journey up, down, or sideways, the heat and water vapor that it contained at the start. Thus, if heat and water vapor are being carried upward in the atmosphere from a warm, moist surface or vegetation canopy, the updrafts will be warmer and wetter than the downdrafts. Hence, if the vertical wind vector, air temperature, and water-vapor density can be measured at high frequency within the turbulent boundary layer, both sensible and latent heat fluxes can be measured directly (Priestley, 1959).

The vertical wind in turbulent eddies that transport the heat and vapor may be separated into two components, a mean velocity, $\overline{w}$, and a fluctuating instantaneous deviation from the mean velocity, w', such that

$$w = \overline{w} + w' \ ,$$

where w is vertical windspeed, ms^{-1}.

Similarly, temperature, T, and water vapor density, ρ, can be separated into mean and fluctuating components:

$$T = \overline{T} + T' \ ,$$

and

$$\rho = \overline{\rho} + \rho' \ ,$$

where

T=temperature, °C; and
ρ=vapor density, gm^{-3}.

In this study, air temperature was measured with a fine-wire thermocouple as the difference between the junction temperature and that of a reference junction in contact with a large thermal mass. Thus, the temperature equation becomes

$$T = \overline{T} - T_0 + T' \ ,$$

where T_0 is the reference-junction temperature.

Assuming that the heat and vapor fluxes are indeed due mainly to convection by the turbulent eddies, as opposed to thermal conduction or molecular diffusion, and that fluctuations of air density with temperature are small, the heat-flux equation can be written

$$H = Cp\overline{\rho}_a(\overline{T}\,\overline{w} - T_0\overline{w} + \overline{T}'\overline{w} + \overline{w}'\overline{T} - T_0\overline{w}' + \overline{w'T'}) \ . \qquad (3)$$

Products of a mean and a fluctuating quantity become nearly zero when averaged over an appropriate time interval, and the mean vertical wind is assumed equal to zero. Hence, the equation reduces to

$$H = Cp\bar{\rho}_a\overline{w'T'} \ , \qquad (4)$$

where

H = sensible heat flux, Wm^{-2};

$\bar{\rho}_a$ = mean density of moist air, gm^{-3};

Cp = heat capacity of air at constant pressure, $Jg^{-1}{}^{\circ}C^{-1}$;

and the overbar signifies the time average of the quantity.

Webb and others (1980) show that the assumption that $\bar{\rho}_a$ is constant is adequate in computing sensible heat flux.

By a similar process, the vapor flux can be shown to be given by the equation (Webb and others, 1980)

$$E = (1+M)\overline{w'\rho'} \ , \qquad (5)$$

where

E = evapotranspiration, $gm^{-2}s^{-1}$; and

M = ratio of moles of water vapor to moles of dry air in a unit volume of moist air, dimensionless.

However, Webb and others (1980) show that, for vapor-flux measurements, the effects of temperature on air density cannot be ignored and the vapor flux must be corrected by using the equation

$$E = (1+M)[\overline{w'\rho'} + (\bar{\rho}/\bar{T}_k)\ \overline{w'T'}] \ , \qquad (6)$$

where

T_k = temperature, °K.

This correction term can add up to 10 percent of the vapor flux when sensible heat flux is large. The vapor flux can be converted to a latent heat flux by multiplying the evapotranspiration rate by the latent heat of vaporization of water, λ, where λ is in Jg^{-1}.

The eddy-correlation fluxes represent one measure of the energy budget:

$$H + \lambda E = R_n - G - \Delta S - P \qquad (7)$$

where

R_n = net radiation, Wm^{-2};

G = soil-heat flux, Wm^{-2};

ΔS = rate change in heat storage in the vegetation canopy during the time of interest, Wm^{-2}; and

P = energy flux used in photosynthesis, Wm^{-2}.

In general, ΔS and P are only a few percent of the energy budget and are ignored. Hence,

$$H + \lambda E \sim R_n - G \ . \qquad (8)$$

Measurements of R_n and G thus provide a means of checking fluxes measured by eddy correlation.

In practice, vertical wind, temperature, and vapor density are sampled a finite number of times during a given sampling period, and the sensible heat flux is computed as

$$H = \rho_a Cp \left(\sum_{i=1}^{N} w_i T_i / N - \sum_{i=1}^{N} w_i \sum_{i=1}^{N} T_i / N^2 \right) \ , \qquad (9)$$

where N is the total number of samples taken during the sampling period.

Likewise, the latent heat flux, L, is computed as

$$L = \lambda(1+M)\left(\sum_{i=1}^{N} w_i \rho_i / N - \sum_{i=1}^{N} w_i \sum_{i=1}^{N} \rho_i / N^2 + \frac{H}{C_p \bar{T}_k} \frac{\bar{\rho}}{\bar{\rho}_a} \right) . \qquad (10)$$

INSTRUMENTATION

The instrumentation used to measure eddy-correlation fluxes included CSI (Campbell Scientific, Incorporated)[3] CA 27–T sonic anemometers equipped with fine-wire thermocouples, CSI Lyman-alpha hygrometers, Fritschen (1965) net radiometers, homemade soil-heat flux plates (Tanner, 1963), and thermocouples for measuring soil temperature. Mean temperatures and mean vapor densities were measured using a Delta T aspirated wet-bulb dry-bulb psychometer, a model 201 Physchem probe that measures temperature with a thermistor and relative humidity with a polystyrene resistance chip, and (or) a manually read Assman wet-bulb dry-bulb psychrometer. Windspeed and direction were measured using a Met-One anemometer and a Met-One wind-direction indicator. The eddy-correlation data were obtained, processed, and recorded on a CSI CR–5 data logger that contained special hardware for 10-Hz sampling and special software to output sensible and latent heat fluxes. The net radiometers, soil-heat flux plates, and soil-temperature thermocouples were read by integrator modules in the CR–5 data logger, and other instrument responses were obtained using a CSI CR–21 data logger.

[3]The use of trade names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

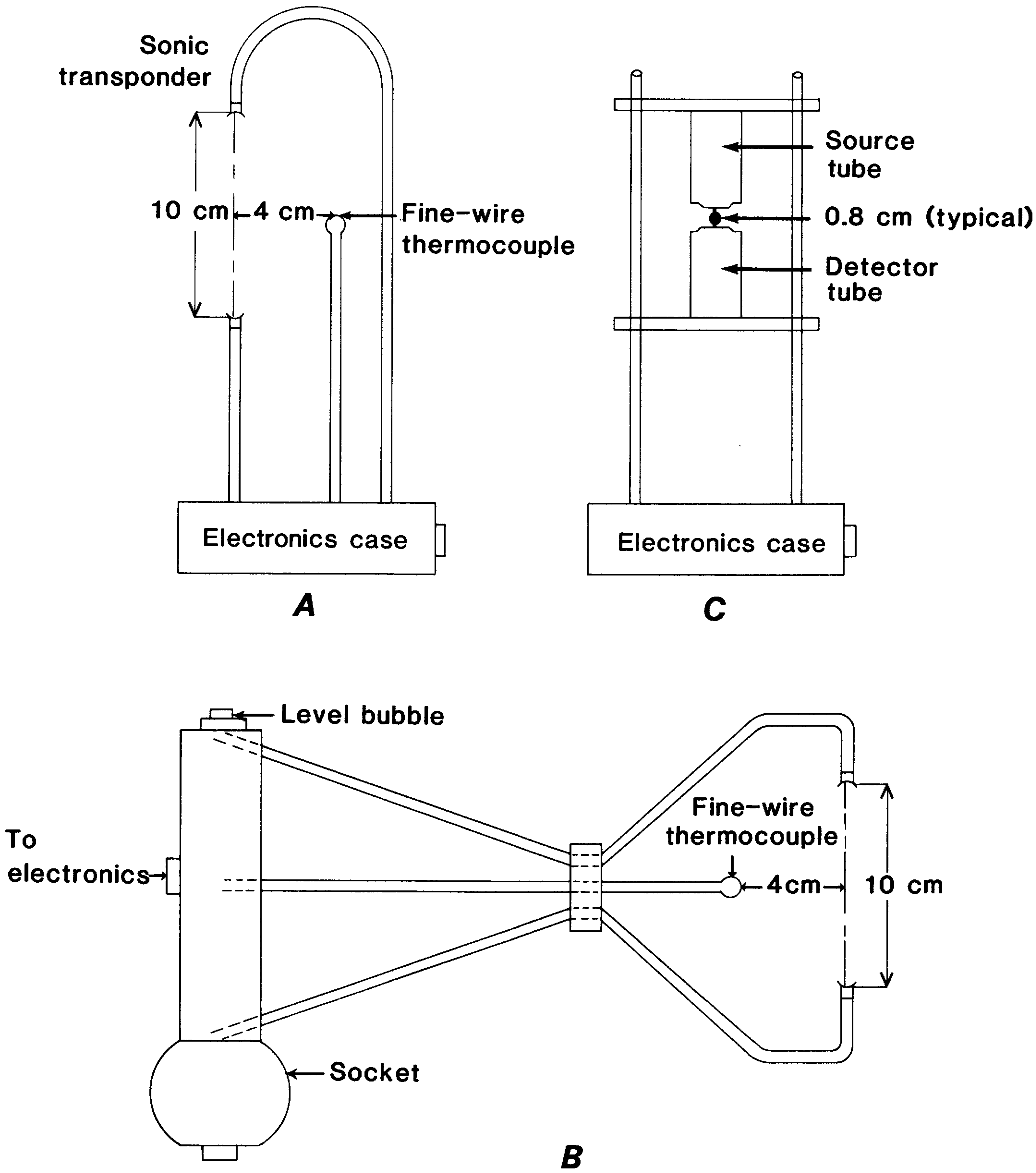

FIGURE 4.—Physical characteristics of (*A*) the original sonic anemometer, (*B*) the revised sonic anemometer, and (*C*) the Lyman-alpha hygrometer.

SONIC ANEMOMETER

The sonic anemometers used in this study determine windspeed by measuring the phase shift between a transponder and a receiver resulting from the upward or downward displacement of the emitted sound waves as they are transported by the vertical wind. This model is an improved version of that described in detail by Campbell and Unsworth (1979). The original model was updated in 1980 to increase its operational temperature range and sensitivity and again in 1982 to improve its cosine response. The transducers in this sonic anemometer (figs. 4*A*, 4*B*) have 10-cm separation. Hence, the velocity of eddies smaller than 10 cm in size will be underestimated owing to space-averaging. The CA–27T sonic anemometer is factory calibrated to generate 1.00 V (volt) in a 1-ms^{-1} wind, and in the anemometer-data logger system resolution is 0.005 ms^{-1}. A wind-tunnel calibration in 1982 indicated that the factory calibration is accurate to about ±7 percent for the units used in this study.

High-frequency temperature fluctuations can also be measured with a sonic anemometer. However, the Campbell-Unsworth design did not function well as a thermometer, and, instead, the CA–27T anemometer has a built-in 12.5-μm chromel-constantan thermocouple mounted 4 cm laterally from the center of the sonic path. This thermocouple has a time constant of about 0.01 s. The reference junction for the thermocouple is located in the metallic mount for the anemometer and has a time constant of about 20 min. The thermocouple signal is amplified to provide an output of 0.25 V/°C.

Output from the sonic anemometer, V_s, and from the fine-wire thermocouple, V_T, is in volts. The fluctuating component of the vertical wind, w', is $w-\overline{w}$, so

$$w_i'=C_s\,(V_{si}-\overline{V}_s)\ , \qquad (11)$$

where

w_i'=the fluctuating component of wind for sample i, ms^{-1};

C_s=sonic anemometer calibration, $ms^{-1}V^{-1}$;

V_{si}=sonic anemometer volt reading for sample i, V; and

$\overline{V}_s$=mean sonic anemometer reading for sampling period, $\sum_{i=1}^{N} V_{si}/N$.

Likewise,

$$T_i'=C_T\,(V_{Ti}-\overline{V}_T)\ , \qquad (12)$$

where

T_i'=fluctuating temperature component, °C;

C_T=thermocouple signal calibration, °C V^{-1};

V_{Ti}=amplified thermocouple output for sample i, V; and

$\overline{V}_T$=mean amplified thermocouple output, V.

