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Isolated Spring Wetlands in the Great Basin and Mojave Deserts, USA: Potential Response of Vegetation to Groundwater Withdrawal

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Abstract Desert springs, often the sole sources of water for wildlife and cattle, support wetland and wetland/upland transition ecosystems including rare and endemic species. In the basin and range province in Nevada, USA, springs in the Great Basin and Mojave deserts are sustained by interconnected deep carbonate and shallow basin-fill aquifers which are threatened by proposed groundwater withdrawal to sustain rapidly expanding urban areas, a common problem in arid regions worldwide. This paper draws on historic groundwater data, groundwater modeling, and studies of environmental controls of spring ecosystems to speculate on the potential effects of groundwater withdrawal and water table decline on spring-supported vegetation. The focus is on springs in the Great Basin and Mojave deserts representative of those that may be affected by future, planned groundwater withdrawal. Groundwater withdrawal is expected to reduce spring discharge directly through reduced flows from the shallow basin-fill aquifer or through reduction of the hydraulic head of the deep carbonate aquifer. This flow reduction will truncate the outflow stream, reducing the areal cover of wetland and wetland/upland transition vegetation. Lowering the local water table may also reduce the amount of upland phreatophytic vegetation by causing water levels to drop below plant rooting depths. Percolation of salts to surface soils may be reduced, eventually altering desert shrub cover from halophytes to nonhalophytes. The extent of these effects will vary among springs, based on their distance from extraction sites and location relative to regional groundwater flow paths. On-site monitoring of biotic variables (including cover of selected hygrophytes and phreatophytes) should be a necessary complement to the planned monitoring of local hydrologic conditions.

Keywords Great Basin Desert · Mojave Desert · Springs · Wetlands · Vegetation · Hydrology · Groundwater · Water table · Salinity

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Introduction

Wetlands, riparian areas, and other types of freshwater- and groundwater-dependent ecosystems can be affected by off-site activities that alter the hydrologic cycle (Pringle 2000, 2001; Burk and others 2005). Such activities include watershed land use changes that affect recharge and other surface water processes, and water extractions that affect subsurface flow paths and other groundwater processes. Maintaining the requisite connectivity between groundwater and surface water resources to sustain freshwater biota is a difficult challenge not only legally but also politically. It also poses a challenge to scientists from an array of disciplines to understand all of the linkages needed to model ecological impacts of off-site hydrologic alterations.

Spring ecosystems are one of several groundwater-dependent ecosystems that increasingly are being affected worldwide by local and regional groundwater withdrawals

(Brussard and others 1999; Burk and others 2005; MacKay 2006). Protection of such isolated spring wetlands, critical habitat for many endemic and threatened species, has become a key conservation issue (Tiner 2003; Deacon and others 2007) (see special issue of *Wetlands* on isolated wetlands, September 2003). In arid regions, these spring environments often are "island" ecosystems surrounded by xerophyte-dominated deserts and may be the sole source of water for most biota. The springs usually are dependent on a limited water source supplied by a complex hydrologic system of basin-fill and/or deep regional aquifers and local watershed recharge. Spring areas usually include the spring orifice area and outflow stream or springbrook. These two systems often support distinct and different assemblages of plants (Jackson and Allen-Diaz 2006), particularly where the spring orifice area is a pool or has been modified by human activity for agricultural or recreational purposes.

Anthropogenic alteration of subterranean hydrosystems is considered one of the greatest threats to long-term sustainability of groundwater-dependent ecosystems of many arid and semi-arid regions throughout the world (Shepard 1993; Grimm and others 1997; Danielopol and others 2003; Munch and Conrad 2007), including those in the Great Basin and Mohave deserts in the United States (Brussard and others 1999; Tiner 2003; Deacon and others 2007). For example, groundwater withdrawal may significantly reduce the shallow water table, leading to a decline or eventual elimination of spring flow (Fiero and Maxey 1970; Dudley and Larson 1976; Hendrickson and Minckley 1985; Schaefer and Harrill 1995; Mudd 2000; Burk and others 2005). This, in turn, will affect the aquatic, wetland, and phreatic biota dependent on the range of spring-associated water sources.

