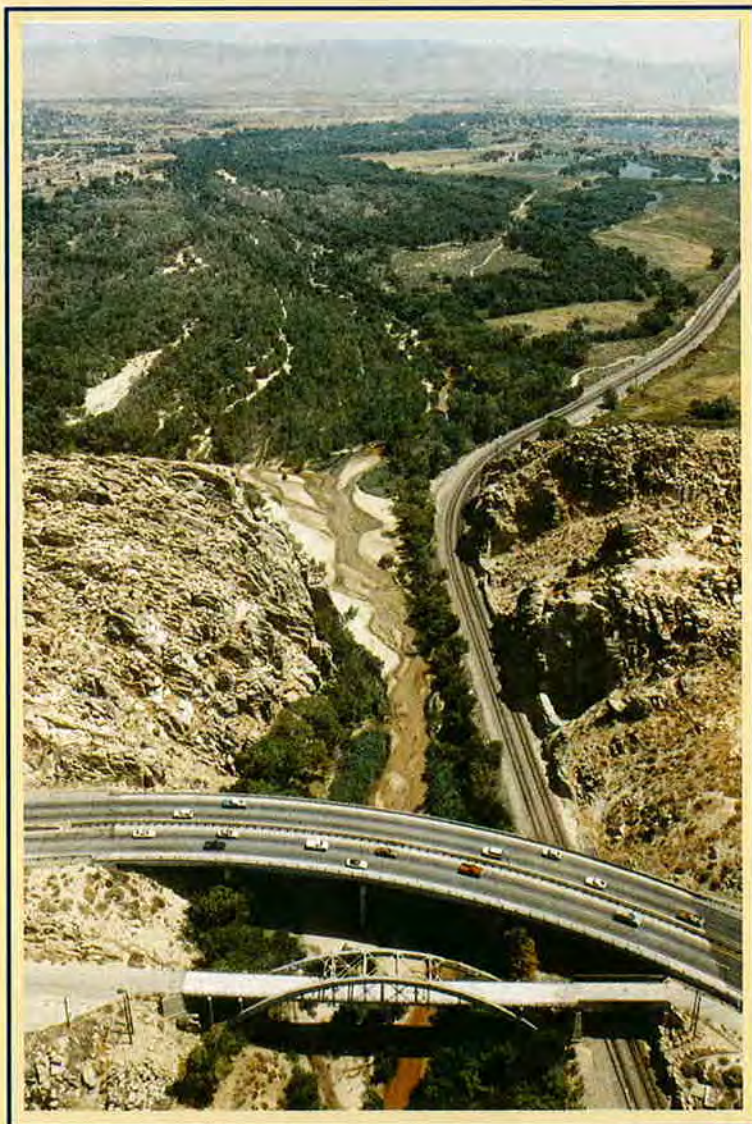


U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

HEALTH OF NATIVE RIPARIAN VEGETATION AND ITS RELATION TO HYDROLOGIC CONDITIONS ALONG THE MOJAVE RIVER, SOUTHERN CALIFORNIA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4112



Prepared in cooperation with the
MOJAVE WATER AGENCY

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By GREGORY C. LINES

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CONVERSION FACTORS AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
bar	0.1	megapascal
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	2.540	centimeter
inch per year (in/yr)	2.540	centimeter per year
mile (mi)	1.609	kilometer

ABBREVIATIONS

DBH	Diameter at breast height
LAI	Leaf-area index

Health of Native Riparian Vegetation and Its Relation to Hydrologic Conditions along the Mojave River, Southern California

By Gregory C. Lines

ABSTRACT

The health of native riparian vegetation and its relation to hydrologic conditions were studied along the Mojave River mainly during the growing seasons of 1997 and 1998. The study concentrated on cottonwood–willow woodlands (predominantly *Populus fremontii* and *Salix gooddingii*) and mesquite bosques (predominantly *Prosopis glandulosa*). Tree-growth characteristics were measured at 16 cottonwood–willow woodland sites and at 3 mesquite bosque sites. Density of live and dead trees, tree diameter and height, canopy density, live-crown volume, leaf-water potential, leaf-area index, mortality, and reproduction were measured or noted at each site. The sites included healthy and reproducing woodlands and bosques, stressed woodlands and bosques with no reproduction, and woodlands and bosques with high mortality.

Tree roots were studied at seven sites to determine the vertical distribution of the root system and their relation to the water table at healthy, stressed, and high-mortality cottonwood–willow woodlands. In the six trenches that were dug for this study in May 1997, no cottonwood roots were observed that reached the water table. The root systems of healthy trees typically ended 1 to 2 feet above the water table. At sites with high mortality, the main root mass was commonly 7 to 8 feet above the water table.

Water-table depth was monitored at each of the study sites. In addition, volumetric soil moisture and soil-water potential were monitored

at varying depths at three cottonwood–willow woodland study sites and at two mesquite bosque sites. Ground, soil, river, lake, and plant (xylem sap) water were analyzed for concentrations of stable hydrogen and oxygen isotopes to determine the source of water used by the trees.

On the basis of the root-distribution, soil- and leaf-water potential, and isotope data, it was concluded that cottonwood, willow, and mesquite trees mainly rely on ground water for their perennial sustained supply of water. The trees mainly utilize ground water that has moved upward from the water table into the capillary fringe and into unsaturated soil nearer to land surface. Most precipitation (average is 4 to 6 inches per year) is lost by evaporation and by transpiration of shallow-rooted xeric plants, and very little reaches the root zone of trees along the Mojave River.

Water-table depth had no strong correlation to many individual tree-growth characteristics, such as density, diameter, height, and live-crown volume. However, leaf-area index (corrected for stem area) of both healthy and stressed cottonwood–willow woodlands had a highly significant statistical relation to water-table depth, and a curvilinear regression model was defined. As in cottonwood–willow woodlands, leaf-area index of mesquite bosques also decreased with increased water-table depth. However, because of the small number of sites, no significant statistical relation could be defined for mesquite bosques. Because it can be accurately measured repeatedly at the same locations, leaf-area index (corrected for stem area)

is recommended as the primary growth characteristic that should be monitored. Future vegetation changes along the Mojave River can be quantified using the sites established for this study.

Mortality was as high as 39 percent in healthy cottonwood–willow woodlands, but mortality of 50 to 100 percent was common where water-table depth was greater than about 7 feet or in areas where permanent water-table declines greater than about 5 feet had occurred. At a healthy mesquite bosque where the water-table depth ranged from about 8 to 11 feet, mortality was about 20 percent. Where the water table had been lowered an additional 10 to 25 feet by pumping, mortality of the mesquite was extremely high (80 to 99 percent).

On the basis of observations of plant reproduction, it was concluded that established cottonwood–willow woodlands probably will reproduce, mainly by root sprouting of mature trees, if the water-table depth during spring and early summer is less than about 5 feet and if there is sufficient sunlight. Likewise, reproduction in established mesquite bosques will probably occur by root sprouting if the water-table depth during spring and early summer is less than about 8 feet. Germination of cottonwood and willow seeds is common during spring in dry channels following winter stormflows in the Mojave River. However, most of the seedlings die before their roots reach a perennial water supply near the water table, and established stands of trees resulting from seed germination are rare.

INTRODUCTION

Cottonwood (*Populus*), willow (*Salix*), mesquite (*Prosopis*), and other native riparian vegetation that grow along streams and on adjacent flood plains are an important natural resource in the arid Southwest. Much of the riparian zone along the Mojave River has been cleared of native vegetation for agricultural, residential, and other uses. Because of ground-water pumping, streambed incision, channel clearing, and other factors, some vegetation along the Mojave River

has died and much of the remaining vegetation shows signs of stress from a shortage of water. Lines and Bilhorn (1996) reported that approximately 10,000 acres of riparian vegetation remained along the Mojave River in 1995 but about 1,600 acres showed signs of stress; in many areas, there is little or no plant reproduction. In addition, saltcedar (*Tamarix ramosissima*), a non-native plant, was the dominant riparian plant species in about 5,200 acres during 1995. Saltcedar tends to replace native vegetation where stress and mortality of native trees are high and where competition with native vegetation for available sunlight and water is diminished.

It has long been recognized that distinctive associations or communities of native riparian plants grow in distinctive hydrologic environments along the Mojave River (Meinzer, 1927; Thompson, 1929). However, hydrologic conditions and the health of riparian vegetation are subject to change from both natural and human-induced processes. Plant-growth characteristics and hydrologic conditions can be monitored; but, if impacts on vegetation are to be mitigated, the relations between hydrologic conditions and the health and reproduction of native riparian vegetation need to be quantified.

Purpose and Scope

In 1995, the U.S. Geological Survey and the Mojave Water Agency agreed to conduct a cooperative study of the remaining riparian vegetation along the Mojave River. The first phase of the study included an inventory of the extent, diversity, and density of riparian vegetation and an estimate of its water use during 1995. The first phase was summarized by Lines and Bilhorn (1996). The second phase of the study, which is summarized in this report, was conducted mainly during 1997–99. The objectives of the second phase were to determine the sources of water utilized by the native riparian vegetation and to relate vegetation health and reproduction to varying hydrologic conditions along the Mojave River. The second phase included study of the three most widespread and prevalent native riparian species along the Mojave River: Fremont cottonwood (*Populus fremontii*), Goodding willow (*Salix gooddingii*), and honey mesquite (*Prosopis glandulosa*).

Acknowledgments

The author expresses his gratitude to a number of people in the U.S. Geological Survey who contributed to the successful completion of this study. Gregor T. Auble and Michael L. Scott (Fort Collins, Colo.) worked with the author to determine the reason for high mortality in a cottonwood–willow woodland near Oro Grande (Auble and others, 1998; and Scott and others, in press). Dennis A. Clark and Allen H. Christensen (both in San Diego, Calif.) and John C. Radyk (Menlo Park, Calif.) assisted with various phases of data collection. Mr. Radyk also was responsible for the laboratory analyses of stable hydrogen and oxygen isotopes in various waters. For their technical reviews and suggestions that immensely improved this report, the author wishes to acknowledge Lorraine E. Flint (Sacramento, Calif.), Robert H. Webb (Tucson, Ariz.), and again Michael L. Scott. And finally, this report would not have been possible without the diligent efforts of Anna C. Borlin (Scientific Illustrator) and Jerrald A. Woodcox (Technical Editor), both in San Diego.

INSTRUMENTED AND SYNOPTIC STUDY SITES

Hydrologic data were collected at five “instrumented” study sites (fig. 1) during 1996–98. Vegetation data were collected at these instrumented sites mainly during the growing seasons (March–October) of 1997 and 1998. Three of the instrumented study sites were located in cottonwood–willow woodlands (figs. 2–4), including a healthy and reproducing woodland (Regional Park), a moderately stressed woodland with no recent reproduction (Lower Narrows), and a heavily stressed woodland with high tree mortality and no recent reproduction (Oro Grande). Two instrumented study sites were located in mesquite bosques (figs. 5 and 6), including a healthy and reproducing bosque (Camp Cady 2) and a stressed bosque with high tree mortality and no recent reproduction (Camp Cady 1). Sites were classified as healthy when leaf volume appeared normal and stand mortality was less than 50 percent. Stressed sites were defined as those where the living trees had less than 50 percent of the leaf volume of healthy trees and the stand mortality was less than 50 percent. Sites were classified as having high mortality when the living trees had less

than 50 percent of the leaf volume of healthy trees and stand mortality was greater than 50 percent.

At the five instrumented study sites (fig. 1), a shallow piezometer was installed to monitor the depth of the water table. Access tubes were installed in unsaturated soil to measure volumetric soil water with a neutron source and counter. Psychrometers were installed at various depths in unsaturated soils to measure soil-water potentials of “dry” soils (soil-water potentials between about -1 and -70 bars) with a dew-point microvolt meter. For “wet” soils (soil-water potentials from 0 to -0.7 bars), such as at the Regional Park study site, a tensiometer was used. Leaf-area indices and stem-area indices were monitored using a LI-COR plant canopy analyzer. Leaf-water potentials were measured with a Scholander-type pressure bomb (Scholander and others, 1965). Ground-water samples for analysis of stable hydrogen and oxygen isotopes were collected from suction-cup lysimeters installed below the water table. Soil-water samples were obtained using a hand auger, and plant water (xylem sap) samples were collected using an incremental borer. A trench was dug with a backhoe at the Oro Grande study site to determine the vertical tree-root distribution and its relation to soil moisture and the water table.

In addition to the five instrumented sites, 14 “synoptic” study sites in cottonwood–willow woodlands (fig. 1) were chosen in order to include a widespread areal distribution of sites and a wide range of hydrologic conditions. One synoptic site in a mesquite bosque (H1) was chosen because of the extremely high mortality of vegetation. For the most part, data collection at synoptic study sites included water-table monitoring and one-time measurements of various tree-growth characteristics. A shallow piezometer was installed, or an existing well was used, to monitor depth of the water table at each site. Trenches were dug with a backhoe to the water table at five synoptic sites (A1, B2, C1, C2, and C3) in both healthy and stressed cottonwood–willow woodlands to determine vertical tree-root distributions and their relation to soil moisture and the water table. Vertical distribution of tree roots also was studied in the eroded bank of a side channel of the Mojave River at synoptic site D1.