For the instruments used here, C_s=1 $ms^{-1}V^{-1}$ and C_T=4°C V^{-1}. Substituting these expressions into the eddy-correlation equation (eq. 4) for sensible heat,

$$H=C_p\overline{\rho}_aC_sC_T\left(\sum_{i=1}^{N}V_{si}V_{Ti}/N-\sum_{i=1}^{N}V_{si}\sum_{i=1}^{N}V_{Ti}/N^2\right)\ . \qquad (13)$$

LYMAN-ALPHA HYGROMETER

High-frequency humidity measurements were obtained with a Lyman-alpha hygrometer (fig. 4*C*), which measures the attenuation by water vapor of ultraviolet radiation having a wavelength of about 121.56 nm (the Lyman-alpha spectral line). Water vapor has a conveniently high attenuation coefficient at this wavelength, while the coefficient for oxygen is about an order of magnitude smaller. Radiation at this wavelength is generated by a hydrogen-glow discharge lamp and is detected by a nitric oxide ion chamber (Buck, 1976). Magnesium fluoride windows set the lower wavelength limit of detected radiation at about 115 nm. The ion chamber itself imposes the upper wavelength limit at about 135 nm. Buck (1976) has poineered the development of Lyman-alpha hygrometers and provides further description of their design and operation.

For monochromatic radiation, the relationship between transmitted radiation and water-vapor density is provided by a form of Beer's law (Campbell, 1977, p. 48):

$$V_H=V_0\ \exp\ (-k\rho x) \qquad (14)$$

where

V_H=hygrometer voltage, which is proportional to the transmitted light intensity;

V_0=voltage proportional to the emitted light intensity;

k=attenuation coefficient, m^2g^{-1};

ρ=water-vapor density, gm^{-3}; and

x=path length, m.

The hydrogen-ion glow tubes in the Lyman-alpha hygrometers emit a low-level radiation continuum in addition to the spectral line at 121.6 nm, which causes departures from the simple Beer's law attenuation. These departures are satisfactorily accounted for by assuming a modified form of Beer's law that includes a vapor-density-dependent attenuation coefficient. The attenuation coefficient was found by laboratory calibration assuming

$$kx=a+b\rho \qquad (15)$$

so that

$$V_H=V_0\ \exp\ [-(a+b\rho)\rho]\ . \qquad (16)$$

The values for a among the different instruments, as determined by calibration in an environmental chamber or by pumping air of known vapor density through the light path, ranged from 0.200 to 0.235 m^3g^{-1}; b ranged from −0.0027 to −0.0043 m^6g^{-2} for different hygrometers but did not shift greatly for a given hygrometer with time.

Noting that $\rho_i'=\rho_i-\overline{\rho}$, substituting ρ_i and $\overline{\rho}$ into equation 16, taking logarithms of both sides, and subtracting, yields

$$\ln \frac{V_{Hi}}{\overline{V}_H} = -(a+b\overline{\rho})(\rho_i - \overline{\rho}) \ , \qquad (17)$$

where

$$\overline{V}_H = \sum_{i=1}^{N} V_{Hi}/N .$$

If fluctuations of V_{Hi} about $\overline{V}_H$ are small, ln $V_{Hi}/\overline{V}_H$ may be approximated by $V_{Hi}/\overline{V}_H$, and equation 17 can be rearranged

$$\rho_i' = \frac{V_{Hi} - \overline{V}_H}{-\overline{V}_H(a+2b\overline{\rho})} \ . \qquad (18)$$

Recalling that $w' = C_s(V_{si} - \overline{V}_s)$,

$$\overline{w_i'\rho_i'} = \frac{C_s}{-\overline{V}_H(a+2b\overline{\rho})} \left(\overline{V_{si}V_{Hi}} - \overline{V}_s\overline{V}_H\right) \ . \qquad (19)$$

Substitution of equation 16 into the eddy-correlation equation for evapotranspiration and multiplying by λ to obtain latent heat flux yields

$$\lambda E = \left[\frac{\lambda(1+M)C_s}{-\overline{V}_H(a+2b\overline{\rho})} \right] \left(\sum^{N} V_{si}V_{Hi}/N - \sum^{N} V_{si} \sum^{N} V_{Hi}/N^2 \right) + \left(\lambda\,\overline{\rho}/\overline{T}_k \right) \overline{w'T'} \ . \qquad (20)$$

The voltage output from the sonic anemometer, the fine-wire thermocouple, and the Lyman-alpha hygrometer are integrated over 0.1-s intervals, and the integrated voltages for alternate 0.1-s intervals are accumulated in the microprocessor to produce means and covariances. The following block averages over 2.5-min (before June 1981) or 5.0-min (during and after June 1981) intervals were accumulated:

$$\sum^{N} V_{si}/N, \ \sum^{N} V_{si}V_{Ti}/N, \ \sum^{N} V_{si}V_{Hi}/N \ ,$$

$$\sum^{N} V_{si}V_{Ti}/N - \sum V_{si} \sum V_{Ti}/N^2 \ ,$$

and

$$\sum V_{si}V_{Hi}/N - \sum V_{si} \sum V_{Hi}/N^2 \ .$$

These were stored by the microprocessor, accumulated, and averaged for a longer (typically 30-min) user-selected interval in the data logger. At the end of the interval, the longer term averages were printed on paper tape and recorded on magnetic cassette tape.

Computation of sensible heat flux from the recorded data-logger counts requires that the counts be multiplied by the density of air, which is a function of air temperature and of vapor density. However, the actual air temperature is not provided by the thermocouple output. Also, latent heat flux computations need to be corrected using the actual mean vapor density. The Lyman-alpha hygrometers show substantial slow diurnal drift about a persistent mean, the drift mainly caused by variations in the intensity of the emitted Lyman-alpha radiation. Consequently, the hygrometer provides a relatively reliable measure of water-vapor-density fluctuations but not of absolute vapor density. Because of these factors, temperature and water-vapor densities were measured independently using the instrumentation described above to provide 30-min averages of air temperature and vapor density simultaneously with the eddy-correlation data on other cassette tapes.

The 30-min average values of the eddy-correlation sensor outputs of temperature and vapor density, and of net radiation and soil heat flux, were read from the cassette tapes into a mainframe or microcomputer, where the appropriate multipliers were computed to provide sensible and latent heat flux in Wm^{-2}. The data were also used to compute the energy-budget closure,

$$(H+\lambda E)/(R_n - G) \ . \qquad (21)$$

The energy-budget closure provides a measure of the accuracy of the flux measurements, as described below.

OTHER INSTRUMENTATION

Net radiation was measured using commercially available miniature net radiometers (Fritschen, 1965) manufactured by Micromet Instruments, Bothell, Wash. These net radiometers have an output of about 5 $\mu VW^{-1}m^2$ (microvolts per watt per square meter) of net radiation. Output from these net radiometers was read out directly in terms of Wm^{-2} through a millivolt-integrating module in the data logger.

Soil-heat flux was measured using soil-heat flux plates and (or) thermocouple pairs. The soil-heat flux plates were constructed and calibrated by one of the authors (Weaver) according to the method of Tanner (1963). They were constructed by winding copper-constantan thermopiles on glass plates covered by electrically insulated aluminum. The thermal conductivity of the plates is about 0.8 $Wm^{-1}K^{-1}$, which is about the same as that for fairly dry soil.

The data loggers, sonic anemometers, and Lyman-alpha hygrometers all operate with very low current drain and were powered in the field using eight D-cell batteries for each data logger and a 12-V lantern battery for each sonic anemometer-Lyman alpha hygrometer pair. The ability to operate the systems with small DC power sources, rather than AC power, greatly enhanced the portability of the systems and minimized power supply maintenance.

FIELD MEASUREMENTS

Three sites were initially chosen for eddy-correlation measurements of evapotranspiration: a thicket of old-growth saltcedar at the New Mexico State Wildlife Refuge at Artesia; a thicket of saltcedar regrowth after mowing located about 1 km to the south; and a site with replacement vegetation, including annual weeds and alkali sacaton grass, located about 5 km south-southeast of the old-growth site. Evapotranspiration from these sites was sampled repeatedly during the growing seasons in 1980 and 1981. In 1982, measurements were made at these and at four other sites within the study area in order to determine the areal representativeness of the three sites that had intensive measurements. The type of vegetative cover for all seven sites is given in table 1, and the locations are shown in figure 1.

Typically, evapotranspiration measurements were made over saltcedar by mounting the eddy-correlation sensors and net radiometer on scaffolding or on a television antenna tower at a height of about 1 m above the average height of the cover. Such a height left the instruments about level with an occasional protruding

TABLE 1.—*Locations and descriptions of the sites at which evapotranspiration measurements were made*

Saltcedar

Site	Location	Water table depth (meters)	Approximate height of vegetation (meters)	Remarks
Old growth	300 m NNW of SE corner of Artesia Wildlife Refuge, NW1/4 of SE1/4 of sec. 35, T. 16 S., R. 26 E.	3.4 ± 0.3	3	--------------------
Mowed regrowth	300 m WSW by W of SE corner of Artesia Wildlife Refuge, SW1/4 of SE1/4 of sec. 35, T. 16 S., R. 26 E.	3.3 ± 0.3	2.5	Mowed in 1977.
Wet old growth	150 m east of Pecos River bank, about 900 m NNE of El Paso Pipeline river crossing; NW1/4 of SE1/4 of sec. 1, T. 8 S., R. 25 E.	0.6–1.0	5	--------------------
Burned regrowth	SE1/4 of NE1/4 of sec. 13, T. 17 S., R. 26 E.	1.5–2.0	2.5	Burned in about 1974.

Replacement vegetation

Site	Location	Dominant species	Water table depth (meters)	Approximate height of vegetation (meters)	Remarks
Grass and forbs	Near the highway crossing of the Pecos River east of Artesia, SE1/4 of SE1/4 of sec. 12, T. 17 S., R. 26 E.	Alkali sacaton grass, kochia, and seepweed	1.7 ± 0.6	0.2	Root plowed in 1974.
Forbs	About 1.5 km west of Lea Lake in the SE1/4 of NW1/4 of sec. 36, T. 11 S., R. 25 E.	Kochia	1.5	0.1	Root plowed in 1974.
Grass	On Bitter Lakes National Wildlife Refuge, SE1/4 of SW1/4 of sec. 34, T. 9 S., R. 25 E.	Alkali sacaton grass	1.6–2.1	0.3	Root plowed in 1974 or 1975.

dead branch or extra-tall plant. However, the fetch requirement that the instruments be no higher above the canopy than .01 times the horizontal distance to the upwind limit of the thicket precluded placing the instruments at greater heights above the vegetation.

Soil-heat flux was measured using a soil-heat flux plate inserted about 1 cm below land surface and by one or two sets of thermocouples placed 2 and 10 cm into the soil. The soil-heat-flux measurements are necessarily point measurements and are subject to substantial variation owing to alternate sunning and shading of the soil at the sampling point and to spatial variability in the thermal properties of the soil.

At the replacement vegetation sites, the instrumentation was mounted on tripods or on guyed 1.9-cm (3/4-in) pipes at heights ranging from 1.6 to 2.0 m above the land surface and at least 1 m above the taller plants in the vicinity of the setup. Soil-heat flux was measured in a manner similar to that for saltcedar.

Measurements were made for approximate 5-d periods in June and October 1980 and in May, June, and September 1981, and for approximate 10-d periods in June and August 1982. For most of the measurements, at least two, and as many as four, sets of instruments were in operation. However, in August 1980 and again in August 1981, rain-associated problems caused both of the available sets of instruments to fail early in the tests, and insufficient data were collected at either time to allow a valid analysis. Schedules of successful runs at each site, along with a key identifying the instruments used for the measurements and the approximate depth to water during the run, are listed in table 2.

DISCUSSION

Typical sets of daily measurements are shown for saltcedar in figure 5 and for replacement vegetation in figure 6. Radiation flux is considered positive toward the canopy or soil surface, and the other fluxes are considered positive away from the soil or canopy surface.

The net-radiation curves are typical of those measured on sunny summer days at this latitude. Time is shown as mountain daylight time, and the locations are slightly east of the 105th meridian, so that peak radiation occurs at about 1300 hours. Maximum net radiation is greater for the saltcedar than for the replacement vegetation because of slightly lower shortwave reflectance and because of substantially lower surface temperatures, which reduce emitted longwave radiation. Net radiation becomes negative at night as shortwave radiation goes to zero and the outgoing longwave radiation exceeds that incoming.

Sensible heat flux typically is negative at night as heat moves from the air to the cool radiating surface, but becomes positive during the day, when the surface becomes warmer than the air. This behavior was followed in all the measurements made over saltcedar and over replacement vegetation. However, a day's run over an alfalfa field located near the burn site showed a negative sensible heat flux throughout the day as heat moved from the air to the evaporatively cooled alfalfa—an example of the oasis effect.

