HYDROLOGIC EFFECTS OF PHREATOPHYTE CONTROL, ACME-ARTESIA REACH OF THE PECOS RIVER, NEW MEXICO, 1967-82

By G.E. Welder

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 87-4148

Prepared in cooperation with the
PECOS RIVER COMMISSION

Albuquerque, New Mexico
1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
Pinetree Office Park
4501 Indian School Rd. NE, Suite 200
Albuquerque, New Mexico 87110

Copies of this report can
be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center
Box 25425
Denver, Colorado 80225

CONTENTS

CONTENTS - Concluded

FIGURES

FIGURES - Concluded

TABLES

CONVERSION FACTORS

In this report, figure measurements are given in inch-pound units. The following table contains factors for converting these units to metric (International System) units:

Multiply inch-pound unit	By	To obtain metric unit
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	0.004047	square kilometer
acre per year	0.004047	square kilometer per year
acre-foot	0.001233	cubic hectometer
acre-foot per year	0.001233	cubic hectometer per year
cubic foot per second	0.02832	cubic meter per second
foot squared per day	0.0929	meter squared per day
acre-foot per acre	0.001233	cubic hectometer per hectare
square foot	0.0929	square meter
inch per month	25.40	millimeter per month

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

HYDROLOGIC EFFECTS OF PHREATOPHYTE CONTROL, ACME-ARTESIA REACH OF THE PECOS RIVER, NEW MEXICO, 1967-82

By G.E. Welder

ABSTRACT

The U.S. Bureau of Reclamation began a phreatophyte clearing and control program in the bottom land of the Acme-Artesia reach of the Pecos River in March 1967. The initial cutting of 19,000 acres of saltcedar trees, the dominant phreatophyte in the area, was completed in May 1969. Saltcedar regrowth continued each year until July 1975, when root plowing eradicated most of the regrowth. The major objective of the clearing and control program was to salvage water that could be put to beneficial use.

Measurements of changes in the water table in the bottom land and changes in the base flow of the Pecos River were made in order to determine the hydrologic effects of the program. Some salvage of water was indicated, but it is not readily recognized as an increase in base flow. The quantity of salvage probably is less than the average annual base-flow gain of 19,110 acre-feet in the reach during 1967-82.

INTRODUCTION

The U.S. Geological Survey, in cooperation with various State and Federal agencies, has collected surface- and ground-water data almost continuously in and near the Acme-Artesia reach of the Pecos River in southeastern New Mexico since about 1937. Data collection continued during the U.S. Bureau of Reclamation's phreatophyte clearing and control program, a program that started in 1967 and, except for minor maintenance, virtually was completed in 1982. The Bureau's major objective was to salvage water being used by saltcedar, the principal phreatophyte in the bottom land of the Acme-Artesia reach (fig. 1), so that this salvaged water could be put to beneficial use.

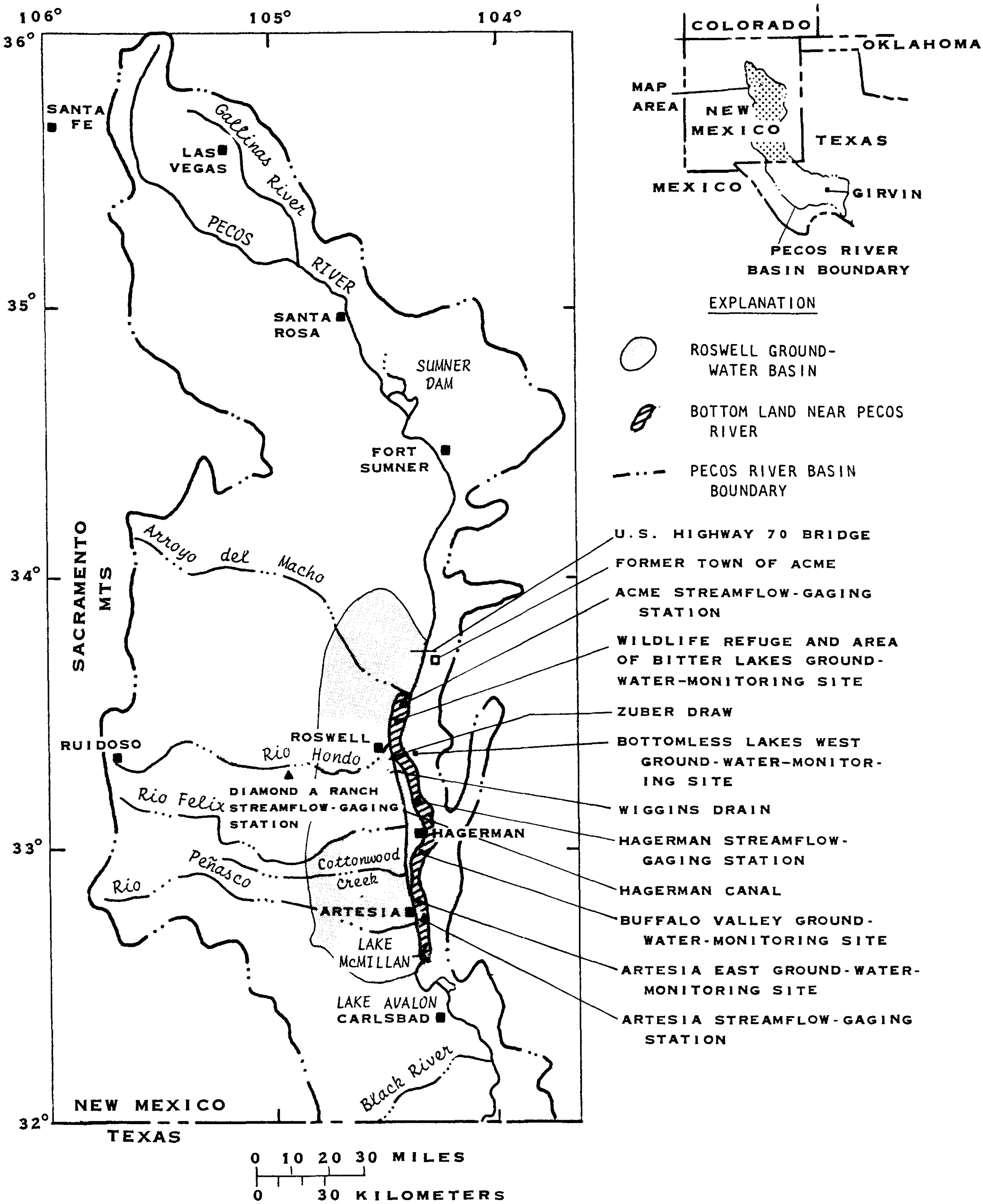


Figure 1.--Location of the Pecos River drainage basin, reach of the Pecos River between the Acme and Artesia streamflow-gaging stations, and the Roswell ground-water basin.

Purpose and Scope

In 1966, the Geological Survey was requested by the Pecos River Commission to continue data collection and analyses to determine the hydrologic effects of the saltcedar-control program. The purpose of this report is to describe hydrologic data collected and the analyses made by the Geological Survey, and, where possible, relate them to the effects of saltcedar control.

"Water salvage" in this report is defined as increased base flow in the Pecos River or an addition to ground-water storage or both. The increases or additions are attributed to a decrease in the use of ground water by saltcedars through the clearing and control program. "Base flow" as used in this report is the gain in the base flow of the Pecos River between the Acme and Artesia gaging stations.

Description of the Acme-Artesia Reach

The principal area of interest is the bottom land of the Pecos River between the Acme and Artesia streamflow-gaging stations, which are 82 river miles and 48 airline miles apart (fig. 1). The Acme and Artesia gaging stations should not be confused with the former town of Acme and the present town of Artesia, which are nearby. The natural limits of the bottom land are close to land-surface contours that are about 20 feet above the low-water channel on both sides of the river. The higher parts of the bottom land are above the present flood plain. Horizontal distances between the 20-foot contours range from about 4,000 to 12,000 feet. The main channel of the Pecos River ranges in width from about 100 to 1,000 feet and descends 216 feet from an altitude of 3,507 feet above sea level at the Acme gaging station to an altitude of 3,291 feet at the Artesia gaging station.

The Pecos River commonly becomes dry at the Acme gaging station for short periods between April and October, but streamflow at the Artesia gaging station generally is continuous. Historically, the Acme-Artesia reach has been a gaining reach because streamflow increases in the downstream direction as a result of ground-water inflow. About 75 percent of the ground-water inflow enters the reach upstream from the Hagerman gaging station (T. 13 S., R. 26 E., sec. 13), which is 26 miles south of the Acme gaging station and 22 miles north of the Artesia gaging station (fig. 1).

The average annual streamflow at the Artesia gaging station during 1938-82 was 167,650 acre-feet and varied from 1,351,000 acre-feet in 1941 (a year of abnormally greater-than-average precipitation) to 44,120 acre-feet in 1964 (table 1). During 1963-82, the average annual streamflow at the Artesia gaging station was 105,770 acre-feet.

Table 1. Annual streamflow of the Pecos River at the Acme and Artesia streamflow-gaging stations, in acre-feet, 1938-82 [1]

Calendar year	Acme	Artesia	Gain or loss (-)
1938	107,500	175,400	67,900
1939	138,100	189,700	51,600
1940	124,700	179,800	55,100
1941	876,400	1,351,000	474,600
1942	406,900	511,700	104,800
1943	120,700	183,900	63,200
1944	98,430	155,800	57,370
1945	77,730	114,100	36,370
1946	83,410	146,000	62,590
1947	55,600	90,640	35,040
1948	74,800	127,700	52,900
1949	164,400	248,300	83,900
1950	156,500	191,500	35,000
1951	110,400	128,100	17,700
1952	96,450	106,600	10,150
1953	73,280	77,890	4,610
1954	127,200	239,700	112,500
1955	153,100	191,900	38,800
1956	85,990	96,430	10,440
1957	81,410	93,530	12,120
1958	225,100	244,800	19,700
1959	99,560	105,100	5,540
1960	218,100	224,600	6,500
1961	121,200	131,200	10,000
1962	108,700	123,500	14,800
1963	118,200	116,800	-1,400
1964	40,990	44,120	3,130
1965	76,180	87,910	11,730
1966	118,600	141,000	22,400
1967	83,750	83,470	-280
1968	76,640	91,170	14,530
1969	176,300	173,000	-3,300

Table 1. Annual streamflow of the Pecos River at the Acme and Artesia streamflow-gaging stations, in acre-feet, 1938-82 [1] - Concluded

Calendar year	Acme	Artesia	Gain or loss (-)
1970	105,100	100,000	-5,100
1971	74,790	75,990	1,200
1972	129,500	148,500	19,000
1973	182,600	177,300	-5,300
1974	99,450	143,700	44,250
1975	62,590	74,970	12,380
1976	73,680	71,880	-1,800
1977	80,300	73,720	-6,580
1978	79,660	106,900	27,240
1979	89,830	106,400	16,570
1980	118,100	117,100	-1,000
1981	48,470	65,590	17,120
1982	106,400	115,900	9,500

1/ Data from streamflow records of the U.S. Geological Survey.

The difference in streamflow between the Acme and Artesia gaging stations, in general, was less during 1963-82 than during 1938-62 (fig. 2). The difference in streamflow during 1943-62 averaged 34,460 acre-feet per year. In contrast, the difference in streamflow during 1963-82 averaged 8,590 acre-feet per year. The streamflow at the Artesia gaging station for 1963-82 was less than streamflow at the Acme gaging station for 8 of the 20 years (fig. 2). Streamflow at the Artesia gaging station, however, does not include surface water diverted for irrigation and water that evaporates from the river surface. Accounting for irrigation and evaporation, the reach is still considered to gain streamflow.

Streamflow is directly affected by irrigation pumpage from the river and releases from Sumner Dam (formerly Alamogordo Reservoir), 116.5 river miles upstream from the Acme gaging station (fig. 1). Generally, one to four dam releases ranging from 20,000 to 50,000 acre-feet are conveyed by the river each summer to Lake McMillan for use in the Carlsbad Irrigation District. Lake McMillan is about 16 river miles downstream from the Artesia gaging station. During the dam releases, which last from 2 to 5 weeks, streamflow ranges from about 700 to 900 cubic feet per second, and the stream level rises from 1.5 to 2.5 feet. Data from Welder (1973), the files of the U.S. Geological Survey, and the New Mexico State Engineer Office indicate that pumpage of surface water for irrigation from the Acme-Artesia reach of the Pecos River and the mouths of four tributaries averaged 11,700 acre-feet per year during 1967-82. This pumpage includes an allotment for drain inflow to the river, but excludes a small quantity of drain inflow to the Hagerman Canal.

Relation of the Roswell Ground-Water Basin and the Acme-Artesia Reach

The Roswell ground-water basin consists of a deep, artesian, carbonate-rock aquifer (artesian aquifer), most of which is in the San Andres Limestone of Permian age, and a shallow, water-table, valley-fill-deposit aquifer (shallow aquifer), generally containing deposits that are of Holocene and Pleistocene age (fig. 3). Some rock of the Artesia Group of Permian age, however, is included in the shallow aquifer along the eastern part of the basin. The aquifers are separated by a leaky wedge of the Artesia Group (confining bed) that thickens eastward. Near the Pecos River, the thickness of the confining bed ranges from about 300 to 800 feet (Welder, 1983, fig. 7).

Valley fill consisting of claystone, siltstone, sandstone, and conglomerate comprises the principal constituents of the shallow aquifer. The upper part of the valley fill contains brown silt with lenses of sand and gravel in the valleys of the Pecos River and near the mouths of tributaries. Fiedler and Nye (1933, p. 29) indicated that this upper material is Holocene in age and named it the Lakewood terrace alluvium. The Lakewood generally forms a dark-brown soil that is fertile except in places where it contains alkali. The low-water channel of the Pecos River overlies the eastern edge of the valley fill in most of the reach and Permian bedrock in several places.

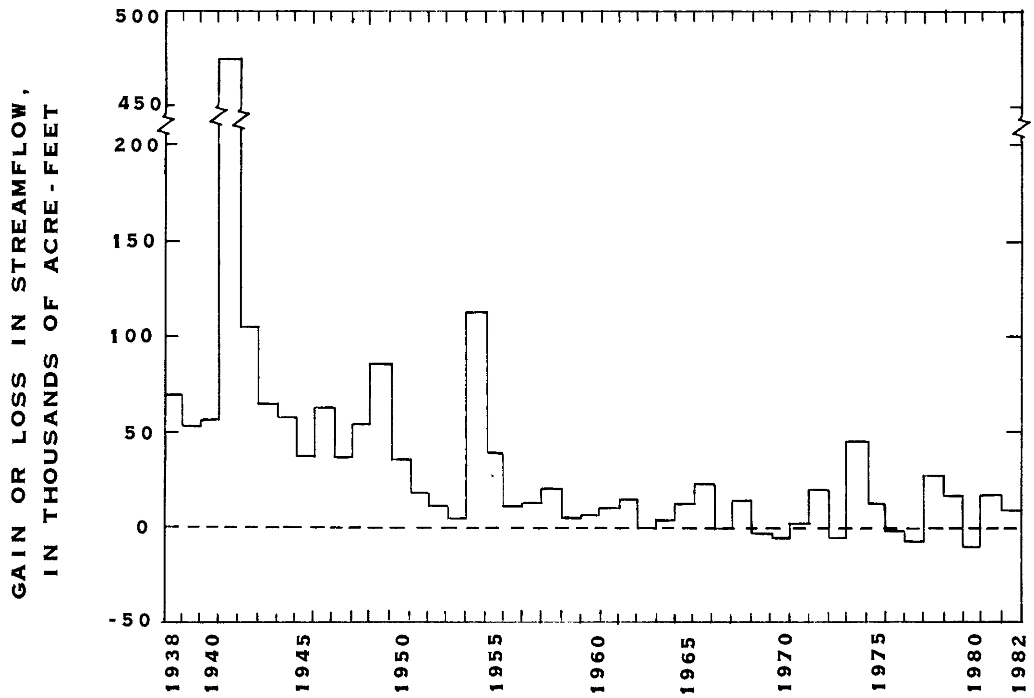


Figure 2.--Difference in streamflow of the Pecos River between the Acme and Artesia streamflow-gaging stations, 1938-82 (prepared from streamflow discharge records collected by the U.S. Geological Survey).