Hydrologic alteration, along with other anthropogenic activities, has altered not only desert spring vegetation in North America and other continents (Pavleko and others 1999; Mudd 2000; Fairfax and Fensham 2003) but also wetland vegetation associated with desert lakes and playas, for example, Owens Valley in the Great Basin Desert of eastern California (Schultz 2001; Elmore and others 2003). In Owens Valley, groundwater pumping near springs resulted in reduced plant species richness and shifts from marsh vegetation to more drought-tolerant species (Perkins and others 1984). Pumping also caused a decrease in vegetation cover and an increase in mortality of phreatophytic shrubs (Sorenson and others 1991). Water table declines that follow from groundwater withdrawal also can affect riverine riparian vegetation in arid regions (Stromberg and others 1992, 1996; Scott and others 1999; Shafroth and others 2000; Horton and Clark 2001; Eamus and Froend 2006).

The extent of the impact by groundwater withdrawal on springs and other freshwater ecosystems depends on the cumulative effects of withdrawal activities relative to the magnitude of groundwater recharge (Winter 1988). For example, water tables and plant cover in the Owens Valley have fluctuated in tandem in response to changes in annual groundwater extraction rate and weather patterns (Elmore et al. 2006). Groundwater levels declined rapidly in the Owens Valley in the 1970s, a result of increasing groundwater pumping and drought which caused the mortality of phreatophytic vegetation. In the 1980s, groundwater levels rose, a result of increased recharge owing to wet weather and decreased pumping because of lower water demand (Schultz 2001). Water levels in Devils Hole, part of Death Valley National Park adjacent to Ash Meadows National Wildlife Refuge (NWR) and habitat for an endangered desert pupfish species (*Cyprinidon nevadensis*), declined from 1969 to 1972 due to agricultural groundwater pumping from the regional aquifer (Dudley and Larson 1976; Minckley and Deacon 1991; Dunham and Minckley 1998). Adjudication by the U.S. Supreme Court finally settled this issue (*United States v. Cappaert* 1976), but again there is concern about the influence of pumping activities for municipal use on desert pupfish and other biota at the Refuge.

Nevada, central to the Great Basin and northern Mojave deserts in the western United States, has one of the fastest-growing populations of all the states. This growth has created a demand for water, as Las Vegas, Nevada's largest urban center, and other expanding desert cities outgrow their present water supply, primarily water from the state's Colorado River allotment. Water sources targeted for development include groundwater basins under distant Great Basin valleys which presently are primarily tapped for agriculture. Natural springs, a critical resource for wildlife and ranching, exist throughout the proposed pumping area and the ecological effects of groundwater withdrawal on them are not fully understood. In addition to affecting biota at Ash Meadows NWR and nearby areas including the Desert NWR and Pahranagat NWR (all in the Great Basin Desert or Great Basin/Mojave Desert transition), potential groundwater pumping may affect biota in other areas such as White Pine County in east-central Nevada and Lincoln County in southeastern Nevada.

The objective of this paper is to address the following questions: (1) How has groundwater withdrawal from distant basins affected local water tables and associated flows at springs of the Great Basin and Mojave deserts? And (2) How might changes in water tables and spring flow affect spring-associated plant communities? As the foundation of our understanding of the response of spring vegetation to alteration of spring associated hydrology, we have developed a conceptual model based on review of hydrologic and ecological studies showing the relationships among groundwater and other hydrologic resources, groundwater withdrawal, soil condition, and plant communities (Fig. 1). Based on our responses to the above questions and projections of effects of groundwater withdrawal, we also suggest additional information needed to allow for quantitative prediction of ecological impacts of distant groundwater pumping on these springs?