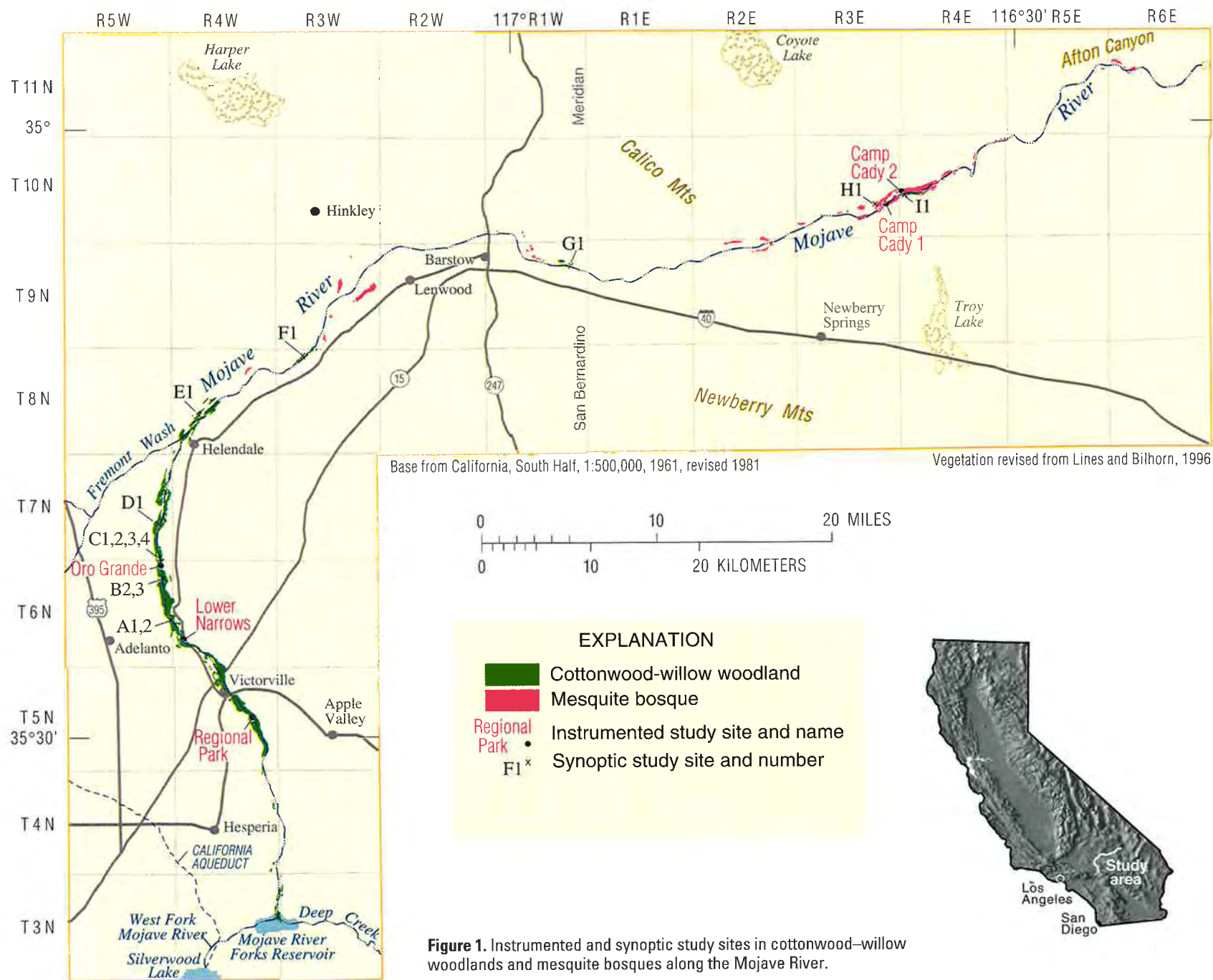




Figure 2. Regional Park instrumented study site in a healthy cottonwood–willow woodland with recent reproduction.



Figure 3. Lower Narrows instrumented study site in a moderately stressed cottonwood woodland with no recent reproduction.



Figure 4. Oro Grande instrumented study site in a stressed cottonwood–willow woodland with high mortality and no recent reproduction.



Figure 5. Camp Cady 1 instrumented study site in a stressed mesquite bosque with high mortality and no recent reproduction.



Figure 6. Camp Cady 2 instrumented study site in a healthy mesquite bosque with recent reproduction.

HYDROLOGIC CONDITIONS AT STUDY SITES

Depth of Water Table

Both healthy and stressed cottonwood–willow woodlands normally are found along the Mojave River where the depth of the water table is less than about 10 ft below land surface (Lines and Bilhorn, 1996). Water-table depths at cottonwood–willow woodland study sites ranged from about 2 to 9 ft during June 1998 (table 1). Even in this environment where the water table is relatively shallow, the health and reproduction of cottonwood–willow woodlands are sensitive to seasonal and longer term water-table fluctuations of only a few feet (Auble and others, 1998).

Mesquite usually grows in a drier environment than that of cottonwood–willow woodlands; it normally grows as a tree (height as much as 20 ft) along the edges of the Mojave River flood plain and as a bush (height generally less than 3 ft) in xeric environments above the flood plain. Water-table depths in mesquite bosques can range from less than 10 ft on the flood

plain to greater than 100 ft in areas above the flood plain. The mesquite generally shows signs of water stress and loses height, however, if water-table depth exceeds about 20 ft.

At the Regional Park instrumented site, a healthy and reproducing cottonwood–willow woodland, water-table depths ranged from about 1.5 to 4.5 ft below land surface during 1996–98 (fig. 7). The water table was highest during winter, and typically it declined about 2 to 2.5 ft to the lowest level in late summer or autumn. Seasonal water-table fluctuations at the Regional Park mainly were due to ground-water flow to and from the river and the transpiration of trees. The Mojave River has been a perennial stream near this site for many years (Lines, 1996).

The water-table depth at the Lower Narrows instrumented site, a moderately stressed monotypic cottonwood woodland with no recent reproduction, ranged from about 8 to 35 ft (fig. 7). The water table was highest during winter and early spring and was lowest during late summer and autumn. The relatively large seasonal water-table fluctuations at the Lower Narrows site mainly were due to ground-water

Table 1. Tree-growth characteristics and depth of water table at cottonwood–willow woodland study sites, 1998

[DBH, diameter at breast height; in., inch; ft, foot; NA, not applicable]

Site name or number (fig. 1)	Live tree density (trees/acre)	Dead tree density (trees/acre)	Mortality (percent)	Live tree mean DBH (in.)	Dead tree mean DBH (in.)	Maximum live-canopy height (ft)	Canopy density (percent)	Live-crown volume (percent)	Leaf-area index, June 1998	Recent reproduction	Depth of water table, June 1998 (ft)
Regional Park	111	9	8	16	11	68	90	83	1.04	Yes	2
Lower Narrows	30	12	29	14	10	45	40	66	.32	No	8
A1	27	18	40	13	14	46	80	87	.59	Yes	4
A2	45	0	0	23	0	56	90	71	.72	Yes	3
B2	30	48	62	14	14	56	30	64	.15	No	9
B3	0	39	100	NA	17	NA	0	0	.00	No	9
Oro Grande	6	138	96	11	9	33	5	54	.01	No	9
C1	27	3	10	31	9	52	40	66	.15	No	7
C2	57	12	17	15	13	52	70	52	.21	No	6
C3	45	6	12	14	4	49	80	64	.36	No	7
C4	24	27	53	17	15	47	70	60	.41	No	7
D1	21	3	12	12	18	47	50	86	.36	Yes	5
E1	18	6	25	22	23	63	60	80	.54	No	6
F1	33	6	18	11	6	32	70	76	.25	Yes	5
G1	30	6	17	14	11	43	80	60	.89	Yes	3
I1	39	9	23	11	10	60	80	68	.61	Yes	5

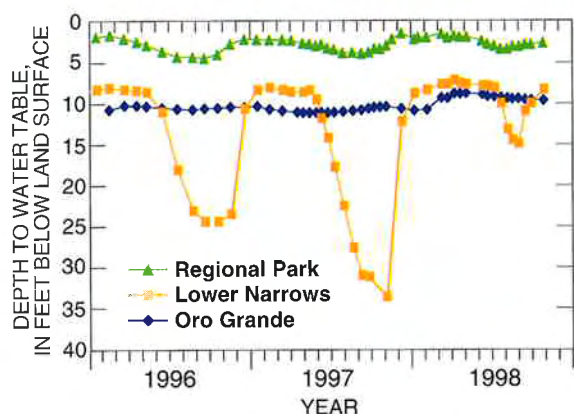


Figure 7. Depth of water table at instrumented cottonwood–willow woodland study sites, 1996–98.

pumping from several nearby wells. The water-table depths shown in figure 7 mainly are based on water-level measurements in the piezometer at the study site. However, the water table dropped below the bottom of the piezometer (24 ft below land surface) during the summer and autumn of 1996 and 1997, and water-level measurements were made in a nearby production well about 300 ft south of the study site when the well was not being pumped. The Mojave River was an ephemeral stream near this site during 1996–98. Most of the river water during summer and autumn was depleted or “captured” by the pumped wells (Lines, 1996).

At the Oro Grande instrumented site, a high-mortality cottonwood–willow woodland with no recent reproduction, water-table depths ranged from about 9 to 11 ft (fig. 7) during 1996–98. Seasonal fluctuations of the water table generally were smaller than at the Regional Park and Lower Narrows sites because transpiration was very low owing to high tree mortality. The Oro Grande site is located several miles from significant ground-water pumping from the flood-plain aquifer, and the water-table fluctuations almost entirely were due to ground-water flow to and from the river. Streambed incision and sustained water-table declines (about 5 ft) have caused the high tree mortality in this area (Auble and others, 1998). The Mojave River was an ephemeral stream near this site during 1996–98.

Water-table depths at the Camp Cady 2 instrumented site, a healthy and reproducing mesquite bosque, ranged from about 8 to 11 ft during 1996–98 (fig. 8). The water table was highest during spring and was lowest during late summer and autumn. Seasonal

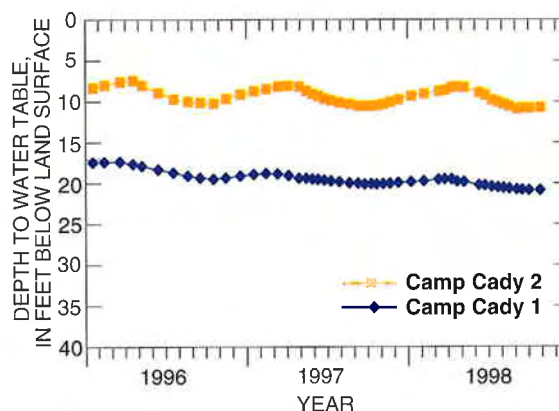


Figure 8. Depth of water table at instrumented mesquite bosque study sites, 1996–98.

fluctuations of the water table averaged about 3 ft. The Camp Cady 2 site is several miles from significant ground-water pumping from the flood-plain aquifer, and most of the seasonal fluctuations in the water table were due to transpiration of the plants. The Mojave River near this site was an ephemeral stream during 1996–98.

During 1996–98 at the Camp Cady 1 instrumented site, a stressed mesquite bosque with no recent reproduction, water-table depths ranged from about 18 to 21 ft (fig. 8). The water table was highest during late winter and early spring, and it was lowest during autumn. Seasonal fluctuations in the water table ranged from 1 to 2 ft. Seasonal and longer term water-table fluctuations mainly were due to ground-water pumping from the flood-plain aquifer at nearby wells. Because of relatively high tree mortality at this site, transpiration was very low. The Mojave River near this site was an ephemeral stream during 1996–98.

Mesquite at synoptic site H1 had sustained extremely high mortality and showed no signs of recent reproduction. Depth of the water table ranged from about 30 to 36 ft during 1996–98, and water-table declines have averaged about 2 ft/yr since 1993 in an observation well at this site. Although most stems of the dead trees remain at this site (height of as much as 12 ft), the live growth was usually less than 3 ft tall and emerged from near the base of trunks. Surviving mesquite at this site had a bush-like stature, and was similar in appearance to mesquite that grows on dunes above the flood plain.