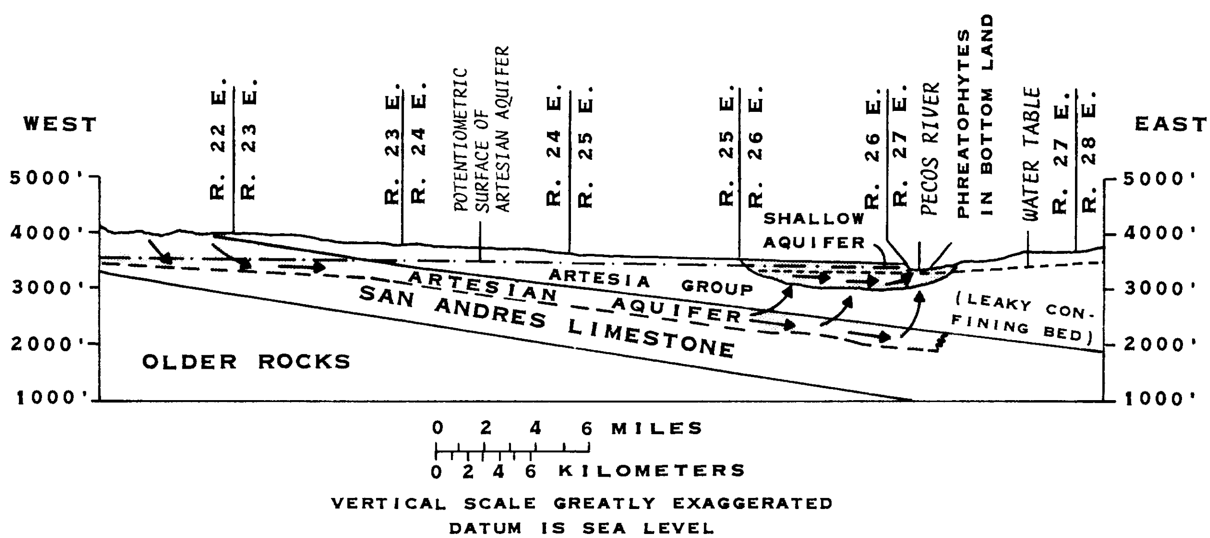


Figure 3.--Generalized geohydrologic section showing relation of the aquifers of the Roswell ground-water basin to the Pecos River and direction of ground-water flow.

The hydraulic connection between the Pecos River and the shallow aquifer of the Roswell ground-water basin and the connection of the shallow aquifer through a leaky confining bed with the artesian aquifer have been recognized for many years (Fiedler and Nye, 1933). Geohydrologic data indicate that, in places, the river and the shallow aquifer along the bottom-land area of former saltcedar growth may be directly connected with the artesian aquifer through permeable zones that were developed by solution and collapse of gypsiferous rock in the confining bed. Evidence for this are the large solution depressions at the base of the valley fill (Lyford, 1973, fig. 12), which overlie similar features mapped at the base of the confining bed by Welder (1983, figs. 3 and 5). An additional indication of the hydraulic connection is the general correlation of the hydraulic head in the artesian aquifer with the base-flow gain in the Acme-Artesia reach (fig. 4). Recharge on the karst outcrop of the artesian aquifer transmits pressure changes quickly through the hydrologic system.

The water table in the shallow aquifer on the west side of the Pecos River slopes eastward and merges with the level of the river (fig. 3). East of the Pecos River valley, the water table in the less permeable Seven Rivers Formation and overlying Yates Formation of the Artesia Group slopes westward and merges with the water table in the shallow aquifer and the level of the Pecos River. The potentiometric surface of the artesian aquifer west of the river also slopes eastward toward the river. More detailed descriptions of the aquifers and their relation to the river are given in Fiedler and Nye (1933), Morgan (1938), Mower and others (1964), and Welder (1973; 1983).

Modified data from the files of the New Mexico State Engineer Office indicate that an average of 371,500 acre-feet of water was pumped annually for irrigation, municipal, industrial, and private (domestic and stock) uses from both aquifers in the Roswell ground-water basin during 1967-82. This does not include a relatively small quantity of ground water diverted to the Hagerman Canal and minor quantities of irrigation and industrial pumpage around the periphery of the basin.

Factors that Affect the Base Flow in the Acme-Artesia Reach

Factors very near and in the bottom land of the Pecos River that add to or deplete base flow of the Acme-Artesia reach either directly or indirectly are shown in figure 5. Ground-water inflow to the bottom land from the shallow and artesian aquifers of the Roswell ground-water basin is the most significant source of base flow. Evapotranspiration from the river and the bottom land and pumping from the river for irrigation cause direct depletions of base flow in the vicinity of the bottom land. Changes in the quantity of inflow to the bottom land from the aquifers west of the bottom land likely cause somewhat similar changes in base flow.

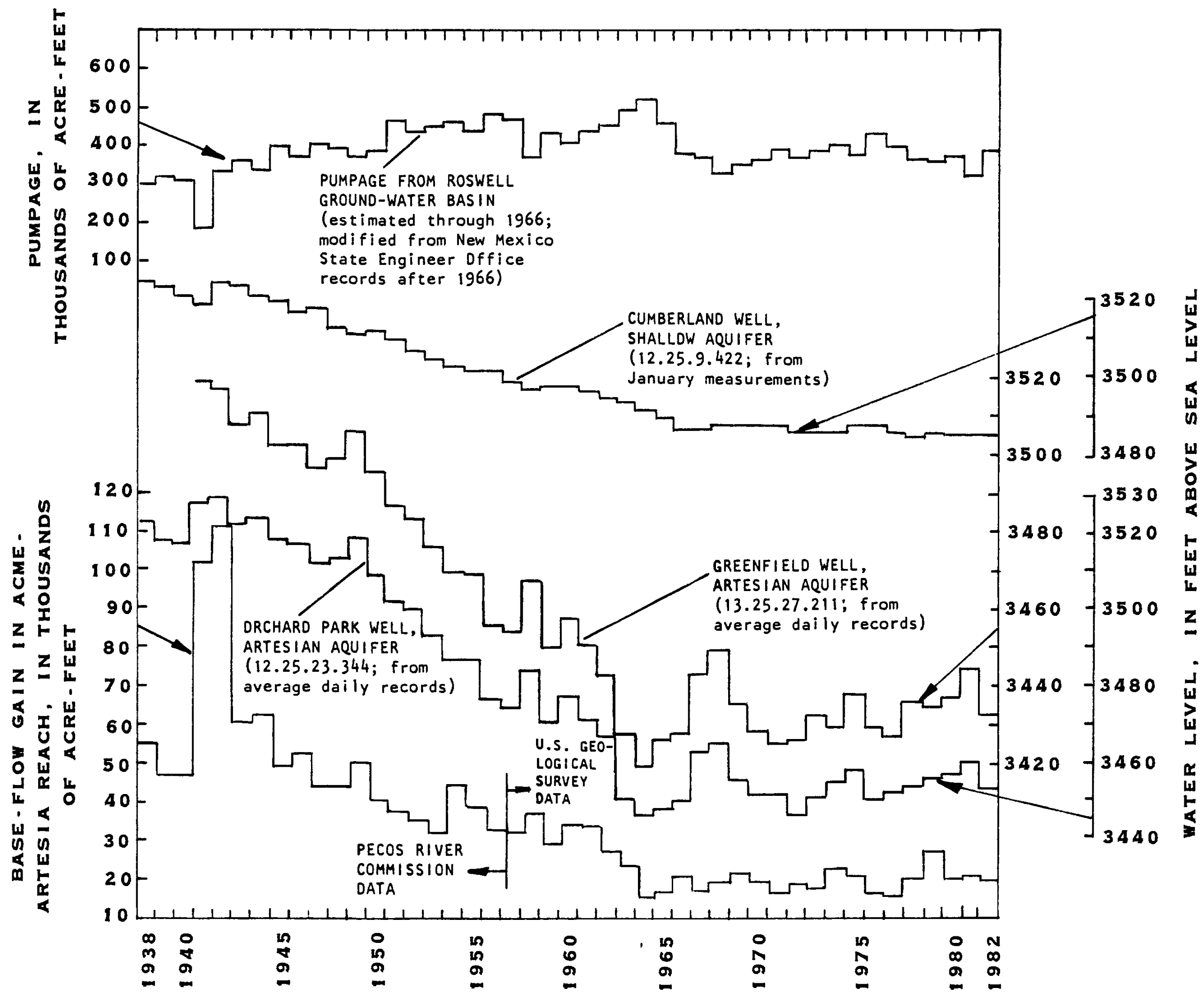
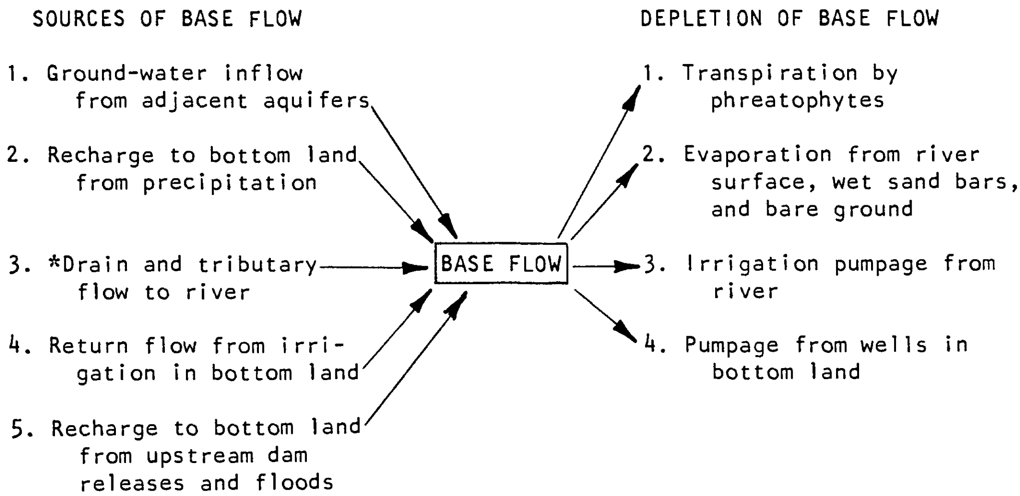


Figure 4.--Relation of annual pumpage from the Roswell ground-water basin, hydraulic heads in the shallow and artesian aquifers, and base-flow gain of the Acme-Artesia reach, 1938-82.



*Ground-water seepage to the drains and the mouths of tributaries from irrigation-return flow; surface runoff from precipitation is excluded

Figure 5.--Factors that affect the base flow of the Pecos River in the bottom land of the Acme-Artesia reach.

Saltcedar-transpiration discharge points in the bottom land are very close to the ground-water discharge points in the riverbed. Because the saltcedars intercept some ground water that otherwise would discharge to the river as base flow, removal of the saltcedars should increase base flow.

Base flow and ground water in the bottom land, for the most part, are a mixture of ground water from the shallow and artesian aquifers west of the river. Regardless of the quantity of inflow to the bottom land from each aquifer or seasonal changes in leakage between the aquifers, elimination of saltcedar transpiration near the river should affect base flow in the river and ground-water storage in the bottom land.

Acknowledgments

Numerous facets of the hydrology were discussed on several occasions with P.D. Akin, New Mexico State Engineer Office, and W.E. Hale, G.A. Hearne, E.V. Thomas, and E.P. Weeks, U.S. Geological Survey. E.V. Thomas made statistical comparisons between the base flow, ground-water levels, ground-water pumpage, and precipitation. The freely given time and expert opinions of these colleagues are gratefully acknowledged. L.D. Marsell and others in the U.S. Bureau of Reclamation's Carlsbad office were always cooperative and provided valuable information about the initial clearing of saltcedars and subsequent maintenance.

Well-Numbering System

The system of numbering wells in southeastern New Mexico is based on the common subdivision of public lands in sections. The well number, in addition to designating the well, locates its position to the nearest 10-acre tract in the land network. The number is divided by periods into four segments. The first segment denotes the township south of the New Mexico base line; the second denotes the range east of the New Mexico principal meridian, and the third denotes the section. The fourth segment of the number, which consists of three digits, denotes the 160-, 40-, and 10-acre tracts, respectively, in which the well is situated. For this purpose, the section is divided into four quarters, numbered 1, 2, 3, and 4 in the normal reading order, for the northwest, northeast, southwest, and southeast quarters, respectively. The first digit of the fourth segment gives the quarter section, which is a tract of 160 acres. Similarly, the 160-acre tract is divided into four 40-acre tracts numbered in the same manner, and the second digit denotes the 40-acre tract. Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 11.25.36.142 is in the NE$\frac{1}{4}$SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 36, T. 11 S., R. 25 E., as shown in figure 6.

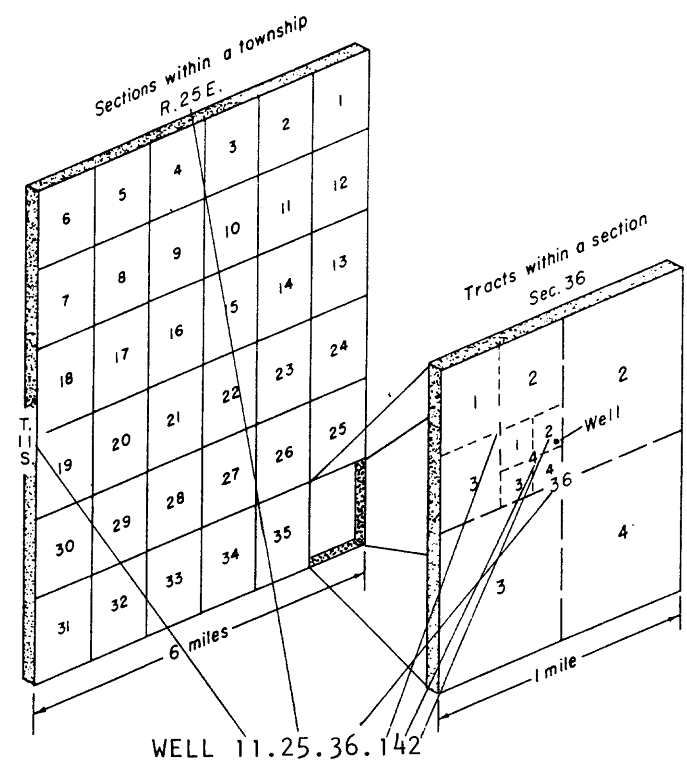


Figure 6.--System of numbering wells in New Mexico.

AREA OF PHREATOPHYTE GROWTH PRIOR TO 1967

Phreatophytes are plants that are capable of extending their root systems to the water table and obtaining a continuous supply of water. The phreatophytes that prosper best along the Acme-Artesia reach are saltcedar (*Tamarix chinensis*), saltgrass (*Distichlis stricta*), and sacaton (*Sporobolus airoides*) (Horton, 1976, p. 3 and 6). Small mesquite bushes also grow in the area, but few grow in the bottom land.