Latent heat flux generally is near zero at night for the vegetative communities studied in this investiga-

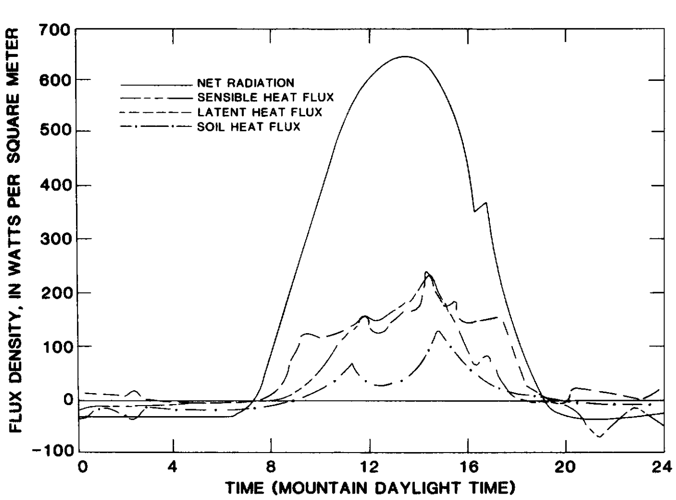

FIGURE 5.—Daily cycle of energy fluxes measured at the wet old-growth site on September 1, 1982.

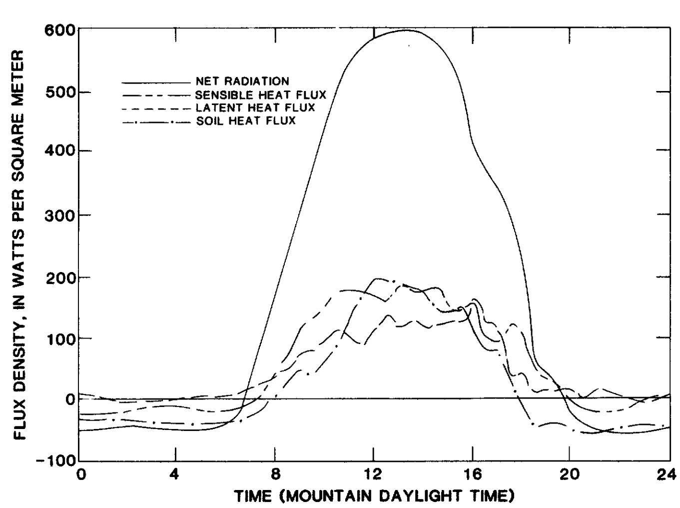

FIGURE 6.—Daily cycle of energy fluxes measured at the grass and forbs site on June 26, 1982.

TABLE 2.—*Schedule of eddy-correlation measurements made during the study*

[Lw, Lyman-alpha hygrometer—Washington State Univ.; Lc, Lyman-alpha hygrometer—property of Campbell Scientific, Inc. (CSI); L(n), Lyman-alpha hygrometer no. n—property of USGS; Hc, Sonic anemometer—property of CSI; H(n), Sonic anemometer no. n—property of USGS; Hw, Sonic anemometer, property of Washington State Univ.; G, Soil heat flux plate; Gt, Soil thermocouple pair; NR, Net radiometer; sc, saltcedar; dashes indicate no data]

Site	Beginning date	Beginning time	Period of record (hours)	Instrument	Number of integrations	Depth to water (meters)
			June 1980			
Grass & forbs	24	1940	34	H1, L2, 2 NR's	2	1.9
				H3, L1, H2, L3, G		
Old-growth sc	25	1000	52	H3, L2, 2 NR's	2	3.7
Saltcedar				H1, L1		
				H2, L3, G		
Mowed sc	26	1830	19	H1, L1	1	3.5
			October 1980			
Grass & forbs	21	1030	27	H1, L2, Gt, NR	4	1.7
				H2, L1, Gt		
Old-growth sc	22	1700	43	H1, L1, Gt, NR	2	3.3
Mowed sc	22	1700	43	H2, L2, Gt	2	3.1
			May 1981			
Grass & forbs	11	1100	26	H2, L2, Gt, NR	1	1.7
Old-growth sc	12	1600	25	H2, L2, Gt, NR	1	—
Mowed sc	13	1700	24	H2, L2, Gt, NR	1	—
			June 1981			
Grass & forbs	22	1600	38	H2, L2, G, NR	2	1.4
				H1, L1, G, NR	2	
Old-growth sc	24	1030	45	H2, L2, Gt, NR	[1]2	3.3
Mowed sc	24	1030	45	H1, L1, Gt, NR	2	3.0
			September 1981			
Old-growth sc	14	0830	57	H1, L1, Gt, NR	[1]3	3.2
Mowed sc	14	0830	80	H2, L2, G, NR	[1,2]3	—
				Hc, Lc	[1,2]3	
Grass & forbs	16	2030	20	H1, L1, G, NR	[1]1	
				Hc, Lc	[1]1	1.2
			June 1982			
Grass & forbs	6-22-82	1430	112	H3, L1, G, NR	7	2.1
				H1, L2		
Old-growth sc	6-24-82	0800	35	H4, L2, G, NR	2	3.3
Burned sc	6-26-82	0700	55	H4, L2, G, NR	3	2.1
Wet old-growth sc	6-28-82	1300	53	H3, L1, G, NR	1	1.0
Grass	6-29-82	0900	15	H4, L2, G, NR	[3]1	2.1
			August 1982			
Grass & forbs	8-24-82	0830	[4]78	H4, Lw, G, NR[5,6]	1	2.1
Old-growth sc	8-25-82	1000	122	H3, L2, G, NR	2	3.3
Burned sc	8-26-82	1230	54	Hc, Lc, NR[7]	2	—
Mowed sc	8-28-82	1000	56	Hw, Lw, G, NR	2	—
Wet old-growth sc	8-29-82		92	H3, L2, G, NR	3	0.6
Grass	8-29-82	1900	88	H4, L4, G[8]	3	2.5
				Hc, L2, G, NR	2	
Forbs	8-31-82	1100	51	Hw, Lw, G, NR	2	1.7

[1]20-hr period; 4-hr shortfall at night.
[2]Two 16-hr periods; 8-hr shortfall at night.
[3]9-hr shortfall, mainly at night.
[4]Record not continuous.
[5]After 0800, 8-26-82, R_n was reconstructed from R_s, T_s, T_a, and ρ_a. (Abbreviations explained in text.)
[6]L3 replaced Lw at 1330, 8-25-82.
[7]No G measured; assumed $G=0.07 R_n$.
[8]Until 1400, 8-31-82, R_n was reconstructed from R_s, T_s, T_a, and ρ_a.

tion, as the plant stomates tend to close and the vapor deficit in the canopy becomes small. Typically, the latent heat flux starts positively upward about sunrise and returns to near zero about sunset.

Soil-heat flux is generally positive (heat moving from the surface into the soil) during the day and is negative at night. Because the measurement is made at a point beneath partial vegetative cover, the measured soil-heat flux fluctuates during the day as the plate is alternately in sun and shade. Soil-heat flux is quite large at the replacement-vegetation sites, which typically have sparse vegetative cover, and maximum daytime soil-heat flux is typically about one-third of maximum net radiation. For the saltcedar sites, on the other hand, maximum soil-heat flux is commonly about 10 percent of maximum net radiation.

ENERGY-BUDGET CLOSURE

Throughout the measurements, the eddy-correlation fluxes have been qualitatively correct. Positive sensible heat flux was consistently indicated whenever upward air temperature gradients were measured or whenever surface temperatures, as measured by an infrared thermometer, exceeded air temperature. Likewise, negative sensible heat fluxes always coincided with downward air-temperature gradients or with surface temperatures cooler than air temperatures. Measured vapor fluxes also always appeared to be qualitatively consistent, showing expected patterns in almost all cases.

Despite the good qualitative behavior of the eddy-correlation fluxes, it is obvious from figures 5 and 6 that the magnitude of the sum of the sensible and latent heat fluxes is substantially less than the net radiation minus soil-heat flux. For example, the daily sums of the energy-flux densities at the wet old-growth saltcedar site for September 1, 1982, included 14.9 MJm^{-2} of net radiation minus 1.1 MJm^{-2} of soil-heat flux, or 13.8 MJm^{-2}. The daily sum of sensible and latent heat fluxes measured by the eddy-correlation system was 8.4 MJm^{-2}, or 0.61 of the energy budget. Similarly, for the grass and forbs site, net radiation minus soil-heat flux was 12.8 MJm^{-2} on June 26, 1982, whereas the sum of sensible and latent heat fluxes was 8.6 MJm^{-2}, or 0.67 of the energy budget. Thus, a substantial portion of the energy budget is missed by the eddy-correlation system, as will be discussed in greater detail below.

On a half-hourly basis, the energy-budget error is largest in the morning and becomes progressively smaller in the afternoon. This probably occurs because of heat storage in the soil above the soil-heat flux plate and in the biomass, and can be minimized by integrating all flux measurements over a 24-h period. The need for such integration is particularly important because of the point-measurement character of the soil-heat flux. Collection of data for short-term analysis would have required the measurement of soil-heat flux by an array of sensors, as recommended by Tanner (1963) and by Fritschen and Gay (1979).

During each run, eddy-correlation data generally were collected at each site for at least 24 h, and sometimes for more than 100 h. Results of these runs were integrated over 24-h periods to minimize diurnal variations in soil and biomass heat storage. If data were collected for other than 24 h, the data commonly were integrated twice, once starting with the beginning time and again starting with a later time that was an even multiple of 24 h previous to the end time. This procedure was followed to ensure full use of the collected data. Fluxes measured by eddy correlation and the energy-budget components measured at the various sites are presented in table 3, along with the fraction of the energy budget measured by the eddy-correlation system. Although this fraction ranges from 0.6 to 1.0, it frequently is in the 0.6 to 0.7 range for all sites except the old-growth saltcedar site, where closure of the energy budget is consistently better.

Failure to close the energy budget has been a matter of persistent concern since the start of the study, and several attempts have been made to identify the cause and correct the problem. Duplicate systems were operated side by side repeatedly throughout the project, and the measured fluxes almost always agree within 10 percent, suggesting that individual sensors and data loggers are consistent. Careful calibration of the Lyman-alpha hygrometers in an environmental chamber in September 1980 and by pumping air containing a known vapor content in January 1983 led to nearly identical calibrations. The good agreement achieved by the careful calibrations suggests that no systematic error due to calibration shifts occurred.

The calibrations indicated that the voltage output of the anemometers deviated by as much as ±7 percent from the factory calibration, suggesting that little bias in the estimates due to the use of the factory calibrations should have occurred.

The shortwave response of the net radiometers was determined periodically by simultaneously shading and exposing both the net radiometer and a precision Eppley pyranometer, and calibrating the net radiometer accordingly. These calibrations showed some deterioration in the response of the net radiometers as the polyethylene shields became scratched, but the original factory sensitivity was restored when new shields

TABLE 3.—*Summary of daily sums of energy-density measurements at the various sites for which eddy-correlation data were collected*

[Energy density in megajoules per square meter. *H*, sensible heat flux; *Lec*, latent energy flux by the eddy-correlation technique; *Leb*, latent energy flux as the residual of $R_n - G - H$; *G*, soil heat flux; R_n, net radiation; *Rec*, recovery ratio, or fraction of energy budget measured by the eddy-correlation system]

Date	*H*	*Lec*	*Leb*	*G*	R_n	*Rec*
Old-growth saltcedar site						
1980						
June 25	10.2	2.7	4.5	1.7	16.4	.88
	11.2	4.1	5.5	1.7	18.4	.92
	10.1	2.5	4.8	1.9	16.8	.85
26	9.7	2.4	4.1	3.0	16.8	.88
	10.0	2.4	4.2	2.7	16.9	.87
Oct. 22	3.7	3.9	4.2	−0.3	7.6	.96
23	4.7	3.9	4.8	−1.0	8.5	.91
1981						
May 12	5.3	7.5	11.8	0.6	17.7	.75
June 24	7.6	1.7	3.9	0.6	12.1	.81
25	13.4	1.9	2.2	0.5	[1]16.1	.98
Sep. 14	3.2	10.8	10.8	0.4	[1]14.4	1.00
15	2.2	9.2	12.3	−0.4	14.1	.79
1982						
June 24	10.9	3.2	7.9	0.8	19.6	.75
25	12.7	2.9	5.2	1.4	[1]19.3	.87
Aug. 28	6.2	3.2	7.6	1.8	15.6	.68
29	7.9	3.1	6.1	2.0	16.0	.79
Mowed saltcedar site						
1980						
June 26	—	4.4	—	2.0	[2]10.0	—
Oct. 22	2.4	3.8	4.6	0.6	7.6	.89
23	3.8	3.0	5.5	−0.8	8.5	.73
1981						
May 13	4.8	5.4	11.7	0.0	16.5	.62
June 24	1.1	8.8	14.6	0.9	16.6	.63
25	2.3	8.4	15.0	0.9	18.2	.62
Sep. 14	3.4	5.8	10.5	1.1	15.0	.66
15	2.3	5.7	10.7	0.8	13.8	.62
16	3.2	7.3	11.0	1.4	[1]15.6	.74
1982						
Aug. 28	3.0	4.8	10.2	1.7	14.9	.59
29	3.0	5.9	10.8	1.7	15.5	.64
Burn site						
1982						
June 26	6.9	5.0	11.4	1.5	19.8	.65
27	6.0	4.1	8.3	1.1	15.4	.71
	7.7	4.7	10.6	1.4	19.7	.68
Aug. 27	[3]4.2	[3]6.6	8.9	1.4	14.5	.82
28	[3]4.6	[3]7.1	6.8	1.3	12.7	1.03
Wet old-growth site						
1982						
June 27	1.0	7.1	12.3	1.9	15.2	.61
28	0.3	12.4	15.6	[4]1.8	17.7	.80
29	0.9	12.0	16.1	[4]1.9	18.9	.76
Aug. 30	2.1	5.8	10.3	0.9	13.3	.64
31	2.8	5.5	11.1	0.5	14.4	.60
Sep. 1	3.2	5.2	10.6	1.1	14.9	.61

