Effects of Groundwater Decline on Riparian Vegetation of Semiarid Regions: The San Pedro, Arizona

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EFFECTS OF GROUNDWATER DECLINE ON RIPARIAN VEGETATION OF SEMIARID REGIONS: THE SAN PEDRO, ARIZONA[1]

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Abstract. Groundwater depletion threatens many riparian ecosystems in arid and semiarid regions of the world. The aquifer that sustains Arizona's San Pedro River riparian ecosystem, for example, is threatened by regional groundwater declines and localized pumping from the alluvial aquifer. This paper demonstrates the important role of shallow groundwater in structuring the San Pedro River plant community, portions of which function as reference areas that indicate site potential for a globally rare forest type (Sonoran riparian *Populus–Salix* forests). Several ecological indicators varied with depth to groundwater, including a weighted average wetland indicator score calculated for herbaceous and woody plant species, cover of plants within wetland indicator groups, and frequency of indicator plant species. These relationships can be used in a space-for-time substitution to predict consequences of groundwater decline. For example, the wetland indicator score changed sharply as depth to groundwater ranged from 0 to 4 m, and abundance of obligate wetland herbs (the group most sensitive to groundwater changes) declined sharply at groundwater depths below ≈0.25 m. Such sequential "desertification" of the riparian flora (i.e., loss or reduction in cover of species based on their probability of occurrence in wetlands) is one predicted response to groundwater decline. Other predicted impacts of groundwater decline include reduced establishment of *Populus fremontii–Salix gooddingii* forests, and reduced cover of herbaceous species associated with the fine-textured soils and shady conditions of floodplain terraces stabilized by these early seral tree species. High floodplain terraces (depth to groundwater of 5–8 m) had wetland indicator scores below those of upland sites and were vegetated by species (e.g., *Prosopis velutina* and *Sporobolus wrightii*) with low sensitivity to groundwater changes.

Key words: ecosystem degradation; floodplain aquifer; groundwater decline; indicator species; Populus fremontii; *riparian ecosystem; San Pedro River, Arizona; semiarid alluvial habitat; weighted average wetland indicator score.*

INTRODUCTION

Groundwater depletion and stream dewatering have contributed to loss and alteration of wetland and riparian ecosystems throughout the world (e.g., Gremmen et al. 1990). This is particularly true in arid and semiarid regions, because surface and groundwater are in high demand for human use and also exert strong influence on abundance and composition of riparian vegetation (Perkins et al. 1984, Groeneveld and Griepentrog 1985, Davies et al. 1992, 1994, Richter 1993, Cooper 1994, Yibing and Chongshun 1994). In arid portions of the US Southwest, low-elevation alluvial rivers have been most affected by stream and aquifer dewatering. In some areas, the combination of surface water diversion and groundwater extraction in excess of recharge has caused perennial rivers to become ephemeral, and has caused shallow water tables to decline by as much as 200 m (Bryan 1928, Judd et al. 1971). Effects of water reduction have ranged from total loss of riparian vegetation (e.g., Judd et al. 1971) to more subtle impacts.

Dewatering continues to threaten riparian ecosystems throughout the world, in part because of the paucity of riparian protection measures. For example, although some states in the USA regulate groundwater extraction, the regulations typically do not provide for riparian protection (Lamb and Lord 1992). Instream flow rights are granted for fish and wildlife habitat in most western states, but often these rights are junior to others. Additionally, surface water and groundwater are generally not conjunctively managed, meaning that instream flows can legally be reduced by groundwater pumping (Glennon and Maddock 1994). Ultimately, protection of riparian areas and their water sources will be accomplished through an interplay of regulation, planning, public participation, and scientific input. Scientific contribution to this effort comes, in part, through quantification of the biological impacts of dewatering, elucidation of the hydrological requirements for establishment and survivorship of riparian biota, and prediction and detection of the ecological consequences of changes in surface and groundwater availability.

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Given the high biodiversity of riparian zones (Naiman et al. 1993), there is much to be learned about plant–water relationships for those species, life stages, or functional groups that are sensitive bioindicators of surface or groundwater decline. However, there are relatively few data upon which to predict impacts of hydrological changes on riparian biota. Because river baseflows often are directly linked with alluvial aquifer levels, it is important to address impacts both to riparian forests dependent on alluvial groundwater (e.g., Busch et al. 1992, Mensforth et al. 1994) and to aquatic species directly dependent on river flows. Relationships between groundwater and Southwest riparian plant species have a long history of study (e.g., Meinzer 1927, Bryan 1928, Gary 1965, Zimmerman 1969, McQueen and Miller 1972), but much remains to be learned. Depth-to-groundwater requirements for recruitment and survivorship have been delineated mainly for woody dominants including *Populus fremontii, Prosopis velutina,* and *Salix gooddingii* (Stromberg et al. 1991, 1992, 1993). Less is known about herbaceous species, which may be more sensitive to groundwater change. There also has been little investigation of indirect effects of groundwater decline, such as may occur when the decline alters successional pathways by affecting abundance of pioneer species.

The general objective of this paper was to predict some of the effects of shallow groundwater decline on the riparian plant community of the upper San Pedro River in southeastern Arizona. This river presently supports a high quality riparian area, but is threatened by regional groundwater declines and localized pumping from the alluvial aquifer. Specific objectives were to: (1) determine the influence of groundwater, relative to other environmental variables, on plant community composition; (2) describe depth-to-groundwater ranges for individual woody and herbaceous plant species, as a precursor to predicting compositional shifts resulting from groundwater decline (e.g., Franz and Bazzaz 1977, Phipps 1979); (3) quantify the relationship between groundwater and guilds of species (e.g., wetland indicator groups) that have similar response to a common stressor (e.g., Menges and Waller 1983, Boutin and Keddy 1993, Auble et al. 1994); (4) identify some of the indirect impacts of water table decline resulting from alteration of successional processes; and (5) quantify projected losses of various wetland groups under various groundwater decline scenarios.

METHODS

Study area

The San Pedro River is a small, low gradient (0.002–0.005 m/m) alluvial river located in a semiarid part of Arizona. The San Pedro drains a watershed of 1909 km^2 at the US–Mexico border (1300 m a.s.l. elevation) and a 4481 km^2 watershed 50 km downstream of the border (1130 m elevation). The watershed is vegetated by Chihuahuan desertscrub, semidesert grassland, and Madrean evergreen woodland (Brown 1982). Mean annual flows of the San Pedro River range from 0.90 m^3/s at the US–Mexican border (Palominas gage) to 1.65 m^3/s at the Charleston gage (Fig. 1). Mean annual precipitation (Fairbank station) is 28 cm/yr, 66% of which falls during July through September. Flood flows occur mainly during the two rainy seasons. Summer floods (July to September), resulting from localized monsoon storms, are generally of shorter duration but greater frequency than winter floods (December and January), which result from Pacific frontal storms.

In common with most alluvial Southwestern rivers, the vegetation, hydrology, and geomorphology of the San Pedro River have been altered from their historical condition. Many of the changes on the San Pedro occurred near the end of the 19th century, due to a suite of interacting climatic and anthropogenic factors. At that time, high intensity flood events scoured floodplains that had been devegetated by wood harvest for mine smelters, overgrazing by cattle, stream diversions, and drought (Bahre 1991). The resulting episode of channel incision caused water tables to decline by several metres, producing a two-tiered floodplain (Fig. 2). Portions of the pre-entrenchment floodplain terrace that have not been cleared for agriculture support *Prosopis velutina* woodlands and *Sporobolus wrightii* grasslands. The lower postentrenchment floodplain that has developed since ≈AD 1900 (Hereford 1991) is vegetated by *Populus fremontii–Salix gooddingii* forests and other Sonoran riparian vegetation types. Although marshlands no longer are a major component of the San Pedro floodplain vegetation mosaic, emergent wetland plants line the river banks in places. There is an abundance of riparian scrubland, which can be an indicator of degradation, but the exotic *Tamarix chinensis* has not displaced the native forests of *Populus, Salix,* and *Prosopis,* as it has on >20,000 ha in Arizona (Valencia et al. 1993). The persistence of native vegetation along the San Pedro is significant, given that most types of Sonoran riparian vegetation now cover only a small portion of their regional historical range, due to stream dewatering, river damming and flow regulation, overgrazing by livestock, development of floodplains for agriculture and urban use, and watershed degradation (Rea 1983, Hendrickson and Minckley 1984).