To address the first question, we draw from hydrologic modeling studies (Schaefer and Harrill 1995; Belcher 2004; Tumbusch and Plume 2006) and analyses of effects of historic groundwater withdrawal from areas with springs (Dudley and Larson 1976; Pavleko and others 1999; Leake and others 2000). Understanding the interconnections within these hydrological systems and potential changes in the regional aquifers resulting from groundwater withdrawal is critical to addressing questions on vegetation response. For the second question, we draw from studies on effects of groundwater withdrawal on springs and wetlands (Perkins and others 1984; Grootjans and others 1988; Davis 1993), including those few studies that are specific to spring-sustained wetland and riparian vegetation in the Great Basin and Mojave deserts in Nevada (Castelli and others 2000). In particular, we refer to our studies that examine spatial patterns of vegetation across moisture gradients at springs of different sizes, as a basis for extrapolating how vegetation might change over time as water table depths and spring discharge change in response to hydrologic alterations.

Using linear models on relationships between community wetland indicator scores (WIS) and water table levels, we project how plant communities might change in composition. WIS weights each species within a sample plot by its cover percentage and wetland indicator status (obligate wetland is 1, facultative wetland is 2, facultative is 3, facultative upland is 4, and upland is 5) (USFWS 1997), resulting in a community wetland indicator score of between 1 and 5 (i.e., wetland to upland). Data used to develop the models were obtained through sampling herbaceous and woody vegetation in plots associated with shallow groundwater wells placed across several transects at spring sites in Spring Valley in the Great Basin in east-central Nevada, and Ash Meadows NWR and Lake Mead National Recreation Area (NRA) in the Great Basin/Mojave Desert transition in southern Nevada. All spring sites are representative of locations that may be impacted by future groundwater withdrawal. We apply the general predictions of hydrologic change resulting from groundwater withdrawal to these areas through interrelating knowledge of spring dynamics with historic evidence of groundwater decline (Pavleko and others 1999; Leake and others 2000; Tumbusch and Plume 2006) and models of water table decline (Schaefer and Harrill 1995; Faunt and others 2004).

How Has Groundwater Withdrawal from Distant Basins Affected Local Water Tables and Associated Flows at Springs of the Great Basin and Mojave Deserts?

To address this question we review information on groundwater systems and historic responses of groundwater to withdrawal and modeling of groundwater extraction in the Great Basin/Mojave deserts region of North America.

Groundwater Systems of Eastern Nevada, USA

Most groundwater systems that will be used to satisfy the expanding water needs of urban Nevada are located in eastern Nevada and western Utah (Fig. 2). Most of eastern Nevada is part of the Basin and Range province (Hunt

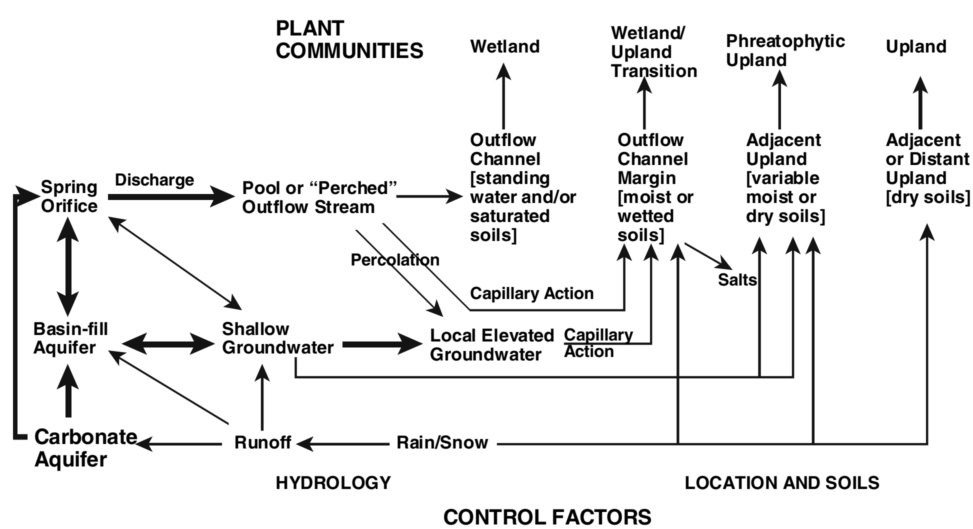

Fig. 1 Conceptual model of processes that interact and affect development of plant communities at Great Basin and Mojave Desert springs. Groundwater withdrawal from the carbonate aquifer directly and indirectly affects other hydrological attributes (broad arrows), which in turn affect soils and other factors that support plant communities