TABLE 3.—*Summary of daily sums of energy-density measurements at the various sites for which eddy-correlation data were collected*—Continued

Date	H	Lec	Leb	G	R_n	Rec
Grass and forbs replacement-vegetation site						
1980						
June 24	6.0	2.5	4.7	4.0	14.7	.79
Oct. 21	3.1	2.3	2.2	0.3	5.6	1.02
	3.4	2.5	2.9	0.5	6.8	0.94
1981						
May 11	6.0	3.5	7.2	0.9	14.1	.72
June 22	8.1	1.7	1.6	0.7	10.4	1.01
	6.9	1.0	3.3	0.6	10.8	.77
23	7.9	1.5	4.3	0.7	12.9	.77
	6.4	0.9	1.1	0.9	8.4	.97
Sep. 16	1.5	2.6	5.4	−0.8	[1]6.1	.59
1982						
June 22	4.8	3.2	8.5	1.8	15.1	.60
	4.6	3.3	7.7	1.1	13.4	.64
23	4.7	3.1	7.5	1.3	13.5	.64
24	5.2	4.1	8.1	2.2	15.5	.70
25	5.7	3.6	8.7	1.9	16.3	.65
26	5.1	3.5	7.7	2.6	15.4	.67
Aug. 24	2.9	3.9	7.2	2.1	[5]12.2	.67
27	2.6	5.5	7.3	3.1	[6]13	.75
28	4.4	3.5	5.3	3.3	[6]13	.59
Grass site						
1982						
June 27	6.6	1.4	7.6	0.6	[7]14.8	.56
Aug. 30	4.1	4.5	—	2.2	[8]—	—
31	2.9	3.4	—	3.0	[8]—	—
	3.8	3.5	7.2	2.1	13.1	.66
Sep. 1	3.1	4.2	—	4.4	[8]13.1	.84
	4.2	4.2	7.2	2.7	14.1	.74
Forbs site						
1982						
Aug. 31	3.6	—	6.4	1.2	11.2	—
Sep. 1	4.0	3.0	7.6	1.9	13.5	.60

[1]Less than 24-hr period; shortfall at night.
[2]Less than 24-hr period; *Lec* three times that at old-growth site.
[3]Includes *Lec* of about 3 MJ/m² and *H* of −0.9 MJ/m² that are night time anomalies. Data not included in evapotranspiration or other analyses.
[4]G not measured, but estimated as 0.1 R_n.
[5]Integration from 0800 to 1800.
[6]Estimates based on measurements of solar radiation, albedo, surface temperature, and air temperature resulted in computed net radiation of 19.5 MJ on Aug. 27, and of 16.8 MJ on Aug. 28. These values are implausibly large and were replaced by the rounded values for net radiation measured at the grass and the forbs sites a few days hence.
[7]Integration for 19-hr period; *Lec* for 16-hr period, including entire daylight interval.
[8]Integration for 21-hr period; R_n not available or indirectly estimated.

were installed. Field calibrations were made frequently enough so that no systematic problem due to calibration drift should have arisen.

The total response of the net radiometers was also checked in 1982 by independently measuring the components making up net radiation, as given by the equation

$$R_n = R_{sd} - R_{su} + L_d - L_u \ , \qquad (22)$$

where

R_{sd} = shortwave incoming radiation;
R_{su} = shortwave outgoing radiation;
L_d = longwave incoming radiation; and
L_u = longwave outgoing radiation.

R_{sd} was measured using a Kipp pyranometer pointed upward. The same pyranometer was periodically inverted to obtain the shortwave reflectance of the canopy. Longwave outgoing radiation was computed from the surface temperature of the canopy measured with the infrared thermometer using the equation

$$L_u = \epsilon\sigma\, T_s^4 \ , \qquad (23)$$

where

ϵ=longwave emissivity of the surface, dimensionless;

σ=Stefan-Boltzman constant, 5.67×10^{-8} $Wm^{-2}K^{-4}$; and

T_s=surface temperature, K.

ϵ was assumed to be 0.98 for the surface in each case, as almost all vegetative and bare-soil surfaces have an emissivity ranging from 0.95 to 1.00. One estimate of L_d was obtained using air temperature in the equation (Montieth, 1973, p. 34)

$$L_d=\epsilon_a \sigma T^4 , \tag{24}$$

where ϵ_a=longwave emissivity of the atmosphere, computed by the empirical equation

$$\epsilon_a=1.2-171/\sigma T_a{}^4 \tag{25}$$

where T_a=air temperature, K.

A second estimate of ϵ_a was obtained using the vapor density of air at a height of approximately 1 m above land surface in the equation (Brutsaert, 1975)

$$\epsilon=0.58\ \rho^{1/7} , \tag{26}$$

where ρ=water vapor density, in gm^{-3}.

These checks consistently indicated a net radiation that is about 10 percent less than that measured by the Fritschen (1965) net radiometer. These estimates suggest that the longwave calibration for the Fritschen net radiometer may be in error, and that net radiation is slightly overestimated on an algebraic basis. However, the error would appear to be substantially smaller than the energy-budget-closure error.

Another potential source of error involves the frequency cutoff for high-frequency eddies that arises because of limits on the rate of sampling imposed by the response time of the sensors or by the processing speed of the data logger. The response times for the fine-wire thermocouple and the infrared hygrometer are on the order of 0.01 s. Response time of the anemometer is difficult to determine, because it can result from averaging the velocity of a small eddy over the 10-cm sonic path length, as well as the speed of response of the electronics. Nonetheless, it almost certainly is substantially less than 0.1 s. The data logger samples by simultaneously integrating each signal for 0.1 s. This integration smoothes and attenuates high-frequency signals, so that 98 percent of a sinusoidal signal with a period of 1 s, 76 percent of a sinusoidal signal with a period of 0.25 s, and none of a sinusoidal signal with a period of 0.1 s is measured. Moreover, the covariances of water-vapor density versus vertical wind and air temperature versus vertical wind are attenuated by the product of the attenuations of the two signals. Hence, sampling by integration results in an effective sampling frequency cutoff of about 3–4 Hz. Tests were conducted to determine whether a significant portion of the fluxes were not being sampled because of this high-frequency cutoff. In one test, the sensors were instantaneously sampled at about 100 Hz using a microcomputer as a data logger. In other tests, data were recorded at heights varying by a factor of 2 to make use of the tendency of the eddy frequency to decrease with height above land surface according to the relationship

$$f \propto \frac{\overline{u}}{z} ,$$

where

f=frequency of eddy, s^{-1};

$\overline{u}$=mean horizontal windspeed, ms^{-1}; and

z=height above land surface or zero-displacement plane, m.

In no case was energy-budget closure improved.

Other tests were made to determine whether some of the flux was not being measured because of the low-frequency cutoff imposed by averaging the fluxes for time blocks of 2.5 or 5.0 min. However, the change from 2.5- to 5.0-min averages showed no effect on budget closure. Another test in 1979 included side-by-side comparison of monitoring systems with 2.5-min and variable 5- to 30-min block averages. In general, the two systems behaved identically. Occasionally, however, the system for which 15-min or 30-min averages were obtained showed a digression in the measured fluxes to give combined flux values that substantially exceeded the energy budget. These excursions were assumed to represent correlations in wind, temperature, and vapor density that do not represent eddy flux. Finally, the fact that systems operating simultaneously at different heights gave flux values that agreed as closely as side-by-side systems suggests that the measured fluxes were not being attenuated by the low-frequency cutoff either.

Another hypothesis concerned possible interference with the vertical wind component by the underlying base of the original sonic anemometer. It was felt that the base could attenuate updrafts but have a smaller effect on downdrafts. One experiment performed in a strong wind during the winter of 1981 at the Denver Federal Center, Colo. suggested that inverted and upright sonic anemometers gave somewhat different sensible heat fluxes. Consequently, the sonic anemometer was redesigned (fig. 4*B*) to eliminate interference by the base. No difference in budget closure was detected during the subsequent 1982 measurements, which were made under much calmer conditions.

Another consideration was the relative spacing of the fine-wire thermocouple and of the position of the Lyman-alpha hygrometer in relation to the sonic path of the anemometer. Both temperatures and vapor density were measured at points spatially removed from the point at which wind was measured. This separation results in some spatial averaging of the correlated wind-temperature and wind-vapor measurements, which in turn would result in at least minor attenuation of the measured fluxes. The fine-wire thermocouple is physically part of the anemometer and is located 4 cm from the sonic path on a perpendicular through the midpoint between the sonic transducers. The Lyman-alpha hygrometer is mounted separately, and it usually was positioned so that the vapor-density measurements were made about 15 cm from the sonic path. Thus, the vertical wind-vapor density correlation should be at least somewhat more attenuated by space-averaging than the vertical wind-temperature correlation. However, an experiment was conducted at the Nevada Test Site in 1983 in which one Lyman-alpha hygrometer was positioned to make vapor-density measurements about 5 cm from the sonic path, while another was positioned to make measurements 15 cm from the same anemometer. The flux measurements determined from measurements from the two hygrometers were almost identical.

The inherent patchiness of the wild land vegetation was also considered a possible cause of the lack of energy-budget closure. Theoretically, this patchiness could cause horizontal gradients in the vertical flux of heat and vapor, at variance with the assumptions made in making the measurements. Deviations in the measured flux due to such surface heterogeniety should decrease as instrument height above the surface increases. However, as mentioned above, instruments operated at different heights produced nearly identical results. Also, experiments were performed over a bare field at a lysimeter installation at Davis, Calif.; in alfalfa fields near Artesia, N. Mex., Logan, Utah, and Kimberley, Idaho; a field with a dense wheat-stubble cover at Kimberley; and over parking lots at Washington State University in Pullman and at the Denver Federal Center, Colo. In all of these cases, the surface for exchange of heat and vapor areally was quite uniform, but the magnitude of departures in the energy-budget closures were similar to those obtained in the Pecos River floodplain.

ESTIMATES OF WATER USE

Although the lack of energy-budget closure casts doubt on the validity of the eddy-correlation measurement of vapor flux, the data can be used to establish lower and upper limits on evapotranspiration. The lower limit is established by assuming that the latent energy flux, λE, measured by eddy correlation (eq. 20) is correct. Such an assumption implies that all the eddy-correlation error occurs in the sensible heat-flux measurement (H, eq. 13). The upper limit of evapotranspiration is obtained by assuming that the sensible heat-flux measurements are correct and that all of the error occurs in the vapor-flux measurement (λE in eq. 20). Under this assumption, the latent heat flux is computed as the residual of the energy budget minus sensible heat flux:

$$Leb = R_n - G - H \ , \qquad (27)$$

where H is as measured by equation 13.

The contention that *Leb* represents a maximum estimate of evapotranspiration is based on the assumption that sensible heat flux is not overestimated by the eddy-correlation measurements. This is a reasonable assumption, in that most of the recognized potential sources of error discussed earlier result in underestimates of flux. Also, during the tests performed over parking lots, latent heat flux was nearly zero yet the eddy-correlation-measured sensible heat flux was less than the measured energy budget. These tests thus show that sensible heat flux is at least somewhat underestimated by the eddy-correlation measurements.