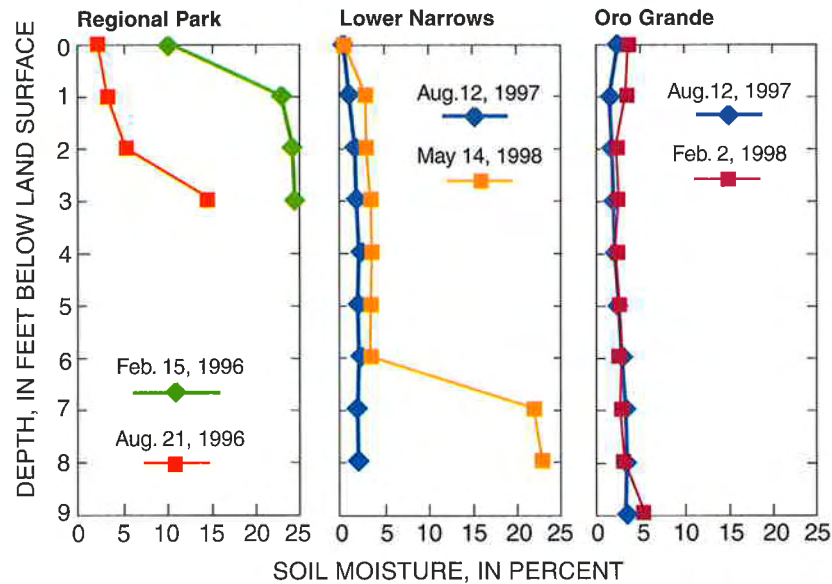


Figure 9. Extremes of volumetric soil moisture at instrumented cottonwood–willow woodland study sites, 1996–98.

Soil Moisture

Volumetric soil moisture was measured quarterly during 1996–98 at the five instrumented sites using neutron logging. Unsaturated soils above the water table in the riparian zone along the Mojave River range from very dry (less than 1 percent volumetric soil moisture) to relatively wet (greater than 20 percent volumetric soil moisture). Except for changes near land surface and near the water table, soil moisture was relatively constant at most sites. Because the measurements were made quarterly, some soil-moisture changes may have gone undetected. Profiles representing the extremes in measured soil moisture at the three instrumented cottonwood–willow woodland sites and the two instrumented mesquite bosque sites are shown in figures 9 and 10, respectively.

Precipitation averages about 6 in/yr at Victorville and about 4 in/yr at Barstow. During 1996–98, annual precipitation was 3.76, 5.26, and 10.13 in. at Victorville; it was 3.51, 5.14, and 7.67 in. at Barstow (National Oceanic and Atmospheric Administration, 1996–98). Thus, the three years of this study included a relatively dry year (1996), a close-to-average year (1997), and a relatively wet year (1998). Most precipitation usually occurs during winter, but isolated summer thunderstorms can produce several inches of rain in a short period of time.

At the Regional Park study site, volumetric soil moisture at land surface ranged from about 2 to 10 percent (fig. 9), and it usually was highest during winter and lowest during summer. Likewise, at depths between 1 and 3 ft below land surface, soil moisture typically was greater than 20 percent during winter and was 3 to 15 percent in summer. Recharge from the river, infiltration of precipitation, transpiration of plants, and evaporation all were factors controlling soil moisture at this site.

Volumetric soil moisture at the Lower Narrows study site generally was lowest during autumn and highest during winter (fig. 9). Soil moisture at depths of 0 to 6 ft was relatively constant (ranged from less than 1 to about 4 percent) in comparison with soil moisture at depths of 7 to 8 ft (ranged from about 3 to 23 percent). Infiltration of precipitation, transpiration of trees, and evaporation partially controlled soil moisture. However, seasonal fluctuations of soil moisture below about 6 ft were mainly due to fluctuations in the water table, which were the result of nearby pumping and infiltration of river water.

Soil moisture was more constant at the Oro Grande site than at any other cottonwood–willow woodland study site. Soil moisture varied no more than about 2 percent from the profile of August 12, 1997 (fig. 9). Because of the extremely high mortality of trees at this site, transpiration had little or no effect on the soil-moisture profile. The small increase in soil

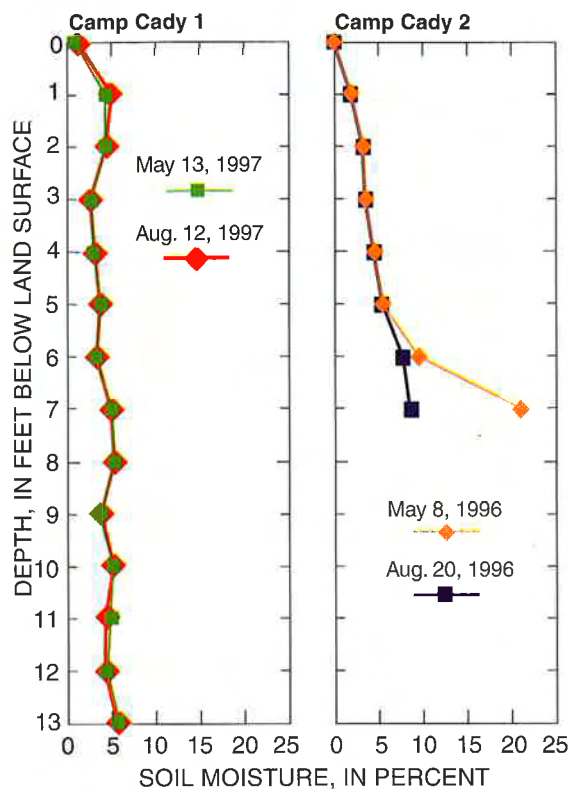


Figure 10. Extremes of volumetric soil moisture at instrumented mesquite bosque study sites, 1996–98.

moisture at a depth of 9 ft probably was due to a rise in the water table during the winter of 1998 when the river stage was at its highest level.

At the Camp Cady 2 instrumented study site, soil moisture generally increased slightly with increasing depth below land surface (fig. 10). Soil moisture increased from less than 1 to about 6 percent between depths of 0 and 5 ft, but the soil moisture in this interval did not change markedly during 1996–98. The greatest measured changes in soil moisture occurred at depths of 6 and 7 ft where the soil moisture varied from about 7 to 21 percent. These soil-moisture changes probably were due to seasonal fluctuations in the water table.

During 1996–98, soil moisture at the Camp Cady 1 site varied from less than 1 to about 6 percent at depths of 0 to 13 ft (fig. 10). The water table at this site was relatively deep (ranged from about 17 to 20 ft), and there was little transpiration owing to the high (80 percent) mortality of mesquite. Because there was little or no infiltration of precipitation from land surface and little soil water was removed by the mesquite, the soil-moisture profile did not change markedly.

Soil-Water Potential

Soil-water potential is a measure of the suction holding liquid water in the interstices of unsaturated soils (Milburn, 1979). Because it is a measure of suction rather than pressure, it is commonly expressed as a negative number. Soil-water potentials vary depending on the type of soil, the water content, and the temperature and the salinity of the soil water. Soil-water potentials are an excellent indicator of the availability of soil water to plants. For example, soil water with a potential of -20 bars would not be available for use by a plant having a water potential in its roots of -10 bars because suction of the plant roots would not be great enough to extract the water from the soil. But a plant with a water potential in its roots of -40 bars theoretically would be able to extract water from this same soil.

Likewise, soil-water potentials also are an indicator of movement of liquid water through soil. Theoretically, water will move from the wettest soils (less negative water potentials) to the driest. In most areas of the Mojave River flood plain, the prevalent vertical direction of water movement is upward from the water table into the capillary fringe and eventually into drier soil near land surface. Water also can move from the capillary fringe to land surface in the vapor phase. Liquid water not captured by plant roots eventually is lost to evaporation within the aerated soil and at land surface. The reader is referred to Meinzer (1923) for further discussion of water movement from a shallow water table to land surface in arid areas.

Soil-water potentials measured during 1996–98 at the three instrumented study sites in cottonwood–willow woodlands are shown in figure 11. Likewise, soil-water potentials at the two instrumented sites in mesquite bosques are shown in figure 12. With psychrometers and a dew-point microvoltmeter, soil-water potentials between about -1 and -70 bars were measurable. Because of relatively wet soil conditions, a tensiometer was used at the Regional Park study site. The range of the tensiometer was from about 0 to -0.7 bars.

Soil-water potentials at 1.5 ft below land surface at the Regional Park study site ranged from -0.02 to -0.23 bars during 1996–98 (fig. 11). The lowest potentials (least negative) occurred during winter and the highest during late summer and autumn. In addition to the seasonal fluctuations, soil-water potentials declined slightly during the 3 years of data collection; the decline is believed to be the result of the slight rise

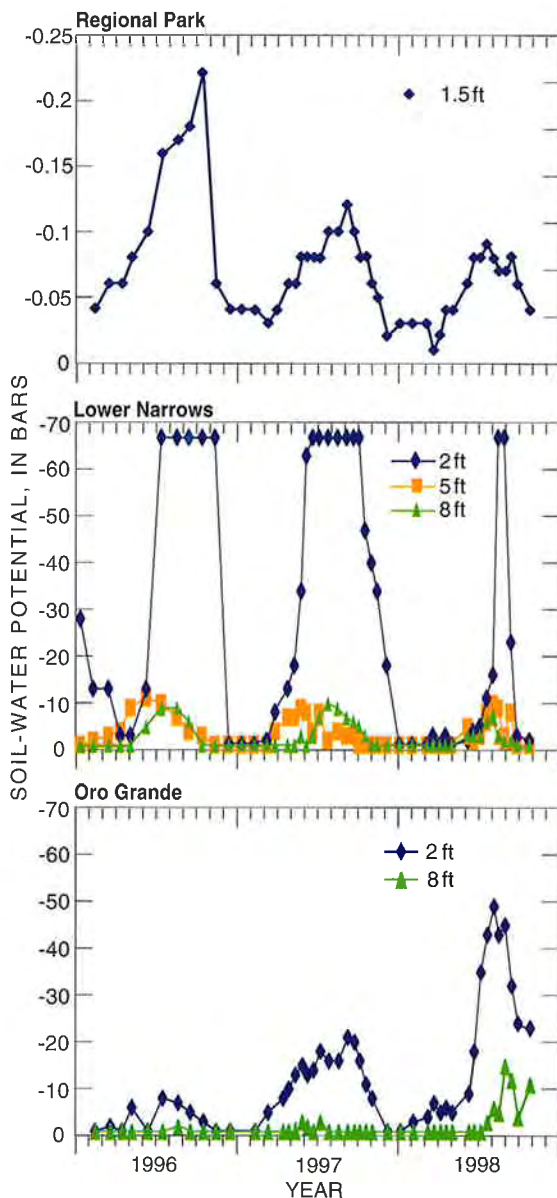


Figure 11. Soil-water potentials at instrumented cottonwood-willow woodland study sites, 1996-98.

in water table owing to recharge from the river. And, in fact, the site was flooded for a few days in the spring of 1998.

At the Lower Narrows study site, soil-water potentials were measured at 2, 5, and 8 ft below land surface (fig. 11). In most cases, the soil-water potentials were less than about -10 bars. However, soils at 2 ft were dried by evaporation, and water potentials rose (were more negative) above the range of the psychrometers (about -70 bars) during summer and

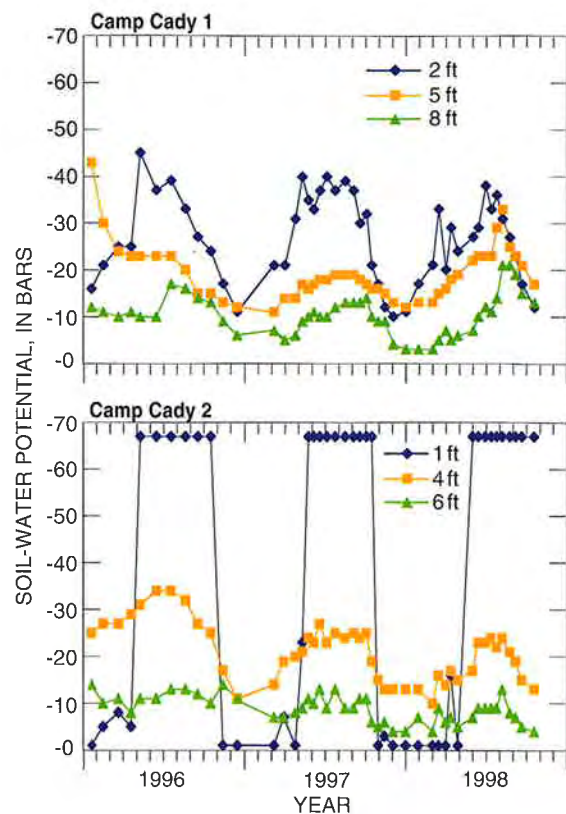


Figure 12. Soil-water potentials at instrumented mesquite bosque study sites, 1996-98.

autumn. Soil-water potentials at depths of 5 and 8 ft were similar, indicating that there probably was little vertical movement of liquid water through the unsaturated soil between these depths.