In 1988, a 50-km reach of the upper San Pedro River with parts of its watershed was designated as a Riparian National Conservation Area, to be managed by the Bureau of Land Management (Fig. 1). This portion of the river supports one of the best remaining examples of the Mixed-Broadleaf series of Sonoran Riparian Forest (Brown 1982). Upon its designation as a Conservation Area, off-road vehicle use, sand and gravel mining, floodplain agriculture, and groundwater pumping were discontinued, and a 15-yr moratorium was placed on cattle grazing (Yuncevich 1993). The river is threatened, however, by groundwater pumping from private

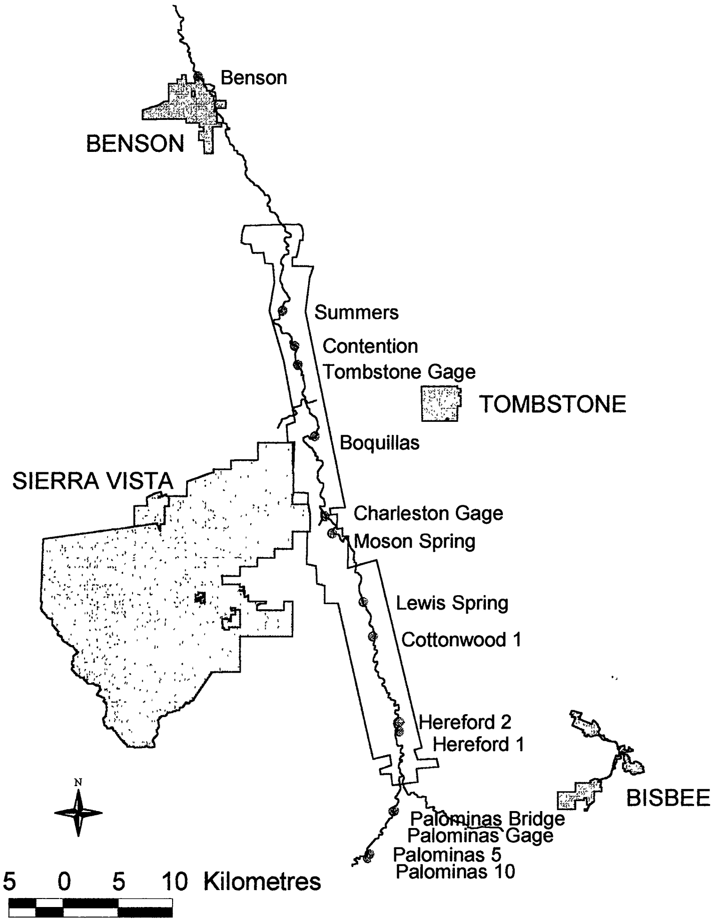

FIG. 1. Site map of the upper San Pedro River study area, indicating boundaries of Conservation Area, stream gages, and groundwater monitoring well sites.

inholdings and from the alluvial floodplain aquifer upstream and downstream of the Conservation Area. Groundwater also is being mined from the regional basin-fill aquifer, which flows along a hydraulic gradient into the San Pedro River's alluvial aquifer. The rate of groundwater flow from the regional aquifer to the alluvial aquifer has declined steadily in recent decades, as the nearby municipalities of Sierra Vista and Fort Huachuca have pumped groundwater from the alluvial aquifer at a rate in excess of the recharge from snowmelt and rainfall drainage off the Huachuca Mountains (Vionnet and Maddock 1992). During this

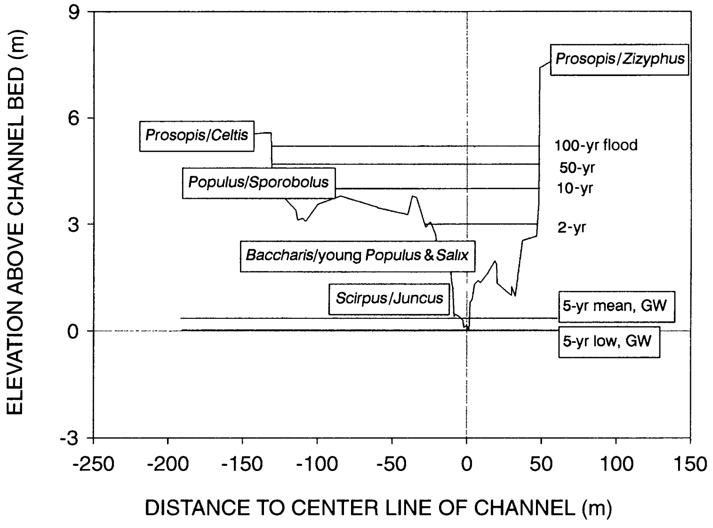

FIG. 2. Cross-section of the San Pedro floodplain, showing dominant vegetation types, position of the groundwater (GW) table (5-yr mean value, and 5-yr low value), and inundation levels of the 2-yr, 10-yr, 5-yr, and 100-yr return floods.

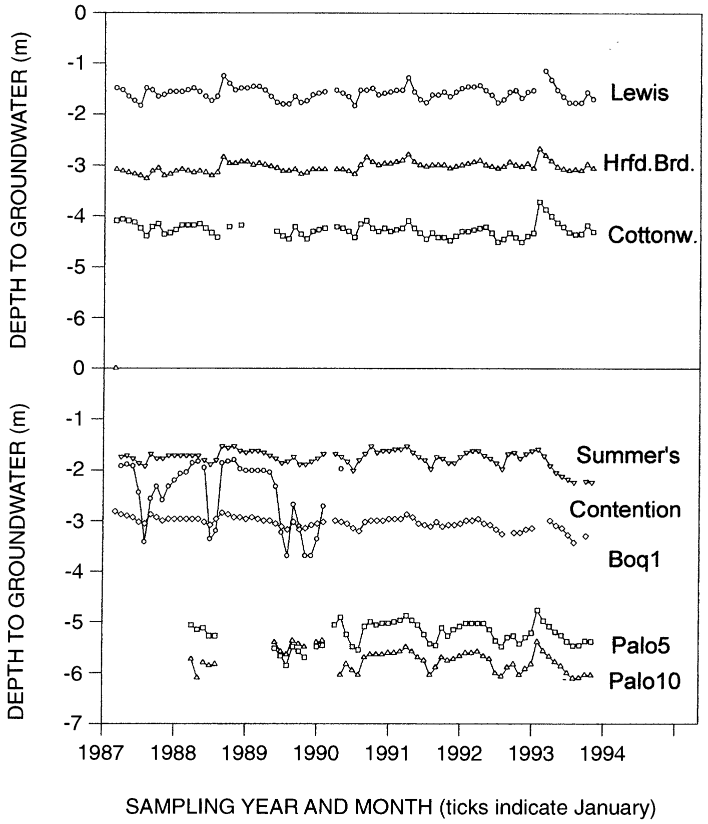

FIG. 3. Depth to groundwater over time for eight wells in the San Pedro River floodplain aquifer. Lewis Springs, Hereford Bridge, and Cottonwood 1 are located in the middle section of the Riparian National Conservation Area; Summers' BOR, Contention, and Boquillas 1 are at the northern end; Palominas 5 and Palominas 10 are at the southern end.

same time period, base flows have declined in the upper San Pedro River (Jackson et al. 1987). Depth to groundwater in the Upper San Pedro River floodplain aquifer is predicted to increase gradually, particularly in areas not underlain by shallow bedrock (Vionnet and Maddock 1992). In the northern section of the Conservation Area, additional threats come from a growing cone of depression (area of groundwater overdraft) created by groundwater pumping in the Benson–St. David area (Jahnke 1994).

In the central sections of the Conservation Area, the San Pedro River gains flow from the groundwater and surface flow is perennial. In this reach, shallow bedrock helps to maintain perennial flows and stable groundwater levels (Fig. 3). In the northern and southern sections, the amount of groundwater flowing from the regional aquifer toward the river is insufficient to maintain alluvial aquifer levels at the elevation of the streambed. In these reaches, inflowing river water percolates downward into the alluvial aquifer, creating a "losing" river condition, cessation of surface flow during dry seasons, and greater fluctuation in groundwater levels. At the northern end of the Conservation Area (e.g., Boquillas 1 and Summer's well), groundwater during 1994 showed uncharacteristic declines despite a flood (<10-yr recurrence interval) in January 1993, perhaps due to the influence of groundwater overdrafts.

Research approach

The research approach involved simultaneously collecting data on vegetation, site hydrology, geomorphology, and soils across natural gradients within the floodplain and at sites with differing hydrological conditions. At each of 11 sites distributed throughout the Conservation Area, a cross-floodplain transect was established that spanned the width of the riparian zone. Transects were ≈5 km apart and were aligned perpendicular to the stream (Fig. 1). The transect line was subjectively stratified into patch types that differed in vegetation composition, vegetation age class, or geomorphic landform. Patch types included sandbars within the active channel, vegetated stream banks, overflow channels, and pre- and postentrenchment floodplain terraces vegetated by various woody or herbaceous dominants. One plot was established per patch type per transect, in stratified random fashion. Per transect, 11–19 plots were sampled, for a total of 158 study plots.

In 1993, woody plants were sampled, by species for stem density and basal diameter in 158 study plots (5 × 20 m, long axis parallel to the stream). Canopy foliage area (leaf area index) was measured with a LI-COR 2000 plant canopy analyzer at each plot at dawn or dusk, and treated as an indirect measure of light availability. Herbaceous vegetation was sampled for cover and composition in June 1993 (premonsoon) and

TABLE 1. Distribution of plant species of the San Pedro River floodplain, Arizona, within wetland indicator classes (Reed 1988).

Wetland indicator class	Frequency of occurrence in wetlands	Wetland score	Number of species		
			Woody	Herbaceous	Total
Obligate wetland	>99%	1	1	11	12
Facultative wetland	67–99%	2	5	15	20
Facultative	34–66%	3	1	12	13
Facultative upland	1–33%	4	4	14	18
Obligate upland	<1%	5	21	59	80

September 1993 (postmonsoon) in 158 smaller nested plots (1 × 1 m). Voucher specimens were deposited in the Arizona State University herbarium. Species names follow Lehr (1978) or, in some cases, chapters of a forthcoming book on vascular plants of Arizona that are initially being published in the Journal of the Arizona–Nevada Academy of Science.