The eddy-correlation values of latent heat flux, symbolized as *Lec*, differ greatly from the energy-budget residual (*Leb*) values. Several arguments can be made in favor of the energy-budget values:

1. The output of the fine-wire thermocouple is stable, and the theoretical calibration is well known, suggesting that the sensible heat flux is well determined. On the other hand, the Lyman-alpha hygrometer must be calibrated experimentally. Although careful calibrations performed in June and September 1980 and in January 1983 are in good agreement, the recommended practice of frequent Lyman-alpha calibration (Redford and others, 1980) was not followed. Moreover, the output of the Lyman-alpha hygrometer shows substantial diurnal drift. It has been assumed that this drift affects the offset, but not the slope, of the voltage-vapor density curve, and that the flux measurements are little affected by the drift. Nonetheless, additional uncertainty is added to the vapor-flux determinations. Finally, when relative humidity is high, current leakage sometimes occurs along the outer surface of the detector tube in the Lyman-alpha hygrometer, creating an additional voltage offset that affects the mean voltage, and possibly the calibration of the hygrometer. This mean voltage is used as a divisor in computing

vapor flux. Also, as discussed above, the vapor-density measurements are made at a point farther away from the wind measurements than are the temperature measurements, potentially resulting in greater error in measuring vapor fluxes. Hence, the vapor-flux computations are subject to many more instrumentation uncertainties than are the sensible heat-flux determinations.

2. The *Leb* estimates for the different saltcedar sites for May, September, and October (described below) are in close agreement, whereas the *Lec* estimates show substantial variance. Soil moisture storage was high at those times owing to recent rains, and it is plausible that the rates should be similar.

3. A multiple regression of the energy budget $(R_n - G)$ against sensible heat flux (H) and latent heat flux (Lec) for the data in table 3 yielded the following equation (forced through the origin):

$$(R_n - G) = 1.13H + 1.61Lec \ . \qquad (28)$$

This relationship suggests statistical confirmation that most of the underestimation occurs in the latent heat determination.

4. Estimates of evapotranspiration by the *Leb* method are in good agreement with those determined by some other studies, as described below, whereas estimates determined by the eddy-correlation technique are much lower than most other measurements.

Because of the preponderance of data favoring the use of the *Leb* values, those values are emphasized.

WATER USE BY SALTCEDAR

Two sets of water-use estimates for saltcedar, derived by multiplying *Lec* and *Leb* in table 3 by a conversion of 0.41 mm water per $MJm^{-2}d^{-1}$, are summarized in table 4 and in figures 7*A* and 7*B*. The conversion factor is based on a value for the latent heat of vaporization of water of 2,450 Jg^{-1}. These figures show the water-use measurements for each saltcedar thicket for the 3-yr period of measurements. Water use varies substantially among sites. Depth to water, plant density, and plant age also vary substantially among sites, but there is no apparent correlation between measured water use and these factors. For example, the old-growth site provides about 80-percent ground cover, although it was mapped as dense saltcedar by Mower in 1958 (Mower and others, 1964). The saltcedar at the old-growth site was burned sometime prior to 1974, but the growth seems to be again quite mature. The mowed saltcedar thicket, located about 1 km southwest of the old-growth site (fig. 1), currently provides about 50-percent ground cover, although it was mapped as moderately dense (70–90-percent cover) by Mower in 1958.

TABLE 4.—*Summary of daily water-use estimates at the various sites*

Site	Date	Water use (Evapotranspiration) (millimeters per day)	
		Eddy correlation	Energy budget residual
Saltcedar			
	1980		
Old growth	June 25-26	1.2	1.9
	Oct. 22-23	1.6	1.8
	1981		
	May 12	3.1	4.8
	June 24-25	0.7	1.3
	Sep. 14-15	4.1	4.7
	1982		
	June 24-25	1.2	2.7
	Aug. 28-29	1.3	2.8
	1980		
Mowed	June 26	1.8	----------
	Oct. 22-23	1.4	2.1
	1981		
	May 13	2.2	4.8
	June 24-25	3.5	6.0
	Sep. 14-16	2.6	4.4
	1982		
	Aug. 28-29	2.2	4.3
Burned	June 26-27	1.9	4.1
	Aug. 27-28	2.8	3.2
Wet old growth	June 27-29	4.3	5.4
	Aug. 30-Sep. 1	2.2	4.4
Replacement vegetation			
	1980		
Grass and forbs	June 24	1.1	1.5
	Oct. 21	1.0	1.1
	1981		
	May 11	1.4	2.9
	June 22-23	0.5	1.1
	Sep. 16	1.1	2.2
	1982		
	June 22-26	1.4	3.3
	Aug. 24-28	1.8	2.7
Grass	June 27	0.6	2.9
	Aug. 30-Sep. 1	1.6	3.1
Forbs	Aug. 31-Sep. 1	1.2	2.9

The site was mowed in the fall or winter of 1977, and no shoots were visible in March 1978. This site has a substantial understory of alkali sacaton grass. Depth to water at both sites ranges from 3 to 3.5 m.

The burn site is located about 1/2 km south of U.S. Highway 83 and about 5 km south-southeast of the old-growth site. The site consists of dense saltcedar and is regrowth from a burn that occurred in 1974. The depth to water is about 2 m, and the vegetation is about 4 m high. The site is south of the area mapped by Mower.

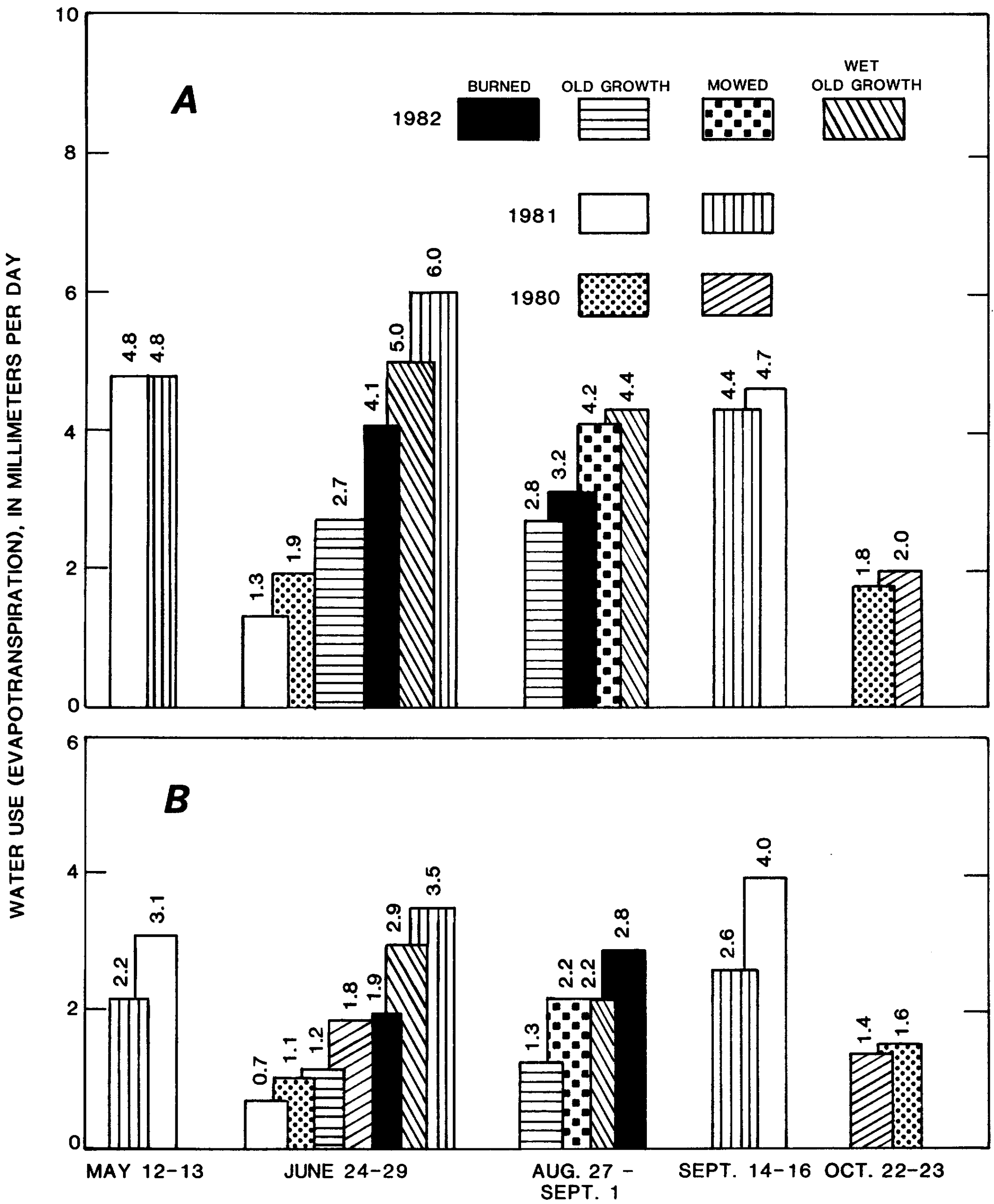

FIGURE 7.—Summary of estimates of daily evapotranspiration by saltcedar by (*A*) the energy-budget-residual method, and (*B*) the eddy-correlation method.

The wet old-growth site is a dense saltcedar thicket about 3 km north of the U.S. Highway 70 crossing. There are no signs that the saltcedar ever burned, and the site has a very shallow (less than 1 m) depth to water. The saltcedar is about 5 m tall.

Water use by the different thickets showed great variation, particularly during June and August. For example, in June 1981 evapotranspiration from the mowed saltcedar was about five times that from the old growth, based on either method. Other supporting data suggest that these differences are qualitatively correct. Stomatal diffusion resistances of fronds of the old growth were about three to five times greater than those of fronds for the mowed saltcedar in June of each year. Also, in June 1982, the old-growth saltcedar had midafternoon frond temperatures, as measured by an infrared thermometer, of 43°–45°C, whereas the mowed saltcedar frond temperatures were 36°–38°C. These frond temperatures suggest that much less evaporative cooling was occurring from the old growth than from the mowed saltcedar. Finally, the old-growth saltcedar showed visible signs of moisture stress and had not flowered, whereas the mowed saltcedar was vigorous and in full bloom. Measurements made during each June followed a long sequence of hot, dry, sunny days, when soil moisture was substantially depleted. Finally, examination of hand-auger samples obtained at the old-growth site indicated that live roots were prevalent in the top 1.8 m of material above the clay layers (fig. 8) but were sparse in and beneath the clay layers. At the mowed site, on the other hand, live roots were prevalent throughout the section down to the water table. These observations suggest that the old-growth saltcedar derives most of its water from soil moisture, while the mowed saltcedar relies heavily on ground water during periods of extreme moisture stress.

Because of the alkali sacaton in the understory, water use at the mowed site represents a combination of water use by the saltcedar and the grass. It is assumed that the saltcedar accounted for most of the evapotranspiration.

Evapotranspiration determined as the energy-budget residual (*Eeb*) for wet old growth (4.4 mm/d) slightly exceeded that for the mowed site (4.3 mm/d) in August 1982. No measurements of evapotranspiration from the mowed saltcedar were made in June 1982, but the June 1981 evapotranspiration from the mowed site (6.0 mm/d) exceeded the June 1982 evapotranspiration from the wet old-growth site (5.4 mm/d) by about 10 percent. Both measurements of *Eeb* from the burn site are intermediate between the old growth and the mowed site.

WATER USE BY REPLACEMENT VEGETATION

Estimates of water use by the replacement vegetation are listed in table 4 and shown in figures 9*A* and 9*B*. Water use, as measured by the residual-energy-budget method, ranged from as low as 1.1 mm/d to as much as 3.3 mm/d and typically averaged about 3 mm/d. The value of 2.2 mm/d measured on September 16, 1981, was measured on a cloudy day and may be atypically low.

The forbs at the grass-and-forbs site varied greatly between measurements, although alkali sacaton and saltbush (*Atriplex patula*) are perennials and were always present. In June 1980, desert seepweed (*Suaeda suffractescens*) was the dominant species, with some Russian thistle present. Large bare patches were present, and young kochia had died. By the ill-fated visit in August 1980, when rain caused instrumentation failures, kochia was the dominant annual and desert seepweed had nearly disappeared. Kochia remained dominant in October 1980.

In May and June 1981, desert seepweed, horsenettle (*Solanum elaeagnifolium*), and an unidentified weed were prevalent. By August and September, kochia, a mustard plant (*Brassica nigra*), and Russian thistle were again common. In June 1982, kochia, the mustard, and desert seepweed were prevalent (the first June in which kochia was dominant). The kochia and mustard were still prevalent in August 1982.

Vegetative cover at the forbs site is dominantly kochia. The dominant cover at the grass site is alkali sacaton, a grass that apparently was one of the common types of cover before the saltcedar infestation began in the Pecos valley.