Generally, the denser stands of saltcedars along the Acme-Artesia reach were in that part of the bottom land where the depth to the water table is 10 feet or less. The width of this zone in the bottom land ranges from about 500 to 6,500 feet and averages about 2,800 feet; the area of the zone is about 19,000 acres.

Mower and others (1964, table 7, p. 63) stated that in 1958, the areas of saltcedar, grass, and mesquite at natural density in the Acme-Artesia reach were 28,100, 9,800, and 3,400 acres, respectively. When adjusted to 100-percent volume density (Mower and others, 1964, p. 60-63), these figures became 8,690, 7,350, and 170 acres, respectively. Grass growing in open areas in the less dense saltcedar tracts would be equivalent to an additional 9,670 acres of grass at 100-percent density.

Mower and others (1964, p. 63, table 7) also indicated that the average rate of spreading of saltcedars was 2,450 acres per year in 1957 and 1958. This may have been a temporary increase in the spreading rate not typical of the average growth and spreading rate in the Acme-Artesia reach because precipitation at Roswell and Artesia during 1958 was one of the greatest since 1941 (fig. 7).

A comparison of aerial photographs taken in 1961 and 1964 to the 1958 phreatophyte-distribution survey of Mower and others (1964, pl. 6) indicates that some of the saltcedar tracts had become slightly denser by 1964, but that there had been little spreading into open areas away from the main 1958 growth tracts. It appears that spreading of the saltcedars was considerably less after 1958 than just prior to that time. Accurate calculations of the 100-percent density of saltcedars along the 82-mile sinuous flood plain of the Acme-Artesia reach are difficult to make. Mower and others (1964, p. 58-61) estimated the saltcedar density from the shading and tone of aerial photographs and field surveys at selected locations.

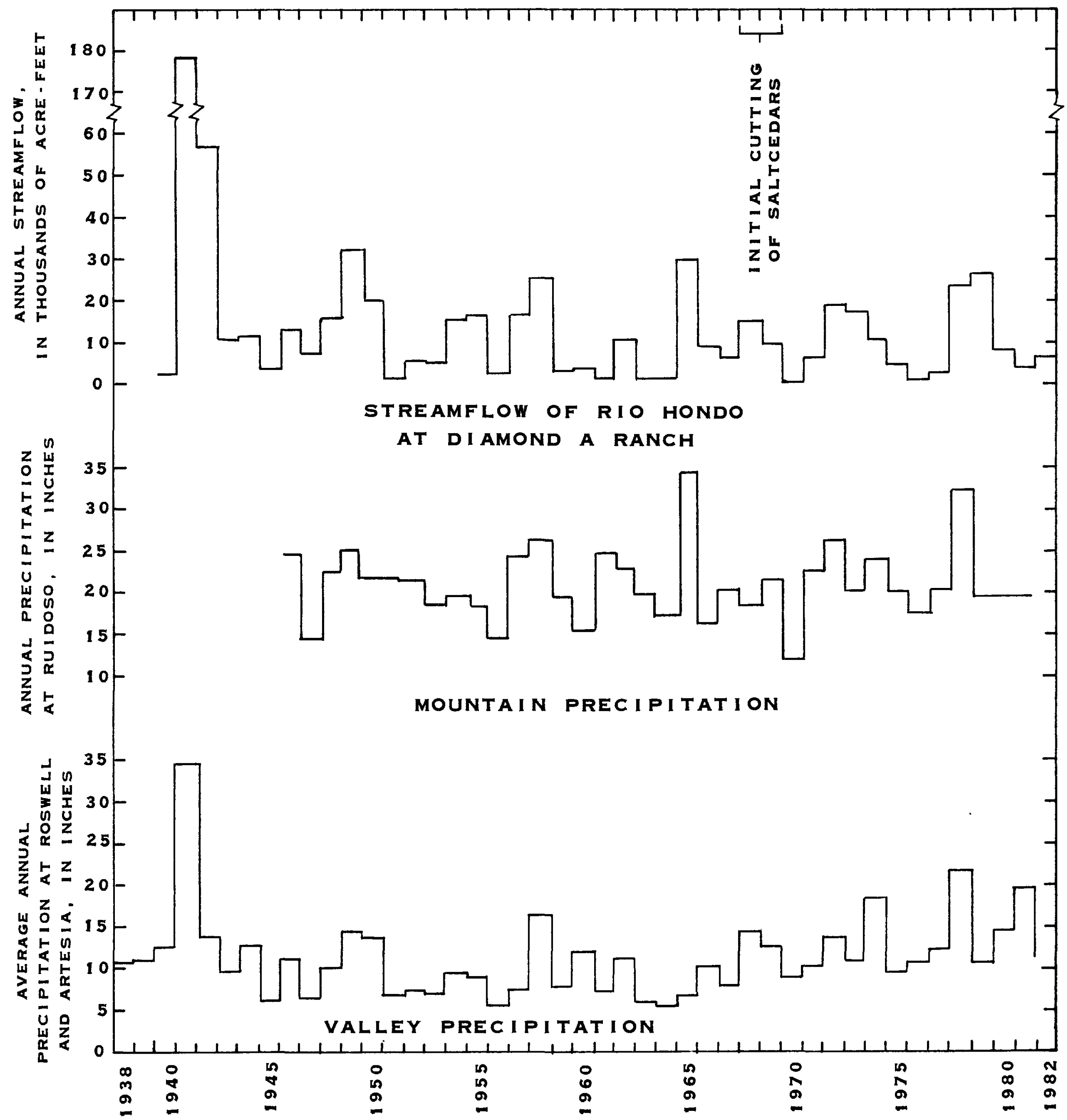


Figure 7.--Relation of annual streamflow in the Rio Hondo at Diamond A Ranch, precipitation at Ruidoso, and precipitation at Roswell and Artesia, 1938-82.

ESTIMATES OF POSSIBLE WATER SALVAGE IN THE PECOS RIVER VALLEY OF NEW MEXICO

Mower and others (1964, p. 64-81) made an appraisal of potential ground-water salvage along the Pecos River between the Acme and Artesia gaging stations for 1956-58. Using four different methods, they concluded that the annual consumptive use[1/] of water by native vegetation in the bottom land between the Acme and Artesia gaging stations was 70,000 to 80,000 acre-feet. They used average annual consumptive-use rates, at 100-percent phreatophyte volume density, of 6 feet for saltcedar, 1.2 feet for grass, and 3 feet for mesquite and estimated that the consumptive use during 1958 was 72,500 acre-feet. They went on to state that "....a water-salvage program consisting of clearing all saltcedar and encouraging a grass cover probably would reduce the 1958 rate of water use in the bottom land by about 28,000 acre-feet a year" (p. 91). This would be a salvage of about 1 acre-foot of water for each acre of saltcedars to be cleared because Mower and others (1964, p. 63) estimated that the gross area of saltcedars during 1958 was 28,100 acres.

The gross area of saltcedars initially cleared during 1967-69 under the Bureau of Reclamation's clearing and control program was 19,000 acres. (See section entitled "Gross acreage treated.") Assuming that the consumptive use of water was about the same during 1966 as it was during 1958 and that a grass cover replaced the saltcedars after clearing, the salvage according to Mower and others (1964, p. 66) would be about 19,000 acre-feet per year. If the consumptive use was somewhat greater during 1966 than during 1958 because of slightly increased saltcedar density, the anticipated salvage with a replacement grass cover would then be about 20,000 acre-feet per year.

Weeks and others (1987) measured consumptive-use rates for saltcedar and replacement vegetation in the Acme-Artesia reach during 1980-82 by the eddy-correlation technique and an eddy-correlation energy-budget technique. Although large uncertainties between the two techniques were noted, the measurements indicated that annual consumptive use of water by saltcedar was about 1.0 foot more than that by replacement vegetation. Weeks and others recognized the difficulties of extrapolating salvage estimates throughout the reach, but indicated that water salvage of 10,000 to 20,000 acre-feet per year could have occurred.

The only tank (evapotranspirometer) study of water use by saltcedar in the Pecos River valley of New Mexico was made at Carlsbad in 1940. Two 6-foot-diameter metal tanks were each planted with one clump of saltcedar (National Resources Planning Board, 1942, p. 197). The results of this study were inconclusive because the study was short and the two plants that were used were not well buffered from the effects of radiation and wind (Horton, 1976, p. 6).

1/ Consumptive use includes transpiration by vegetation and evaporation from the ground in the vicinity of the vegetation, if the latter is occurring.

PHREATOPHYTE CLEARING AND CONTROL PROGRAM OF THE U.S. BUREAU OF RECLAMATION

Authorization

The Congress, by an act approved September 12, 1964 (Public Law 88-594), authorized the Secretary of the Interior to initiate a continuing program to decrease water losses along the Pecos River from its headwaters near Las Vegas, New Mexico, to Girvin, Texas (fig. 1). The U.S. Bureau of Reclamation was assigned responsibility for the program, which is a cooperative endeavor among the Federal Government, New Mexico and Texas, and the landowners along the river. The phreatophyte area between Artesia and Lake McMillan was temporarily excluded from the program to avoid possible increased sedimentation in Lake McMillan, a terminal storage reservoir for the Carlsbad Irrigation District.

Gross Acreage Treated

The U.S. Bureau of Reclamation's program for the Acme-Artesia reach was devoted almost exclusively to the clearing and control of saltcedars. Natural grasses were disturbed only where they were difficult to avoid. A special effort to clear the few mesquite in the area was not made, although some mesquite was cut with the saltcedars.

The area of about 21,000 acres in which saltcedars were cleared in the reach extended from the U.S. Highway 70 bridge, 3 river miles upstream from the Acme gaging station, to the Artesia gaging station (H.J. Boyd, U.S. Bureau of Reclamation, written commun., 1976). This included about 600 acres upstream from the Acme gaging station and about 1,100 acres of the river channel and wet sand bars. It also included stands of saltcedars purposely left for wildlife shelter on the Bitter Lakes National Wildlife Refuge (about 300 acres) and 30-foot-wide bands on either side of the river (about 400 acres). Adjusting for these areas, the gross area between the Acme and Artesia gaging stations in which saltcedar clearing actually took place was about 19,000 acres. This is somewhat less than the estimate of 28,100 acres for saltcedar-occupied areas made by Mower and others (1964, table 7, p. 63) in 1958. The areas left for wildlife shelter and the 600 acres north of the Acme gaging station were included in the estimate of Mower and others, but also included are some sparsely vegetated tracts some distance from the river that were not cleared by the Bureau of Reclamation.

Schedule and Type of Treatment

The original clearing of saltcedars along the Acme-Artesia reach by the Bureau of Reclamation was as follows: Acme gaging station to Roswell, March 1967 through September 1967; Roswell to Hagerman, July 1967 through April 1968; Hagerman to Artesia gaging station, April 1968 through May 1969. This operation consisted of breaking the trees off above the crown without removing the roots.

Between June 1968 and June 1972, maintenance consisted of repeated mechanical chopping of fallen trees and regrowth, mowing of regrowth, and some spraying with herbicides in selected areas. The drum of the chopper had blades that could penetrate the soil to a depth of 6 to 12 inches and could cut, fracture, and shatter growth, leaving the woody vegetation in a flattened mat. Fallen trees as much as 15 feet in length and 8 inches in diameter could be chopped. Mowing left about 10 inches of stubble that could grow 3 to 7 feet in one season.

Root plowing and grubbing have been the principal means of maintenance since June 1972, although some mowing continued. Root plowing, which is designed to extract medium- to large-sized material, cuts and removes roots from 10 to 18 inches below the land surface. The grubber is similar to a root plow, but has a smaller blade. It is used to grub out small stands or clumps of vegetation. These latter methods are much more effective in preventing regrowth than are chopping and mowing.

By late 1974, after the reach had been root plowed at least twice, regrowth began to decrease. Root plowing had apparently halted the saltcedar regrowth in most of the treatment area by late 1975, some 9 years after the project had started. Little regrowth could be found in the maintained area in 1982.

Replacement Vegetation

Much of the cleared area supported only deciduous forbs (mainly weeds) in September 1977. The forbs grow from about 1 to 6 feet in height and provide a sparse to dense ground cover between areas of bare ground. The roots of these forbs do not penetrate the soil deeply; they are sustained by moisture in the upper 6 to 18 inches of the soil. Grass has not yet (1987) spread naturally throughout much of the area, possibly because the periodic root plowing or other maintenance practices to control saltcedar regrowth tend to hinder development of a grass cover. Experimental grass seeding in selected tracts by the Bureau of Reclamation has not been satisfactory because precipitation did not occur soon after planting. In the summer of 1979, the forb *Kochia scoparia*, which sometimes is called summer cypress, was being used for cattle feed near the Bottomless Lakes West ground-water-monitoring site where saltcedars formerly had grown (fig. 1).

WATER-SALVAGE APPRAISAL TECHNIQUE OF THE U.S. GEOLOGICAL SURVEY

Base-Flow Analysis

The Geological Survey's original proposal for appraising the hydrologic effects of phreatophyte clearing and control was a comprehensive data-collection and analysis program of the Pecos River from its source to Girvin, Texas. A less expensive, alternative approach was to analyze streamflow records from a relatively small, but representative, part of the valley in order to determine if streamflow had changed after phreatophyte control was established. The latter option was chosen, and the 48-mile reach between the Acme and Artesia gaging stations was selected for study. There was an abundance of saltcedars in the area, and many years of reliable streamflow records were available. The appraisal technique to be used was designed to detect changes in the base flow of the river and not alterations in evapotranspiration from the bottom land adjacent to the river.

This study differs from other saltcedar studies in that the base flow was observed over long continuous periods before (20+ years) and after (14 years) the initial clearing of a large area of saltcedars (19,000 acres). Previous saltcedar studies generally involved artificial tank-type evapotranspirometers or water budgets in areas where smaller tracts had been cleared and where observation periods were shorter than in this study.

Calculation of Base-Flow Gain

Phreatophytes intercept water moving through the aquifers of the Roswell ground-water basin to the Pecos River. Removal of the saltcedars, therefore, should result in an increase in the base flow of the river, provided the salvaged water was not again diverted by increased evaporation or by some other means.

In order to detect the anticipated change in base flow, streamflow records from the Acme and Artesia gaging stations were used to calculate the base-flow gain for 1957-82 (table 2). Mean daily streamflow records from the two stations were plotted on the same hydrograph, and daily estimates of pumpage from the reach were added to the streamflow record at the Artesia gaging station. Next, lines separating base flow from surface runoff were drawn on the hydrographs (fig. 8), and the areas between lines were planimetered to obtain the monthly base-flow gain for 1957-82. A more detailed description of the method is given by Welder (1973).

The base-flow-gain values for 1957-82 (figs. 4 and 9, table 2) are believed to be fairly accurate, although the method of calculation may include some errors. Base-flow-gain determinations for the summer months depend on whether true base-flow conditions have been reached between surface-water releases from Sumner Dam (Welder, 1973, fig. 3) and on how well the separation between base flow and runoff can be made. Any error involved in the method probably is less than about 10 percent of the annual base-flow gain. Because the method of separation of base flow and surface runoff is consistent, any error from year to year also would be consistent. Base-flow-gain estimates prior to 1957 (Pecos River Commission, 1960, table 8-A-1) also are included in this report (fig. 4).