Herbaceous and woody plant species were classified within one of five wetland indicator categories, each of which represents a probability of occurrence in wetlands (Reed 1988). The national indicator value was used if the regional value was not reported. Weighted average wetland indicator scores were calculated for each plot by assigning weights of one through five for the wetland categories (Table 1), summing the products of the class weights and the relative abundance of all species in each class, and dividing by 100 (Atkinson et al. 1993). Wetland scores were calculated separately for herbaceous (cover values) and woody species (basal areas). For herbaceous species, the wetland score was classified in two ways because *S. wrightii,* a prominent species in the study area, was not listed in Reed (1988) and, thus, would be scored as a 5 (upland). This species, however, is sometimes treated as a variety of *S. airoides,* which has a score of 3 (facultative). Unless otherwise indicated, the score was calculated using a value of 5 for *S. wrightii.*

Each of the 11 study sites was located adjacent to a Bureau of Land Management monitoring well located within the floodplain alluvium. The wells have been monitored since 1987 for depth to groundwater. Well locations, transect lines, and plot locations were topographically surveyed for elevation above the stream thalweg (low point in the channel) and above the stream water level, using an autolevel transit (TOPCON model ATG-7). Survey data, in conjunction with groundwater data for the transect wells, were used to calculate mean and maximum depth to groundwater from 1987 to 1993 for each plot. Groundwater levels did not decline with distance from the stream within the range of the study plots, and a uniform water level was assumed.

Three sets of data were used to calculate inundation frequency per plot (i.e., mean number of years between inundation episodes): plot elevation; rating curves (stage–discharge relationships) developed for each transect using the XSPRO channel cross section analyzer program (Grant et al. 1992); and recurrence intervals for peak flows of varying magnitude, calculated for two long-term stream gages (Charleston, gaged since 1905, and Palominas, gaged since 1926). Reliability of the inundation frequency data may be reduced because stage–discharge relationships were developed for only one transect per study site, rather than for multiple transects.

Soils were collected from three depths (0–15 cm, 16–60 cm, and 61–100 cm). Coarse soil particles were separated with sieves, but were pooled in this paper into one gravel category (soil particles >2 mm in diameter). Sand, silt, and clay percentages were calculated using a modified version of the hydrometer method described by Day (1965). Electrical conductivity (EC) was determined according to the saturation extract procedure (Bower and Wilcox 1965). Percent moisture at saturation was determined as a by-product of the EC analysis, by calculating the difference in mass between the saturated and ovendried soil pastes, and was used as an indicator of the moisture-holding capacity of the soil. Soil samples were analyzed for nitrate nitrogen, available phosphorus, and organic matter percentage by a local analytical laboratory. Data presented in this paper are for the upper surface layer (0–15 cm).

Data analyses

Woody plant density and herbaceous cover data sets (natural log-transformed) were analyzed with detrended correspondence analysis (DCA) to determine the interrelationships of species and sites within the San Pedro floodplain (ter Braak 1992). Woody plants were classified by species and, for large shrubs and trees, by size class (juvenile plants <1 m tall and mature plants >1 m tall). The woody data set contained 42 species–age classes and 122 plots, and the herbaceous data set contained 88 species and 118 plots, after omitting rare species and unvegetated plots. Pearson product–moment correlation coefficients (using Bonferonni adjustments) were calculated between site scores for the first three ordination axes and the following environmental variables: mean and maximum depth to groundwater; inundation frequency; elevation relative to the stream thalweg; distance from the channel edge; gravel, sand, silt, and clay content of the upper soil layer; soil moisture-holding capacity, electrical conductivity, nitrate, phosphorus, and organic matter content of the upper soil layer; leaf area index; and elevation of the transect relative to sea level. Data were not analyzed with canonical correspondence analysis because the number of species (e.g., 88 herbaceous species) was high in relation to the number of plots and environmental variables (ter Braak 1992).

A curve estimation regression procedure (Norusis 1993) was used to determine the relationship of individual species with groundwater. For this analysis, the frequency of occurrence of all common herbaceous species (those in ≥10 plots) within 10 depth-to-groundwater classes was quantified using the appropriate curve (i.e., quadratic, cubic, inverse, or linear). The depth-to-groundwater classes were: 0 to 0.25 m, 0.26 to 0.50 m, 0.51 to 1.00 m, 1.01 to 1.50 m, 1.51 to 2.00 m, 2.01 to 2.50 m, 2.51 to 3.00 m, 3.01 to 4.00 m, 4.01 to 6.00 m, and 6.01 to 8.00 m. From 10 to 20 plots were represented in each class. Curve-fitting regression analysis also was used to relate mean and maximum depth to groundwater to the weighted average wetland score (for woody and herbaceous plants) and to the cover of herbaceous plants in each of five wetland indicator classes. To identify some of the possible consequences of altered seral changes within the floodplain, we used an independent samples *t* test to compare soil characteristics and the weighted average wetland score (herbaceous) between *Populus fremontii* forests and *Chrysothamnus nauseosus* shrublands of similar elevation above the thalweg.

The following technique was used to estimate losses of vegetation types under groundwater decline scenarios. First, the 10 depth-to-groundwater classes were consolidated into four classes (0 to 0.25 m, 0.26 to 1.00 m, 1.01 to 3.00 m, and 3.01 to 8.00 m), each of which supports a different assemblage of indicator species. The width of each of these groundwater zones within the floodplain was calculated per transect, based on the topographical surveys. Values were then averaged for all transects to determine the relative abundance of each zone as it exists in the study area today. The changing abundance of each zone was then calculated for three hypothetical water table drawdown scenarios, i.e., uniform groundwater declines of 0.3 m, 1 m, and 2 m. The results of this exercise indicate the changing potential of the study area to support various plant species, based on their described relationships with groundwater.

RESULTS

Environmental influences on plant community composition

Woody and herbaceous species assemblages were arrayed in ordination space in similar fashion (Fig. 4, Table 2). For both ordinations, mean depth to groundwater was the variable most highly correlated with axis 1 (Table 3). Axis 1 species scores increased linearly as depth to groundwater ranged from 0 to ≈4 m, at which point the relationship became more level, particularly for the herbaceous ordination (Fig. 5). Maximum depth to groundwater, inundation frequency, plot elevation, and electrical conductivity were significantly correlated with mean depth to groundwater and were also significantly related to axis 1 for both ordinations.

For both the herbaceous and woody ordinations, the second axis was most highly correlated with soil texture and moisture-holding capacity (Table 3). Nitrate and organic matter also were significantly correlated with herbaceous axis 2. Leaf area index, an index of light availability, was the variable most significantly correlated with herbaceous axis 3. Transect elevation (relative to sea level) also was significantly correlated with herbaceous axis 3, perhaps because canopy foliage area tended to increase at the downstream end of study area where *Sporobolus wrightii* grasslands gave way to *Prosopis velutina* woodlands on high terraces. Transect elevation was the variable most significantly ($P < 0.10$) related to axis 3 of the woody ordination.

Woody species

Obligate wetland plants (*Salix gooddingii*), facultative wetland plants (*Populus fremontii, Baccharis salicifolia, Tamarix chinensis*), and facultative plants (*Fraxinus velutina*) dominated the wet end of the axis 1 moisture gradient (Fig. 4, Table 2). With increasing depth to groundwater, these species gave way to facultative upland species (e.g., *Celtis reticulata, Prosopis velutina*) and upland species (e.g., *Rhus microphylla, Zizyphus obtusifolia, Atriplex canescens*). Juveniles had narrower ranges for depth to groundwater than did adults, and grew where groundwater was shallower (Table 4). Juveniles of *Salix gooddingii* and *Populus fremontii,* both pioneer species that establish after flood flows, grew where depth to groundwater averaged <1 m below the floodplain surface. Floodplains vegetated by 50–80-yr-old *Populus fremontii* trees, in contrast, were ≈3 m above the water table. Juveniles of *Fraxinus velutina, Tamarix chinensis, Morus microphylla,* and *Juglans major* grew where depth to groundwater averaged between 1 and 2 m below the floodplain surface, whereas juveniles of *Celtis reticulata* and *Prosopis velutina* had broad ranges and grew where depth to groundwater was as shallow as 1 m or as deep as 7 m (Fig. 6, Table 4). Mature *Prosopis velutina* dominated the highest floodplain terraces (5–8 m).

Most of the shrub species had wide ranges but distinct optima for depth to groundwater (Fig. 6, Table 4). *Baccharis salicifolia,* the only facultative wetland shrub, had peak frequency where groundwater was <1 m below the floodplain surface. *Chrysothamnus nauseosus* and *Hymenoclea monogyra* were associated with midrange groundwater depths (mean depth of 2 m) and coarse-soiled, open sites. *Acacia greggii, Zizyphus obtusifolia, Lycium andersonii, L. pallidum,* and *Atriplex canescens* were among the shrubs and small trees found in the fine-soiled understory of woodlands on high floodplain terraces, and *Yucca elata* and *Opuntia spinosior* were among those found on high, open floodplains.