COMPARISON WITH POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration is defined as the evapotranspiration rate from a well-watered reference crop that completely shades the ground, such as short grass (Penman, 1956) or alfalfa (Jensen, 1973). Potential evapotranspiration is dependent on climatic factors, including solar radiation, air temperature, vapor pressure or vapor density, and windspeed, and on crop properties, including the aerodynamic roughness of the vegetation, reflectance of the canopy surface to shortwave radiation, the canopy temperature, and the resistance to vapor loss imposed by the leaf stomates. The vegetative properties of short grass or alfalfa can be estimated, so that potential evapotranspiration can be defined by climate alone. The concept is widely used to estimate evapotranspiration from phreatophytic vegetation. Hence, a comparison of values measured in this study with potential evapotranspiration is useful to evaluate the suitability of the potential evapotranspiration concept for such estimates.

Many different equations exist for computing potential evapotranspiration; the selection depends on the climatic data available and on usually site-specific calibration constants (Jensen, 1973). The Jensen-Haise equation (Jensen, 1973, p. 73, 74) was used to compute potential evapotranspiration for this study. The equation is

$$E_p = 0.41\ (T_a - T_x)\ R_s/(C_1 + C_2\ C_H)\ , \qquad (29)$$

where

E_p = potential evapotranspiration, in mm/d;
T_a = mean monthly air temperature, in °C;

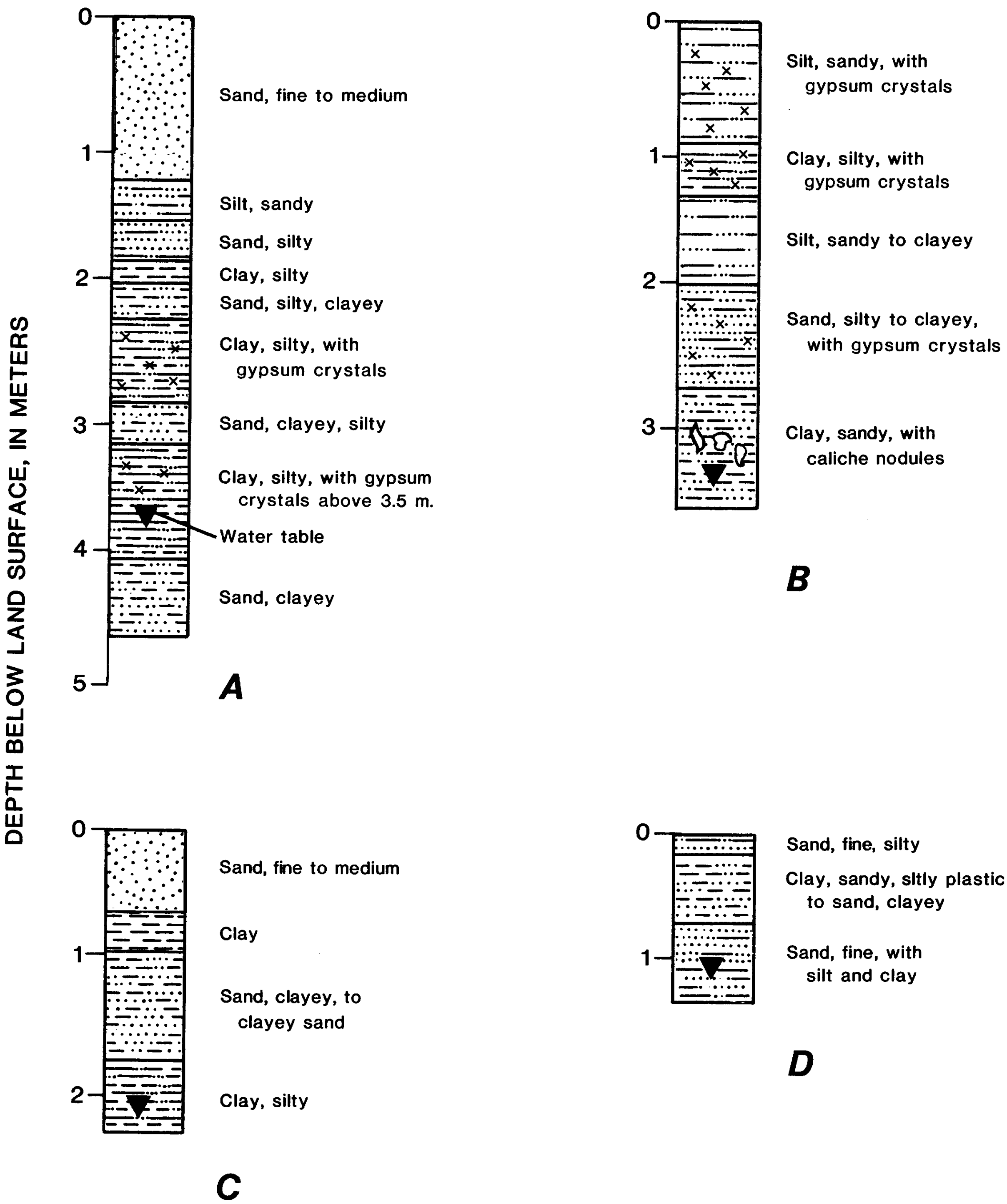

FIGURE 8.—Sample logs showing the nature of the materials from land surface to the water table for each saltcedar measurement site: (*A*) old-growth site, (*B*) regrowth site, (*C*) burn site, and (*D*) wet old-growth site.

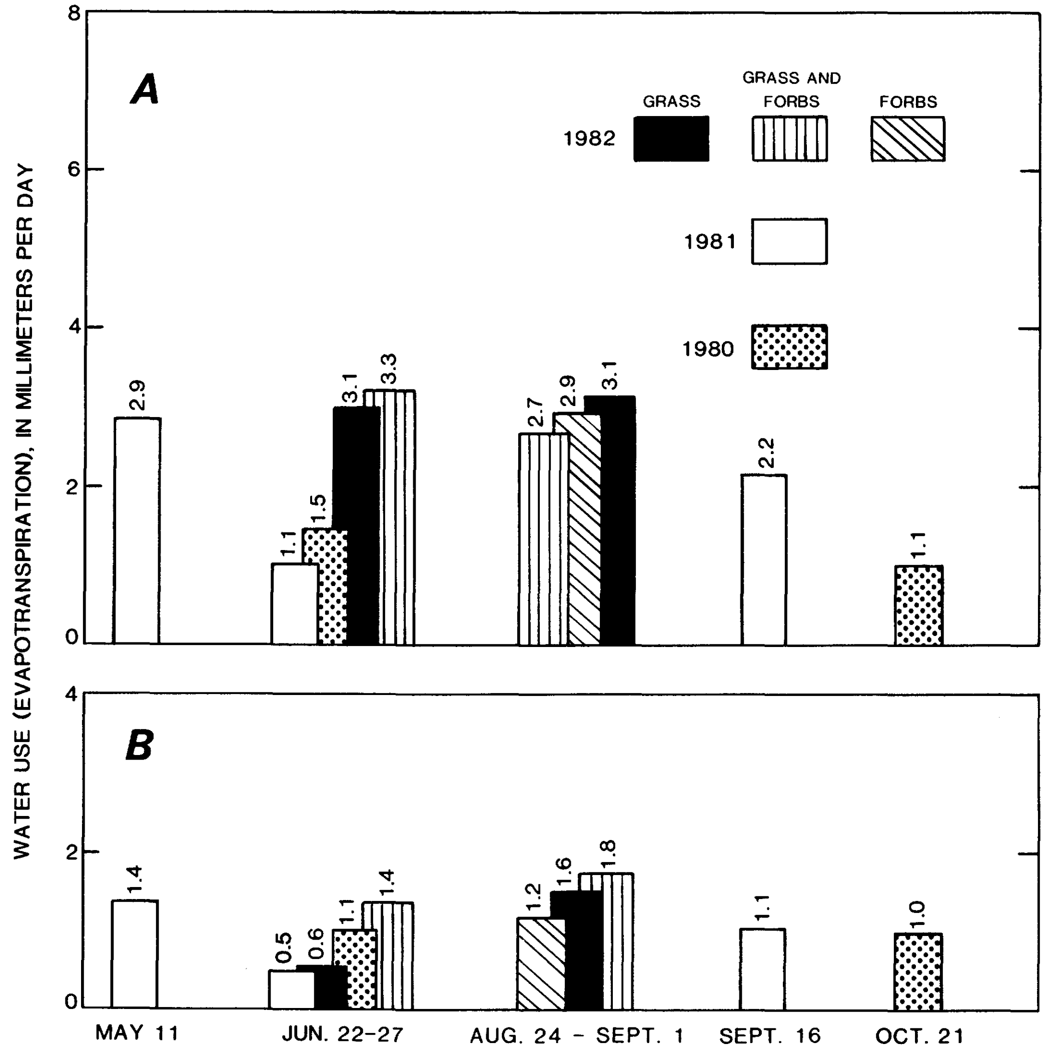

FIGURE 9.—Summary of estimates of daily evapotranspiration by replacement vegetation by (*A*) the energy-budget-residual method, and (*B*) the eddy-correlation method.

T_x = −2.5°C − 1.4(e_2 − e_1)°C/kPa − (altitude in m/550 m)°C;

R_s = incoming solar radiation, in $MJm^{-2}d^{-1}$;

C_1 = 38°C + (−2°C × altitude in m/305 m);

C_2 = 7.6°C;

C_H = 5.0 kPa/(e_2 − e_1); and

e_1, e_2 = saturation vapor pressures, in kPa, at the maximum and minimum average temperatures for the warmest month of the year.

Solar radiation records from El Paso, Tex., and mean monthly temperatures at Roswell, N. Mex., as provided by the National Weather Service, were used for the computations. El Paso is located about 205 km southwest of Artesia, and Roswell is located about 60 km north of Artesia. The climates of the two cities are relatively similar to the climate of Artesia, although solar radiation at El Paso might be 10 percent or so greater than at Artesia on an annual basis. Results of these computations are shown by the potential evaporation curves in figures 10 and 11. Annual potential evapotranspiration was computed to be 1.75 m.

The energy-budget-residual estimates of water use by saltcedar ranged from 13 percent of potential evapotranspiration for the lowest value measured at the old-growth site to about 65–70 percent for the largest values measured during each month.

The fact that the estimated maximum water use by saltcedar is less than Jensen-Haise potential evapotranspiration is consistent with observations made during the study. The empirical constants used in the Jensen-Haise method were developed to provide estimates that agree with the measured water use by alfalfa. The stomatal resistance to vapor loss from alfalfa is very low, so that the resistance to vapor transport from the canopy is comparable to the resistance to heat transport. Hence, the alfalfa behaves as a freely transpiring surface and is usually cooler during daytime in summer in the Artesia area than the air, owing to evaporative cooling. All of our observations indicated that saltcedar is less freely transpiring, and that the resistance to vapor transport is greater than the resistance to heat transport. This is evidenced by the fact that saltcedar surface temperatures during sunny summer days, as measured by an infrared thermometer, were always higher than the air temperature, both at our eddy-correlation measurement sites and at various other saltcedar thickets in the floodplain, as spot-measured in June and August 1982. Thus, the Jensen-Haise equation will overestimate water use by saltcedar, at least in the Roswell basin area, unless a crop coefficient is used to adjust the values downward. A similar conclusion regarding water use by saltcedar in the Gila River floodplain was reached by Culler and others (1982, p. P39) on the basis of their water-budget measurements of saltcedar evapotranspiration.

ANNUAL WATER USE

The potential for salvage of ground water by saltcedar eradication is dependent on annual water use by both the saltcedar and the replacement vegetation. However, only spot measurements were made, and these were made only during the growing season. Hence, it was necessary to interpolate between measurements, and to extrapolate the measurements through the nongrowing season.

For the growing season, maximum, median, and minimum estimates of water use were made by drawing straight-line segments through selected data. (More formal interpolation schemes were attempted initially, but these schemes inferred low water use after the start of the wetter "monsoon" season in July. Hence they were deemed less realistic than the use of straight-line segments.) For the energy-budget-residual estimates, minimum water use by saltcedar was obtained by drawing line segments through the measured values for the old-growth site, including the average of only the two lower June measurements. The median estimates are based on average values for all available saltcedar measurements for each month. The maximum water use was determined by the data from the mowed site, which gave the largest water-use values in midsummer. Evapotranspiration during the nongrowing season (approximately November 15 to April 1), both for saltcedar and for replacement vegetation, was arbitrarily assumed to be 40 percent of potential evapotranspiration. Saltcedar in the Roswell area drops its fronds after a killing frost and leafs out again in mid-April. Hence, it is reasonable to assume that evapotranspiration for both cover types, consisting mainly of evaporation from the soil surface, is about equal during the nongrowing season.