Table 2. Monthly and annual base-flow gain in the Acme-Artesia reach, in acre-feet, 1957-82

[Values corrected for pumpage from streams]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1957	3,740	2,980	3,120	3,300	3,010	2,010	1,360	1,540	1,410	1,830	3,560	3,970	31,830
1958	3,860	3,430	3,490	3,060	2,700	1,890	1,700	1,740	2,740	3,940	4,320	3,770	36,640
1959	3,270	2,950	3,980	3,130	2,740	2,240	1,880	1,340	790	1,330	2,310	3,000	28,960
1960	4,150	3,440	2,850	2,280	1,980	1,700	1,720	1,610	1,740	2,980	4,060	5,470	33,980
1961	5,490	3,790	4,200	3,430	1,750	1,990	1,970	1,600	1,390	1,460	2,730	3,670	33,470
1962	3,330	2,920	2,260	2,080	1,870	1,380	1,290	1,080	1,200	2,800	3,130	3,070	26,410
1963	3,220	2,860	2,820	2,000	1,930	1,230	930	910	960	1,150	2,150	2,620	22,780
1964	2,420	2,390	2,240	1,420	1,150	760	520	280	270	550	1,190	2,060	15,250
1965	2,030	1,700	1,640	1,270	1,150	920	750	910	1,060	780	1,700	2,420	16,330
1966	2,540	2,240	1,980	1,770	1,660	1,090	670	880	1,390	1,940	2,340	2,090	20,590
1967	2,620	2,280	1,920	1,240	1,040	1,070	810	670	850	780	1,340	2,000	16,620
1968	2,540	2,640	2,210	1,460	1,190	810	950	1,130	1,010	950	1,730	2,310	18,930
1969	2,340	1,850	1,910	1,800	1,720	1,300	880	780	1,130	1,640	2,240	3,120	20,710
1970	3,150	2,120	1,950	1,340	1,030	1,040	1,120	1,060	1,090	1,610	1,670	2,030	19,210
1971	2,280	1,830	1,660	910	880	750	390	660	1,060	1,360	2,040	2,250	16,070
1972	2,210	1,690	1,280	940	920	810	820	1,090	1,280	1,700	2,390	3,040	18,170
1973	3,040	2,220	2,070	1,490	1,330	1,090	890	690	750	890	1,340	1,770	17,570
1974	2,180	1,360	1,220	1,010	600	450	570	780	1,340	3,520	4,590	4,470	22,090
1975	3,610	2,800	2,730	1,720	1,240	920	880	780	970	980	1,830	2,090	20,550
1976	2,240	1,830	1,100	880	850	760	790	870	1,100	1,190	2,030	2,340	15,980
1977	2,240	1,650	1,420	980	870	680	570	670	950	1,610	2,120	2,090	15,850
1978	2,310	2,000	1,510	820	1,060	980	940	890	950	1,770	2,690	3,970	19,890
1979	4,750	3,470	3,270	1,370	1,010	1,210	1,540	1,510	1,040	1,300	1,740	2,490	24,700
1980	2,590	2,140	2,100	1,280	1,190	950	810	990	1,100	1,810	2,180	2,350	19,490
1981	2,270	2,150	1,740	1,190	920	760	850	1,190	1,740	2,230	2,520	2,820	20,380
1982	2,820	2,730	2,150	1,440	1,530	1,110	770	770	880	1,300	1,650	2,360	19,510

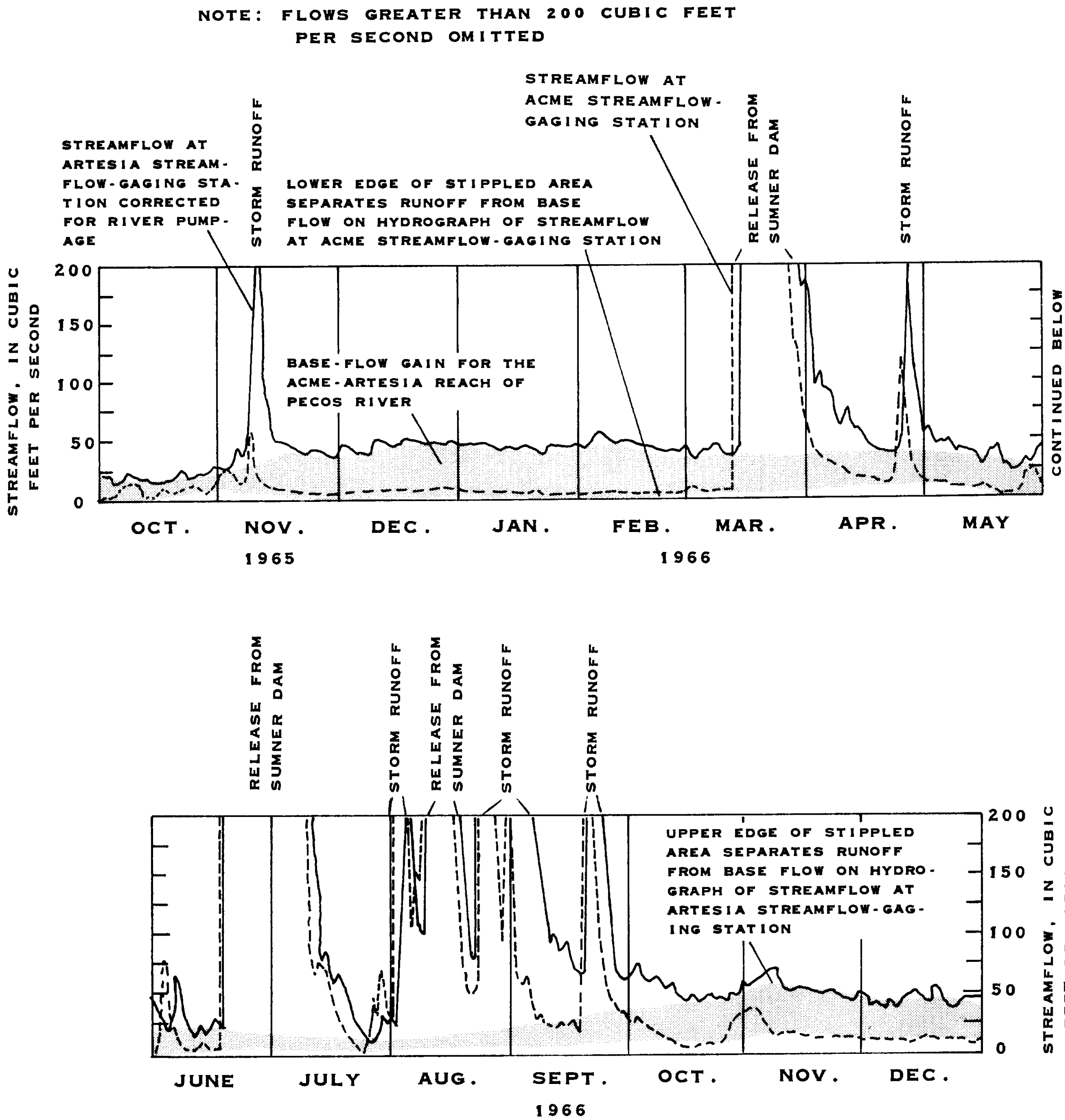


Figure 8.--Method of separating base flow on streamflow hydrographs of the Acme and Artesia streamflow-gaging stations (modified from Welder, 1973, fig. 3).

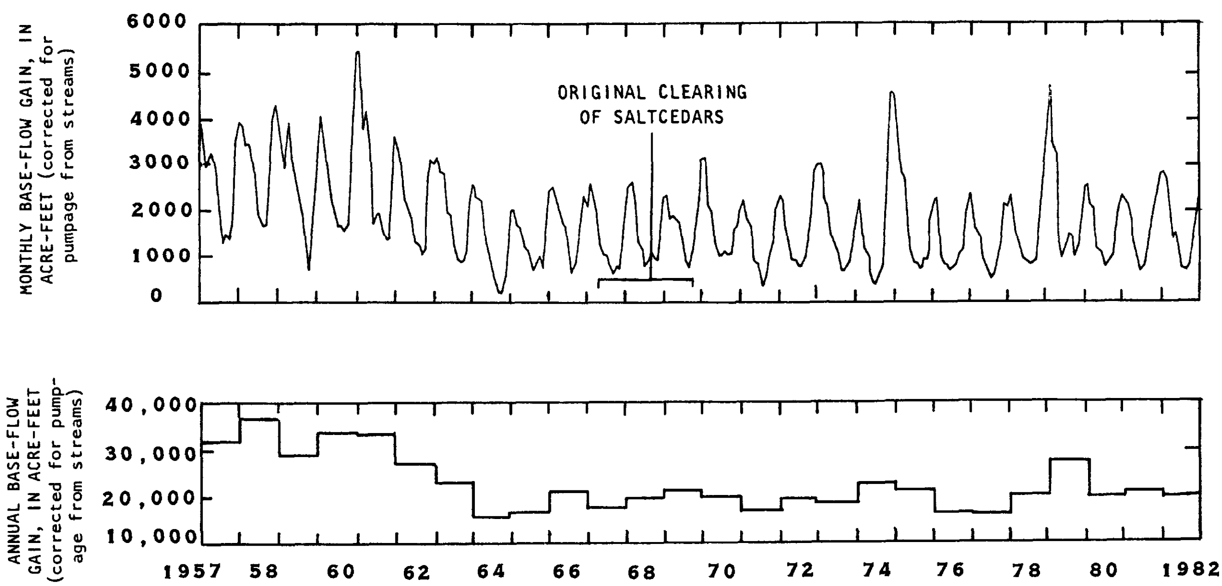


Figure 9.--Monthly and annual base-flow gain in the Acme-Artesia reach, 1957-82.

The base-flow-gain calculations for 1957-82 (figs. 4 and 9, table 2) include corrections for pumpage from the Pecos River and from near the mouths of Cottonwood Creek, Rio Felix, Zuber Draw, and the Rio Hondo downstream from the Hagerman Canal. This pumpage includes an allotment for the flow from drains that reach the Pecos River. It is the amount of water pumped from the river and selected tributaries; no adjustments have been made for conveyance loss.

Adjustments for the following were excluded from the base-flow-gain calculations: (1) evaporation from the Pecos River, tributaries, and wet sand bars; (2) pumpage from the Wiggins drain (13.26.27.333), which is diverted 1 mile west of the river and averages less than 100 acre-feet per year; and (3) flow in the Hagerman Canal, which is supplied by water from wells, surface water, and drain water.

Trends in Base-Flow Gain

A general, but erratic decrease in base-flow gain occurred from 1938 to 1964. The abnormally excessive precipitation during 1941, which averaged 34.61 inches between the Roswell and Artesia weather stations, increased base-flow gain greatly in 1941 and 1942. Not until 1947 did the base-flow gain decrease to less than that during 1940.

The decrease in base-flow gain after 1942 was interrupted during years when precipitation was substantial in the Pecos River valley or the Sacramento Mountains west of the valley or both. During 1965, precipitation of 34.81 inches at Ruidoso (fig. 7) resulted in increased tributary streamflow and recharge to the aquifers of the Roswell ground-water basin. Streamflow in the Rio Hondo at Diamond A Ranch, for example, was 30,500 acre-feet during 1965 as compared to about 1,000 acre-feet during 1964 (fig. 7). The subsequent recharge probably resulted in an increase of base-flow gain during 1965 and 1966. Base-flow gain for these years would have been less had the decrease prior to 1964 continued. In 1967 through 1982, the trend of base-flow gain (fig. 4) in the Acme-Artesia reach changed from a general decrease to a moderate increase that tended to level off within a range of 15,850 to 24,700 acre-feet per year (table 2).

Causes of Trend Change in Base-Flow Gain after 1966

The principal factors in the Pecos River/Roswell ground-water basin hydrologic system that could have caused the 1967-82 trend of base-flow gain in the Acme-Artesia reach after 1966 are the following:

1. Decrease in transpiration.
2. Decrease in ground-water pumpage.
3. Increase in precipitation.

A decrease in transpiration by saltcedars without an equivalent increase in evapotranspiration from bare ground and replacement vegetation after clearing should have resulted in a rise in the water table in the bottom land and an increase in ground-water seepage to the river. If the base-flow gain shown in figure 4 is related to the consumptive use of ground water by saltcedars, then the cessation in the decrease of the base-flow gain after 1966 can be attributed, at least in part, to the clearing and control of saltcedars.

A decrease in ground-water pumpage would have decreased artificial discharge from the aquifers and increased natural discharge to the river, provided that the average annual recharge had not decreased. In 1967, the discharge from all irrigation, municipal, industrial, and commercial wells was metered for the first time. Flowmeters were installed on the wells, which are maintained by the Pecos Valley Artesian Conservancy District.

Annual ground-water pumpage (fig. 4) was compiled as follows:

1938-51 Estimates of irrigation pumpage compiled by Mower (1960, p. 72-73), using the gross duty or quantity of water required to irrigate 1 acre of cropland, the number of acres irrigated annually, and the quantity of precipitation during the growing season.

1952-57 Estimates of irrigation pumpage compiled by Mower (1960, p. 65), using electric-power records and average water-level changes in the Roswell ground-water basin.

1958-66 Estimates of irrigation pumpage compiled by the U.S. Geological Survey, using electric-power records and average water-level changes in the Roswell ground-water basin.

1967-82 Metered pump-discharge measurements of irrigation, municipal, industrial, and commercial water use, compiled by the New Mexico State Engineer Office.

The estimates for 1938-66 were increased by adding estimates of pumpage for municipal, industrial, commercial, domestic, and stock use, which ranged from 1,700 to 2,000 acre-feet per year. The estimates for 1967-82 were increased by adding estimates of domestic and stock use, which ranged from 2,000 to 3,000 acre-feet per year. A small proportion of metered pumpage, about 2 percent, that was outside of the main part of the Roswell ground-water basin was not included in the 1967-82 estimates.

In general, the annual pumpage was about 16 percent less after meter installation in 1967 than during the 1951-66 premetered period. This apparent decrease in pumpage could account for an increase in ground-water discharge to the river and the general change in the trend of base-flow gain after 1966 (fig. 4).

The average annual precipitation at the Roswell and Artesia weather stations was 8.76 inches during 1951-66 and 13.20 inches during 1967-82 (fig. 7). The average annual increase in precipitation of 4.44 inches could have resulted in a decrease in pumpage for irrigation and an increase in recharge to the Roswell basin aquifers. This, in turn, would increase the ground-water flow to the river and slow down the decrease in base-flow gain.

Relation of Base-Flow Gain and Hydraulic Heads of the Aquifers in the Roswell Ground-Water Basin

The hydrographs of water levels in the three observation wells shown in figure 4 and data from many other wells (Welder, 1983, figs. 15 and 23) indicate that there was a widespread decline in water levels in both aquifers of the Roswell ground-water basin from 1942 to 1964. Since 1964, water levels in both aquifers, in general, have stabilized, and in some areas near the Acme-Artesia reach, they have risen. However, in a few areas of the Roswell ground-water basin, water levels in the shallow aquifer have continued to decline. The similarity in patterns of the water levels in the aquifers and base-flow gain (fig. 4) and the fact that the aquifers are the principal sources of the base flow indicate that changes in the hydraulic heads of the aquifers cause related changes in the base-flow gain.

A statistical analysis of base-flow gain and artesian water levels in the Orchard Park well (fig. 10) indicates that the two variables were well correlated during 1957-66, but not during 1967-76. The simple linear equation, $Y = a + bX$, where Y is the dependent variable (base-flow gain), a and b are standard linear-regression-equation coefficients (Riggs, 1968, p. 11), and X is the independent variable (artesian water level), was used. Correlation coefficients for 1957-66 and 1967-76 were 0.93 and 0.05, respectively. The solid line depicting base-flow gain in figure 10 is base-flow gain calculated from streamflow and river-pumpage data. The dashed line for 1957-66 is base-flow gain derived from a linear-regression equation relating base-flow gain and water levels for 1957-66, a period prior to clearing and control of phreatophytes. The dashed line for 1967-76 is the predicted base-flow gain if the 1957-66 relation between base-flow gain and water levels had not changed. The predicted base-flow gain for 1967-76 generally was greater than the calculated base-flow gain, except in 1972 (fig. 10), which indicates that the consumptive use of saltcedar regrowth after 1967 may have been greater than the consumptive use of saltcedar trees prior to 1967.