Herbaceous species

Graminoids including *Eleocharis montevidensis, Equisetum laevigatum, Juncus torreyi, J. balticus, Scirpus acutus,* and *Typha domingensis* dominated the wet end of the herbaceous moisture gradient (Fig. 4). In general, species that grew where groundwater was shallow had narrow ranges for depth to groundwater and had dis-

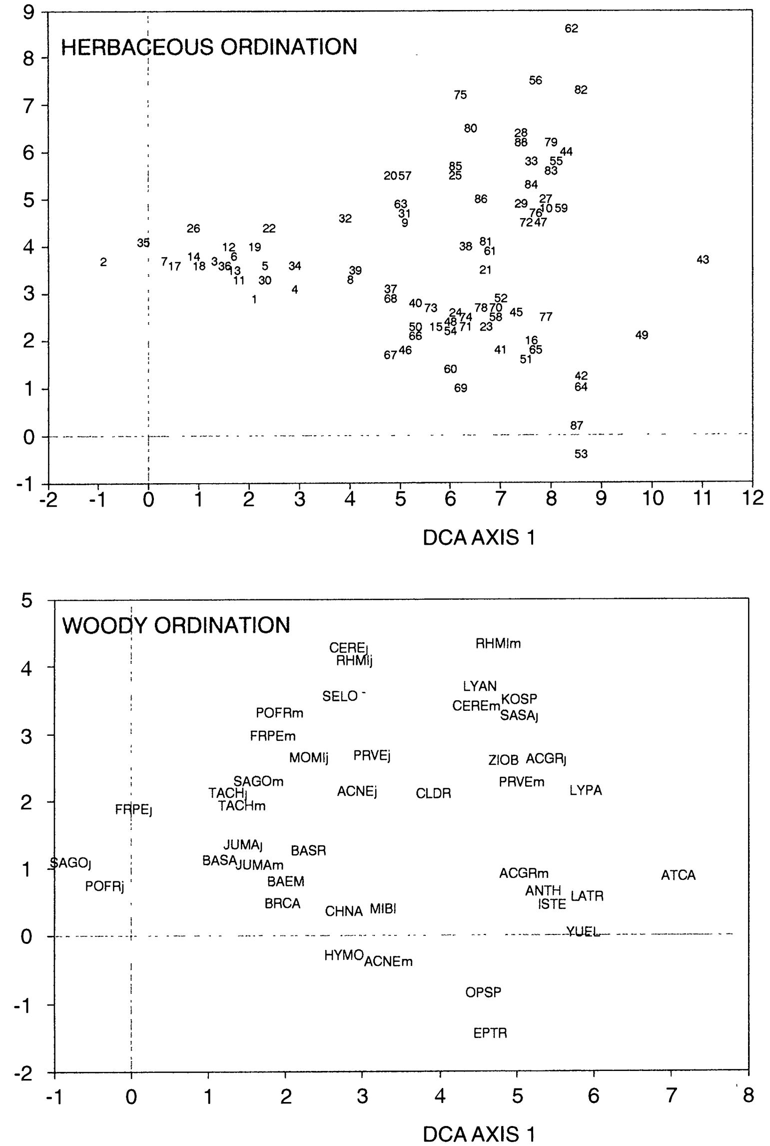

FIG. 4. Distribution of San Pedro River woody and herbaceous species in DCA ordination space. Number codes for herbaceous species and four-letter codes for woody species are listed in Table 2 (j, juvenile; m, mature).

tributions significantly associated with depth to groundwater (Table 5). *Juncus torreyi* and *Eleocharis montevidensis* (facultative wetland) had distributions best fit by inverse curves, and declined sharply in frequency as groundwater declined below 0.5 m (Fig. 7). *Equisetum laevigatum (*facultative wetland), and many facultative and facultative upland species including *Ambrosia psilostachya, Aster spinosus, Elymus canadensis, Xanthium strumarium,* and the exotics *Cynodon dactylon, Melilotus albus,* and *Sorghum halepense,* had significant cubic-fit distributions, with their frequency peaking at a midpoint (<1–3 m depth) along the groundwater gradient. *Sporobolus wrightii* grew over a wide range of groundwater depths, but had highest frequency where depth to groundwater was 4–6 m.

Many facultative, facultative upland, and upland species (e.g., *Conyza canadensis, Sporobolus cryptandrus, Pleuraphis mutica*) had distributions that were not significantly related to groundwater depth, whereas others, such as the upland species *Viguiera dentata,* increased as depth to groundwater increased. Two loose guilds related to soil texture preference were apparent among the dry-end herbaceous species. One guild, which included *Heterotheca psammophila, Helianthus petiolaris, Sporobolus contractus, S. cryptandrus, Euphorbia hyssopifolia,* and *Bouteloua rothrockii,* grew on coarse-textured soils such as those occurring on open floodplains or floodplains dominated by *Hymenoclea monogyra* and *Chrysothamnus nauseosus* (Fig. 4). Another guild was associated with fine-textured soils, and

TABLE 2. Number codes (herbaceous) or four-letter codes (woody) for plant species shown in Fig. 4. Species without codes were not included in the ordination analyses.

Class	Herbaceous species	Woody species
Obligate wetland	*Aster subulatus* (1) *Juncus balticus* (2) *Nasturtium officinale** (3) *Paspalum distichum* *Polygonum lapathifolium** (4) *Polygonum pensylvanicum* *Polygonum punctatum* (5) *Polypogon interruptus* *Scirpus acutus* (6) *Typha domingensis* (7) *Veronica anagallis-aquatica*	*Salix gooddingii* (SAGO)
Facultative wetland	*Agrostis semiverticillata** *Ambrosia aptera* (8) *Aster spinosus* (9) *Conyza coulteri* (10) *Cyperus odoratus* (11) *Echinochloa crusgalli* (12) *Eleocharis montevidensis* (13) *Equisetum laevigatum* (14) *Eriochloa acuminata* (15) *Eriochloa aristata* (16) *Festuca arundinacea** *Hordeum jubatum* *Juncus torreyi* (17) *Polypogon monspeliensis** (18) *Xanthocephalum gymnospermoides* (19)	*Baccharis salicifolia* (BASA) *Baccharis emoryi* (BAEM) *Juglans major* (JUMA) *Tamarix chinensis** (TACH) *Populus fremontii* (POFR)
Facultative	*Ambrosia psilostachya* (20) *Bidens leptocephala* (21) *Elymus canadensis* (22) *Eragrostis pectinacea* (23) *Ipomoea coccinea* (24) *Lactuca serriola** *Panicum obtusum* (25) *Paspalum dilatatum** (26) *Portulaca retusa* (27) *Sporobolus airoides* (28) *Verbesina encelioides* (29) *Xanthium strumarium* (30)	*Fraxinus velutina* (FRPE)
Facultative upland	*Amaranthus palmeri* *Conyza canadensis* (31) *Cynodon dactylon** (32) *Elymus triticoides* *Eragrostis cilianensis** *Hoffmanseggia glauca* (33) *Melilotus albus** (34) *Melilotus officinalis** (35) *Muhlenbergia rigens* (36) *Polanisia dodecandra* (37) *Salsola iberica** (38) *Sorghum halepense** (39) *Sporobolus contractus* (40) *Sporobolus cryptandrus* (41)	*Bricellia californica* (BRCA) *Celtis reticulata* (CERE) *Morus microphylla* (MOMI) *Prosopis velutina* (PRVE)
Upland species	*Acalypha neomexicana* (42) *Acalypha ostryaefolia* *Acourtia nana* *Allionia incarnata* (43) *Ambrosia confertiflora* (44) *Aristida adscensionis* (45) *Aristida ternipes* (46) *Aristolochia watsoni* *Atriplex wrightii* (47) *Boerhaavia coccinea* (48) *Boerhaavia spicata* (49) *Bothriochloa barbinodes* (50) *Bothriochloa laguroides* *Bouteloua aristidoides* (51) *Bouteloua curtipendula* (52) *Bouteloua rothrockii* (53)	*Acacia greggii* (ACGR) *Acacia neovernicosa* (ACNE) *Anisacanthus thurberi* (ANTH) *Atriplex canescens* (ATCA) *Baccharis sarathroides* (BASR) *Chrysothamnus nauseosus* (CHNA) *Clematis drummondii* (CLDR) *Ephedra trifurca* (EPTR) *Hymenoclea monogyra* (HYMO) *Isocoma tenuisecta* (ISTE) *Koeberlinia spinosa* (KOSP) *Larrea tridentata* (LATR) *Lycium andersonii* (LYAN) *Lycium pallidum* (LYPA) *Mimosa biuncifera* (MIBI) *Opuntia spinosior* (OPSP)

TABLE 2. Continued.

Class	Herbaceous species	Woody species
Upland species	*Brayulinea densa*	*Rhus microphylla* (RHMI)
	Cenchrus insertus (54)	*Senecio longilobus* (SELO)
	Chenopodium berlandieri (55)	*Yucca elata* (YUEL)
	Chenopodium fremontii (56)	*Zizyphus obtusifolia* (ZIOB)
	Chenopodium palmeri (57)	
	Chloris virgata (58)	
	Commelina erecta (59)	
	Crotalaria pumila (60)	
	Cucurbita foetidissima	
	Datura meteloides (61)	
	Elymus elymoides (62)	
	*Eragrostis lehmanniana** (63)	
	Erigeron concinnus	
	Eriogonum polycladon (64)	
	Euphorbia albomarginata (65)	
	Euphorbia heterophylla (66)	
	Euphorbia hyssopifolia (67)	
	Helianthus petiolaris (68)	
	Heterotheca psammophila (69)	
	Ipomoea hirsutula (70)	
	Jatropha macrorhiza	
	Lepidium thurberi (71)	
	Leptochloa dubia (72)	
	Machaeranthera pinnatifida (73)	
	Machaeranthera tanacetifolia (74)	
	Matelea producta (75)	
	Mirabilis longiflora (76)	
	Muhlenbergia repens	
	Nama hispidum	
	Panicum hirticaule (77)	
	Phaseolus angustissimus (78)	
	Pleuraphis mutica (79)	
	Rhynchosia senna var. *texana* (80)	
	Setaria leucopila (81)	
	Sicyos ampelophyllus (82)	
	Sida physocalyx (83)	
	Solanum elaeagnifolium (84)	
	Sphaeralcea emoryi (85)	
	Sporobolus wrightii (86)	
	Stephanomeria tenuifolia	
	Tidestromia lanuginosa	
	Trianthema portulacastrum (87)	
	Viguiera dentata (88)	

* Species not native to North America.

included *Viguiera dentata, Panicum obtusum, Plueraphis mutica, Sporobolus wrightii, S. airoides,* and others.