The estimation procedure is illustrated in figure 10*A*. The daily water-use rates for saltcedar measured by the energy-budget-residual method are plotted

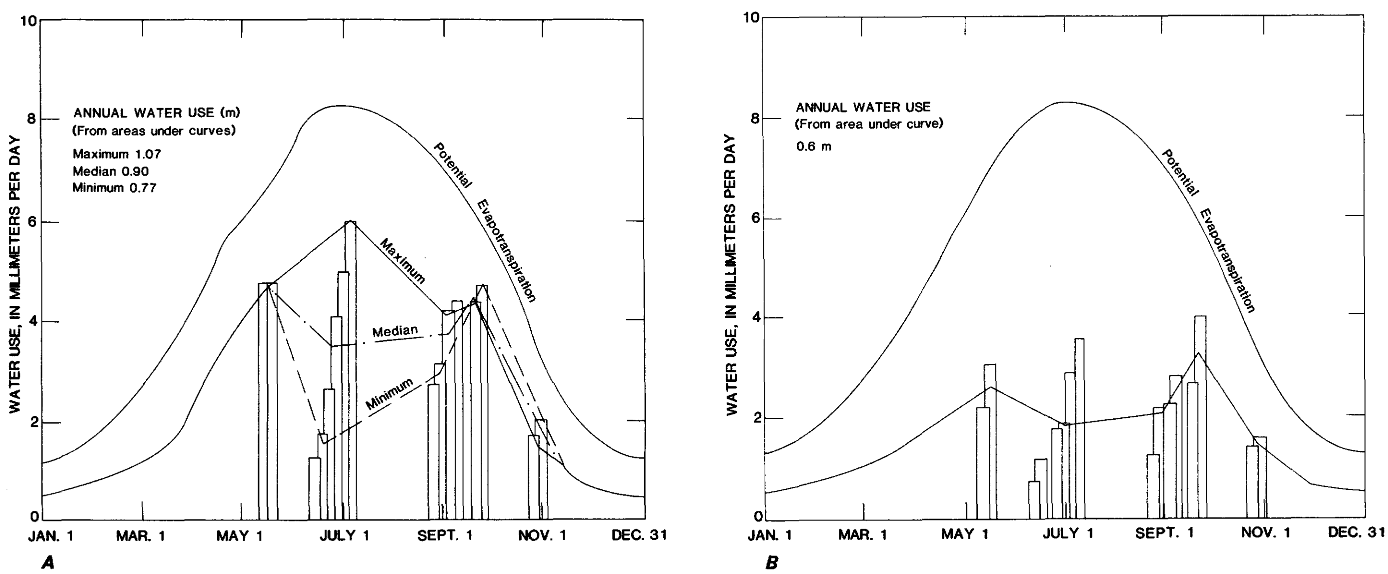

FIGURE 10.—Estimated annual water use by saltcedar in the Pecos valley, New Mexico, as determined by (*A*) the energy-budget-residual method, and (*B*) the eddy-correlation method.

as bar graphs. Line graphs through the selected values or means show the estimated minimum, median, and maximum rates. The areas under these line graphs were integrated to determine the annual water-use rates given in table 5. This procedure indicates that water use by saltcedar at the old-growth site (the minimum value) may be about 0.77 m/yr, whereas that for the mowed site (the maximum value) is about 1.07 m/yr. The average for the four sites tested is about 0.9 m/yr.

Estimates of annual water use by saltcedar based on the eddy-correlation measurements (fig. 10*B*) were made only for the mean of the values for all sites for each month. These measurements indicated that water use at the mowed site in May and September was less than that at the old-growth site, although the mowed-site measurements were greater in June and August (table 4). Hence, the approach described above for analyzing the energy-budget-residual measurements would have resulted in maximum, mean, and minimum values that are all of about the same magnitude. The analysis of the eddy-correlation measurements indicates that the minimum value for average water use by saltcedar is 0.6 m/yr.

Estimates of annual water use by the replacement vegetation (fig. 11) were obtained in a similar manner. For the energy-budget-residual measurements, minimum water use was determined as that for the grass-and forbs-site, using only the seasonally low values for June 1980 and June 1981, the minimum value measured in August 1982, and measured values for May, September, and October (table 4). The median value was obtained using the averages of all the monthly measurements. The maximum estimate is based on the highest measurement each month, and, in addition, it was assumed that the September measurement, made on a cloudy day, was equal to the average of the maximum August measurement and the September measurement. These data indicate that water use by replacement vegetation ranged from 0.57 to 0.67 m/yr (table 5).

TABLE 5.—*Estimates of the range in annual water use by saltcedar and by replacement vegetation in the Pecos River floodplain and of projected water salvage due to saltcedar eradication*

[In meters per year]

	Saltcedar	Replacement vegetation	Salvage
Based on the energy-budget residual			
Maximum	1.07	0.67	0.40
Median	.90	.62	.28
Minimum	.77	.57	.20
Based on eddy correlation			
Median	0.60	0.40	0.20

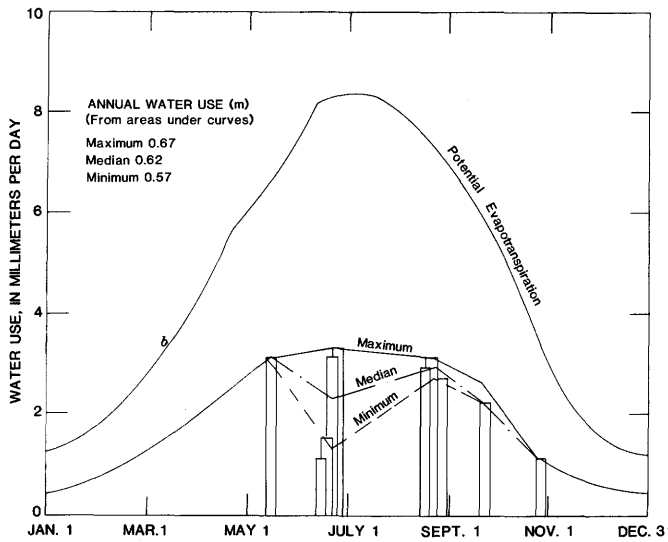

FIGURE 11.—Estimated annual water use by replacement vegetation in the Pecos valley, New Mexico, as determined by the energy-budget- residual method.

Estimates of annual water use based on the eddy-correlation measurements of evapotranspiration (not shown in fig. 11) were made in a manner similar to those for saltcedar. This analysis resulted in a water-use estimate for the replacement vegetation of 0.4 m/yr, as listed in table 5.

COMPARISON WITH PREVIOUS RESULTS

In this study, the best estimates indicate that summertime daily water use by saltcedar is as little as 1.0 mm/d or as much as 6 mm/d, but estimated rates in the range 4 to 5 mm/d are common (table 4). Annual water use is estimated to range from 0.77 to 1.07 m. These values are at the low end of the range of those measured by other investigators. For example, the minimum annual value coincides with the estimate of consumptive use by floodplain vegetation determined by Gatewood and others (1950) using the inflow-outflow technique. However, only about half the area for which they determined consumptive use contained saltcedar or other brush. Moreover, their analysis was based on 1 yr of record, and changes in soil-moisture and ground-water storage were not measured. Hence, their estimates could be in error, being either too large or too small.

The median and maximum estimates of annual evapotranspiration compare closely with those Culler and others (1982) obtained using a water-budget technique. They measured annual water use, including precipitation, of about 1.0 m as an average for three

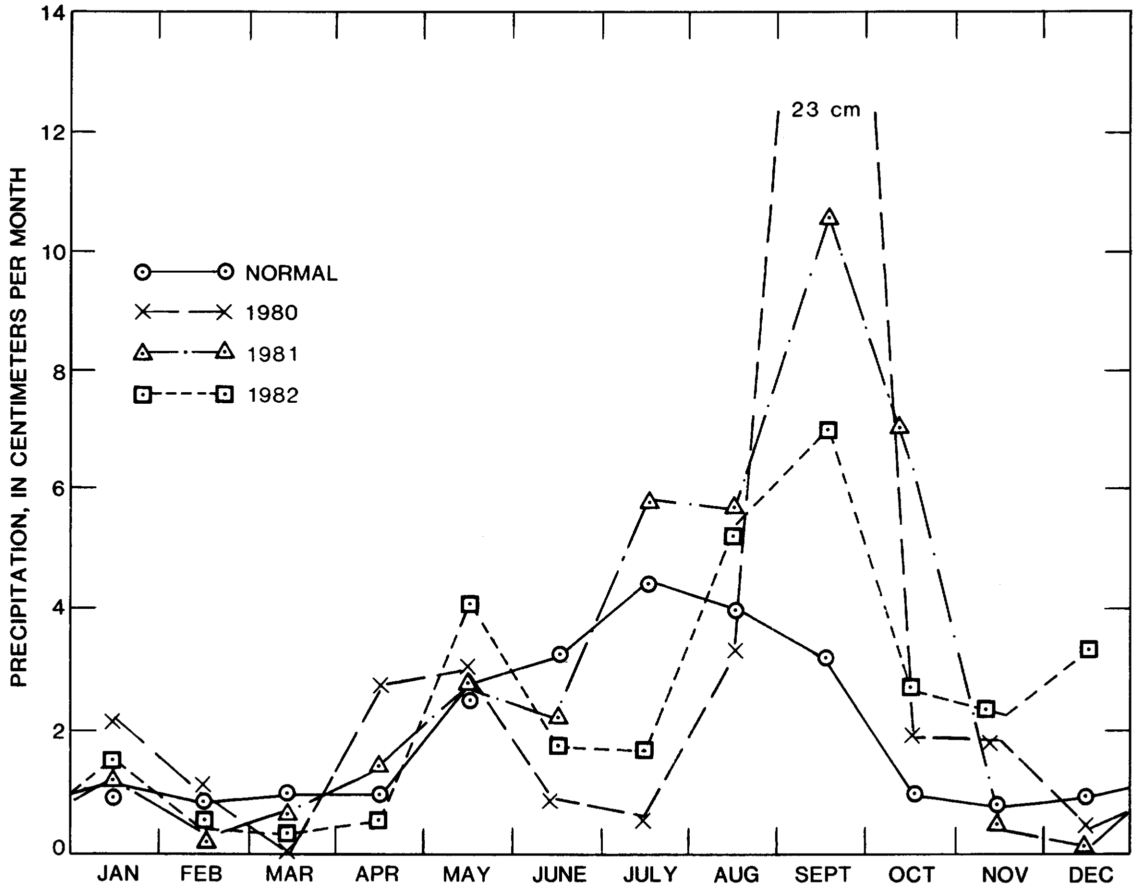

FIGURE 12.—Monthly precipitation at Roswell, N. Mex., during the period 1980–82.

reaches that include some mesquite and bare ground. The climate of the Gila River floodplain in the vicinity of Safford, Ariz., where both of the above studies were conducted, is similar to that of the Pecos River floodplain near Artesia. The latitudes are the same (33° N.), and rainfall is similar (292 mm at the Gila site versus about 320 mm at Roswell, N. Mex.). The altitude of the Gila site (about 770 m) is somewhat lower than that for the Artesia, N. Mex., site (about 1,000 m). On the basis of these comparisons, evapotranspiration rates might be anticipated to be slightly lower in our study area than in the Gila River study site.

Our estimates of annual evapotranspiration may be somewhat low because most of the measurements were made during dry weather, partly by design and partly because equipment malfunctions induced by rain prevented measurements immediately afterward. Evaporation rates from wet canopies and wet soil are quite high but may be about equal for the saltcedar and the replacement vegetation. If the periods following rain had been sampled more representatively, our estimates of annual evapotranspiration would be at least a little higher. Monthly rainfall at Roswell, N. Mex., for the study period is shown in figure 12.

Measurements of daily evapotranspiration using the Bowen-ratio method made by Gay and Fritschen (1979) and by Leppanen (1981) resulted in typical evapotranspiration rates of 7 mm/d. These values are about 50 percent larger than those measured during our study. Leppanen's measurements were made over rapidly growing young saltcedar, which may not be comparable to mature stands. On the other hand, there is no obvious explanation for the difference between our results and those of Gay and Fritschen.

The Bowen-ratio measurements by Gay (1980) and the eddy-correlation measurements by Fritschen and others (1980) both indicate evapotranspiration rates of about 3 mm/d. However, their measurements were made on a cloudy day, and the results are not fully comparable to most of those in this study. The portion of the energy budget used in evapotranspiration during their studies was about the same as that which would result in an evapotranspiration rate of about 5 mm/d on a sunny day. Estimates of evapotranspiration based on the temperature and humidity profiles, net radiation, and soil-heat-flux data presented by van Hylckama (1980) for a saltcedar thicket near Gila Bend indicate that daily evapotranspiration rates at that site are on the order of 8 mm/d, which is in better agreement with the results of the other Bowen-ratio studies than with our results. On the other hand, the analyses of van Hylckama's data are uncertain enough to preclude definitive comparisons.