The relation between base-flow gain and artesian water levels, however, could be different before and after January 1967, and the projection of the base-flow gain after 1966 is questionable, although the standard error of the estimate of the dependent variable on the independent variable (2,100 acre-feet) was not excessive. Efforts to establish a specific relation between base-flow gain and artesian water levels for a longer period of record (1946-80) were unsuccessful. Graphs of the changes in base-flow gain and artesian and shallow water levels were prepared for 1946-80 using a smoothing technique (Velleman and Hoaglin, 1981, p. 159). The graphs appeared to be similar but did not have a significant statistical correlation. The relations between artesian and shallow water levels, ground-water pumpage, precipitation, and base-flow gain for 10, 20, and 30 years were studied by multiple-regression methods. Significant results were not obtained because changes in the recharge-discharge relations in the Roswell ground-water basin have occurred through the years.

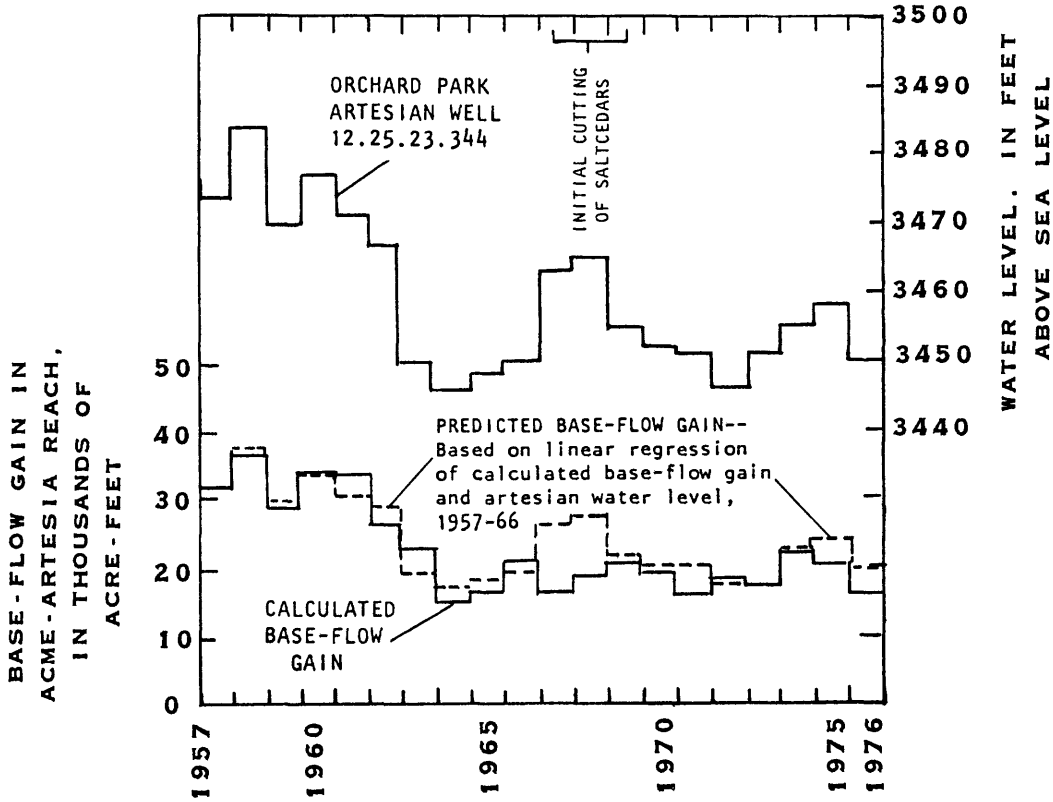


Figure 10.--Relation of artesian hydraulic head in the Roswell ground-water basin and calculated and predicted base-flow gain in the Acme-Artesia reach, 1957-76 (prepared from U.S. Geological Survey data).

Time of Salvage Accrual

The time of salvage accrual is the calculated time that it would take for the anticipated quantity of salvage to move from the perimeter of the cleared area through the shallow alluvium of the bottom land to the river. Using a method described by Jenkins (1970), the time calculated for most of the anticipated 20,000 acre-feet of water salvage produced by clearing and control of 19,000 acres of saltcedars to accrue to the river is about 1½ years. The following assumptions were made in making the calculation: two uniform strips of saltcedar growth, one on each side of the river, and each having a width of 1,633 feet and a length of 48 miles; an aquifer transmissivity of 1,500 feet squared per day; and an aquifer specific yield of 0.15. The transmissivity is based on aquifer tests in the flood plain listed in Mower and others (1964, p. 28-29), and the specific yield is based on estimates by Hantush (1957, p. 28).

The anticipated annual salvage rate of 20,000 acre-feet per year (as increased river flow), according to Jenkins' (1970) method, would be achieved as follows: 15,200 acre-feet per year after 1 year; 16,600 acre-feet per year after 2 years; 17,200 acre-feet per year after 3 years; 17,600 acre-feet per year after 4 years; 18,900 acre-feet per year after 20 years, and so forth. About 88 percent of the anticipated salvage rate of 20,000 acre-feet per year would occur 4 years after saltcedar control became effective. For the same periods, the cumulative volumes of salvage at the anticipated annual salvage rate of 20,000 acre-feet, according to Jenkins' (1970) method, would be as follows: 11,700 acre-feet after 1 year; 28,000 acre-feet after 2 years; 45,000 acre-feet after 3 years; 62,000 acre-feet after 4 years; and 357,000 acre-feet after 20 years.

The rates and volumes of salvage calculated above indicate that an increase in base-flow gain in the Acme-Artesia reach probably would be detectable after about 2 years. An increase of this magnitude is not evident (table 2). The Jenkins' (1970) method used to determine this increase utilized an arbitrary stream depletion factor that may not be applicable to the conditions in the Acme-Artesia reach. The stream depletion factor at any location in the system according to Jenkins (1970, p. 2) depends on the integrated effects of the following: irregular impermeable boundaries, stream meanders, aquifer properties and their areal variation, distance of the phreatophytes from the stream, and imperfect hydraulic connection between the stream and the aquifer.

Monitoring of Water Levels

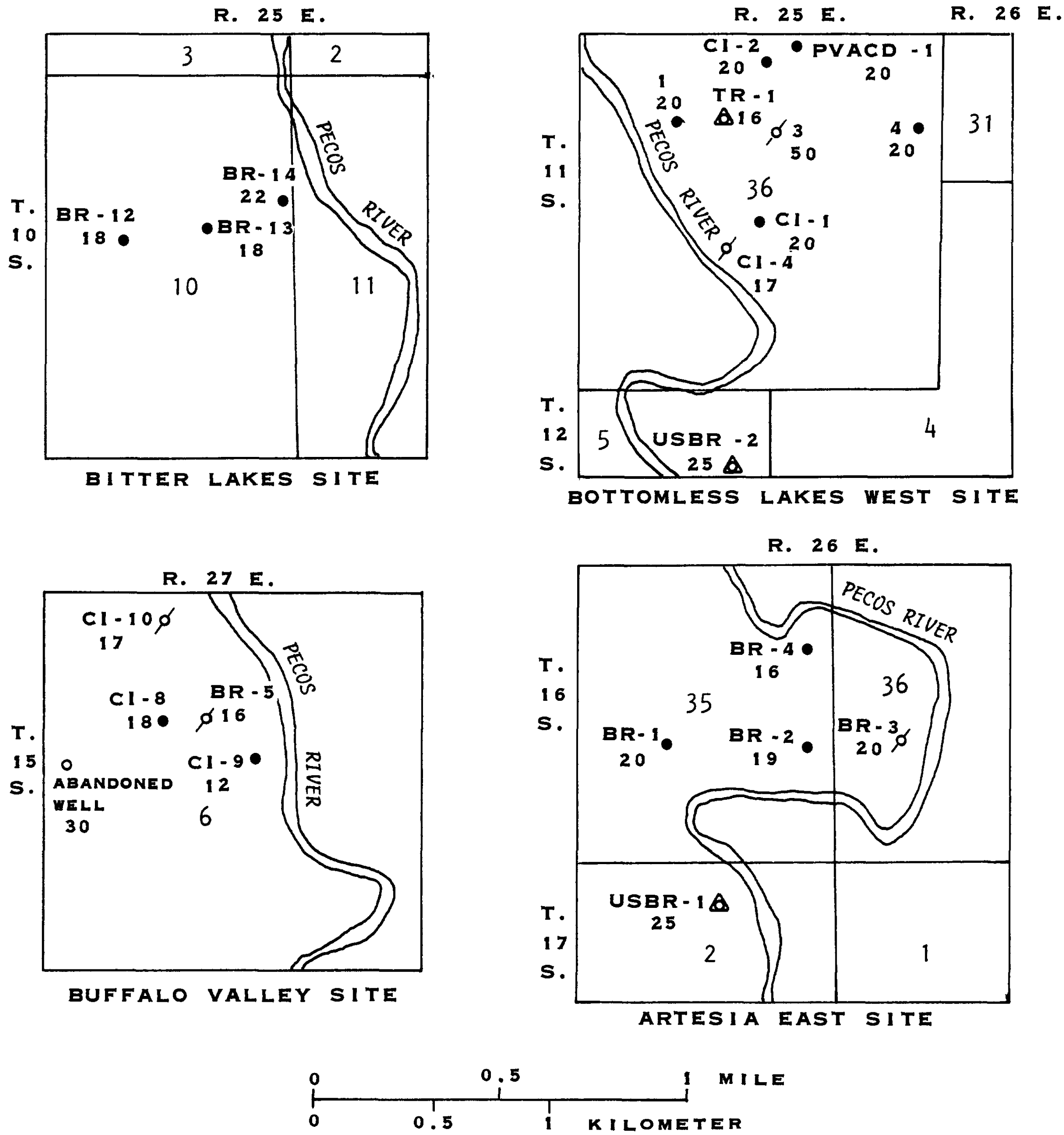
Observation-Well Network

Only a token number of observation wells for monitoring water-level changes in the bottom land in order to determine the effects of saltcedar control were used because evaluation of changes in the base-flow gain was the primary analytical technique to be used. From November 29 to December 13, 1967, the Bureau of Reclamation drilled 14 observation wells in areas of phreatophyte growth along the Acme-Artesia reach of the Pecos River. Plastic pipes 21 feet long and 1½ inches in diameter were placed in the drill holes at depths of about 19 feet below land surface. These wells, plus 19 existing wells of somewhat similar construction, were utilized to monitor water levels at seven different sites along the reach. Three of the sites were eliminated from the monitoring program because of flooding from irrigation, altered drainage for flood control, and accidental destruction of observation wells. The remaining sites are 43, 32, 14, and 4 miles north of the Artesia gaging station (fig. 1). Three analog recorders were installed in March 1973, one on an existing observation well and two on new observation wells (fig. 11).

The observation wells at the four sites did not monitor water-level changes along the entire 82 river miles of the meandering Acme-Artesia reach. Each river meander tends to isolate a segment of the flood plain that may have unique conditions of recharge and discharge, aquifer permeability, depth of water table, and phreatophyte growth. Many more observation wells would be needed to completely monitor the reach and to accurately calculate changes in ground-water storage.

Annual Water-Level Fluctuations

Hydrographs of water levels in key observation wells completed in the alluvium of the bottom land at the four sites are shown in figures 12 and 13. The most conspicuous water-level pattern is an annual high level in February and March and an annual low level in August and September. Water levels in the principal aquifers west of the bottom land clearly show this, and wells 4, CI-2, and TR-1 at the Bottomless Lakes West site (fig. 12) are examples of this type of response in the bottom land. A combination of pumping of irrigation wells in the Roswell ground-water basin and evapotranspiration is a probable cause of such annual fluctuations. Water levels in well BR-13 at the Bitter Lakes site and in well CI-4 at the Bottomless Lakes West site show a probable partial response to these stresses, particularly in late summer. Annual water-level fluctuations in well CI-4, which is very close to the river, probably are affected by river stage. The near cessation of an annual response of water levels during 1975 and 1976 in wells TR-1 and CI-2 (fig. 12) at the Bottomless Lakes West site may have resulted from unusually excessive precipitation during 1974 and more vigorous root plowing by the Bureau of Reclamation in 1974-76.



EXPLANATION

BR-1 ● 20 — OBSERVATION WELL--Upper letters and number are well name; lower number is depth of well, in feet below land surface; active (●), equipped with analog recorder (△), destroyed (ø)

Figure 11.--Location of observation wells at four sites in the bottom land of the Acme-Artesia reach.

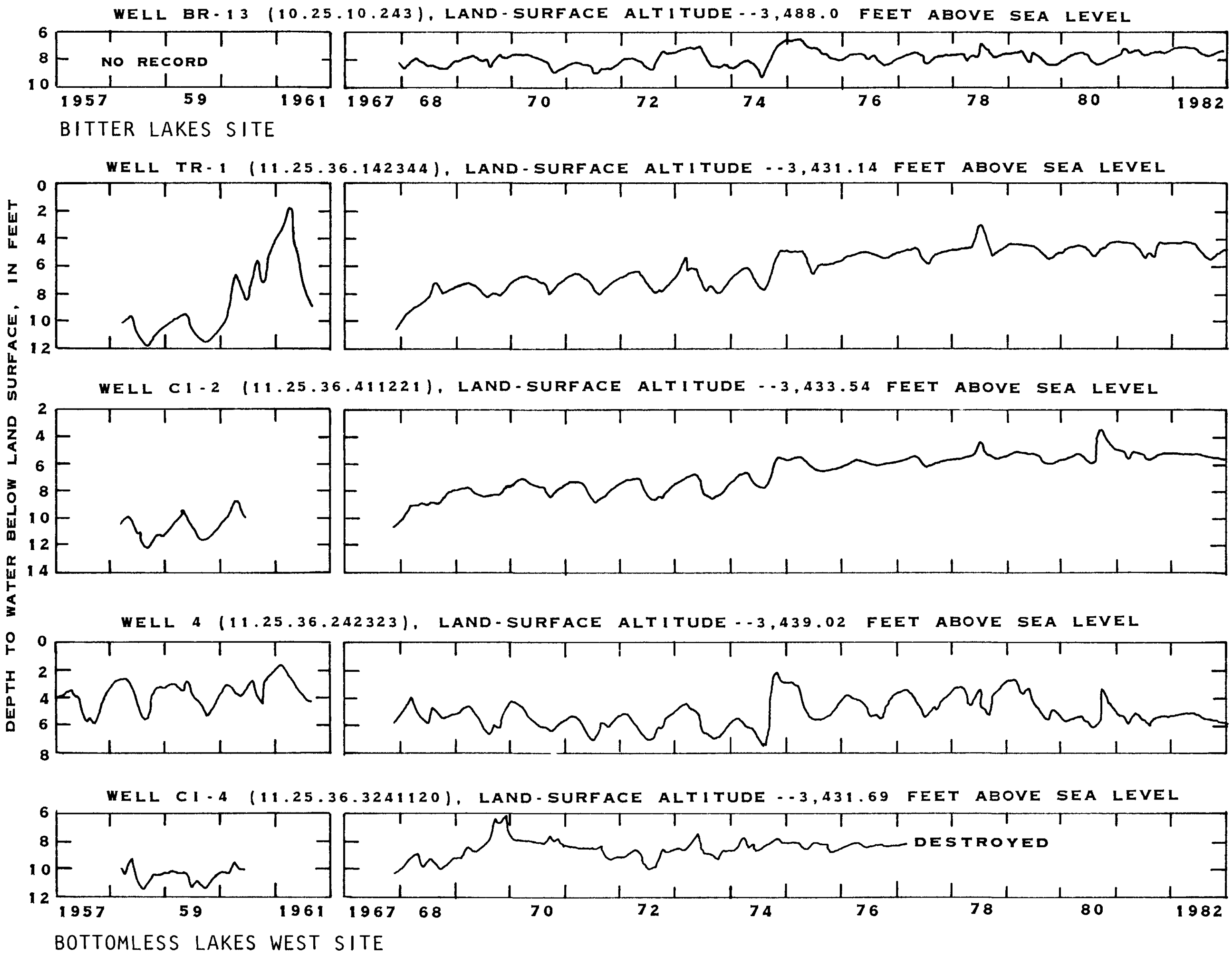


Figure 12.--Water levels in observation wells at the Bitter Lakes and Bottomless Lakes West sites, 1957-61 and 1967-82.