Wetland indicator groups

Cover of herbaceous plants in each of the five wetland indicator groups varied significantly ($P < 0.05$) with depth to groundwater (Fig. 8). Eleven of the 111 herbaceous plant species were obligate wetland plants (Table 1), and cover of this group declined sharply as groundwater declined below ≈0.25 m. Cover of the facultative wetland herbs, which included 15 species, declined substantially as groundwater dropped below ≈1 m. Facultative and facultative upland groups maintained relatively high cover between depths of <1 and ≈4 m. Relative cover of obligate upland species, the group that contained the most species, increased with each additional increment in depth to groundwater.

The weighted average wetland indicator scores (composite indicators of the relative abundance of species in each of five wetland categories) also varied significantly ($P < 0.01$) with mean depth to groundwater (Fig. 9). Relationships were stronger for herbs than for woody plants, and were stronger with mean depth to groundwater than with maximum depth (respective r^2 values of 0.41 and 0.38 for herbs, df = 124; and 0.38 and 0.35 for woody species, df = 128). Scores for the woody plants were concentrated at 2, 4, and 5, reflecting the dominance in the floodplain of *Populus fremontii* (facultative wetland, score of 2), *Prosopis velutina* (facultative upland, score of 4), and *Chrysothamnus nauseosus–Hymenoclea monogyra* shrublands (upland, score of 5). For herbs, the wetland score ranged between 1 ("perfect" wetland) and 3 where water was at the soil surface; between 2 and 5 as groundwater increased to a depth of 3 m; and between

TABLE 3. Correlation coefficients between DCA site scores and environmental variables, for ordinations of herbaceous and woody plant assemblages of the upper San Pedro River floodplain, Arizona.

	Herbaceous			Woody		
	Axis 1	Axis 2	Axis 3	Axis 1	Axis 2	Axis 3
Eigenvalue	0.88	0.66	0.55	0.79	0.40	0.32
Depth to groundwater (mean)	0.71*	0.30	0.05	0.76*	0.19	−0.04
Depth to groundwater (max)	0.68*	0.27	0.05	0.71*	0.17	−0.01
Inundation frequency	0.46*	0.24	0.02	0.63*	0.08	−0.04
Plot elevation	0.69*	0.29	0.05	0.74*	0.22	−0.04
Distance to channel	0.53*	0.31	−0.02	0.36	0.25	0.03
Electrical conductivity	−0.47*	0.18	0.08	−0.18	0.05	−0.13
Nitrate	0.35	0.53*	0.16	0.49*	0.19	−0.04
Percentage moisture at saturation	0.00	0.57*	0.09	0.11	0.46*	−0.08
Sand (%)	−0.04	−0.50*	0.03	−0.13	−0.41*	0.08
Silt (%)	0.09	0.44*	−0.09	0.15	0.49*	−0.03
Clay (%)	−0.03	0.48*	0.04	0.09	0.25	−0.12
Gravel (%)	0.01	−0.28	0.07	0.23	−0.35	−0.06
Organic matter	0.18	0.52*	0.02	0.30	0.38*	−0.10
Phosphorus	−0.01	0.19	−0.11	0.01	0.09	0.01
Leaf area index	−0.07	0.30	0.45*	−0.05	0.44*	−0.14
Transect elevation	−0.21	−0.10	−0.43*	−0.15	−0.22	−0.38

* $P < 0.05$.

4 and 5 (upland) where groundwater was deeper than ≈4 m below the floodplain surface. Herbaceous plots under mature *Prosopis velutina* woodlands on high terraces (mean depth to groundwater of 5.2 m) had an average wetland score of 4.5, a value below that of upland sites. Among patch types, herbaceous wetland scores were higher for open, shrub-dominated sites with coarse soils than for forested, finer-soiled sites of similar groundwater depth (Table 6). For example, herbaceous plots in *Chrysothamnus nauseosus* shrublands had a wetland indicator score of 4.6, compared to 3.3 in *Populus fremontii* forests (t = 5.6, $P < 0.01$, df = 19). *Chrysothamnus* shrublands had significantly more sand and less clay (t = 4.8 and −5.3, respectively, $P < 0.01$, df = 19) than *Populus fremontii* forests of similar elevation.

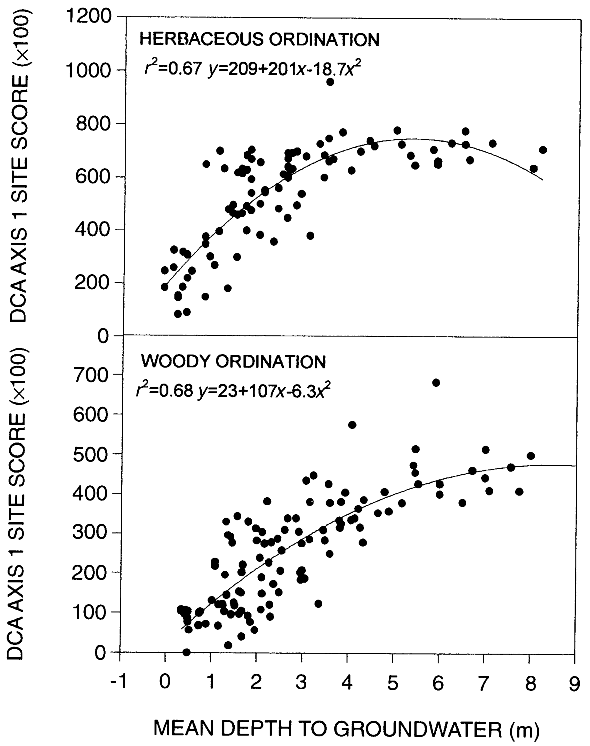

FIG. 5. DCA axis 1 ordination scores in relation to mean depth to ground water, for herbaceous and woody species assemblages. Regression equations were significant at $P < 0.01$.

Projected changes in wetland vegetation abundance

At the present time, a relatively small proportion of the San Pedro River floodplain is within the depth-to-groundwater zone (Zone 1) that provides optimum habitat for obligate wetland plants such as *Scirpus acutus* and *Juncus balticus,* and some facultative wetland plants including *Juncus torreyi* (Fig. 10, Table 7). With a hypothetical groundwater decline scenario of 0.3 m, the floodplain area that could support these wetland indicator plants would decline by 28%. A uniform groundwater decline scenario of ≥1 m would result in local extirpation of this group of species, assuming no major future geomorphic adjustment. Respective groundwater declines of 0.3 m and 1 m also would result in a 37% and 51% decline in potential habitat potential for Zone 2 indicator plants, including facultative wetland *Equisetum laevigatum* and obligate wetland *Salix gooddingii* juveniles. Habitat for plants indicative of Zone 3 (e.g., mature *Baccharis salicifolia* and *Salix gooddingii*) would undergo small to large decline depending on the extent of the groundwater decline. Potential habitat for plants characteristic of greatest depth to groundwater (i.e., Zone 4 plants)

TABLE 4. Mean depth to groundwater, standard deviation, minimum and maximum depth, range, and wetland indicator class (Reed 1988) for common woody species in San Pedro River floodplain study plots.

Species	Depth to groundwater (m)				Wetland class
	Mean ± 1 SD	Min	Max	Range	
Juvenile tree species					
Salix gooddingii	0.6 ± 0.6	0.1	2.0	1.9	Obligate wetland
Populus fremontii	0.9 ± 0.5	0.2	2.0	1.8	Facultative wetland
Fraxinus velutina	1.2 ± 0.7	0.3	2.1	1.8	Facultative
*Tamarix chinensis**	1.3 ± 0.6	0.2	2.5	2.2	Facultative wetland
Juglans major	1.9 ± 1.0	0.3	3.9	3.6	Facultative wetland
Celtis reticulata	2.8 ± 1.3	1.2	6.2	6.0	Facultative upland
Prosopis velutina	2.9 ± 1.6	0.7	6.6	5.9	Facultative upland
Rhus microphylla	3.2 ± 2.1	0.7	6.6	5.9	Upland
Acacia greggii	4.4 ± 1.8	1.7	6.2	4.5	Upland
Mature tree species					
Salix gooddingii	1.4 ± 0.9	0.1	3.2	3.1	Obligate wetland
Populus fremontii	1.5 ± 1.1	0.1	5.1	5.0	Facultative wetland
Fraxinus velutina	1.6 ± 1.1	0.4	3.2	2.8	Facultative
*Tamarix chinensis**	1.4 ± 0.6	0.4	2.5	2.1	Facultative wetland
Juglans major	2.0 ± 1.2	0.4	4.2	3.8	Facultative wetland
Acacia neovernicosa	2.8 ± 1.1	1.3	4.2	2.9	Upland
Celtis reticulata	3.8 ± 2.1	0.9	7.1	6.2	Facultative upland
Prosopis velutina	3.4 ± 1.7	0.9	8.0	7.1	Facultative upland
Acacia greggii	4.6 ± 1.8	1.7	7.1	6.4	Upland
Shrub species					
Baccharis salicifolia	1.2 ± 0.9	0.0	2.8	2.8	Facultative wetland
Baccharis emoryi	1.5 ± 1.3	0.5	2.9	3.4	Facultative wetland
Senecio longilobus	2.0 ± 0.5	1.4	2.8	1.4	Upland
Chrysothamnus nauseosus	2.1 ± 0.8	0.7	3.5	2.8	Upland
Hymenoclea monogyra	2.1 ± 1.3	0.8	5.8	5.0	Upland
Zizyphus obtusifolia	4.2 ± 2.2	1.0	8.0	7.0	Upland
Lycium pallidum	4.2 ± 1.5	2.7	6.2	3.5	Upland
Lycium andersonii	3.9 ± 2.0	1.2	6.2	5.0	Upland
Atriplex canescens	5.3 ± 1.0	3.7	6.5	2.8	Upland
Opuntia spinosior	5.1 ± 2.2	3.4	8.0	4.6	Upland
Anisacanthus thurberi	6.7 ± 0.5	6.2	7.1	0.9	Upland

* Species not native to North America.

would increase in relative abundance under all groundwater decline scenarios.