At the Oro Grande study site, soil-water potentials were measured at depths of 2 and 8 ft (fig. 11). Soil-water potentials varied seasonally; however, unlike those at the Regional Park study site, soil-water potentials at the Oro Grande site generally rose (became more negative) during 1996-98. Ground-water recharge from the river probably was not sufficient to compensate for the evaporative losses from the soil. In fact, because of incision of the river channel in this area following flooding in 1993 (Auble and others, 1998), ground-water drainage probably was toward the river, and there may not have been any recharge from the river in this area during 1996-98. Because of extremely high mortality of cottonwoods and willows, there was very little absorption of subsurface water by plants at the site.

Soil-water potentials at the two instrumented study sites in mesquite bosques (fig. 12) generally were much higher than at cottonwood–willow woodland sites. At both Camp Cady 1 and 2, soil-water potentials varied seasonally at all measured depths. Soils near land surface (1- and 2-foot depths) had the widest range of water-potential fluctuation owing to rainfall and subsequent evaporation near land surface. In general, soil-water potentials decreased with increasing depth at both sites, indicating upward movement of water from the water table to the capillary fringe and eventually into drier, unsaturated soil nearer to land surface.

CHARACTERISTICS OF RIPARIAN VEGETATION

Distribution of Tree Roots

A backhoe was used to expose tree roots (fig. 13) at six cottonwood–willow study sites (A1, B2, Oro Grande, C1, C2, and C3) on May 7, 1997. Tree-root distribution also was studied at a seventh site (D1) where erosion of the banks of a side channel of the Mojave River had exposed the root system. The sites were chosen for excavation in order to define the

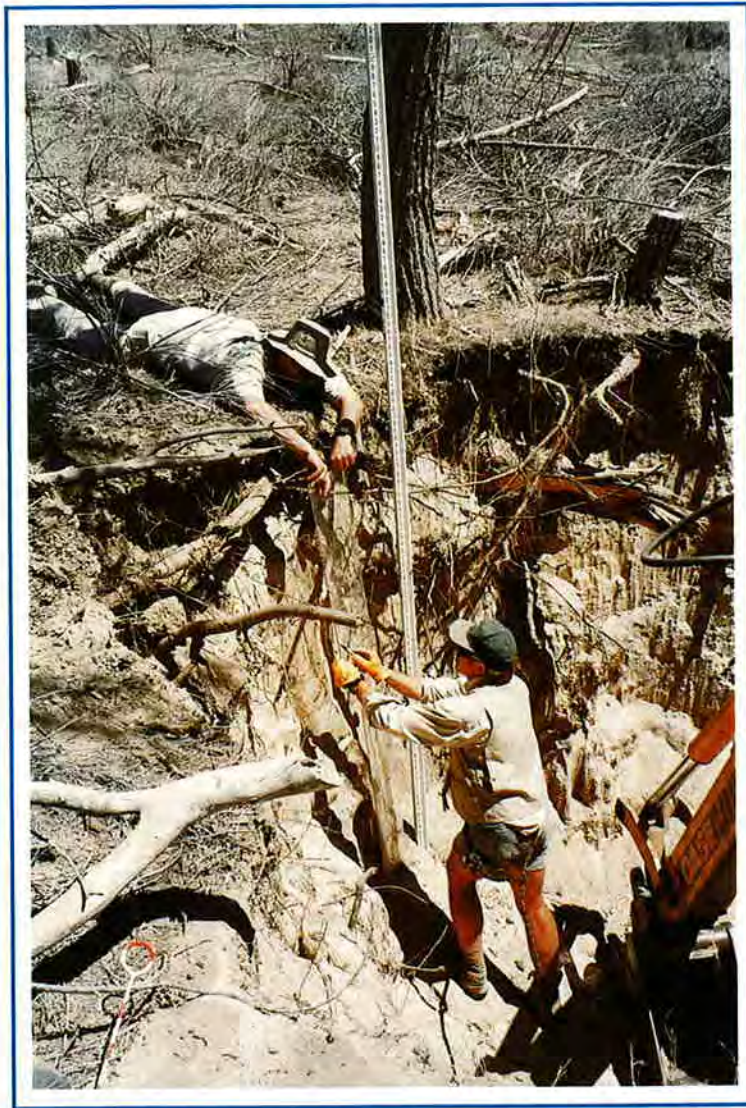


Figure 13. Roots of a stressed cottonwood exposed in trench at Oro Grande instrumented study site.

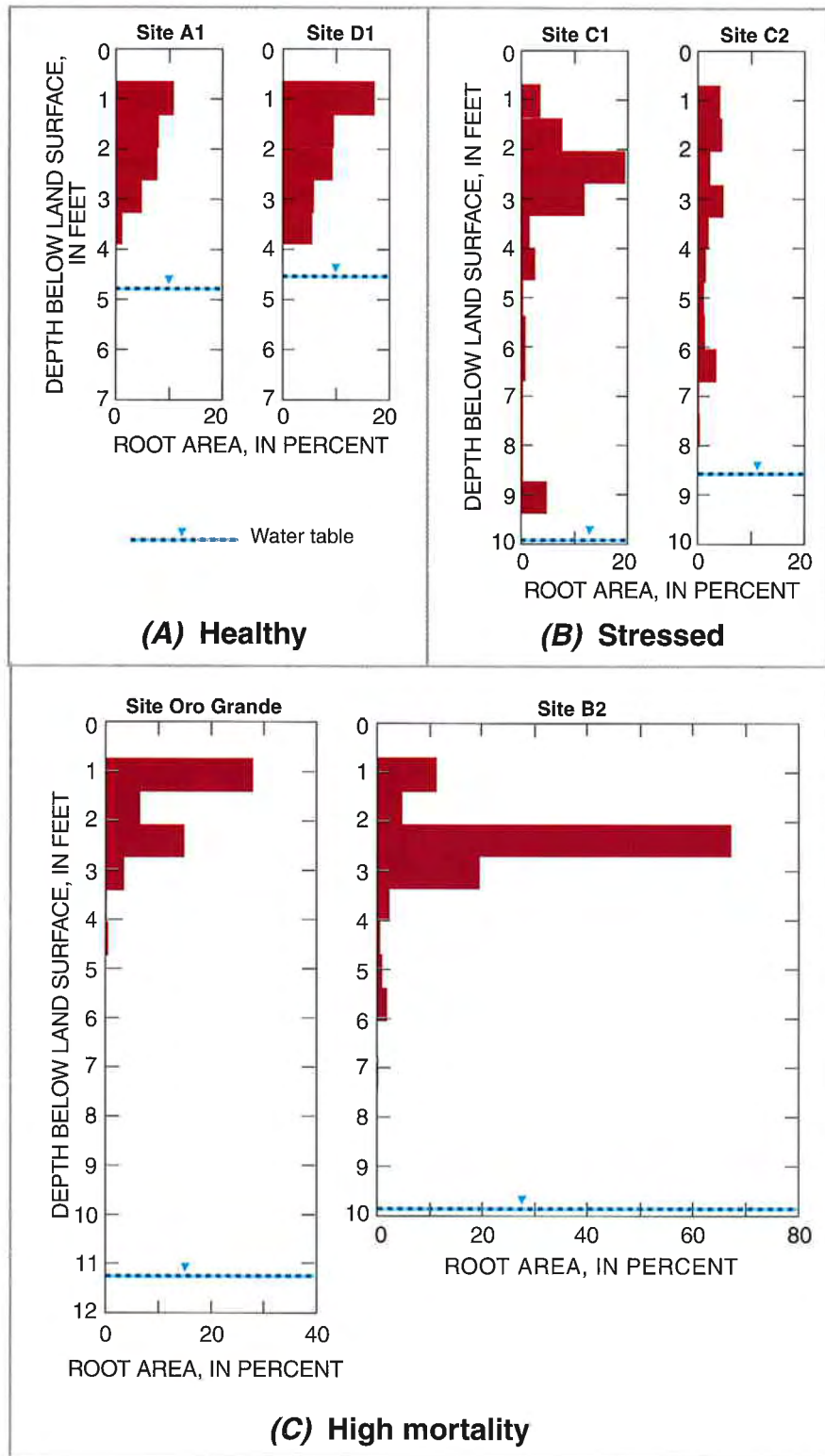


Figure 14. Vertical distribution of cottonwood tree roots and its relation to the water table at healthy, stressed, and high-mortality study sites. (Modified from Scott and others, in press.)

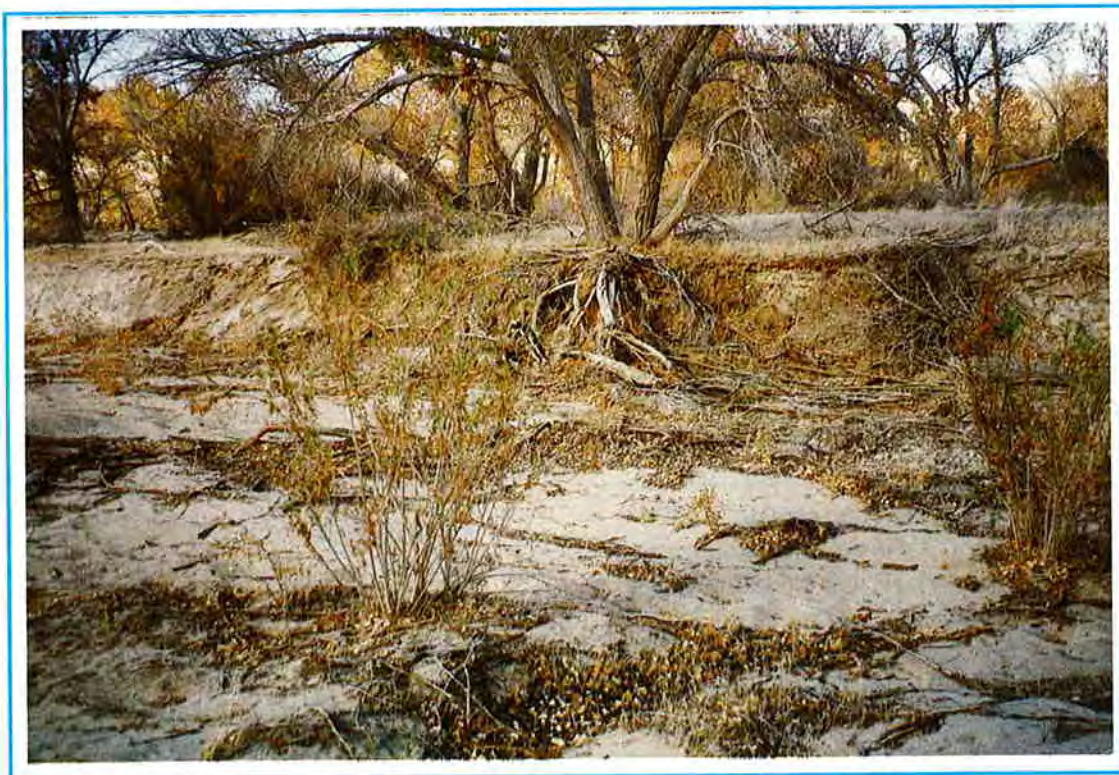


Figure 15. Roots radiating from a cottonwood tree where scouring of the ephemeral channel has exposed them at land surface.

vertical distribution of the root systems in healthy, stressed, and high-mortality woodlands. Roots of trees exposed in the sides of the trenches were traced onto Plexiglas sheets, and the root areas were then quantified.

As shown in figure 14, tree roots at healthy sites (A1 and D1) were concentrated in about the upper 1 to 4 ft of soil. From the tracings on the Plexiglas sheets, tree-root area in figure 14 is expressed as a percentage of the area of the trench wall. Water-table depths measured in trenches at the two healthy sites were 4.5 to 4.8 ft below land surface, and the bottoms of the root systems were about 1 ft above the water table. At stressed sites (C1 and C2), the root systems had a much larger vertical distribution than at healthy sites and extended to within 1 ft of the water table. Water-table depths ranged from 8.6 to about 10 ft at these two stressed sites. The root distribution at site C3 is not shown in figure 14, but it was very similar to that at stressed sites C1 and C2. At high-mortality sites (B2 and Oro Grande) root systems were concentrated in about the upper 1 to 4 ft of soil, much as at the healthy sites, but the main root mass was 7 to 8 ft above the

water table. Water-table depths at the two high-mortality sites were 10 to 11 ft below land surface.

No tree roots that reached the water table were observed in the excavations on May 7, 1997. The root systems of healthy and stressed trees bottomed in wet soil 1 to 2 ft above the water table, in what normally would be considered the capillary fringe. In some areas, the water table probably rises temporarily into the root system of the trees following periods of flooding of the river and recharge to the flood-plain aquifer. Observations in the trenches indicated that soil 1 to 2 ft directly above the water table had a markedly larger volume of moisture than did soil closer to land surface. This observation is verified by the volumetric soil-moisture profiles at some instrumented sites.