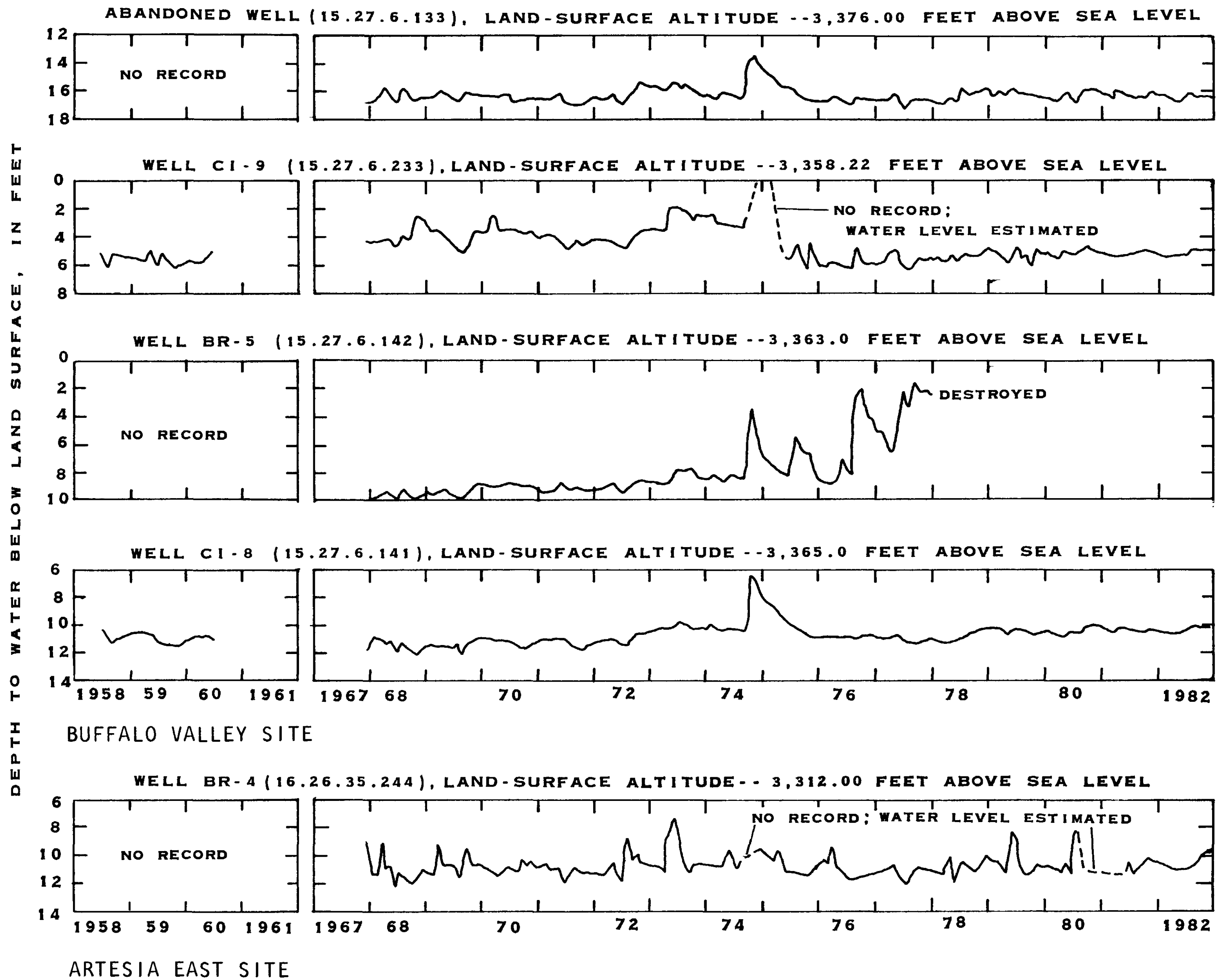


Figure 13.--Water levels in observation wells at the Buffalo Valley and Artesia East sites, 1958-61 and 1967-82.

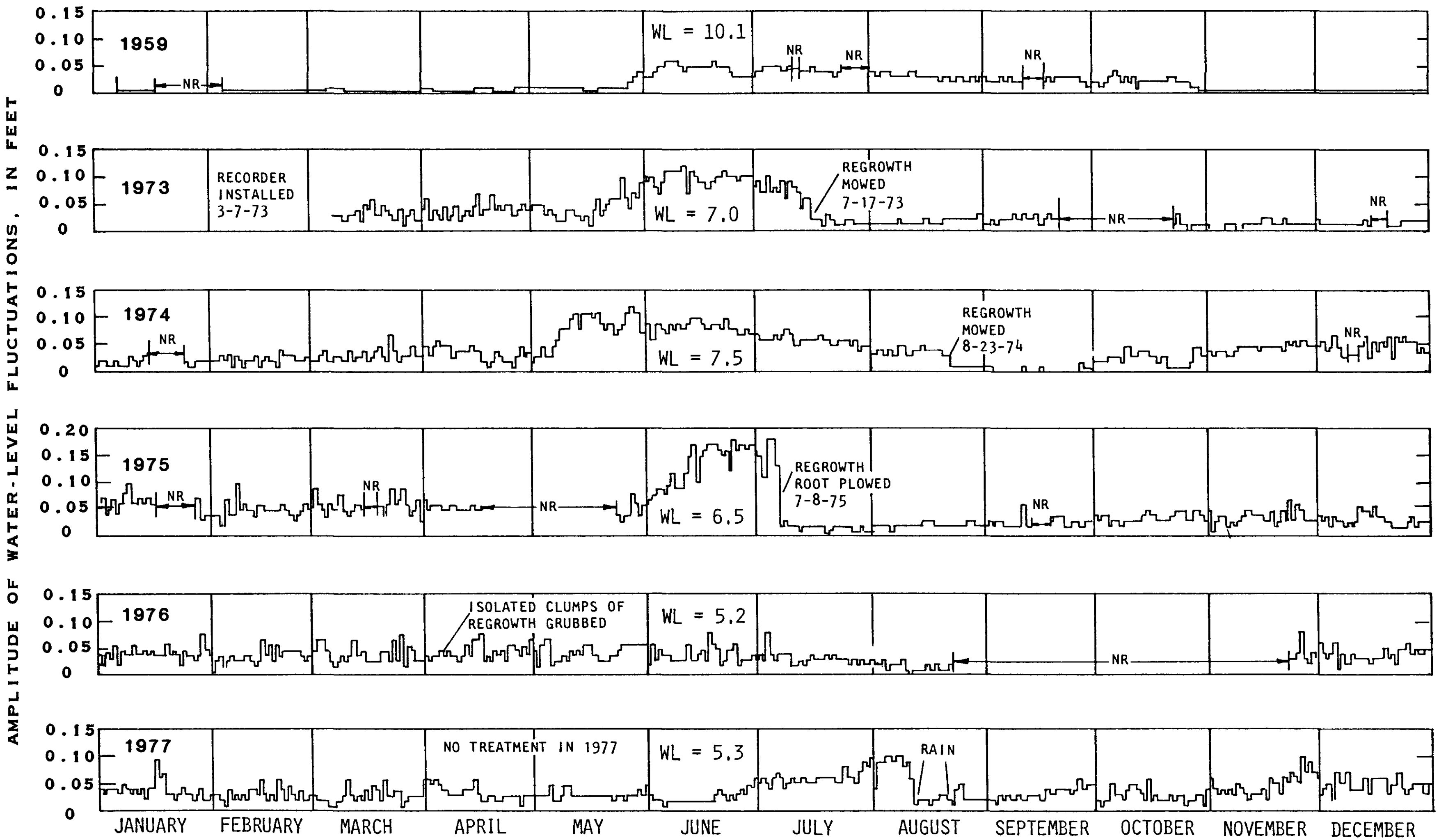
The reasons water levels in all wells do not fluctuate the same in response to a uniform stress probably are related to the maturity and capability of vegetation to transpire water under variable soil conditions, erratic climatic conditions, and possibly the depths to the water table.

Diurnal Water-Level Fluctuations

Diurnal fluctuations of the water table occur almost all year long. They are caused by various combinations of stresses imposed on the hydrologic system, particularly by transpiration, evaporation, and changes in atmospheric pressure. Diurnal fluctuations due to transpiration and evaporation tend to be in phase with each other, but are generally out of phase with the barometric fluctuation due to atmospheric-pressure changes. The effects of transpiration and evaporation may obscure the effects of barometric pressure during warm summer months.

Diurnal water-level fluctuations caused by transpiration have been recorded in wells TR-1 and USBR-2 at the Bottomless Lakes West site. Water levels start to rise in the evening and continue to rise gradually until late the following morning. Then, water levels decline rapidly until about midafternoon, when water levels stabilize and the cycle is again repeated. The amplitudes of diurnal fluctuations of the water table at well TR-1 for 1959, which was 7 years prior to the initial clearing of saltcedars in 1967-69, and for 1973-77, several years after the initial clearing, are shown in figure 14. The recorded amplitudes of fluctuations in water levels at well TR-1 ranged from about 0.05 to 0.18 foot (fig. 14). The fluctuations begin and end at various times of the year, depending on when plants start to grow in late spring and when they become dormant in autumn. These diurnal fluctuations were caused, at least in part, by transpiration because they decreased noticeably when saltcedars surrounding the wells were mowed or root plowed (fig. 15). The rise in the water table after the fluctuations ceased in 1973 and 1975 (fig. 15) coincided with a rise in river stage after releases of water from Sumner Dam and is not necessarily due to clearing of saltcedars.

A number of relations between the use of water by saltcedars and the physical environment around well TR-1 are indicated by the water-table fluctuations shown in figure 14. Well TR-1 is about 1,200 feet east of the Pecos River on the first bottom-land terrace above the river. Saltcedars with a density of 70 to 90 percent grew on the terrace (Mower and others, 1964, pl. 9, sheet 3) prior to 1967, whereas only scattered forbs were present in 1977. Well TR-1, which is 16 feet deep, was equipped with a continuous analog water-level recorder from March 1958 to August 1961 and from March 7, 1973, through December 1985.



EXPLANATION

NR NO RECORD

WL AVERAGE DEPTH TO WATER TABLE IN JUNE, IN FEET BELOW LAND SURFACE

Figure 14.--Diurnal fluctuations of the water table at well TR-1, Bottomless Lakes West site, 1959 and 1973-77.

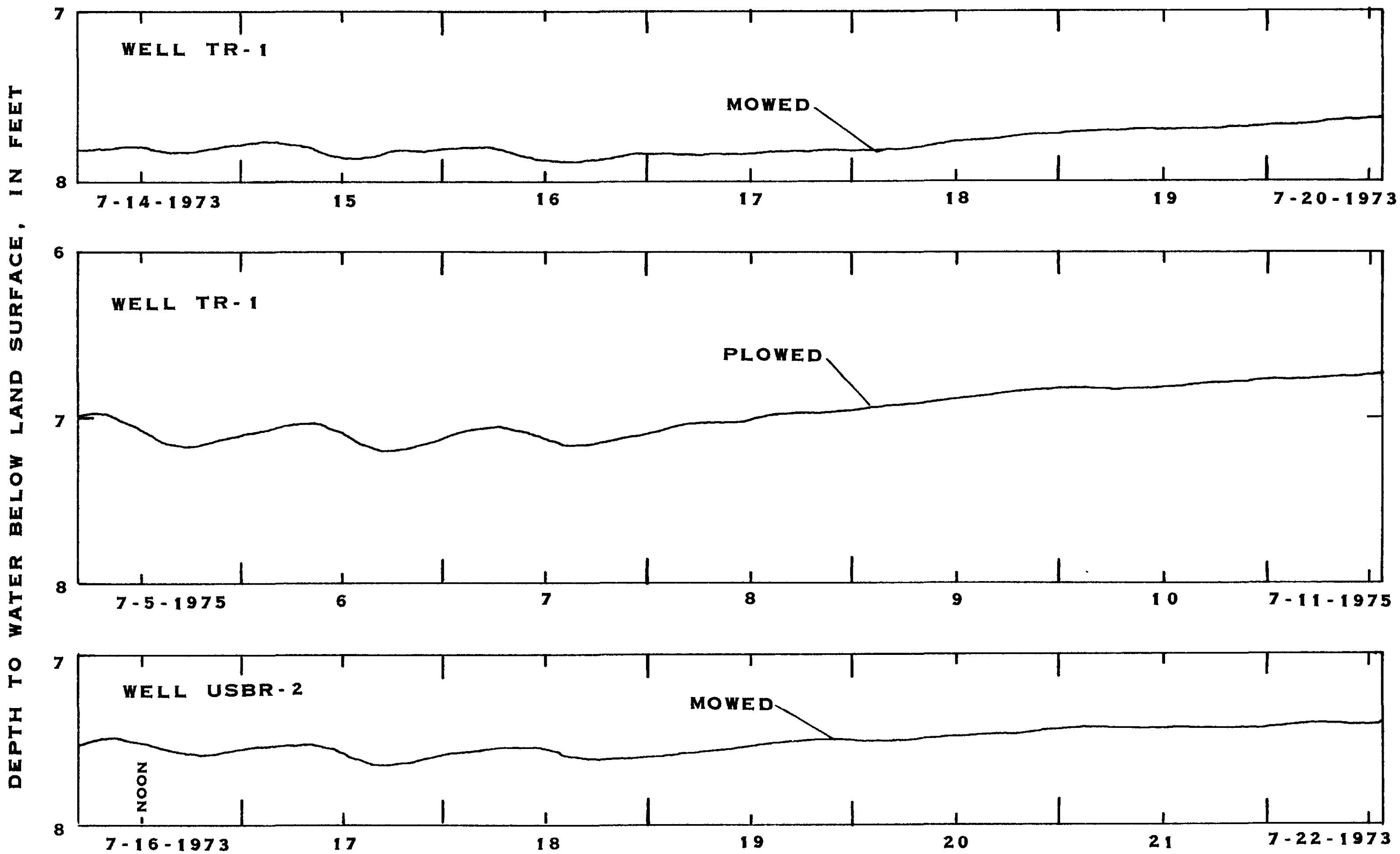


Figure 15.--Effect of saltcedar-regrowth treatment on the diurnal fluctuation of the water table at well TR-1 (July 14-20, 1973; July 5-11, 1975) and at well USBR-2 (July 16-22, 1973), Bottomless Lakes West site.