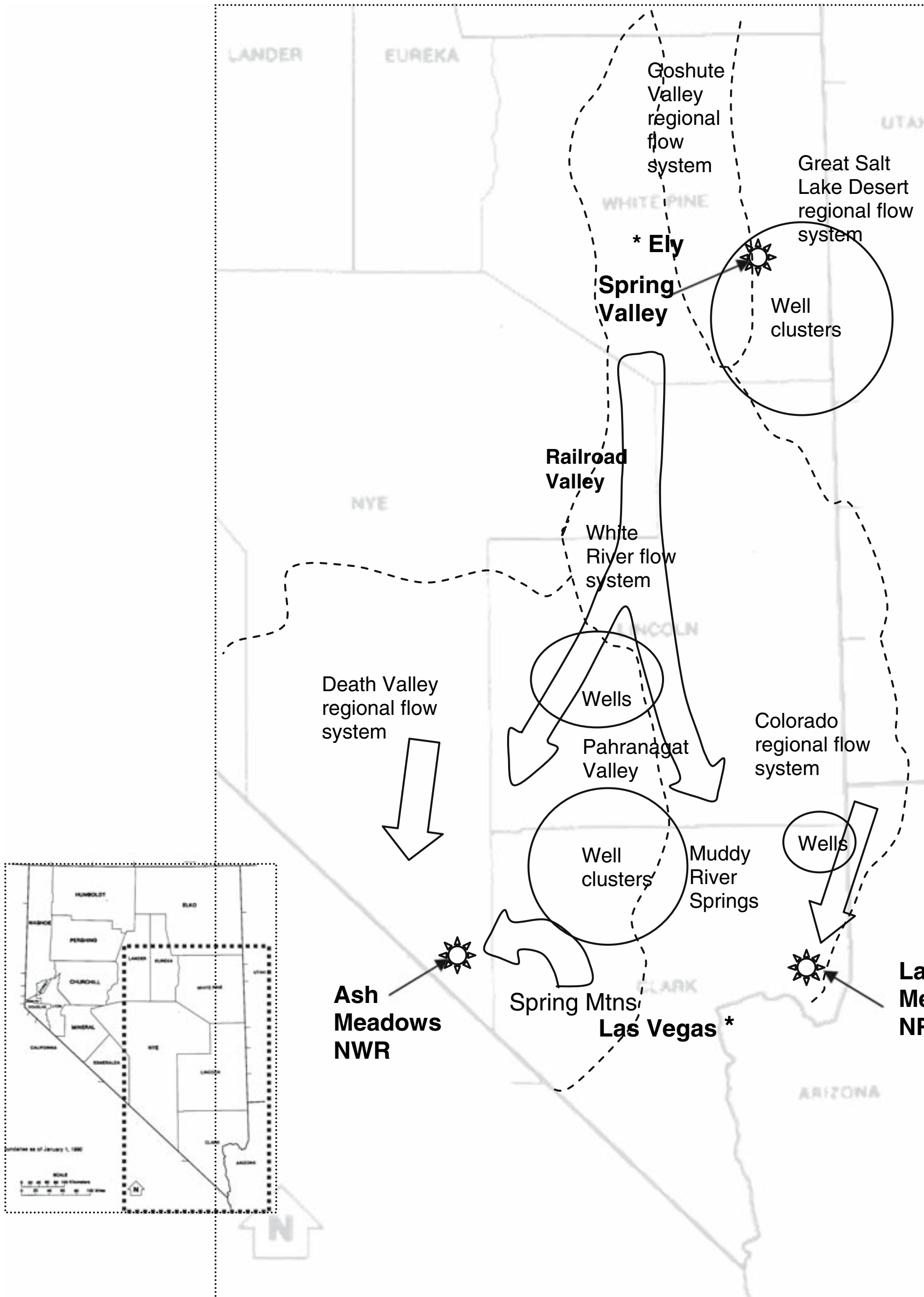

Fig. 2 Map of eastern Nevada, USA, showing location of study springs (stars), outline of regional flow systems (dashed lines), regional groundwater flows (open arrows), and potential well cluster locations for groundwater withdrawal for urban use (circles)

1974), in which groundwater flow systems occur in individual basins or in two or more hydraulically connected basins (Plume 1996; USGS 1997). One main aquifer type in eastern Nevada is Cenozoic valley or basin-fill (Fenelon and Moreo 2002). Much of the groundwater in this region flows through these basin-fill deposits, with mountains serving as boundaries of some of the flow systems. Another aquifer type is Paleozoic carbonate rock, which commonly underlies the basins and provides hydraulic connections under mountains between basins (Dettinger 1969; Plume 1996). Groundwater flow in this aquifer is from east-central Nevada and western Utah near Spring Valley south toward Ash Meadows, Death Valley, and Lake Mead (Fig. 2) (Dudley and Larson 1976; Dettinger and others 1995; Prudic and others 1995; Laczniak and others 1996; Plume 1996; Thomas and others 1996). Approximately two-thirds of this flow is discharged into the Muddy River Springs north of Lake Mead NRA, and about one-third to springs in Ash Meadows NWR (Dettinger 1969). None of it discharges at Lake Mead NRA springs. However, groundwater in the Virgin River subflow system in southeastern Nevada and southwestern Utah, a subsystem of the Colorado River regional flow system, apparently discharges at larger springs in Lake Mead NRA (Prudic and others 1995). Many springs are sustained, at least proximately, by the basin-fill aquifer. The carbonate aquifer, the aquifer most likely to be tapped for urban use, is considered the ultimate water source for regional springs, through its replenishment of the basin-fill aquifer. It also directly supports some springs.