Although the horizontal distribution of roots in cottonwood–willow woodlands is not known precisely, the roots are believed to extend several tens of feet from the base of mature trees. In one area (about one-quarter mile north of synoptic site C2) where the roots of a stressed cottonwood were exposed along a side channel of the Mojave River, the roots extended at least 60 ft horizontally from the base of the tree (fig. 15). At this site, the roots exposed in the bottom of the scoured

channel presumably were at one time 4 to 5 ft below the land surface of the flood plain.

No honey mesquite trees were excavated for this study. Heitschmidt and others (1988), however, excavated several mature honey mesquite trees growing in a variety of soils in north-central Texas. The trees in the Texas study ranged in height from about 10 to 20 ft (about 5 ft taller than the tallest honey mesquite trees along the Mojave River). The main root mass extended from land surface to a depth of about 6 ft, and the number of roots decreased with increasing depth. Some horizontal roots at a depth of about 1 ft eventually turned upward and extended to land surface beneath the tree canopy. Some roots were excavated that extended as much as 20 ft horizontally from the base of trees. The depth of the water table was several tens of feet below land surface, and the source of water used by the mesquite was shallow soil water originating from infiltration of precipitation, which averaged about 26 in/yr (R.J. Ansley, Texas Agriculture Experiment Station, Vernon, Tex., oral commun., 1999).

In contrast to north-central Texas, annual precipitation averages only about 4 in. in mesquite bosque areas along the lower reaches of the Mojave River, but the water table is generally shallower than 10 ft below land surface in healthy bosques growing on the flood plain. Healthy honey mesquite along the Mojave River probably has developed a root system capable of absorbing water mainly from the capillary fringe, but also from drier soils near land surface. However, along the Mojave River, little precipitation is available to mesquite and other riparian vegetation. Much of the scant precipitation is lost very quickly by evaporation or by transpiration of shallow-rooted xeric grasses and brush.

During the spring and summer of 1998, mesquite roots periodically clogged the piezometer at Camp Cady 2. The roots grew through the perforations of the PVC (polyvinyl chloride) pipe 1 to 2 ft above the water table, and they undoubtedly were tapping the capillary fringe.

The root systems of small honey mesquite bushes growing on dunes in southern New Mexico were excavated by Gile and others (1997). The mesquite had similar stature (about 2 ft tall) to mesquite growing in high-mortality areas, such as synoptic site H1, along the Mojave River flood plain and in areas above the flood plain where water-table

depths are 100 ft or more. Gile and others found that the roots extended downward 3 to 4 ft to the base of the dunes and ended at a pre-dune hardpan surface. Some roots turned upward, extending to within about 2 in. of the dune surface. The longest root excavated was about 70 ft in length. Depth of the water table was 300 to 400 ft below land surface, and the mesquite undoubtedly was a xerophyte utilizing meager soil moisture in the dune material that originated as precipitation on the dune surface (L.H. Gile, U.S. Department of Agriculture, Las Cruces, N.M., oral commun., 1999).

Leaf-Area Index

Leaf-area index (LAI) is a function of the number and size of leaves in the canopy, and it is an excellent indicator of the overall health of riparian vegetation. Leaf-area index, which is dimensionless, is a measure of the total leaf area in the canopy in comparison with the area of land surface in a study plot. For example, in a woodland having an LAI of 0.6, all the leaves would cover 60 percent of land surface if arranged on the ground with no overlap.

The LAI periodically was measured during the growing seasons of 1997 and 1998 at the Regional Park and Lower Narrows cottonwood–willow woodland study sites (fig. 16) and at the Camp Cady 2 mesquite bosque study site (fig. 17). At the B3, Oro Grande, Camp Cady 1, and H1 study sites, where tree mortality ranged from 80 to 100 percent (see tables 1 and 2), LAI was visually estimated because the leaves were too sparse to be measured accurately. The LAI was measured at four locations along a transect through the middle of each 20 × 60 meter (66 × 197 ft) plot that was established at each site for an inventory of riparian vegetation. Most measurements were made a few minutes before sunrise to avoid reflection of sunlight from leaves in the canopy. Because the meter measures gray matter in the canopy in comparison to open sky, both leaf area and stem area were measured. In order to correct for stem area, measurements were made at all sites in January 1999, following the abscission of most leaves. Stem-area index varied from about 0.06 to 0.43 at the cottonwood–willow woodland study sites.

Cottonwood and willow trees at the Regional Park and Lower Narrows study sites started to leaf in March of both 1997 and 1998 (fig. 16). The LAI peaked at both sites during May of 1997. During 1998, the LAI peaked in June at the Lower Narrows site and in July at

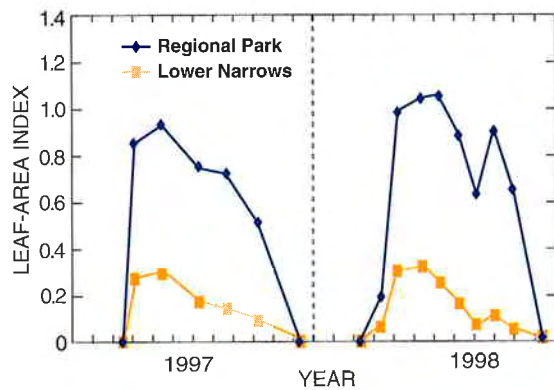


Figure 16. Leaf-area indices at Regional Park and Lower Narrows instrumented cottonwood–willow study sites, 1997–98.

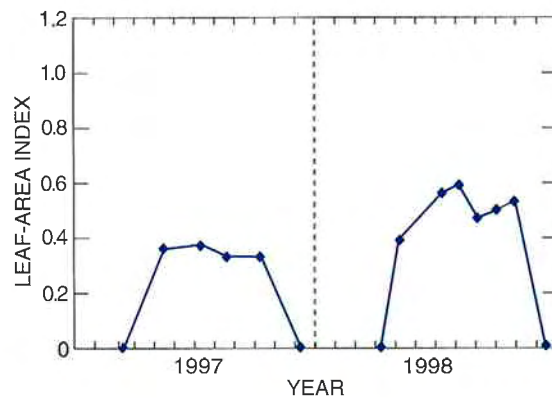


Figure 17. Leaf-area indices at Camp Cady 2 instrumented mesquite bosque study site, 1997–98.

Table 2. Tree-growth characteristics and depth of water table at mesquite bosque study sites, 1998

[ft, foot]

Site name or number (fig. 1)	Mortality (percent)	Maximum live-canopy height (ft)	Canopy density (percent)	Live-crown volume (percent)	Leaf-area index, August 1998	Recent reproduction	Depth of water table, August 1998 (ft)
H1	99	3	1	1	0.01	No	36
Camp Cady 1	80	12	10	20	.1	No	21
Camp Cady 2	20	15	30	70	.6	Yes	11

the Regional Park site. Declines in leaf area during summer were due to water stress, with the trees dropping leaves as a mechanism to counter water loss by transpiration. Leaf abscission during autumn is a normal yearly process of all deciduous trees. The Regional Park had the shallowest water table of any study site, and the LAI peaked during June of 1998 at 1.04. In contrast, the LAI peaked at 0.32 at the Lower Narrows study site; the lower value reflects both the sparser density of trees and the smaller number of leaves in each tree. It should be pointed out that LAI increased fairly rapidly at both sites following abnormally large rainfall (1.76 in. at Victorville and 1.21 in. at Barstow) during late August and early September 1998 (National Oceanic and Atmospheric Administration, 1998). The trees probably utilized some of the increased soil moisture near land surface, and likely also benefited from the cooler air temperatures and lower transpiration losses associated with the rainfall, which are conditions conducive to additional growth of existing leaves.

At the other 14 cottonwood–willow woodland study sites, LAI during June 1998 ranged from 0.0 at site B3 to 0.89 at site G1 (table 1). Site B3 is in an area where incision of the river has caused a permanent lowering of the water table as much as 5 ft (Scott and others, in press). Mortality of riparian vegetation on the B3 study plot was 100 percent. Site G1 is in a relatively small cottonwood–willow woodland near Barstow where the water table was about 3 ft below land surface during June 1998.

Leaf-area index of cottonwood–willow woodland study sites generally declined as water-table depth increased, and there was a strong linear relation between June LAI and water-table depth [correlation coefficient (r) of -0.89, table 3]. However, the best regression model for these two variables was curvilinear (fig. 18). Using this regression model, June LAI can be predicted using the following equation: $LAI = 1.426 - (0.242 \times \text{water-table depth}) + (0.011 \times \text{water-table depth squared})$. The coefficient of determination (r -squared) of the curvilinear regression model is 0.82, and the level of significance of the statistical test

Table 3. Correlation coefficients of linear relations between depth of water table, leaf-area index, and other tree-growth characteristics at cottonwood–willow woodland study sites, June 1998

[DBH, diameter at breast height; NA, not applicable]

	Depth of water table (foot)	Leaf-area index
Depth of water table (foot)	NA	-0.89
Leaf-area index	-0.89	NA
Live tree density (trees per acre)	-0.57	0.57
Dead tree density (trees per acre)	0.57	-0.50
Mortality (percent)	0.68	-0.56
Live tree DBH (inch)	-0.24	0.23
Dead tree DBH (inch)	0.20	-0.10
Maximum live-canopy height (foot)	-0.47	0.58
Canopy density (percent)	-0.83	0.80
Live-crown volume (percent)	-0.57	0.52

(p-value) is less than 0.0001. June was chosen for the statistical test because, during spring and early summer, water availability is usually at its highest potential and leaf-area index is usually at or near its peak in woodlands along the Mojave River.

The correlation coefficient, r , is a quantitative measure of the linear relation between two variables. A correlation coefficient of -1 indicates that large values of one variable are exactly associated with the small values of the other variable. Likewise, a correlation coefficient of +1 indicates that large values of one variable are exactly associated with the large values of the other variable. One might assume, for example, that larger values of water-table depth would correlate with larger values of tree mortality; and for that assumption to be true, the correlation coefficient would have to be positive. However, unless the absolute value of the correlation coefficient is greater than about 0.5, the linear relation between two variables usually is not considered statistically significant.

The coefficient of determination, r -squared, is used to assess the quality of a regression model. It is the proportion of the dependent variable's variability that is explained by the independent variable. The maximum value is 1. Thus, the r -squared of 0.82 for the above curvilinear regression model for LAI and water-table depth means that 82 percent of the variability in LAI is explained by the variability in water-table depth. The p -value is an indicator of whether the

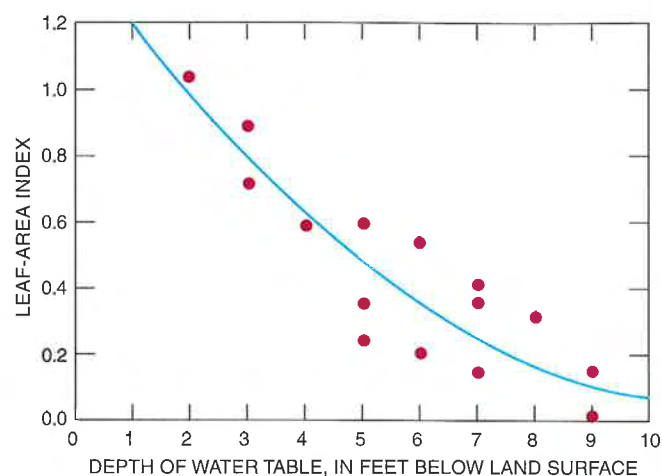


Figure 18. Relation of leaf-area index to depth of water table during spring in both healthy and stressed cottonwood–willow woodlands along the Mojave River.

regression model is real or whether the model is based solely on chance. A p -value of less than 0.0001 indicates that the probability of the above regression model being real is greater than 10,000 to 1. Generally, regression models are considered to be real if the p -value is less than 0.05, which indicates that there is a greater than a 95-percent probability that the model is real.

Mesquite at the Camp Cady 2 study site began to leaf in March 1997, but it began to leaf about a month later in 1998 (fig. 17). Likewise, the LAI peaked in July 1997 at about 0.4, but it peaked about a month later in 1998 at about 0.6. As was observed at the cottonwood–willow study sites, LAI increased slightly during September 1998 and it continued to increase at least through October. Increased leaf area during this period probably was due to increased shallow soil moisture and decreased transpiration. At the Camp Cady 1 and H1 mesquite bosque study sites, LAI was estimated at 0.1 and 0.01, respectively. Mesquite at both sites had greater than 80-percent mortality, and the lack of leaf area precluded accurate measurements.

Comparison of the three mesquite bosque study sites indicates that LAI declines as the depth of the water table increases (table 2). However, no regression model could be developed for the relation between LAI and water-table depth because of the small number of mesquite bosque study sites. Additional sites, probably 10 or more, would be needed in mesquite (tree size) bosques in order to develop and test the validity of a regression model relating water-table depth to LAI.