In 1959, when the terrace around well TR-1 was overgrown with mature saltcedar trees, the summer transpiration caused diurnal water-level fluctuations of about 0.03 to 0.05 foot, and the winter amplitudes ranged from 0.005 to 0.01 foot (fig. 14). In contrast, summer diurnal water-level fluctuations as large as 0.12 to 0.18 foot occurred in 1973-75 when small, new saltcedar plants were vigorously growing; the winter amplitudes also were relatively large. However, the average depth to water in June, a month of vigorous saltcedar growth, was 10.1 feet in 1959 and 6.5 to 7.5 feet in 1973-75. It might be concluded, therefore, that if the water-level-fluctuation amplitudes increased with water use by saltcedar and if the climatic factors were constant, then more water was discharged to the atmosphere in the vicinity of well TR-1 during each of the summers of 1973-75 than during the summer of 1959.

When the saltcedar regrowth was mowed around well TR-1 in July 1973 and August 1974, the amplitudes of diurnal water-level fluctuations were decreased substantially for several weeks before growth started again (fig. 14). After the root plowing in July 1975, however, the regrowth virtually was stopped, and diurnal water-level fluctuations due to transpiration at well TR-1 virtually ceased. The diurnal water-level fluctuations that occurred at well TR-1 between July 1975 and December 1977 were caused principally by evaporation from bare ground and by barometric-pressure changes. Comparison of the preclearing and postclearing amplitudes, however, indicates that the average fluctuation of the water table was greater after the July 1975 root plowing in late 1975 and in 1976 and 1977 than it was in 1959 prior to clearing. The relatively large fluctuations in July and early August of 1977 are discussed in the section entitled "Significance of evaporation from bare ground after clearing."

Rises in river stage cause substantial rises in water levels at some of the observation wells. Water levels in wells at the Buffalo Valley site and well BR-4 at the Artesia East site, for example, have sharp peaks that correspond with releases from Sumner Dam and with storm runoff (fig. 13). Diurnal fluctuations of the altitude of the river stage also occurred, but they were only a few hundredths of a foot in magnitude, and they did not occur at regular times. A correlation between the river stage and water-table diurnal fluctuations has not been recognized. Pumpage diversions from the river, releases from Sumner Dam, tributary and drain inflow, weather conditions, and ground-water pumpage tend to obscure diurnal fluctuations of the river stage.

Long-Term Change in the Water Table under the Bottom Land

The water-level hydrographs in figures 12 and 13 indicate that water levels in some of the wells were higher in later years than in the early years of record. Water levels in some of the wells, however, declined or had little or no change during the period of record. Rises in water levels at wells CI-2, TR-1, and CI-4 at the Bottomless Lakes West site were about 1 to 5 feet during 1958-76. The general rise of about 1 foot at the Buffalo Valley site, which started in July 1972, coincides with the time the area was first root plowed. The generally lower water level in well CI-9 at the Buffalo Valley site after 1974 probably was caused by a lowering of the river's base level or bank erosion during flooding in late 1974 (fig. 13). Unusually excessive precipitation in 1974 (fig. 7) caused water levels in many of the observation wells to rise in the fall of 1974. Short-term water-level rises that occurred in 1973 and 1975 after the mowing and plowing of saltcedar regrowth at the Bottomless Lakes West site (fig. 15) appear to have been caused, at least in part, by decreased transpiration.

Water levels in 13 of 19 observation wells at the four sites indicate fairly long-term rises in the water table in some areas of the bottom land. The number and distribution of data points, however, were insufficient to prove that there was a net rise throughout the entire bottom land of the Acme-Artesia reach. If there was a net rise, it probably did not exceed 2 feet. It is equally difficult to specify what part of the rise in water levels might have been caused by saltcedar clearing and control and what part might have been caused by recharge from precipitation that exceeded the average during 1974, 1978, and 1981.

A permanent rise in the water table due to saltcedar control would increase ground-water seepage to the river; thus, water salvage in the form of ground-water storage and base-flow gain would occur. A 2-foot rise in water levels throughout the 19,000 acres of cleared bottom land would be equivalent to about 6,000 acre-feet of water, assuming that the specific yield of the aquifer was 0.15. If the water table remained at the same higher altitude, then in time the annual increase in discharge to the river would be about 6,000 acre-feet, provided there were no other losses from the system.

DIFFICULTY OF ASCERTAINING WATER SALVAGE IN THE ACME-ARTESIA REACH

Many environmental factors in the vicinity of the cleared area of the bottom land and some distance away in the complex dual aquifer system of the Roswell ground-water basin have affected the detection of water salvage by the saltcedar-control program in the Acme-Artesia reach of the Pecos River. Three factors of particular concern are the determination and application of consumptive water-use rates, the isolation of the causes of a change in base-flow gain, and the assessment of the significance of evaporation from bare ground after clearing of saltcedars.

Determination and Application of Consumptive-Use Rates

Commonly cited tank or evapotranspirometer studies of water use by saltcedars were in the Gila River valley, near Glenbar, Arizona (Gatewood and others, 1950); the Gila River valley near Buckeye, Arizona (van Hylckama, 1974); and the Rio Grande valley near Bernardo, New Mexico (Robert Schembera, U.S. Bureau of Reclamation, written commun., 1973). These studies list annual (April-October) consumptive-use rates of saltcedars for water-table depths comparable to depths in the Acme-Artesia reach before saltcedar clearing of 6.3, 4.5, and 3.2 acre-feet per acre at Glenbar, Buckeye, and Bernardo, respectively (table 3). The average depths to the water table for these particular water-use rates were 6.2 feet at Glenbar, 6.9 feet at Buckeye, and 5.7 feet at Bernardo. The considerable divergence in these water-use rates casts some doubt on their applicability in other areas.

Horton (1976, p. 6), in reference to the Glenbar, Arizona, study, stated that, "These tanks had large single shrubs planted in duplicates at different water-table depths. The readings during the first year are very comparable to the Carlsbad readings. During the second year, however, growth was vigorous and the water losses high, probably much higher than typical saltcedars. Nevertheless, these figures have been widely used to estimate losses from flood-plain reaches."

The two principal methods used by Mower and others (1964, p. 65-70) to compute the consumptive use of ground water by phreatophytes in the Roswell ground-water basin involved extrapolation and modification of a consumptive-use rate from Glenbar, Arizona, (Gatewood and others, 1950, p. 203) to this area and determining the residual of a water-budget equation. Selection of the appropriate consumptive-use rate and determination of the correct density and area of growth of saltcedar could involve large errors. van Hylckama (1974, p. E28) and Horton (1976, p. 6-7) discussed the problem of using volume density to predict water consumption. Tank studies (van Hylckama, 1974) near Buckeye, Arizona, indicate that the assumption that consumptive use is directly proportional to volume density is not necessarily valid. "If a certain use of water by a stand (of saltcedars) of 50-percent volume density is measured, a prediction as to what might happen when this stand develops to 100-percent volume density will lead to conclusions which may be grossly overestimated" (van Hylckama, 1974, p. E28).

Table 3. Comparison of tank studies in other areas with study of Acme-Artesia reach

Area	Latitude	Altitude (feet above sea level)	Type of tank	Surface area of tank (square feet)	Depth of tank (feet)	Specific conductance of supply water (microsiemens per centimeter at 25 °Celsius)	Age of oldest saltcedar growth / Period of measurement[1]	Annual consumptive use (acre-feet per acre) / Water-table depth (feet)
Glenbar, Ariz.	33°00'N	2,900	Metal	28-79	6-10	[2]346	1 year[3] / Oct. 1943, Apr.-Sept. 1944	[4]6.3 / 6.2
Buckeye, Ariz.	33°21'N	850	Plastic	900	14	[2]7,570	3 years[3] / 1962-63	[5]4.5 / 6.9
Bernardo, N. Mex.	34°27'N	4,730	Butyl rubber	1,000	12	[2]1,250	7 years[3] / 1968	[6]3.2 / 5.7
Acme-Artesia reach	33°12'N	3,291-3,507	—	—	—	[7]2,000-10,000	25+ years[8] / —	[9]6.0 / 7±

[1]Period of measurement is for the same growing seasons (April through October) as the water use in column to right.
[2]Salinity buildup in tanks exceeded these values.
[3]Relatively small plants, which grew vigorously, were planted in the tanks.
[4]Precipitation excluded; tank 12; 88 percent average saltcedar volume density (Gatewood and others, 1950, table 26).
[5]Precipitation excluded; average for tanks 1 and 4; 84 percent average saltcedar volume density (van Hylckama, 1974, tables 3 and 4).
[6]Precipitation excluded; tank 6; 84 percent average saltcedar volume density (Robert Schembera, U.S. Bureau of Reclamation, written commun., 1973).
[7]Water samples from alluvial test holes (Mower and others, 1964, fig. 16).
[8]Saltcedars in the Acme-Artesia reach prior to clearing generally were older and larger than plants used in tanks.
[9]Precipitation excluded; adjusted from Gatewood and others (1950, p. 203) by Mower and others (1964, p. 66).

The transfer of consumptive-use rates from one area and their application to another area depend on the similarity of the characteristics of the two areas--particularly climate, maturity of vegetation, salinity of water, soil type and permeability, and water-table depth. Saltcedar growth south of the Artesia gaging station in the bottom land of the Pecos River was observed to be less vigorous where the depth of the water table was deep and more vigorous where the water table was shallow. Many other factors such as the hydrology of adjacent areas and stresses imposed by humans are also involved.

Two important sources of error in determining consumptive use of water as a water-budget residual in the Acme-Artesia reach involve ground-water inflow from the west and upward leakage from the artesian aquifer (Mower and others, 1964, p. 70). These are large factors in the water budget, and they are controlled by aquifer characteristics that are not well known. The same factors also hinder accurate determination of the consumptive use of water from bare ground or replacement vegetation after saltcedar clearing. For these and other reasons, estimates of the consumptive use of water in the Acme-Artesia reach and the predicted, potential water salvage could be considerably in error.

The consumptive use of ground water in the bottom land and the hydraulic heads of the aquifers must affect the base-flow gain of the Acme-Artesia reach. The relation of one or the other to the base-flow gain might have been better established had both the decrease in ground-water pumpage and the clearing of saltcedars in the bottom land not started about the same time in 1967 (fig. 4).

The direct measuring of consumptive water use (Weeks and others, 1987) over natural saltcedar groves and replacement vegetation by utilizing the latest equipment was a practical approach. By doing so, some of the stresses in the complex ground-water system could be ignored. The disparity of estimates obtained by use of the eddy-correlation and energy-budget methods used by Weeks and others (1987), the less than ideal study sites in some cases, and the lack of measurements prior to the initial saltcedar cutting were problems that affected the results of the study by Weeks and others (1987).

The lack of a correlation between depth to water and consumptive water use noted in the study by Weeks and others (1987) and by Culler and others (1982, p. 29) is in contrast to observations in this study. The decrease in the amplitudes of the diurnal fluctuations of the water table with depth measured at well TR-1 (fig. 14) and the less vigorous saltcedars observed in the bottom land south of the Artesia gaging station and north of Lake McMillan where the water table is relatively deep indicate that consumptive water use by saltcedars is related to the depth of the water table. Current (1987) vegetation and water-level data in files of the Geological Survey indicate that saltcedars were sparse in places north of Lake McMillan where the water table is deeper than about 25 feet below land surface. Nevertheless, results of the study by Weeks and others (1987) are evidence that consumptive use of water from areas of existing replacement vegetation in the Acme-Artesia reach is less than the consumptive use of water from areas of mature saltcedar growth. The difference, however, may not be as great should the replacement vegetation eventually become dense because evaporation from bare ground may be less than the transpiration of vegetation that fills in bare spaces. Culler and others (1982, p. 49) indicated that replacement vegetation of grass would decrease water salvage substantially.

Isolation of the Causes of the Change in Base-Flow Gain along the Acme-Artesia Reach after 1964

Isolation and quantification of causes of change in the trend of base-flow gain along the Acme-Artesia reach of the Pecos River after 1964 cannot be made with certainty because the hydrologic system is complex and because three significant hydrologic events started about the same time. Reasonable speculations on how the causes are related to base-flow gain and their relative importance, however, can be made.

The decreasing trend of base-flow gain along the Acme-Artesia reach from 1947 to 1964 changed to an erratic but generally stable trend from 1965 to 1982 (fig. 4). The average decrease in base-flow gain for 1947-64 was 1,630 acre-feet per year, and the average base-flow gain for 1965-82 was 19,040 acre-feet per year. The three principal causes of the trend change in base-flow gain after 1964 were as follows:

1. Decreased transpiration due to saltcedar removal.
2. Decreased ground-water pumpage from aquifers in the Roswell ground-water basin.
3. Increased precipitation.

Causes 2 and 3 are reflected in the hydraulic heads of the artesian and shallow aquifers of the Roswell ground-water basin. The trends in the hydraulic heads of the two aquifers are remarkably similar to the trend of the base-flow gain (fig. 4). Water in the two aquifers flows through the bottom land to the river and is the main source of base flow. Prior to removal of saltcedar in the bottom land, the saltcedar intercepted and consumed part of the ground water before it reached the river.

The trend change in base-flow gain during 1965 and 1966 must be related to the hydraulic heads of the aquifers and not to a decrease in transpiration because removal of saltcedars did not begin until March 1967. Runoff from intense precipitation in the mountains west of the Roswell ground-water basin during 1965 (fig. 7) recharged the artesian aquifer, which then recharged the shallow aquifer through upward leakage (fig. 3). Decreased ground-water pumpage and the increase in precipitation maintained erratic but relatively constant hydraulic heads of the aquifers from 1966 through 1982. These conditions resulted in a fairly constant inflow of ground water to the bottom land and the river for 1967-82, with one possible exception that is discussed below.

After the initial clearing of mature saltcedar from March 1967 to May 1969, saltcedar regrowth returned each year until August 1975, when root plowing virtually eradicated all of the new growth. Diurnal water-level fluctuations at the Bottomless Lakes West site indicate that the quantity of water consumed in saltcedar-regrowth areas might have been relatively large. Therefore, the effects of saltcedar removal on base-flow gain probably occurred in small increments each year until about 1976. Had the full effect of the program occurred immediately after the initial cutting of mature trees in May 1969, the 1969 base-flow gain of 20,710 acre-feet (table 2) would have almost doubled, provided that the predicted salvage rate of 20,000 acre-feet per year was reasonably accurate. A large increase in base-flow gain in a short time was not recognized because any possible accrual to base-flow gain as salvage probably occurred during the eight growing seasons during 1968-75. The cumulative increase during the 8 years also would have been relatively large if salvage had occurred at the anticipated rate.

The water-salvage rate might have been greater during 1977 than predicted because there was very little vegetation, and evaporation from bare ground could be less than transpiration from a continuous canopy of replacement vegetation. Regardless of whether or not water salvage reached the river quickly during 1 or 2 years or slowly during 8 years, a large increase in base-flow gain did not occur.

One possible reason that more water formerly transpired by saltcedar was not recognized as salvage in the form of base-flow gain is that a substantial part of the water that was transpired was seepage from precipitation to the bottom-land topsoil. During precipitation, the upper few feet of soil absorbs water that later is transpired back to the atmosphere before it can move down to the water table. Mower and others (1964, p. 66) referred to this type of water as "effective precipitation" and indicated that it was a large part of the water used by phreatophytes. Some seepage from precipitation does reach the water table, but it is probably much less than ground-water inflow from adjacent areas. Water from precipitation that was transpired may be regarded as temporary water that cannot be salvaged and cannot add to base-flow gain in the river. After saltcedar removal, this type of water would return to the atmosphere by evaporation from bare ground and transpiration by replacement vegetation. If the replacement vegetation was beneficial, then some water salvage would be involved, but water salvage is defined in this study as increased base-flow gain or an addition to ground-water storage even if ground-water storage is decreasing or both.