Historic Response of Groundwater Levels to Urban, Agriculture, and Mining Withdrawal

Groundwater decline and fluctuation is not a recent phenomenon in Nevada. Agriculture and mining were dependent on available groundwater from artesian wells early in the 20th century and later from wells drilled into deep regional aquifers. Groundwater use in the first half of the 20th century lowered water tables in several parts of the state by as much as 10 to >50 m (Leake and others 2000). The Death Valley regional flow basin, which lies west of Las Vegas and includes Ash Meadows NWR, has had water table fluctuations of >10 m, resulting from wet/dry climate cycles and periodic suspension of groundwater withdrawal for agriculture (Belcher 2004). One of the better-documented consequences of groundwater withdrawal is in the Las Vegas Valley, where extensive water extraction from the aquifer and tapping of artesian wells dried up local springs and lowered the water table by >100 m in some areas (Pavleko and others 1999). In central Nevada from 1950 to 2005 water tables declined 15 to 30 m in Diamond Valley, with the level of one well dropping from near surface (~1 m) to ~25 m.

Dudley and Larsen (1976) studied the effects of local groundwater withdrawal from 1969 to 1972 on springs and water table levels in Ash Meadows and nearby Devil's Hole. At the peak of withdrawal the water table at Devil's Hole dropped from 0.42 to 1.12 m, while other wells declined 0.1 to 0.2 m. Discharge from springs at Ash Meadows was greatly influenced by the 1969–1972 pumping, for example, Jack Rabbit Spring declined from 2000 m^3/day (0.0231 cm) to 0; Collins Spring, from 42 to 21 m^3/day (0.00049 to 0.00024 cm), a 50% reduction; and Fairbanks Spring discharge was reduced about 10% (8600 to 7800 m^3/day; 0.0995 to 0.0902 cm).