Figure 19. Cottonwood seedlings in an ephemeral channel of the Mojave River between synoptic sites A2 and B3, June 1995.

A single model probably would not be usable for both bush-like mesquite in xeric areas and tree-like mesquite in wetter riparian areas.

Reproduction

Reproduction of riparian vegetation along the Mojave River occurs mainly from clonal reproduction (root sprouting of established trees) and sexual reproduction (germination of seeds). Reproduction can also occur from vegetative reproduction (dislodged limbs that become buried in the river channel and that grow roots), but this is rare.

In most established cottonwood–willow woodlands along the Mojave River, reproduction occurs mainly from root sprouting. If sunlight and subsurface water are available, new plants commonly emerge from the roots of mature trees. The new sprouts take advantage of the existing root system of the “parent” tree, and they are not heavily dependent on near-surface soil moisture. The sprouts are usually

widely spaced and appear to be independent but are in fact a part of the larger tree.

Seed germination of cottonwoods and willows usually occurs along ephemeral high-flow channels of the Mojave River. The channels may have some surface flow during winter but they are usually dry during spring through autumn. Thousands of cottonwood and willow seeds deposited on the moist channel bottoms can germinate if sunlight is sufficient (fig. 19). But shallow soil moisture usually is not sufficient during summer and autumn to allow the roots of seedlings to reach a sustained source of water (the capillary fringe). Mortality of the seedlings may be near 100 percent owing to lack of shallow soil water and to water-table declines following surface flows in the ephemeral channels. From experiments in outdoor planters near Fort Collins, Colo., Segelquist and others (1993) found that there was about 50-percent mortality of Eastern cottonwood seedlings (*Populus deltoides*) if daily water-table declines were greater than about 0.1 ft and if the final water-table depth was greater than about 2.6 ft. At sites along the Mojave River where the cottonwood seedlings do reach a sustainable water



Figure 20. Cottonwood and willow saplings in the channel of the Mojave River near synoptic site I1, June 1995, about 2 years after floods of 1993.

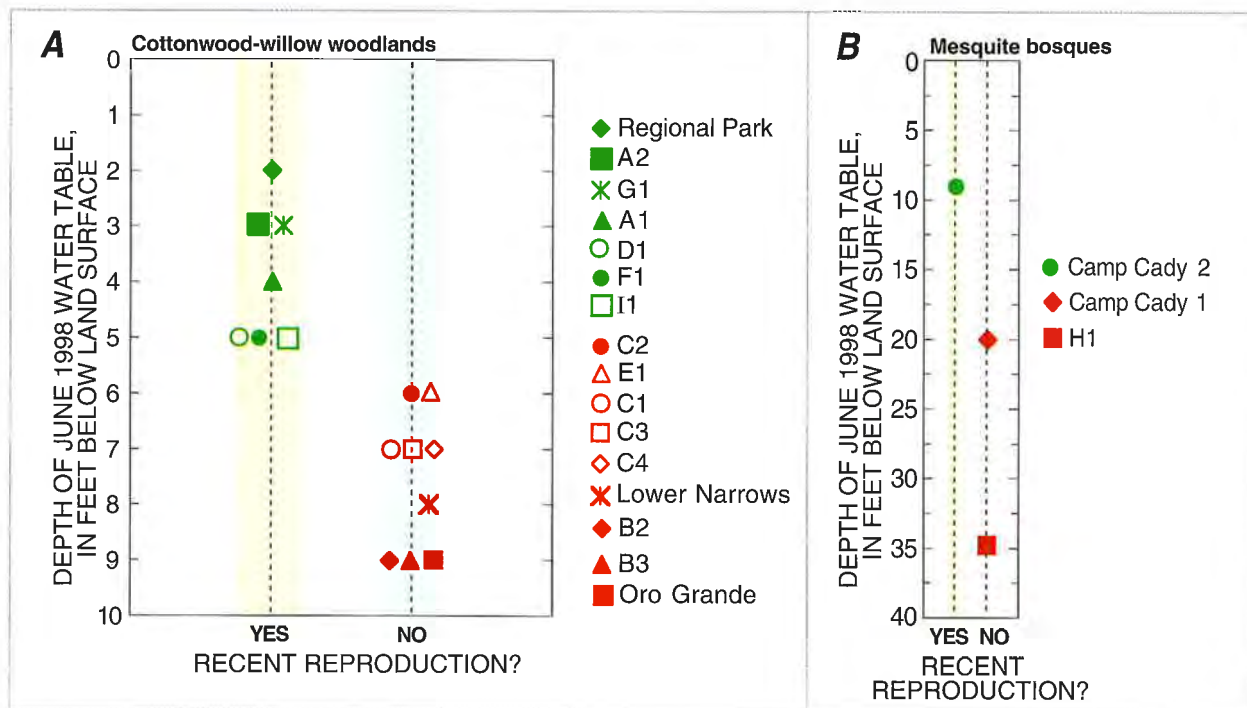


Figure 21. Relation of plant reproduction to depth of water table during June 1998 in cottonwood-willow woodlands (**A**) and in mesquite bosques (**B**).

supply (fig. 20), the trees typically are lost owing to channel clearing for flood control or during the actual flooding when the channel bottom is scoured. Thus, established stands of trees resulting from seed germination are rare along the Mojave River.

Because of very dry near-surface soil conditions during summer and autumn and the relatively deep (commonly 10 to 35 ft) water table, no mesquite germination was observed along the Mojave River during this study. In a manner similar to that of the cottonwoods and willows, mesquite reproduced mainly by root sprouting.

As indicated in figure 21, cottonwood–willow woodlands generally were reproducing only where the water-table depth during spring was 5 ft or less below land surface. It should be noted that one cottonwood root sprout did emerge during the spring of 1998 near the Lower Narrows study plot, where the water-table depth was about 8 ft below land surface in June. This was the only reproduction observed on several acres surrounding the study plot. Because of the rarity of this root sprout, the woodland in this area was considered as not having recent reproduction.

The relation between reproduction and water-table depth in established mesquite bosques is not as clearly defined as in cottonwood–willow woodlands. However, reproduction of mesquite probably will occur by root sprouting from mature trees where the water-table depth during spring is less than about 8 ft and where there are no seasonal or long-term water-table declines caused by pumping. For example, reproduction was occurring at the Camp Cady 2 study site where water-table depth during the spring of 1998 was about 8 ft and where the water table had not been significantly affected by pumping. But, there was no reproduction at the Camp Cady 1 and H1 sites where water-table depths during spring were about 20 and 35 ft, respectively, and where pumping probably had caused long-term water-table declines of 10 to 25 ft.

Other Tree-Growth Characteristics

On each of the cottonwood–willow 20 × 60-meter study plots, a number of tree-growth characteristics, in addition to LAI and reproduction, were measured or estimated (table 1) to define 1997–98

conditions and to allow future comparisons. If there were fewer than 10 trees on the original plot, measurements also were made on a second 20 × 60-meter plot adjoining the original plot. The number of trees on each plot with diameters greater than 1.5 in. (greater than about 10 years in age) were counted, and densities (trees per acre) of live and dead trees were computed. Tree mortality was calculated on the basis of number of living and dead trees. Live-crown volume (percentage of the tree-crown volume occupied by live foliage and branches) was estimated. Canopy density (percentage of land-surface area of the plot covered by live canopy) was estimated from color infrared photographs (referred to as “areal density” by Lines and Bilhorn, 1996). The diameter of selected trees at breast height (DBH) and at 1 ft above land surface was measured with a caliper in order to develop a relation that could be used to estimate mean DBH of dead trees, which often were sawed or broken below breast height. The maximum live-canopy height on each plot was measured with a clinometer. Recent reproduction, either by root sprouting or seed germination, also was noted.

The highest density of living trees in a cottonwood–willow woodland was at the Regional Park study site, and the highest density of dead trees was at the Oro Grande site. In fact, the Oro Grande study site had the highest combined density of living and dead trees (138 trees per acre). Mortality was as high as 39 percent in healthy and reproducing woodlands, but higher mortality (50 to 100 percent) was common where the depth of the water table was greater than about 7 ft or where permanent water-table declines were greater than about 5 ft.

As shown in table 3, the linear relation between canopy density and water-table depth was strong (absolute value of correlation coefficient greater than 0.75) for cottonwood–willow woodlands. This is not surprising since LAI had a strong linear relation to canopy density. The DBH and maximum height of trees varied mainly owing to age, and there were only weak linear relations with the water-table depth (absolute values of correlation coefficients less than 0.5). Density of live and dead trees, mortality, and live-crown volume had moderately strong linear relations with water-table depth (absolute values of correlation coefficients between 0.50 and 0.75).

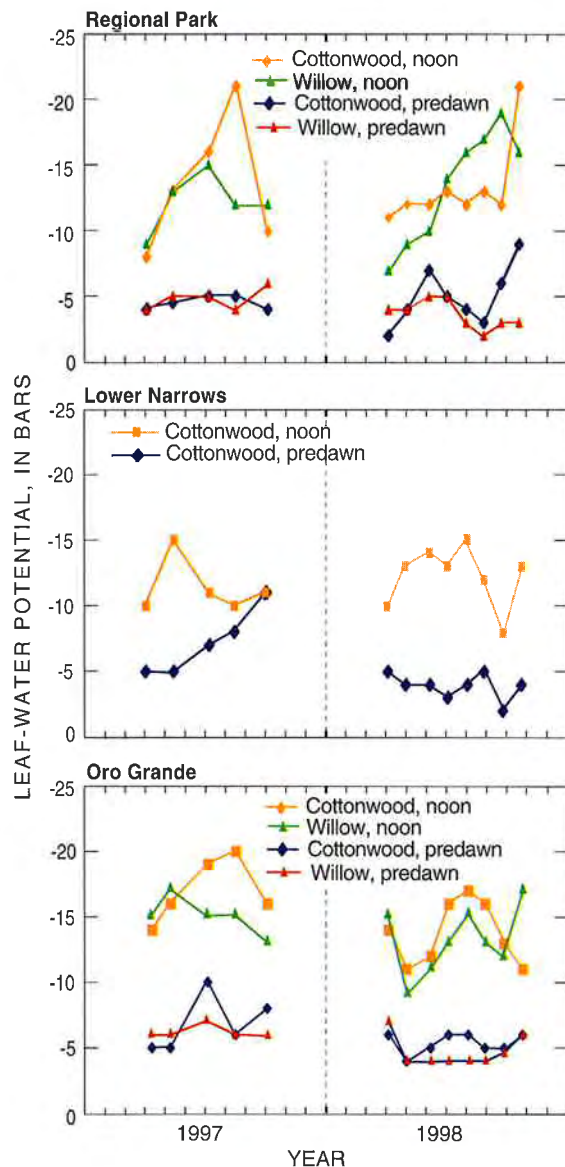


Figure 22. Leaf-water potentials at instrumented cottonwood-willow woodland study sites during the growing seasons of 1997 and 1998.

Live-crown volume, canopy density, maximum live-canopy height, LAI, and mortality also were measured or estimated for the mesquite bosque study sites (table 2). Mesquite reproduction, or lack thereof, also was noted. Comparison of the three mesquite bosque study sites indicates that mortality increased with increased depth of the water table. Also, maximum live-canopy height, canopy density, live-crown volume, and LAI decreased with increased

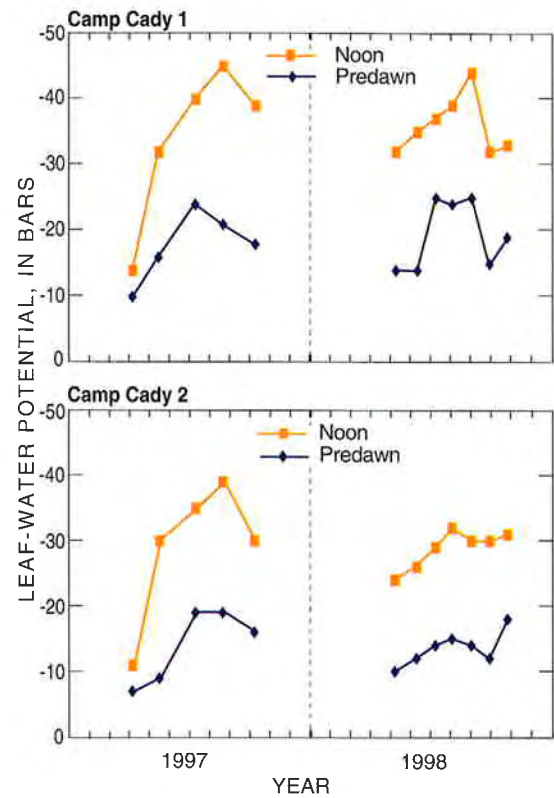


Figure 23. Leaf-water potentials at instrumented mesquite bosque study sites during the growing seasons of 1997 and 1998.

depth of the water table. However, because of the relatively small number of mesquite study sites, significant statistical relations could not be defined for the various tree-growth characteristics and water-table depth.