A second possible reason that more salvage is not recognized as increased base-flow gain is that water salvage could be offsetting a decreasing inflow of ground water to the bottom land from the shallow aquifer of the Roswell ground-water basin. Although water-level declines in much of the shallow aquifer were decreased or stopped after 1965, there are places where the water table is still declining (Welder, 1983, fig. 23). The water level in the Cumberland well (fig. 4) almost leveled off after 1965, but it still had a small declining trend from 1965 to 1982. If this were a controlling factor in the ground-water system, then the trend in base-flow gain would have started to decrease after 1975; however, it did not (fig. 4). The artesian aquifer is much larger than the shallow aquifer, and it probably leaks directly to the bottom land where the river overlies thin alluvium or the leaky confining bed (fig. 3). It appears, however, that ground-water inflow to the bottom land was not affected by water-level declines in parts of the shallow aquifer from 1965 to 1982. If it had been, the base-flow gain would have continued to decrease.

To summarize, the base-flow gain in the Acme-Artesia reach of the Pecos River from 1965 to 1982 appears to have been controlled mainly by ground-water inflow, which was relatively stable during 1965-82. Cessation of the decreasing trend in base-flow gain occurred at about the same time that hydraulic heads in the aquifers of the Roswell ground-water basin ceased to decline. The effect of saltcedar removal on base-flow gain probably is less than the effect of the stabilization of the hydraulic heads on base-flow gain. Water salvage from saltcedar control in the form of base-flow gain or an addition to ground-water storage probably is less than 19,110 acre-feet per year, which was the average annual base-flow gain for 1967-82.

Significance of Evaporation from Bare Ground after Clearing

The rate of evaporation from bare ground is a function of weather conditions and characteristics of the unsaturated zone that facilitate transfer of water from the saturated zone to the land surface by capillary action. A steady rate of capillary rise and evaporation depends on the depth of the water table, suction of the land surface, and characteristics of the soil profile that limit the maximum flux to the land surface (Hillel, 1971, p. 189).

Evaporation from bare ground generally is considered to be small, especially where the water table is several feet deep. van Hylckama (1974, table 16) listed evaporation rates from bare ground (excluding precipitation) for January through October 1964 of 3.35 inches in tank BS3 of the Imperial Camp study site near Yuma, Arizona, and 16.63 inches in tank 11 of the Buckeye study site. The water-table depth at both places was about 4 feet. van Hylckama (1974, p. E25) suggested that the finer soil at Buckeye might account for some of the difference in evaporation rates from bare ground at the two sites.

Hanson, Kipple, and Culler (1972, p. 19) implied that evaporation from bare ground west of Safford, Arizona, after phreatophyte clearing was 20 inches per year. The average depth to water near Safford ranges from 5 to 8 feet below land surface near the river and from 15 to 20 feet near the edges of the flood plain (Hanson and others, 1972, p. 4). Depth to water in the cleared area of the Acme-Artesia reach probably averages about 7 feet, which may be a little less than in the Safford area. Evaporation from bare soil in the Acme-Artesia area, therefore, could be about 20 inches per year if soil grain size and other conditions are similar to those at Safford. A substantial rise in the water table of the Acme-Artesia reach after clearing probably would increase the evaporation rate and partly offset the decrease of the consumptive use of water by the clearing of saltcedars.

On September 27, 1977, trenching with a backhoe 90 feet west of well TR-1 indicated that the silty clay and very fine grained sand (table 4) above the water table were damp. The water table was 5.4 feet deep. The capillary fringe appeared to extend from the water table to the land surface at that time. In this situation, evaporation from bare ground can remove water from the water table through capillary action. The increase in amplitudes of water-level fluctuations from June 20 to August 11, 1977 (fig. 14), probably was caused by evaporation from bare ground because no saltcedar regrowth or substantial number of forbs were present to cause diurnal fluctuations due to transpiration. As mentioned earlier, the amplitudes of the 1977 water-level fluctuations were generally greater than the amplitudes during the summer of 1959 when mature saltcedar trees occupied the same area. The water table, however, was deeper at well TR-1 in 1959 than in 1977.

In contrast to the environment near well TR-1, trenching on September 28, 1977, 30 feet south of well CI-9 at the Buffalo Valley site where the water table was about 6 feet deep, indicated that all the material above the water table was dry. This material consisted of a 1.5-foot layer of silty clay that was underlain by 5.5 feet of fine- to medium-grained sand (table 4). The pore spaces between the sand grains were too large to produce more than a small capillary rise, and evaporation from the water table could not occur at this site.

In evaluating the effects of phreatophyte clearing and control, it is important to know how much the consumptive use of water by saltcedars before clearing is offset by evaporation from bare ground after clearing and prior to the time that fairly extensive vegetation takes place. As late as 1982, much of the bottom land in the Acme-Artesia reach still had not been extensively revegetated. In areas where the water table was less than about 5 or 6 feet below the land surface and where the material above the water table was fine grained, evaporation from bare soil could have been substantial.

Using an equation from Hillel (1971, p. 185) to compute the capillary rise from a water table in soil of average silt-sized grains (0.0332 mm), as occurs at the Bottomless Lakes West site (table 3), the capillary rise is about 11 feet. In a fine- to medium-grained sand (0.250 mm), such as at the Buffalo Valley site (table 3), the capillary rise was calculated to be only 1.5 feet. Hillel (1971, fig. 9.2) indicated that a sandy loam can evaporate water at a rate of 1.2 inches per month from a water table 5.9 feet below the land surface. Sandy loam is coarser than the soil at the Bottomless Lakes West site and finer than the soil at the Buffalo Valley site. Data are not available to accurately calculate the total evaporation from bare ground in the bottom lands of the Acme-Artesia reach.

Table 4. Grain-size analyses of bottom-land soil[1]

Type of soil and particle size, in millimeters	Percentage, by weight, of particle size for indicated sample depth below land surface, in inches							
	5	13	22	31	40	49	64	74
Bottomless Lakes West site (90 feet west of well TR-1)[2]								
Coarse sand (0.5000-1.0000)	0	0	0	0.03	0	0	0	0
Medium sand (0.2500-0.5000)	0	0	0	0.17	0.01	0.1	0	0.3
Fine sand (0.1250-0.2500)	0.1	0.1	0.1	0.10	0.09	7.9	29.3	1.1
Very fine sand (0.0625-0.1250)	1.2	12.2	1.6	4.20	1.20	49.8	60.2	52.9
Silt (0.0039-0.0625)	30.4	74.6	37.3	82.20	53.40	32.9	9.3	38.9
Clay (0-0.0039)	68.3	13.1	61.0	13.30	45.30	9.3	1.2	6.8

Type of soil and particle size, in millimeters	Percentage, by weight, of particle size for indicated sample depth below land surface, in inches		
	11	34	59
Buffalo Valley site (30 feet south of well CI-9)[3]			
Coarse sand (0.5000-1.0000)	0.003	1.1	4.3
Medium sand (0.2500-0.5000)	.005	50.2	67.4
Fine sand (0.1250-0.2500)	.042	41.2	23.4
Very fine sand (0.0625-0.1250)	.150	6.7	3.4
Silt (0.0039-0.0625)	35.500	0.2	0.3
Clay (0-0.0039)	64.300	0.6	1.2

1 Sieve, pipette, or visual-accumulation-tube analyses by U.S. Geological Survey
2 Samples collected 9-27-77 by E.P. Weeks and G.E. Welder
3 Samples collected 9-28-77 by E.P. Weeks and G.E. Welder

CONCLUSIONS

The following conclusions concerning the hydrologic effects of saltcedar control (1967-82) on 19,000 acres of bottom land along the Acme-Artesia reach of the Pecos River are based on observations of the types and distribution of vegetation, diurnal water-level fluctuations, water-level depths, base-flow-gain trends, and physical aspects of the geohydrologic system:

1. Initial clearing of mature saltcedar from March 1967 to May 1969 did not stop transpiration by saltcedar because the plant roots continued to produce new growth for several years.

2. On the basis of the magnitude of diurnal water-level fluctuations, evapotranspiration from saltcedar regrowth and bare ground consumed more water per year during 1973-75 than did mature saltcedar during 1959, but the water table was shallower during 1973-75.

3. Saltcedar regrowth largely was eradicated by late 1975 because of root plowing.

4. On the basis of the magnitude of diurnal water-level fluctuations, evaporation from bare ground consumed more water during 1977 than did transpiration by mature saltcedar during 1959, but the water table was about 5 feet shallower during 1977.

5. Water use by saltcedar in the vicinity of well TR-1 appeared to decrease as the depth of the water table increased. This is indicated by the magnitude of diurnal water-level fluctuations. Saltcedar growth was less vigorous in many parts of the bottom land south of the Artesia gaging station where the water table was deep.

6. Water-level rises in 13 of 19 observation wells at four study sites in the bottom land indicate that an increase in ground-water storage, possibly as much as 6,000 acre-feet, could have occurred after saltcedar removal. Such an increase in storage should increase ground-water seepage to the river. An equivalent increase in base-flow gain could not be detected, and the quantity of water that may have been salvaged probably is considerably less than 6,000 acre-feet per year. Precipitation could have caused some of the rise in water levels.

7. The change in trend of base-flow gain during 1965 and 1966 was related to the hydraulic heads of the shallow and artesian aquifers of the Roswell ground-water basin and not to a decrease in transpiration because removal of saltcedars did not begin until March 1967. Decreased ground-water pumpage and increased precipitation maintained an erratic, but relatively stable trend in the aquifer heads during 1965-82. These conditions resulted in a fairly constant inflow of ground water to the bottom land and to the river.

8. The effects of saltcedar removal on base-flow gain probably occurred incrementally each year until about 1976 because saltcedar regrowth continued to transpire water until it was largely eradicated by root plowing in July 1975. If the anticipated annual salvage rate (20,000 acre-feet) had been achieved, the base-flow gain of the river would have nearly doubled. This did not happen.

9. One possible reason that more of the water formerly transpired by saltcedar was not recognized as salvage in the form of base-flow gain is that a substantial part of the water being transpired was seepage from precipitation to the bottom-land topsoil. This water would return to the atmosphere through evapotranspiration before and after saltcedar removal and, therefore, would not add to base-flow gain in the river. In places where the water table was relatively shallow (6 feet or less), evaporation from bare ground may have consumed fairly large quantities of ground water that formerly had been used by saltcedars. This would tend to decrease the quantity of salvage.

   A second possible reason that more salvage was not recognized as increased base-flow gain is that water salvage could have been offsetting a decreasing quantity of ground-water inflow from the shallow aquifer of the Roswell ground-water basin. If water-level declines in the aquifer, however, had caused a substantial decrease in ground-water flow to the river, then the decreasing trend in base-flow gain would have started after 1975. This did not happen. During 1965-82, the trend of base-flow gain was somewhat erratic, but relatively stable.

10. A final conclusion drawn from an analysis of base-flow-gain changes in the river and water-level measurements in the bottom land is that some salvage of water by saltcedar removal and control had occurred. The abrupt cessation of diurnal fluctuations in the water table after mowing and root plowing of saltcedar indicates that transpiration was stopped. The rise in the water table in parts of the bottom land indicates that some water went into ground-water storage, which could have contributed to base-flow gain. Salvage in the form of base-flow gain, at least in small quantities, may have taken place if a potential increase in seepage to the river because of saltcedar control offset water-level declines in parts of the shallow aquifer. Recognition of water salvage in the form of base-flow gain, however, is not evident. The effects of the saltcedar removal and control program are masked by the effects of increased precipitation and decreased ground-water pumpage. The quantity of water salvage as base-flow gain or an addition to ground-water storage in the Acme-Artesia reach of the Pecos River probably is less than the 1967-82 average annual base-flow gain of 19,110 acre-feet.

REFERENCES CITED

Culler, R.C., Hanson, R.L., Myrick, R.M., Turner, R.M., and Kipple, F.P., 1982, Evapotranspiration before and after clearing phreatophytes, Gila River flood plain, Graham County, Arizona: U.S. Geological Survey Professional Paper 655-B, 67 p.

Fiedler, A.G., and Nye, S.S., 1933, Geology and ground-water resources of the Roswell artesian basin, New Mexico: U.S. Geological Survey Water-Supply Paper 639, 372 p.

Gatewood, J.S., Robinson, T.W., Colby, B.R., Hem, J.D., and Halpenny, L.C., 1950, Use of water by bottom-land vegetation in lower Safford Valley, Arizona: U.S. Geological Survey Water-Supply Paper 1103, 310 p.

Hanson, R.L., Kipple, F.P., and Culler, R.C., 1972, Changing the consumptive use on the Gila River flood plain, southeastern Arizona--Age of changing priorities for land and water: Irrigation and Drainage Division, Specialty Conference, 1972, Spokane, Washington, p. 309-330.

Hantush, M.S., 1957, Preliminary quantitative study of the Roswell ground-water reservoir, New Mexico: New Mexico Institute of Mining and Technology, State Bureau of Mines and Mineral Resources Division, 118 p.

Hillel, Daniel, 1971, Soil and water, physical principles and processes: New York, Academic Press, Physiological Ecology Series, 288 p.

Horton, J.S., 1976, Management of moist-site vegetation for water; past history, present status, and future needs: U.S. Forest Service and U.S. Bureau of Reclamation publication, prepared at the request of Pacific Southwest Inter-Agency Committee, 41 p.

Jenkins, C.T., 1970, Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, Chap. D-1, 17 p.

Lyford, F.P., 1973, Valley fill in the Roswell-Artesia area, New Mexico: U.S. Geological Survey open-file report, 26 p.

Morgan, A.M., 1938, Geology and shallow-water resources of the Roswell artesian basin, New Mexico: New Mexico State Engineer Office Bulletin 5, 95 p.

Mower, R.W., [1960], Pumpage in the Roswell basin, Chaves and Eddy Counties, New Mexico: U.S. Geological Survey open-file report, 88 p.

Mower, R.W., Hood, J.W., Cushman, R.L., Borton, R.L., and Galloway, S.E., 1964, An appraisal of potential ground-water salvage along the Pecos River between Acme and Artesia, New Mexico: U.S. Geological Survey Water-Supply Paper 1659, 98 p.

National Resources Planning Board, 1942, Pecos River joint investigation reports of the participating agencies: Washington, D.C., U.S. Government Printing Office, 40 p.

Pecos River Commission, 1960, Report on review of basic data to Engineering Advisory Committee: New Mexico and Texas, Pecos River Commission Report, 36 p., 21 appendices.

Riggs, H.C., 1968, Some statistical tools in hydrology: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, Chap. A-1, 39 p.

van Hylckama, T.E.A., 1974, Water use by saltcedar as measured by the water-budget method: U.S. Geological Survey Professional Paper 491-E, p. E1-E30.

Velleman, P.F., and Hoaglin, D.C., 1981, Applications, basics, and computing of exploratory data analysis: North Scituate, Mass., Duxbury Press, 354 p.

Weeks, E.P., Weaver, H.L., Campbell, G.S., and Tanner, B.D., 1987, Water use by saltcedar and by replacement vegetation in the Pecos River flood plain between Acme and Artesia, New Mexico: U.S. Geological Survey Professional Paper 491-G, 33 p.

Welder, G.E., 1973, Base flow in the Acme-Artesia reach of the Pecos River, New Mexico, 1957-71: U.S. Geological Survey open-file report, 50 p.

_____1983, Geohydrologic framework of the Roswell ground-water basin, Chaves and Eddy Counties, New Mexico: New Mexico State Engineer Office Technical Report 42, 28 p.

U S GOVERNMENT PRINTING OFFICE: 1988—574-786/85,108 REGION NO 8