DISCUSSION AND MANAGEMENT IMPLICATIONS

Riparian vegetation–environment interactions

This study revealed that several key environmental variables influence the composition of riparian and wetland vegetation growing in the floodplain of a semiarid region river. Depth to groundwater and its spatial correlates of floodplain elevation and inundation frequency exerted the greatest influence on composition of the floristically rich plant assemblage associated with the San Pedro River, followed by soil texture and moisture-holding capacity, light availability, and site elevation. Depth to groundwater exerts strong influence on the composition of arid region floodplain vegetation, in large part, due to between–species differences in rooting depth combined with the fact that shallow groundwater often supplies a more permanent water source than does periodic overbank flooding (Groeneveld and Griepentrog 1985, Richter 1993, Busch and Smith 1995). Depth to groundwater and standing water depth also influence riparian and wetland ecosystems in mesic regions (Frye and Quinn 1979, Pautou and DeCamps 1985, Popov 1985, Mountford and Chapman 1993). Frequency, timing, and duration of inundation (i.e., hydroperiod) also play strong roles in arid and mesic regions, due to differential species tolerances for factors such as soil saturation and habitat disturbance (Bell 1974, Franz and Bazzaz 1977, Robertson et. al 1978, Fenner et al. 1985, Hupp and Osterkamp 1985, Hughes 1990, Auble et al. 1994). Flood waters, particularly in arid regions, also provide the additional supplemental water needed for recruitment of various plant seedlings, and conversely, flood-interim (drawdown) periods provide the exposed soil for recruitment of some mesic region seedlings. Soil texture influences floodplain vegetation composition, in part, by interacting with water availability to influence germination and survivorship of riparian plants (Marks 1950, McBride and Strahan 1984, Hupp and Osterkamp 1985, Bush and Van Auken 1986, Dunham 1989, Mahoney and Rood 1992, Stevens et al. 1995). Canopy cover exerts strong influence on many floodplain herbs and woody seedlings by moderating ambient temperatures and affecting light quantity and quality (Menges and Waller 1983, Cross 1991).

It is difficult to separate the effects on vegetation

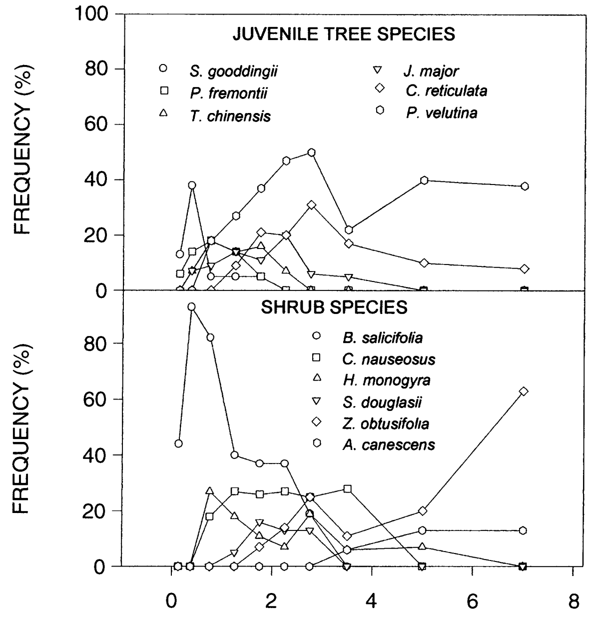

FIG. 6. Distribution of several common shrub species and juvenile tree species of the San Pedro River floodplain in relation to depth-to-groundwater class. Symbols denote midpoints of 10 groundwater classes (see *Methods*).

composition of spatially correlated variables such as depth to groundwater and inundation frequency. Because vegetation responds to the combination of these factors, space-for-time substitution approaches for predicting responses to changes in a single variable, such as groundwater decline, must be interpreted with some caution. For example, a flood in January 1993 (peak flow rates of 314 m^3/s at the Palominas gage, a <10-yr recurrence interval) undoubtedly influenced vegetation composition as measured in 1994, although effects of the flood were not as great as on many other Arizona rivers, where the combination of high peak flows and long duration flows caused major geomorphic change (Huckleberry 1994). Interactions between flood-related fluvial processes and vegetation also play a large role in creating the natural gradients in hydrological site variables that exist within and between floodplain sites, which allow for use of the space-for-time substitution approach. For example, vegetation contributes to terrace aggradation by enhancing sedimentation and stabilizing fine-textured soil particles, thus affecting depth to groundwater, inundation frequency, and soil moisture-holding capacity. Subsurface geology (e.g., differences in depth of alluvium and depth to bedrock) also contributes to differences among sites in groundwater depth and fluctuation.

Impacts of groundwater decline on indicator species

Along the San Pedro River, many species had a narrow range for depth to groundwater and thus can be considered as being sensitive indicators of groundwater decline. As a general trend, plant species associated with shallow groundwater had narrow ranges, while species of higher elevation floodplains had large ranges for depth to groundwater. Among shallow groundwater species, herbaceous species had narrower ranges than

TABLE 5. Mean depth to groundwater, standard deviation, minimum and maximum depth, range, and wetland indicator class (Reed 1988) of common herbaceous species (i.e., those with >10 occurrences in San Pedro River floodplain study plots). Regression curve type and significance of relationship between frequency and mean depth to groundwater also are indicated. NS, not significant.

Species	Depth to groundwater (m)				Wetland class†	Curve type	r^2	P
	Mean ± 1 SD	Min	Max	Range				
Juncus torreyi	0.1 ± 0.1	0.0	0.3	0.4	FacWet	Inverse	0.94	0.01
Eleocharis montevidensis	0.2 ± 0.2	0.0	0.5	0.6	FacWet	Inverse	0.60	0.01
Xanthium strumarium	0.4 ± 0.5	0.0	1.5	1.5	Fac	Cubic	0.67	0.07
Equisetum laevigatum	0.4 ± 0.4	0.1	1.3	1.3	FacWet	Cubic	0.90	0.01
Elymus canadensis	0.9 ± 0.5	0.3	2.3	2.0	Fac	Cubic	0.66	0.07
*Melilotus albus**	1.0 ± 0.8	0.1	2.8	2.7	FacUp	Cubic	0.77	0.02
*Sorghum halepense**	1.4 ± 0.7	0.3	2.6	2.3	FacUp	NS		
*Cynodon dactylon**	1.4 ± 1.1	0.3	5.3	5.0	FacUp	Cubic	0.35	0.05
Helianthus petiolaris	1.9 ± 0.6	0.8	2.9	2.1	Up	Cubic	0.72	0.04
Conyza canadensis	1.9 ± 0.9	0.8	3.6	2.8	FacUp	NS		
Ambrosia psilostachya	2.0 ± 0.7	0.7	3.6	2.9	Fac	Cubic	0.64	0.09
Aster spinosus	2.3 ± 0.8	1.2	4.0	2.8	FacWet	Cubic	0.64	0.09
Sporobolus cryptandrus	2.6 ± 1.2	1.6	5.4	3.8	FacUp	NS		
Heterotheca psammophila	2.7 ± 0.8	1.4	4.4	3.0	Up	Quad	0.56	0.06
Sporobolus contractus	2.8 ± 1.9	1.4	8.2	6.8	FacUp	NS		
Bidens leptocephala	3.0 ± 1.7	1.2	6.6	4.4	Fac	NS		
Machaeranthera pinnatifida	3.2 ± 1.9	1.6	8.2	6.6	Up	NS		
Sporobolus wrightii	3.4 ± 1.6	1.4	7.1	5.7	FacUp	Cubic	0.89	0.01
Setaria leucopila	3.7 ± 2.0	1.7	7.1	5.4	Up	NS		
Viguiera dentata	5.0 ± 2.0	1.2	8.2	6.0	Up	Cubic	0.98	0.01

* Species not native to North America.

† Facultative wetland (FacWet), facultative (Fac), facultative upland (FacUp), or upland (Up).