Leaf-Water Potential

Leaf-water potentials were measured at instrumented cottonwood-willow and mesquite bosque study sites during the growing seasons of 1997 and 1998 (figs. 22 and 23). Leaf-water potential is an approximate measure of the suction applied by the tree's roots to absorb water in the subsurface. Ideally, the water potential would be measured in the roots, but this is not practical. Instead, the water potential can be measured in the leaves with only a small error arising from the elevation difference between roots and leaves (1 bar is equivalent to about 33 ft in elevation

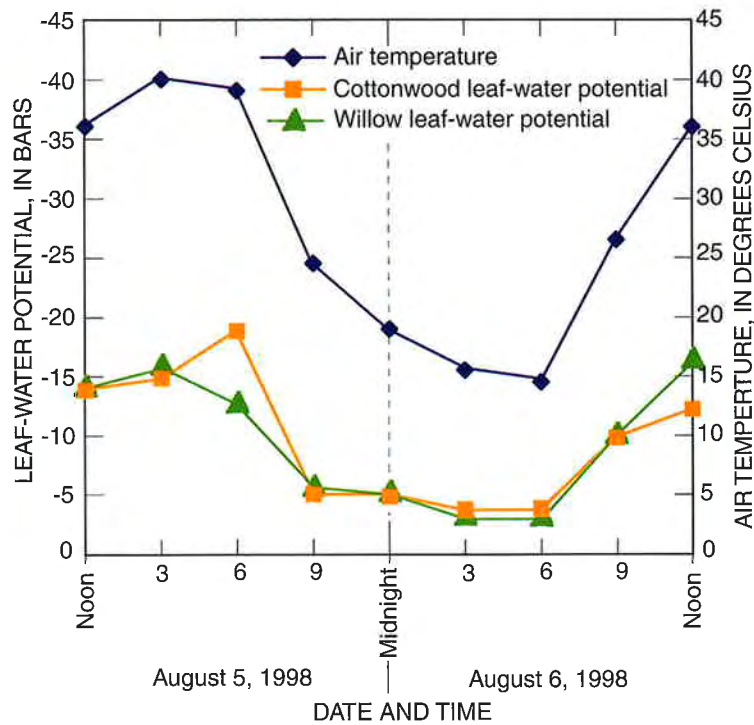


Figure 24. Diurnal fluctuations of cottonwood and willow leaf-water potential and air temperature at Regional Park study site.

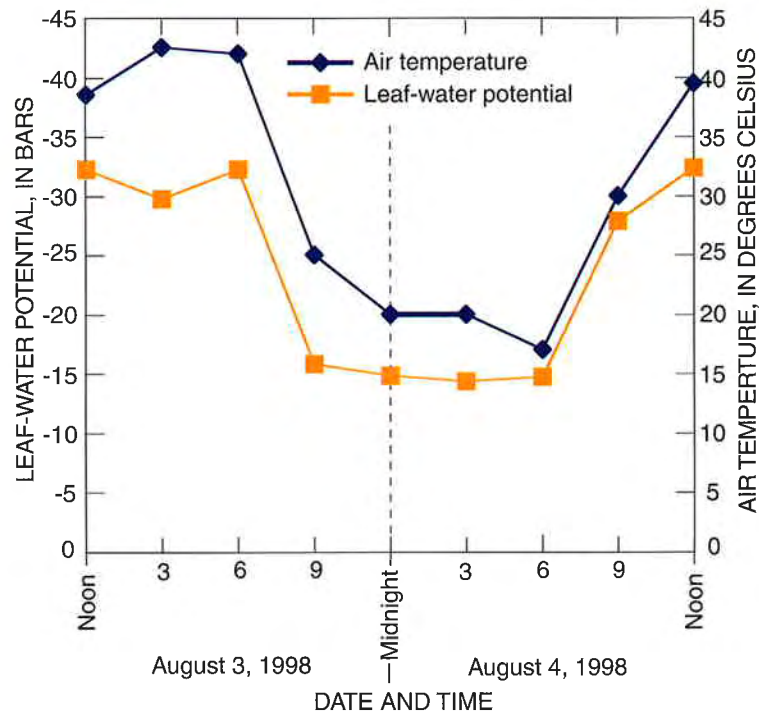


Figure 25. Diurnal fluctuations of honey mesquite leaf-water potential and air temperature at Camp Cady 2 study site.

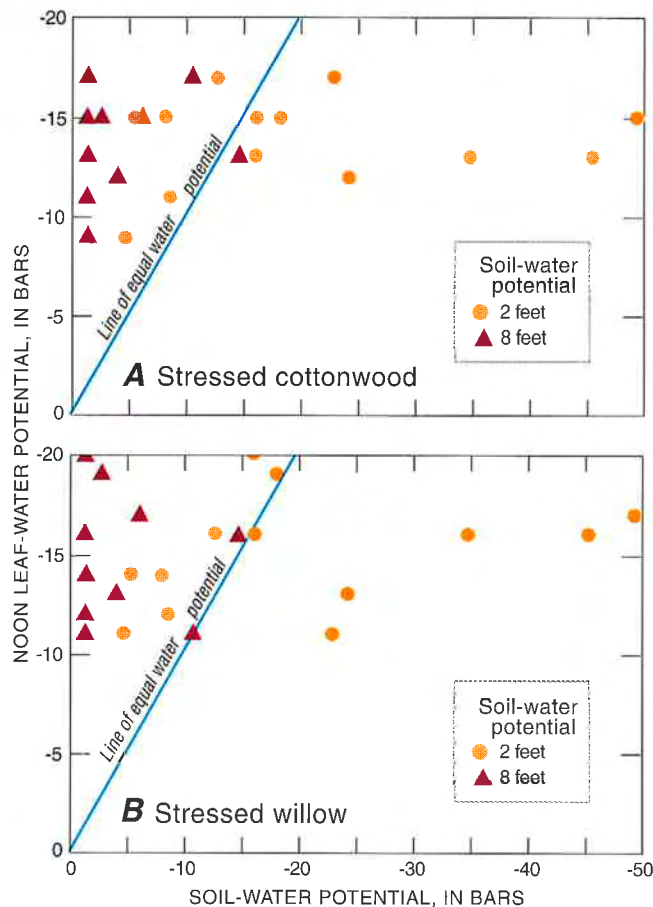


Figure 26. Relation of noon leaf-water potential to soil-water potential during 1997–98 at Oro Grande study site: (A) stressed cottonwood and (B) stressed willow.

difference). For example, the difference in water potential for roots that are 10 ft below land surface and leaves that are 6 ft above land surface would be about 0.5 bar. Water potentials were measured in leaves that were collected at about head height (about 6 ft above land surface).

At each site, three leaves were collected from different trees, and the three water potentials were averaged. The differences in leaf-water potential for different trees were usually less than about 2 bars. Leaves were collected prior to sunrise (predawn) and at midday (noon). Leaf-water potentials are at their lowest during predawn hours when plant water losses owing to transpiration are at their minimum. Leaf-water potentials usually are at their highest in early afternoon during the hottest part of the day. During two

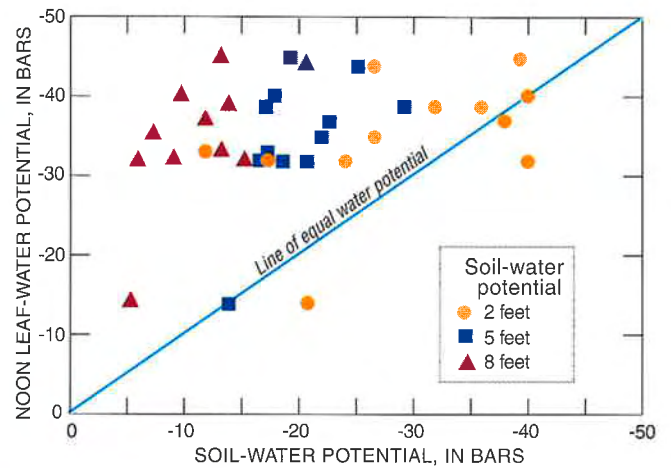


Figure 27. Relation of noon leaf-water potential of stressed mesquite to soil-water potential during 1997–98 at Camp Cady 1 study site.

24-hour tests (figs. 24 and 25), leaf-water potentials and air temperature were strongly related (correlation coefficients of 0.95 for cottonwoods and mesquite and 0.96 for willows).

At the three instrumented cottonwood–willow study sites, no clear seasonal pattern in leaf water-potential was evident (fig. 22). However, noon leaf-water potentials were generally higher (more negative) during summer (as much as -22 bars for cottonwoods and -20 bars for willows) than during spring (usually less than -15 bars for both cottonwoods and willows). The noon water potentials were almost always higher than the predawn potentials. It should be noted that noon leaf-water potentials were similar for both healthy and stressed cottonwoods and willows. Although more subsurface water was generally available to healthy trees, their leaf-water potentials were as high as those of stressed trees. High leaf-water potentials were needed to compensate for the added transpiration losses resulting from increased leaf area in the healthy trees.

On the other hand, both predawn and noon leaf-water potentials at the two instrumented mesquite bosque study sites did have discernible seasonal trends (fig. 23). Leaf-water potentials of the mesquite were lowest in spring and usually peaked during late summer. At the stressed mesquite site (Camp Cady 1), noon leaf-water potentials commonly were greater than -40 bars during summer, and even predawn potentials

ranged from about -15 to -25 bars during summer. In contrast, at the healthy mesquite study site (Camp Cady 2), noon leaf-water potentials were less than -40 bars during summer, and predawn potentials commonly ranged from -10 to -20 bars.

Comparison of leaf- and soil-water potentials during the growing season can be used to determine a plant's ability to absorb water from soil. At all instrumented sites, noon leaf-water potentials usually were large enough to allow water absorption from all monitored soil depths, except during some periods when soil-water potentials of near-surface soil increased owing to evaporation. For example, shown in figure 26 is the relation of leaf-water potential (in stressed cottonwoods and stressed willows) and soil-water potential at depths of 2 and 8 ft at the Oro Grande study site. Points above the line of equal potential indicate that the trees were capable of absorbing water from soil at the specified depth. Likewise, points below the line of equal potential indicate that the trees were not capable of absorbing water from soil at the specified depth. Except for dried soil at 2 ft, the stressed cottonwoods and willows were capable of absorbing water in unsaturated soil during most periods. Likewise, stressed mesquite at Camp Cady 1 study site also was capable of absorbing water from below about 2 ft most of the time (see fig. 27). Similar relations between leaf-water potential and soil-water potential also were observed at the Lower Narrows (stressed cottonwoods) and Camp Cady 2 (healthy mesquite) study sites, but they are not shown in this report. At the Regional Park study site, leaf-water potentials of healthy cottonwoods and willows were always larger than the soil-water potential at 1.5 ft.