Pumping Simulations and Groundwater Withdrawal Analyses: Response of Water Tables

A recent study modeled simulated effects of proposed groundwater pumping in eastern Nevada from two aquifer layers—the deep (lower) carbonate layer and the upper shallow basin-fill layer—in areas proposed for future withdrawals for urban use (Schaefer and Harrill 1995). The model showed that withdrawal from either carbonate or basin-fill aquifers tapped storage in the carbonate layer, which is water that otherwise would discharge to spring-fed streams or be lost as ET. After 7 years of simulated pumping following a hypothetical groundwater withdrawal schedule, the upper basin-fill aquifer north of Lake Mead (Muddy River area) declined ~0.3 m, while 18 years of simulated pumping in Spring Valley, east-central Nevada, resulted in the shallow aquifer decline of up to 3 m. Other analyses of effects of proposed groundwater withdrawal by the Southern Nevada Water Authority (SNWA), one using the Schaefer and Harrill (1995) model and one the Durbin model developed for SNWA (Durbin and Bond 1998), reported at a Spring Valley Water Rights Hearing, September 11–25, 2006, that the water table in the alluvial aquifer in Spring Valley could decline by as much as 60 m following more than 75 years of extraction (exhibits at http://www.water.nv.gov/hearings/spring%20valley%20hearings).

Although the deep carbonate aquifer that supports springs from Spring Valley south to Ash Meadows NWR does not support springs at Lake Mead NRA, groundwater from the Virgin River subregion aquifer in southeastern Nevada discharges at several larger springs in Lake Mead NRA (Prudic and others 1995). Groundwater withdrawal proposals to tap this aquifer have been challenged by the U.S. National Park Service in 1998, while in 2006 the U.S. Bureau of Land Management announced its intent to prepare an Environmental Impact Statement for production wells tapping this aquifer to supply water to nearby Mesquite, NV, another rapidly growing area in southern Nevada.

Faunt et al. (2004) modeled effects of simulated pumping from 1960s through 1990s, in the Death Valley regional groundwater flow system located in south-central Nevada. They showed that, for areas near Ash Meadows NWR, simulated pumpage of <500 to >10,000 m^3/day could result in a water table decline of a few meters at locations 15 to 20 km from the pumpage site to as much as 10 to 25 m near the pumps.

Pumping Simulations and Groundwater Withdrawal Analyses: Response of Spring Flows and Outflow Distance

The extent to which flow of springs is predicted to decrease seems strongly dependent on the distance of the pumping source from the spring (Schaefer and Harrill 1995). Some springs may be unaffected; others, however, showed slight to substantial declines after more than 100 years of simulated pumping. For example, Schaefer and Harrill's model showed a decrease in flow of almost 10% for the Muddy River complex, a decrease of 14% for Pahranagat Valley springs, and a decrease of 2% for the Ash Meadows complex, all areas that may be affected by future groundwater withdrawal.

Outflow Distance

The greater the regional groundwater decline and associated reduction in spring discharge, the greater should be the corresponding decline in length of the outflow stream. However, the relationships between spring discharge and outflow distance have not been quantified and likely vary with surface morphology of outflow streams. We have found that outflow distance at springs with low discharge rates (<0.0002 cm) is usually not >200 m, while outflow distance at springs with large discharges (>0.01 cm) can be many kilometers, often terminating in reservoirs or larger rivers.

How Might Changes in Water Tables and Spring Flow Affect Spring-Associated Plant Communities?