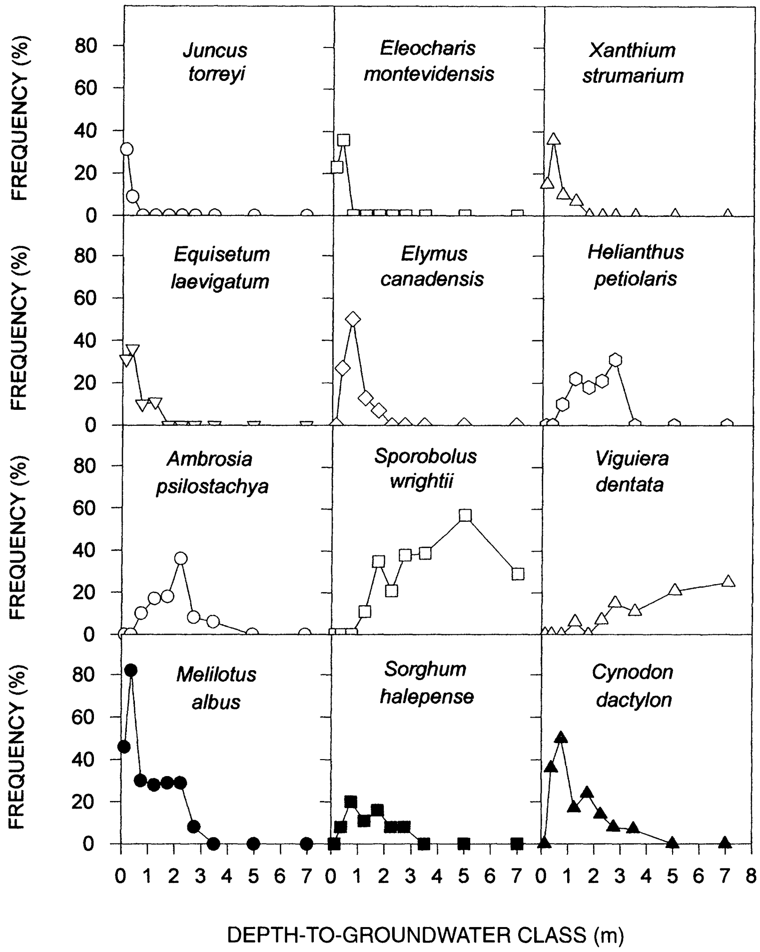

FIG. 7. Distribution of 12 common herbaceous plants of the San Pedro River floodplain in relation to mean depth to groundwater. Symbols denote midpoints of 10 groundwater classes (see *Methods*). Open symbols denote native species and solid symbols denote introduced species.

woody species. Common herbaceous species with small ranges for groundwater included *Eleocharis montevidensis* and *Juncus torreyi.* These facultative wetland species, as well as all obligate wetland herbs (e.g., *Juncus balticus, Scirpus acutus, Typha domingensis*) declined sharply in abundance where groundwater was greater than ≈0.25 m below the surface. Many of these obligate and facultative wetland plants are emergents

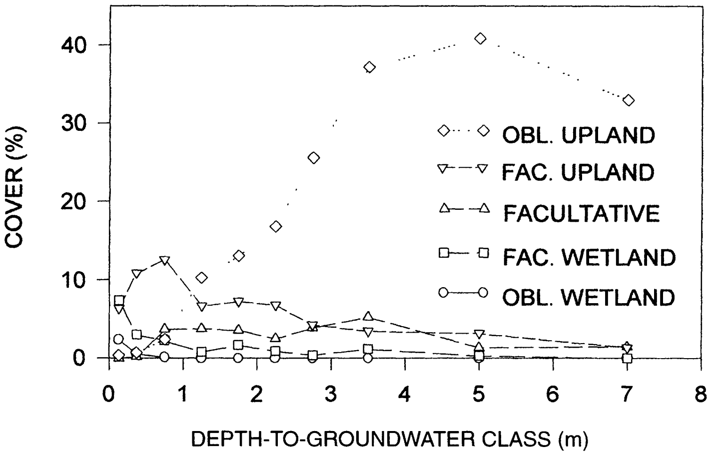

FIG. 8. Cover of San Pedro River herbaceous plants in each of five wetland indicator classes (Reed 1988) in relation to depth-to-groundwater class. Symbols denote midpoints of 10 groundwater classes (see *Methods*). Respective r^2 values for classes 1 (obligate wetland) through 5 (obligate upland) are: 0.51, 0.65, 0.78, 0.56, and 0.91 (regression lines are not shown).

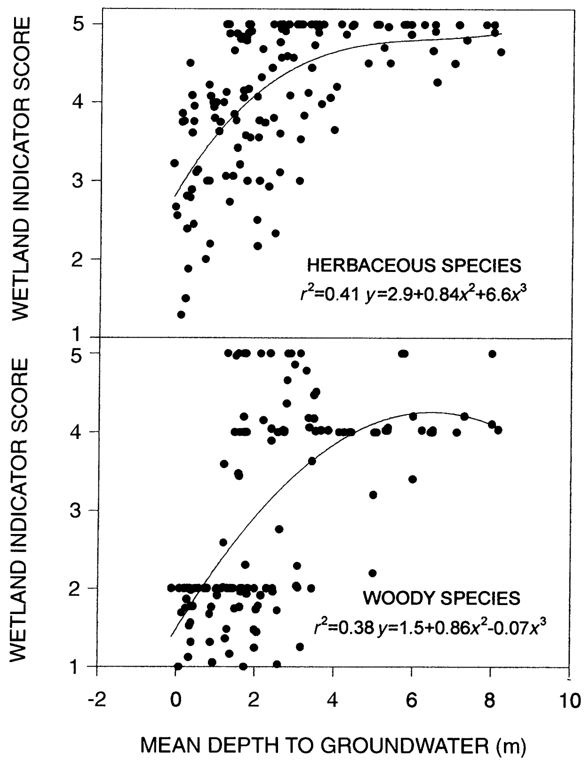

FIG. 9. Weighted average wetland indicator score for woody and herbaceous species in relation to mean depth to groundwater of study plots within the San Pedro River floodplain.

that typically grow in standing water and would be among the first to decline in abundance in response to groundwater decline. Abundance would be affected by changes of only a few decimetres. *Typha domingensis* and *Scirpus acutus,* for example, have highest biomass where water is up to 1 m above the surface, and survive only small (5–10 cm) water declines below the surface (Grace 1989; E. Rejmankova, *unpublished manuscript*). *Juncus balticus* and *J. torreyi* have been reported from sites where the water level was from 10 cm above the surface to 25 cm below (Yatskievych and Jenkins 1981, Manning et al. 1989). These species would be extirpated from the San Pedro floodplain if groundwater declined uniformly by ≥1 m (Fig. 10).

Juveniles of *Salix gooddingii* (obligate wetland) and *Populus fremontii* (facultative wetland) were the most sensitive indicators among the woody plants. Juveniles of these tree species grew along the San Pedro River where groundwater ranged between 0 and 2 m. Other studies have shown that 1st-yr seedlings of these and related species survive only where depth to groundwater is less than ≈1 m, and tolerate daily groundwater declines of no more than a few centimetres per day (Stromberg et al. 1991, Mahoney and Rood 1992, Segelquist et al. 1993). Impacts to these species from gradual groundwater decline most likely will be initially expressed through loss of young age classes, and ultimately through death of older trees. Dense forests of mature *Populus fremontii* and *Salix gooddingii* typically grow where the water table is at a depth of less than ≈3 m (Busch et al. 1992, Stromberg 1993). Groundwater declines of ≥1 m have resulted in loss of canopy vigor, declines in radial growth and shoot increment, and tree death for related species (E. D. Eggleston, M. L. Scott, G. T. Auble, and L. S. Ischinger, *unpublished manuscript*; S. Rood, *personal communication*). *Baccharis salicifolia,* the dominant shrub of low elevation floodplains, also is sensitive to groundwater decline, and would undergo sequential reduction in abundance under increasingly greater groundwater decline scenarios (Fig. 10). The optimum depth to groundwater (≈1 m) for this species along the San Pedro is consistent with values reported elsewhere (Gary 1963, Stromberg et al. 1991).

Many of the facultative, facultative upland, and upland plant species of the San Pedro River floodplain terraces had distinct optima but large ranges for depth

TABLE 6. Mean depth to groundwater, soil texture, and wetland indicator score for vegetation–landform patch types within the San Pedro River floodplain. Values shown are means ± 1 SD.

Vegetation–landform type	Mean depth to groundwater (m)	Combined silt + clay (%)	Wetland score*	Wetland score**
Sandbar/streambank	0.1 ± 0.3	22 ± 14	2.5 ± 0.9	2.5 ± 0.9
P. fremotnii/S. gooddingii sapling	0.7 ± 0.6	31 ± 05	3.5 ± 0.6	3.5 ± 0.6
P. fremontii/S. gooddingii young forest	1.0 ± 0.6	36 ± 10	3.7 ± 0.9	3.7 ± 0.9
Overflow channel	1.0 ± 0.8	62 ± 10	3.5 ± 0.5	3.5 ± 0.5
B. salicifolia shrubland	1.2 ± 0.9	37 ± 11	3.5 ± 0.8	3.5 ± 0.8
P. fremontii/S. gooddingii forest	1.9 ± 0.7	45 ± 14	3.7 ± 0.9	3.3 ± 0.6
Open floodplain	2.1 ± 0.6	27 ± 13	4.2 ± 0.5	4.2 ± 0.5
H. monogyra shrubland	2.4 ± 1.4	37 ± 07	4.4 ± 0.7	3.8 ± 0.7
C. nauseosus shrubland	2.7 ± 0.7	21 ± 14	4.6 ± 0.4	4.6 ± 0.5
P. fremontii old-growth forest	3.5 ± 1.8	50 ± 08	4.7 ± 0.5	3.3 ± 0.2
P. velutina young forest	3.6 ± 1.5	47 ± 11	4.6 ± 0.5	3.6 ± 0.7
S. wrightii grassland	4.3 ± 1.2	70 ± 09	4.6 ± 0.4	3.1 ± 0.2
P. velutina mature forest	5.2 ± 1.4	50 ± 14	4.7 ± 0.5	4.5 ± 0.7

* Calculated with *S. wrightii* as a ‘‘5’’.
** Calculated with *S. wrightii* as a ‘‘3’’.