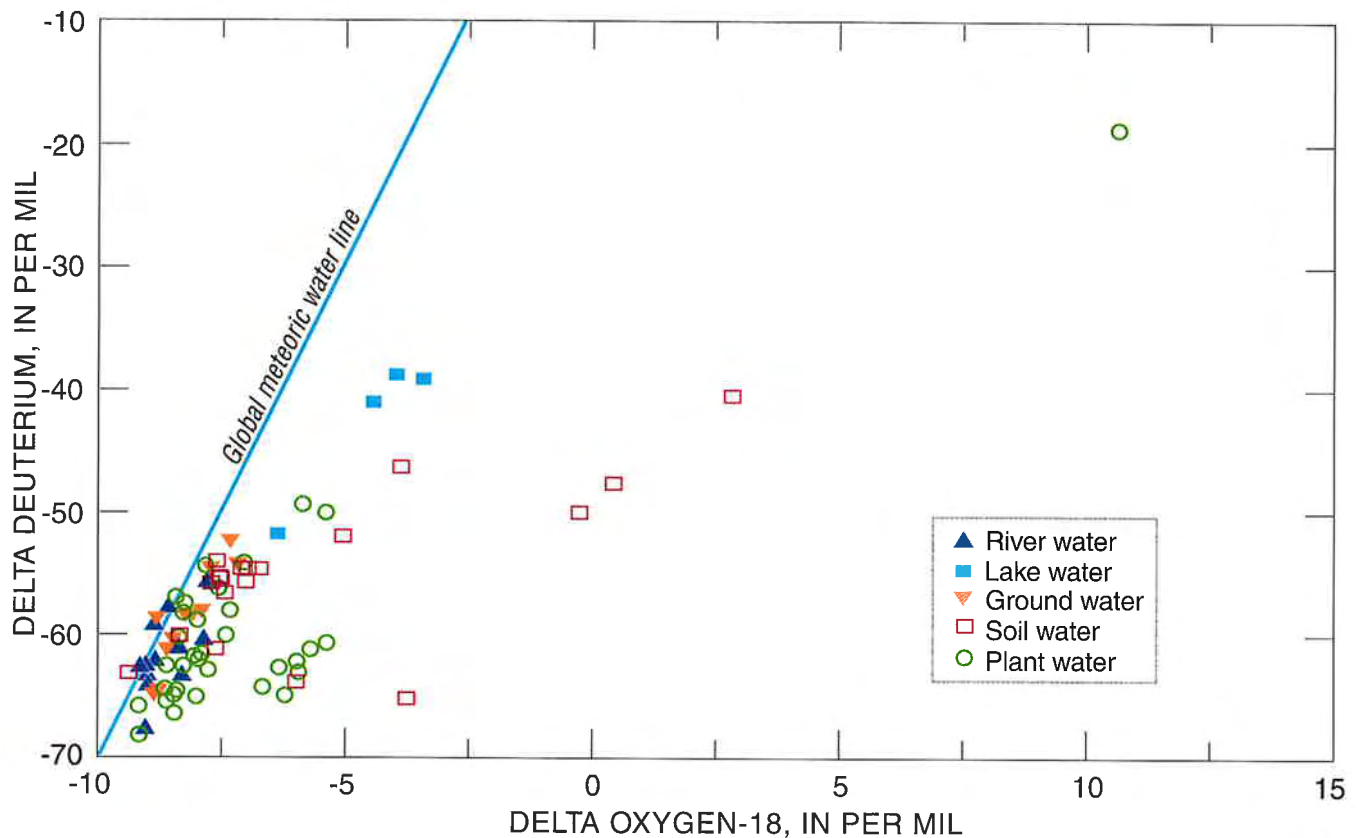
SOURCES OF WATER USED BY RIPARIAN VEGETATION

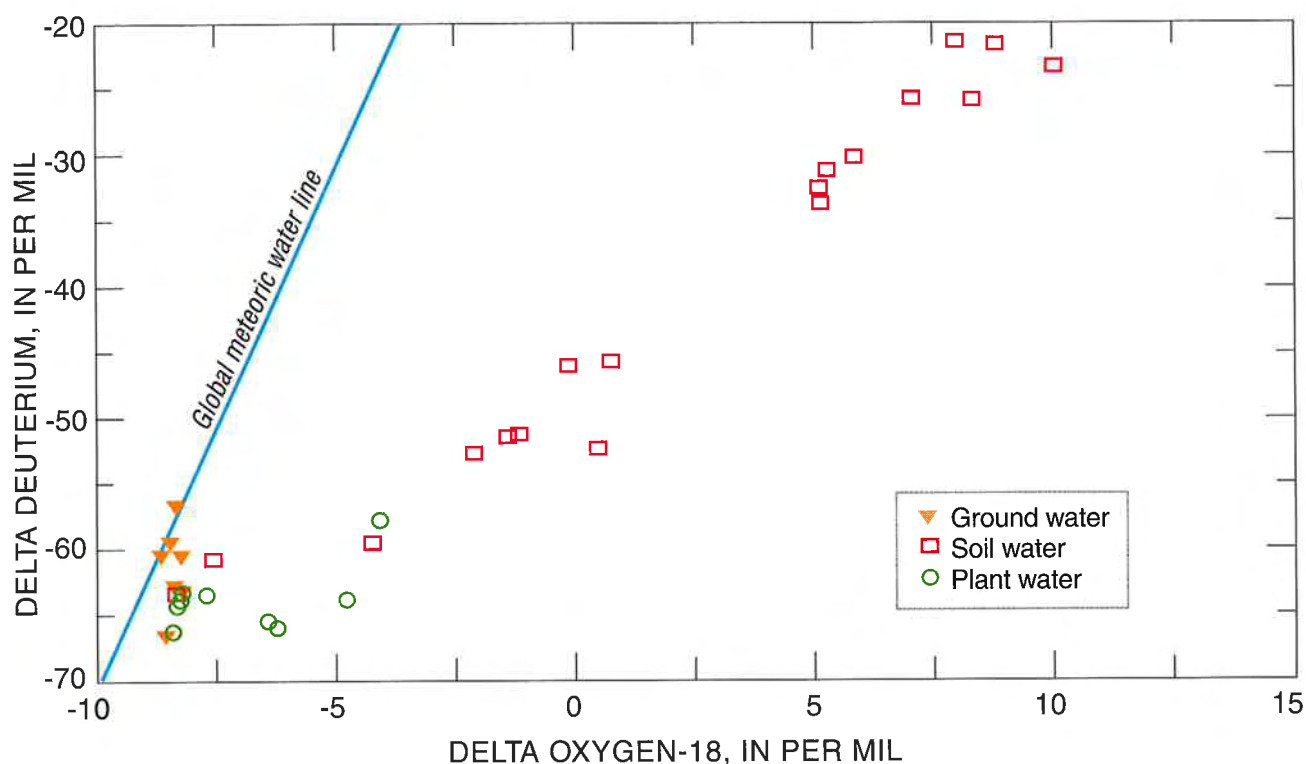
As pointed out earlier, most of the roots of cottonwood, willow, and mesquite trees probably are in unsaturated soil above the water table. In addition, comparison of leaf-water potentials and soil-water potentials indicates that the trees are capable of absorbing water from unsaturated soils at all of the depths monitored. The exception being at some sites where evaporation dries near-surface (upper 1 to 2 ft)

soil and the soil-water potential is greater than about -50 bars.

Annual water use by cottonwoods and willows along the Mojave River was estimated as 4.1 ft in dense woodlands (70 to 100 percent canopy density), and dense mesquite was estimated to use about 1.4 ft (Lines and Bilhorn, 1996). In contrast, mean annual precipitation is only about 6 in. at Victorville and about 4 in. at Barstow. Precipitation alone is not sufficient to sustain riparian vegetation. Most of the precipitation probably is evaporated from near-surface soil or transpired by xeric brush and grasses. Infiltration of precipitation to the root zone of riparian vegetation, if it occurs at all, may be no more than a fraction of an inch in most areas. Also, as pointed out earlier, the main root mass in high-mortality cottonwood–willow woodlands is spread vertically several feet through unsaturated soils, but roots are 7 to 8 ft above the water table (fig. 14). Clearly, the trees cannot survive entirely on moisture in soil that is several feet above the water table. Except for the trees living at the edge of perennial reaches of the Mojave River, the only other perennial and secure source of water is ground water near the water table.

Mojave River water (if available), moisture in unsaturated soils, ground water, and tree water (xylem sap) were sampled at the five instrumented study sites. Overflow from a lake near the Regional Park site also was sampled. The samples were analyzed for concentrations of stable hydrogen isotopes (hydrogen-1 and deuterium) and oxygen isotopes (oxygen-16 and oxygen-18). When the concentrations of the hydrogen and oxygen isotopes are expressed as ratios compared to a standard known as Vienna Standard Mean Ocean Water (Gonfiantini, 1978), the information can be used to identify the source of water utilized by riparian vegetation (see figs. 28 and 29). Craig (1961) found that a linear relation exists between delta deuterium and delta oxygen-18 in meteoric waters throughout the world. This relation is referred to as the global meteoric water line (GMWL). Water that has not undergone significant evaporation will plot near the GMWL. The more evaporation a water has undergone, the greater will be the enrichment of delta deuterium and delta oxygen-18 (and less negative their values) and the further the water will plot below the GMWL.





water table. Most cottonwoods, willows, and mesquite trees along the Mojave River mainly rely on this water that has moved upward into the root zone. However, stressed mesquite that has developed a bush-like stature where water-table depth is several tens of feet probably relies entirely on infiltration of precipitation into shallow soils.

Cottonwoods, willows, and mesquite trees along the Mojave River mainly rely on ground water for their perennial sustained supply of water. They utilize ground water that has moved upward from the water table into the capillary fringe and into unsaturated soil nearer to land surface. Most precipitation that falls on the land surface is lost by evaporation and by transpiration of shallow-rooted xeric plants. Heavily stressed mesquite that has the stature of a bush (height less than about 3 ft) probably relies on meager soil moisture from infiltration of precipitation.

density, and mortality of trees), there are strong linear relations to LAI (corrected for stem area) and canopy density at the 16 cottonwood–willow woodland study sites. Leaf-area index is an excellent indicator of the overall health of trees because it is related to their density, live-crown volume, height, and mortality. Leaf area is very sensitive to water stress, and LAI changes quickly in response to stress caused by the imbalance between transpiration and water availability. The LAI can be accurately measured repeatedly at the same locations, and it is the primary plant characteristic that should be monitored. Canopy density, on the other hand, must be estimated from aerial photographs or from extensive measurements on the ground.

as those growing at the Lower Narrows study site, rely heavily on soil moisture left behind as the water table declines during summer and autumn. However, mortality is extremely high (95 to 100 percent) where water-table declines greater than about 5 ft are sustained for more than a few months.

Reproduction of cottonwood–willow woodlands occurred mainly as root sprouting from established mature trees. Germination of seeds was common in ephemeral channels that had been wetted by surface flows and where there was abundant sunlight, but shallow soil moisture usually is not sufficient to sustain seedlings until their roots can reach a perennial water supply. No reproduction occurs at sites where the water-table depth during spring exceeded about 5 ft.

Comparison of data from the three mesquite bosque study sites indicated that mortality increased with increasing water-table depth; whereas LAI, canopy height, live-canopy density, and live-crown volume decreased with increasing water-table depth. At a healthy and reproducing mesquite bosque, where the water-table depth ranged from about 8 to 11 ft, mortality was about 20 percent. Where the water table had been lowered more than about 10 ft by pumping, mortality was extremely high (80 to 99 percent). The relation between mesquite reproduction and water-table depth is not clearly defined. Although no mesquite germination was observed, root sprouting did occur where water-table depth during spring was about 8 ft. No mesquite reproduction was observed where the water-table depth during spring exceeded about 20 ft.

Natural processes such as channel incision and draining of the adjacent flood-plain aquifer will continue to affect the health of riparian vegetation. However, long-term survival of cottonwood–willow woodlands and mesquite bosques along the Mojave River will depend on their reproduction. In the absence of seasonal water-table fluctuations caused by pumping, reproduction will occur in cottonwood–willow woodlands where the water-table depth during spring is less than 5 ft. Likewise, reproduction in established mesquite bosques will probably occur if the water-table depth during spring is less than about 8 ft and there are no significant seasonal or long-term water-table declines caused by pumping.

REFERENCES CITED

- Auble, G.T., Scott, M.L., Shafroth, P.B., and Lines, G.C., 1998, Responses of riparian cottonwoods to alluvial water-table declines (abs.): American Geophysical Union Transactions, v. 79, no. 45, p. F344.
- Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-3.
- Gile, L.H., Gibbens, R.P., and Lenz, J.M., 1997, The near-ubiquitous pedogenic world of mesquite roots in an arid basin floor: Journal of Arid Environments, v. 35, p. 39–58.
- Gonfiantini, R., 1978, Standards for stable isotope measurements in natural compounds: Nature, v. 271, p. 534–536.
- Heitschmidt, R.K., Ansley, R.J., Dowhower, S.L., Jacoby, P.W., and Price, D.L., 1988, Some observations from the excavation of honey mesquite root systems: Journal of Range Management, v. 41, no. 3, p. 227–231.
- Lines, G.C., 1996, Ground-water and surface-water relations along the Mojave River, southern California: U.S. Geological Survey Water-Resources Investigations Report 95-4198, 43 p.
- Lines, G.C. and Bilhorn, T.W., 1996, Riparian vegetation and its water use during 1995 along the Mojave River: U.S. Geological Survey Water-Resources Investigations Report 96-4241, 10 p.
- Meinzer, O.E., 1923, Outline of ground-water hydrology with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p.
- , 1927, Plants as indicators of ground water: U.S. Geological Survey Water-Supply Paper 577, 95 p.
- Milburn, J.A., 1979, Water flow in plants: New York, Longman, 225 p.
- National Oceanic and Atmospheric Administration, 1996–98, Climatological data, California, 1996–98: v. 100–102.
- Scholander, P.F., Hammel, H.T., Bradstreet, E.D., and Hemmingsen, E.A., 1965, Sap pressure in vascular plants: Science, v. 148, p. 339–346.
- Scott, M.L., Lines, G.C., and Auble, G.T., in press, Response of riparian cottonwoods to channel incision along the Mojave River, California, USA: Journal of Arid Environments.
- Segelquist, C.A., Scott, M.L., and Auble, G.T., 1993, Establishment of *Populus deltoides* under simulated alluvial groundwater declines: American Midland Naturalist, v. 130, p. 274–285.
- Thompson, D.G., 1929, The Mojave Desert region, California—a geographic, geologic, and hydrologic reconnaissance: U.S. Geological Survey Water-Supply Paper 578, 759 p.