The estimates of daily evapotranspiration from saltcedar made during this study are one-fourth or one-fifth those measured in tanks in Arizona by Gatewood and others (1950) or by van Hylckama (1980), but are nearly the same as those measured in tanks at Bernardo, N. Mex. (U.S. Bureau of Reclamation, 1973). The discrepancies with the Arizona tank studies probably arise from oasis effects on those tanks, as described in the section "Discussion of Previous Results."

Energy-budget estimates of water use by replacement vegetation (fig. 11) are in the general range of those determined by other workers. Culler and others (1982, fig. 10) found that replacement vegetation in the Gila floodplain generally was 1–1.5 mm/d in April and May and about 2–2.5 mm/d during June through August. Their values are slightly lower than those found in this study. However, their vegetative cover was mainly poorly established bermuda grass, annual weeds, and bare ground. Also, many of their measurements were made immediately after clearing and before the replacement vegetation could become well established. Hence, the differences are easily accepted. Measurements by Fritschen and others (1980) and by Gay (1980) at the forbs site indicated that evapotranspiration was about 3 mm/d in July 1979, which agrees with our results.

Although several evapotranspirometer-tank studies of evaporation from bare soil and evapotranspiration from saltgrass, sacaton, and Russian thistle have been made, the depths to water are not comparable to those in this study and no comparisons are warranted.

In summary, the energy-budget evapotranspiration measurements made during this study agree exceptionally well with the results of the water-budget study conducted by Culler and others (1982), and with Bowen-ratio and eddy-correlation measurements made in the Pecos River floodplain by Gay (1980) and by Fritschen and others (1980). Agreement is less good with energy-budget studies conducted in other areas, and agreement with tank-measured evapotranspiration is very poor. The extensive water-budget measurements of Culler and others (1982) probably are the most representative of the entire floodplain environment, and the good agreement of our results with those of that study give substantial credence to our results.

ESTIMATES OF EVAPOTRANSPIRATION SALVAGE

Evapotranspiration salvage can be estimated as the difference in water use between saltcedar and the replacement vegetation. Such estimates are, of course, fraught with uncertainty, because of the limited number of measurements (17 for saltcedar and 10 for replacement vegetation), the potential error in the measurements, and the difficulty in extrapolating the measurements in time and space. Nonetheless, the high, low, and median estimates for evapotranspiration provide probable bounds to the magnitude of evapotranspiration salvage. One set of salvage estimates can be obtained by comparing high, median, and low estimates for each cover type (table 5). These estimates suggest that the reduction in evapotranspiration might be as much as 0.4 m/yr or as little as 0.2 m/yr, with a median estimate for the energy-budget method of about 0.3 m/yr. These represent estimates of the maximum anticipated annual salvage.

An estimate of the minimum anticipated annual water salvage can be obtained by subtracting annual water use by the replacement vegetation, as determined by the eddy-correlation method, from the eddy-correlation-based estimate of annual water use by saltcedar. This analysis indicates that annual water salvage by saltcedar eradication is about 0.2 m.

The above analyses indicate that annual water salvage by saltcedar eradication probably is more than 0.2 m but less than 0.4 m. Because the energy-budget residual or maximum values are considered more reliable than the eddy-correlation values, a salvage estimate of about 0.3 m/yr is the best available.

Alternate estimates of salvage can be obtained from the energy-budget values in table 5 by subtracting the minimum evapotranspiration for replacement vegetation (0.57 m/yr) from the maximum water use estimate for saltcedar (1.07 m/yr) to determine an upper limit for water salvage of 0.5 m/yr. Similarly, the minimum estimate can be obtained by subtracting maximum water use by replacement vegetation (0.67 m/yr) from the minimum for saltcedar (0.77 m/yr). This minimum is 0.1 m/yr and tends to confirm studies of base flow gain. However, the validity of both these high and low estimates is suspect because the measured low saltcedar water use generally was coincident with measured low replacement-vegetation use. Hence, these alternate estimates lack credence.

A major assumption in the foregoing analyses of water salvage is that saltcedar at the measurement sites uses water at a rate typical of that formerly used by saltcedar in the now-cleared areas. Selection of sites for measurement of water use by saltcedar was limited, as most of the remaining saltcedar thickets in the floodplain in the Acme-Artesia reach of the Pecos River were too small to provide adequate fetch for micrometeorological measurements. Hence, it was necessary to select sites upstream and downstream from the cleared reach to obtain additional sample sites. Of all the sites, only the burn site had a depth to water typical of much of the cleared area, whereas all three replacement-vegetation sites had typical depths to water. However, the lack of any apparent relationship between depth to water and measured water use by saltcedar, coupled with the fact that the water-use rate at the burn site was intermediate among rates measured at the other sites, suggests that water use may have been adequately sampled.

Use of water-salvage values to estimate the base-flow gain in the Pecos River between the Acme and Artesia gaging stations also is difficult. Although the USBR has cleared about 8,700 ha (21,500 acres) of saltcedar in the reach (Leon Marcell, written commun., 1983), Mower and others (1964, table 7) indicate that in 1958, 7,160 ha (17,900 acres) had an areal saltcedar density of greater than 10 percent and 5,280 ha (13,000 acres) had an areal saltcedar density of greater than 25 percent. Neither this study nor that of van Hylckama (1980) confirmed a linear relationship between water use and area or volume density. However, it seems likely that water use by very sparse stands of saltcedar is substantially less than that from moderate to dense stands. The lack of transpiring material and the sparseness of the thickets suggest that the plants are not able to obtain large quantities of ground water. Hence, it may be reasonable to assume that water use by saltcedar of greater than 10-percent cover is equal to that measured, while that at less than 10-percent cover might be substantially smaller. However, the expected low use by the less than 10-percent cover might be compensated for by a large-scale oasis effect on the evapotranspiration from the remaining 15-m-wide strips of saltcedar along either side of the river. Also, the 30-m-wide strip of saltcedar along the 132-km-long river reach contains about 400 ha (1,000 acres) of saltcedar, all or most of which probably constituted dense stands at the time Mower and others (1964) prepared vegetation-density maps. Thus, about 6,800 ha (17,000 acres) of saltcedar of greater than 10 percent density may have been cleared. Such a clearing operation would have resulted in roughly 1.2×10^7 to 2.5×10^7 m^3 (10,000–20,000 acre-ft) of salvage annually, based on the measurements described in this report. This value is less than the 3.5×10^7 m^3 (28,000 acre-ft) of salvage predicted by Mower and others (1964, table 14), but it is still sizable.

The indicated 10,000–20,000 acre-ft of salvage is large enough that it should appear as a base-flow gain in the reach. The reason it has not been detected to date may be that it is masked by large variations in the annual water budget. For example, saltcedar mowing appears to have been an ineffective means of control that had little impact on water use. The root plowing in 1974 coincided with an unusually wet year, resulting in large base-flow gains that year and some residual gains the next. Variations in ground-water pumpage and precipitation may have masked the instantaneous impact, and the overall base-flow gains that would be expected to occur for stable conditions actually may be compensated for by continuing declines resulting from ground-water pumpage in the shallow aquifer in the Roswell basin.

SUMMARY AND CONCLUSIONS

The eradication of saltcedar from 8,700 ha of the Pecos River floodplain between Acme and Artesia, N. Mex., did not result in base-flow gains in the reach that could be reliably related to saltcedar clearing. This suggests that consumptive use by the replacement vegetation, mainly annual weeds and alkali sacaton, was about equal to that by saltcedar. To investigate that possibility, water use by selected saltcedar thickets and selected plots of replacement vegetation was periodically measured using an eddy-correlation method. Measurements were made at approximately monthly intervals at two saltcedar sites and one replacement-vegetation site during the growing season in 1980 and 1981, and at four saltcedar sites and three replacement-vegetation sites in 1982.

The eddy-correlation approach provides direct measures of the sensible heat flux and the vapor flux, which may be converted to latent heat flux, from the thickets or plots. The sum of these fluxes should equal the energy budget; however, the measurements frequently were only 60 to 70 percent of the energy budget on a daily basis. A second estimate of latent heat flux and evapotranspiration was obtained by subtracting sensible heat flux from the energy budget. These estimates provided minimum and maximum values of water use from the two types of vegetative cover. Extrapolation of the measurements indicates that water use by the saltcedar thickets is between 0.6 and 1.1 m/yr, and by the replacement vegetation, 0.4 to 0.7 m/yr. The estimated probable range of water salvage by saltcedar eradication is 0.2 to 0.4 m/yr. Use of these estimates to compute the possible salvage for the entire reach is difficult because of the areal variability in hydrologic and soil conditions and in the density and vigor of the saltcedar prior to their eradication. However, salvage of $1.2–2.5\times10^7$ m^3/yr (10,000 to 20,000 acre-ft/yr) may have occurred, but is not recognized as base-flow gain because it is masked by declines in base flow related to ground-water development.

Measurements of evapotranspiration by saltcedar made during this study are in agreement with those of some other studies but are in wide disagreement with still others. In summary, measurements of water use by saltcedar for this study are in good agreement with those determined by the massive water-budget study by Culler and others (1982) and with measurements in the U.S. Bureau of Reclamation evapotranspirometers at Bernardo, N. Mex. (U.S. Bureau of Reclamation, 1973). Results of our study and that of Culler and others (1982, p. P39) indicate that evapotranspiration by saltcedar is substantially less than potential evapotranspiration. Also, Hughes (1972) showed that the saltcedar evapotranspiration rates measured by the U.S. Bureau of Reclamation (1973) could be simulated by the Penman (1956) equation for potential evapotranspiration only if a stomatal-resistance term was added.

Results of this study indicate that evapotranspiration from different saltcedar thickets varied greatly, but no relationship among volume density of the plant cover, depth to water, and water use was apparent. The lack of dependency of water use on depth to water also was noted for the data from the evapotranspirometer tanks at Bernardo, N. Mex. (Hughes, 1972; U.S. Bureau of Reclamation, 1973). The lack of a linear relationship between volume density and water use also was noted by Hughes (1972) and by van Hylckama (1974).

RECOMMENDATIONS FOR FUTURE STUDIES OF EVAPOTRANSPIRATION

The main purpose of this study was to determine water use by saltcedar and by the vegetation that replaced it in areas of the Pecos River floodplain from which it had been eradicated. A strong second motive among all of the authors was to test the eddy-correlation method for measuring evapotranspiration on the basis of newly developed equipment for making and recording the measurements. The method has many desirable attributes, including portability of the instruments, ability to make measurements at a single height above the canopy, and ability to check the fluxes by comparing them with the energy budget. In addition, the conventional wisdom for many years has been that the eddy-correlation method would provide reliable estimates of evapotranspiration once the instrumentation problems were solved (Tanner, 1967, p. 545; van Hylckama, 1980, p. F13).

Perhaps as a consequence of high expectations, our inability to close the energy budget, or even to improve closure in light of equipment modifications made during the study, has been very frustrating. Although we are confident that the eddy-correlation and energy-budget estimates of evapotranspiration flux do bracket actual water use, the range between the estimates is disappointingly large. Consequently, in future studies, estimates of evapotranspiration should also be obtained by the Bowen-ratio method. Battery-operated data loggers that provide user-programmable instrument control, such as the Campbell Scientific CR–21, CR–21X, or CR–7 data loggers, can be used to control a battery-operated device that switches the thermometer and psychrometer positions periodically (Simpson and Duell, 1984). Such a device is sufficiently portable to be used for the measurement of evapotranspiration at fairly remote wild land sites. Estimates of evapotranspiration based on the Bowen-ratio technique would provide a useful adjunct to eddy-correlation-based estimates, or vice versa.

A disadvantage exists in attempting to determine possible evapotranspiration salvage by saltcedar eradication from a previously cleared area because of uncertainty about whether the remaining or offsite thickets are representative of those already cleared. Such uncertainty would be reduced by making measurements before and after clearing. However, climatic variability is large, even in the arid Southwest, so that it is desirable to obtain measurements for a few years before clearing and for a few years after the replacement vegetation is established. As it may take a few years to fully establish the replacement vegetation, a sequential study might require several years to complete. Consequently, it is difficult to judge, even in hindsight, whether a sequential or a parallel approach is more desirable.

Extrapolating measurements in time and transferring them in space, even to nearby areas, requires that assumptions of uncertain reliability be made. The plant-soil-atmosphere modeling study now in progress, as preliminarily described by Weaver (1984), should provide insights into evaluating the effects of soil type, depth to water, ground-water and soil-water salinity, and plant vigor on evapotranspiration by saltcedar and replacement vegetation. These results in turn might be used to estimate evapotranspiration at other sites.

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