Groundwater inflows interact with local geomorphologic features to create gradients of soil moisture, salinity, and depth to groundwater near the spring orifice and along the outflow channel, thus supporting a mosaic of plant communities at Great Basin and Mojave Desert springs (Fig. 1). Vegetation response to changes in spring flow and water tables will vary among the different zones, which include the wetland (hydroriparian) zone near the orifice, usually with standing water; the wetland/upland transition (mesoriparian) zone along the margin of the outflow stream; and the surrounding phreatophytic-upland and upland zones. Spatial patterns of water quality (soil water salinity, in particular) and water quantity both will change in response to groundwater withdrawal, thereby affecting abundance patterns of halophytes vs. nonhalophytes and hygrophytes vs. xerophytes within these zones. Vegetation change would be expected to occur along a continuum as wetland and wetland/upland transition areas shrink laterally and longitudinally, and various species undergo reductions in cover and ultimate loss as spring discharge declines and basin-fill water tables drop (Fig. 3). Although wetland area has not been quantified as a function of spring discharge, observations suggest that wetlands at large springs extend considerably farther downstream than at small springs. Even though large springs may lose extensive amounts of wetland and wetland/upland transition area, small springs are expected to lose a higher percentage of such areas in response to decline in spring discharge.

Wetlands

If, following groundwater withdrawal, the spring continued to flow, but at a reduced volume, the orifice pond would continue to exist, but wetlands supported by the outflow stream would be greatly truncated. The amount of area suitable to support herbaceous wetland species such as those of *Eleocharis, Carex, Juncus*, and *Phragmites* would be greatly reduced and the area covered by these species would shrink back toward the orifice area. As wetlands recede, species least tolerant of drying conditions such as *Eleocharis rostellata* at southern springs and *Eleocharis palustris* and *Berula erecta* at northern springs would be extirpated first. Some of these wetland species may survive at low cover and be intermixed with wetland/upland transition species but they will not form high-cover, monotypic stands as they presently do. These species might then be

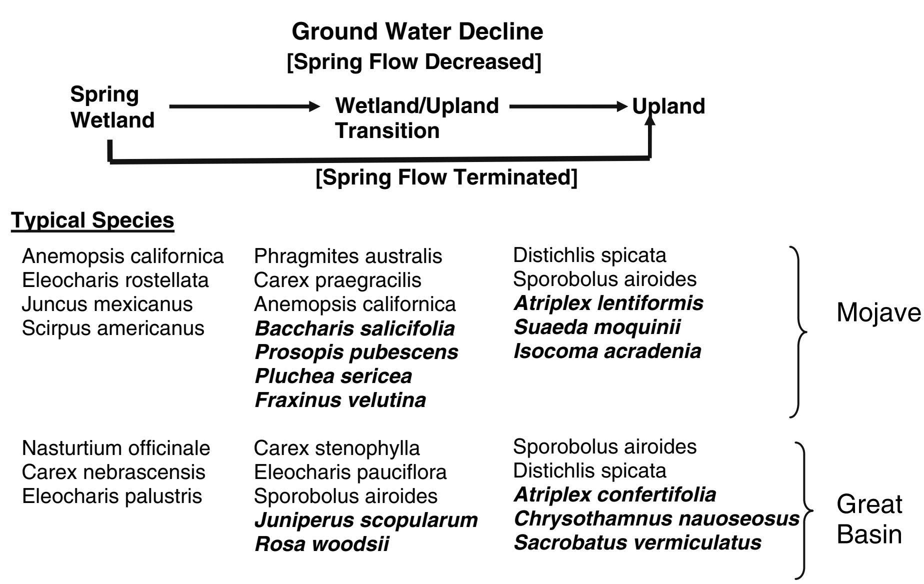

Fig. 3 Diagram showing the gradient of plant communities from wetland to upland and, thus, potential changes in vegetation resulting from groundwater decline. If spring flow is terminated, vegetation will change to upland; however, if spring flow is reduced, wetland/transition vegetation may replace wetland. Typical species found at each vegetation zone are listed for Great Basin and Mojave Desert springs. Woody genera are in boldface italics

replaced by transition species, such as *Anemopsis californica* and *Iva acerosa*, or phreatophytic-upland species, such as *Distichlis spicata*, especially at the extreme ends of the outflow stream.