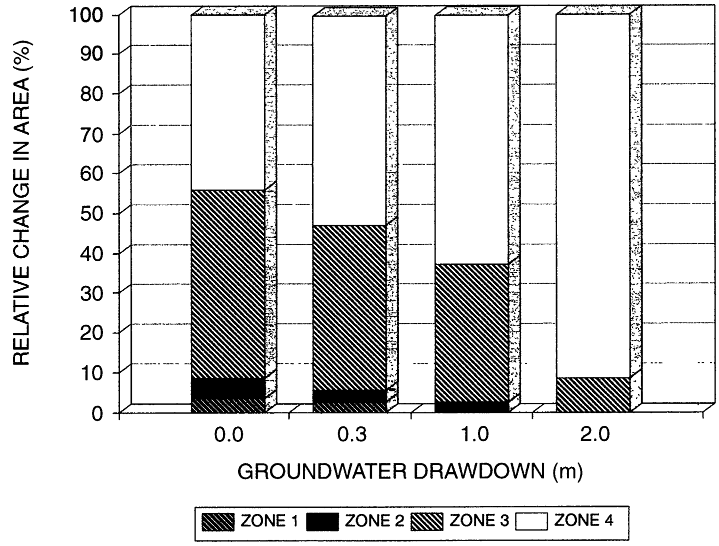

FIG. 10. Relative change in extent of four depth-to-groundwater zones within the San Pedro River floodplain (see Table 7), for three hypothetical groundwater decline scenarios.

to groundwater. Although small groundwater declines would not be expected to cause large changes in abundance of these species, they might affect factors such as size and productivity. *Prosopis velutina,* for example, is a deep-rooted species that grows over a wide range of groundwater depths, but that varies in height, foliage area, leaf size, and xylem water potential as groundwater declines (Stromberg et al. 1992, 1993). *Chyrsothamnus nauseosus* has responded to experimentally induced groundwater declines of several metres (from 1–2 m to ≈4–5 m) by undergoing changes in cover and growth rate, although effects were mediated by reduced competition (Sorenson et al. 1991). This species grew along the San Pedro where depth to groundwater ranged from 0.7 to 3.5 m, consistent with patterns at other sites (Groeneveld 1989). *Sporobolus wrightii,* a deep-rooted species that uses water from the unsaturated zone above the water table, grew along the San Pedro where depth to groundwater ranged from 1.4 to 7.1 m, but has been reported to decline in vigor and size when groundwater declines below ≈5 m (Meinzer 1927).

With the exception of *Sporobolus wrightii,* there appeared to be a shift among herbaceous plants from predominance by phreatophytes to aphreatophytes as depth to groundwater declined below ≈4 m. High floodplain terraces were vegetated by many species (e.g., *Setaria leucopila, Panicum obtusum, Bouteloua rothrockii*) that also grow in the surrounding uplands and that do not depend directly on groundwater. Many of these species have greater abundance in the riparian zone (Bock and Bock 1986), however, because phreatophytic overstory trees increase soil fertility, moderate temperature extremes, and increase surface soil moisture via hydraulic lift (McQueen and Miller 1972, Yavitt and Smith 1983, Dawson 1993). Thus, they would be expected to decline in abundance if groundwater declines were to affect the size, productivity, and water uptake of overstory dominants. Local abundance of the species also could decline if riparian subpopulations contribute disproportionately to total seed production for the species in the area (Kadmon 1993).

TABLE 7. Characteristic vegetation (partial list) of four depth-to-groundwater zones depicted in Fig. 10.

Groundwater zone	Depth to groundwater (range, m)	Indicator plants
1	<0.25 m	*Juncus balticus, Juncus torreyi, Scirpus acutus*
2	0.25–1 m	*Equisetum laevigatum, Salix gooddingii* juveniles
3	1–3 m	*Ambrosia psilostachya, Aster spinosus, Baccharis salicifolia, Salix gooddingii*
4	3–8 m	*Prosopis velutina, Setaria leucopila, Sporobolus wrightii, Zizyphus obtusifolia*

Impacts on wetland indicator groups and seral guilds

Wetland indicator scores provide a useful tool for predicting some of the consequences of groundwater decline for the San Pedro River floodplain vegetation, as they have in other regions (Gremmen et al. 1990, Mountford and Chapman 1993). Regression equations presented in this study suggest how abundance of herbaceous plants within each of five wetland indicator groups (Reed 1988) would vary along a continuum of groundwater depth, with obligate and facultative wetland groups being expected to decline or be eliminated when the mean depth to groundwater declines below ≈0.25–0.5 m. The composite weighted average wetland score also would be expected to change sharply as depth to groundwater changes over the range from 0 to 4 m.

The wetland indicator values showed more variability for woody than for herbaceous plants in relation to depth to groundwater, perhaps due to greater diversity of the herbaceous flora (and thus lower susceptibility to misclassification errors) and to the small groundwater ranges of many herbs. Among the species that appeared to be classified within an inappropriate wetland category were *Juglans major* and *Aster spinosus,* both of which perhaps should be facultative vs. facultative wetland. Such errors could be rectified by additional studies of arid region riparian communities. The wetland indicator scores also were more sensitive to groundwater changes at the wet end of the riparian moisture continuum than at the riparian–upland interface. Many riparian species commonly found on high floodplains in arid regions are not listed in Reed (1988) and are thus considered as upland species by default. Nonetheless, many sites on the highest terraces had upland scores between 4 and 5, and thus were distinct from "pure" uplands. This contrasts with findings by Wentworth et al. (1988), who found a weighted average wetland score of "3" useful as a breakpoint to distinguish between upland and wetland vegetation of river floodplains.

Besides directly affecting species sensitive to water table changes, groundwater decline is predicted to indirectly affect guilds of plants associated with certain seral stages. Seedlings of *Juglans major* and *Celtis reticulata,* for example, and many herbaceous plants including *Elymus canadensis, Ambrosia psilostachya,* and *Sporobolus wrightii,* were associated with the fine-textured soils and shady conditions that occur under *Populus fremontii–Salix gooddingii* stands. If groundwater declines were to reduce seedling establishment of these pioneer species, seral changes initiated by the stabilization of floodplain terraces would be disrupted. In the absence of colonization by invading exotics such as *Tamarix chinensis,* soil textures would be predicted to remain coarse and light intensities and soil surface temperatures would be high. This would favor species, such as *Sporobolus cryptandrus, Polanisia dodecandra,* and *Helianthus petiolaris,* that are associated with open, coarse-soiled sites, but would reduce abundance of the aforementioned guild and result in a net loss of biodiversity. Preliminary studies indicate that these changes have occurred along nearby rivers (e.g., the upper Santa Cruz River) where groundwater declines have reduced *Populus* and *Salix* density (J. C. Stromberg, *unpublished data*).

Introduced species are another group that might be affected by groundwater decline. Many successful exotic species have large tolerances for environmental factors, as is true for the most common herbaceous exotics along the San Pedro River (*Melilotus albus, Cynodon dactylon, Sorghum halepense*) with respect to depth to groundwater. *Tamarix chinensis* also grows over a wide range of groundwater depths and tolerates greater depths as a seedling and adult than do its native analogues (Graf 1982). Shallow groundwater decline could increase abundance of these exotics, and, in turn, affect biodiversity of native species.

CONCLUSION

The topics of groundwater management and effects of groundwater decline on San Pedro River riparian vegetation have arisen relatively recently, although overdraft of the regional groundwater aquifer has been evident for >20 yr. Groundwater models have predicted that gradual alluvial groundwater declines are imminent, although buffered in some river reaches by geological structures (Vionnet and Maddock 1992). This paper confirms the primary importance of hydrologic factors, notably depth to groundwater and inundation frequency, in structuring the San Pedro River plant community. Several ecological indicators varied along a continuum with depth to groundwater, including a weighted average wetland indicator score, cover of plants within wetland indicator groups, and frequency of indicator species (i.e., obligate wetland herbs). Using a space-for-time substitution approach with our data, we predict that future declines in groundwater levels will cause a sequential "desertification" of the riparian flora. The net result will be loss of local biodiversity through loss of sensitive wetland plants and, given greater declines, through loss of *Populus–Salix* stands and of later seral species associated with *Populus–Salix* forest development.

History tells us of the sensitivity of riparian zones in semiarid regions to water level changes. Cienegas, a regional marshland type that is very sensitive to water changes, were formerly extensive along streams of the Southwest. Most cienegas were destroyed during the late 19th century when groundwater tables declined by several metres, following channel incision along many Southwestern streams including the San Pedro (Hastings 1959, Bahre 1991). Over the last ≈80 years, the San Pedro River floodplain has been widening and revegetating in response to this past disturbance (Hereford 1991). Today, portions of the San Pedro River function as a benchmark ecosystem (Doppelt et al. 1993) in the sense that they provide an indication of site potential and a valuable comparative reference for degraded systems. To maintain the biological integrity (Karr 1991) of the San Pedro River ecosystems, it is essential to monitor vegetation composition in permanent plots, particularly within areas that support sensitive indicators of change; to monitor an adequate number of wells in the alluvial and regional aquifers for depth to groundwater; and to adopt water management changes that reverse or stabilize projected groundwater declines. Additional studies also are needed, particularly on effects of increased groundwater fluctuation on riparian and wetland vegetation (e.g., Oosterbaan and Nabuurs 1991), as well as effects of groundwater decline on plant performance factors such as reproductive output and productivity.

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