Wetland/Upland Transition

The plant community in the wetland/upland transition will be affected both by changes in mean water table depth during the growing season, which presently ranges from <0.5 to ~1.5 m, and its degree of intra-annual fluctuation (~0.5 m). Woody species in this zone that tolerate greater water table fluctuations, such as *Atriplex lentiformis, Prosopis glandulosa, Isocoma acradenia*, and *Artemisia tridentata*, presently grow in adjacent uplands; these might be expected, over decadal time scales, to replace the less tolerant obligate and facultative wetland trees and shrubs. The obligate and facultative wetland woody species, such as *Salix exigua, Baccharis emoryi, Baccharis salicifolia, Pluchea sericea*, and *Tamarix ramosissima*, might decline in stature or become extirpated in a fashion similar to woody riparian species in the semi-arid West, which show physiological and morphological responses such as reduced growth in adults and dieback in saplings with a declining water table (Scott and others 1999; Shafroth and others 2000; Cooper and others 2003). As the quantity of outflow water available for wetting soils and diluting salts along the outflow channel margin declines or is eliminated, the transition areas should become more saline. This would cause reductions in nonhalophytic plants that are sensitive to conditions with elevated EC such as species of *Salix* and *Populus* (Shafroth and others 1995) and expansion and/or encroachment of upland halophytes such as *Atriplex* spp. and *Suaeda moquinii* (Burk and others 2005).

If the outflow stream continued to flow to the normal extent expected of large springs with extended outflows, but the flow volume was reduced, the width of influence of the stream might be reduced and woody plants along the wetland/upland transition, such as species of *Prosopis*, *Pluchea*, and *Baccharis*, would have reduced cover compared to their present extent. Continued groundwater withdrawal may reach a point when flow ceases and all wetland and wetland/upland plant communities that exist today are extirpated and replaced by upland vegetation.

Phreatophytic-Upland

Vegetation in the upland zones immediately adjacent to the areas influenced by the outflow stream may be affected by water table decline via two mechanisms. First, upland phreatophytes may be replaced by nonphreatophytes as water levels exceed their rooting zones. Declining or fluctuating water tables have been shown to greatly reduce productivity of phreatophytes such as *Atriplex* spp., *Chrysothamnus nauseosus, Distichlis spicata*, and *Sporobolus airoides*, especially in high-porosity soils (Naumburg and others 2005). The water table in areas of the study springs occupied by upland phreatophytes was near the ground surface (<1 to ≥2 m among springs) and underwent intra-annual water table fluctuations from <0.5 to >1.5 m as measured in monitoring wells. Groundwater withdrawal could cause water tables to decline by a few meters to tens of meters during the dry season. Although some woody phreatophytic species such as *Prosopis glandulosa*, *Atriplex canescens*, and *Sarcobatus vermiculatus* may have very deep root systems (e.g., ~6 to >15 m) (Robinson 1958; Nilsen and others 1983; Freckman and Virginia 1989; Canadell and others 1996; Gibbens and Lenz 2001), others such as *Chrysothamnus* spp. are more shallowly rooted (≤4 m) and might be more affected by declining water tables (Reynolds and Fraley 1989; Hartle and others 2006). Species such as *Larrea tridentata* and *Artemisia tridentata* with shallower root systems (~2 m) are mostly dependent on shallow soil water and would be expected to replace deeper rooted phreatophytic species (Richards and Caldwell 1987; Caldwell and Richards 1989; Freckman and Virginia 1989; Hartle and others 2006). Rooting depth also varies widely among herbaceous species. *Distichlis spicata* (found in the wetland/upland transition and phreatophytic-upland zones) and *Sporobolus airoides* (found in the wetland/upland transition zone) have root depths from <1 to >4 m and >5 m, respectively, based on water table depths (Robinson 1958), and effective rooting depths of ~2 m (Elmore and others 2006). Such species would better survive water table decline than herbaceous species in wetland zones (e.g., *Anemopsis californica*), most of which have shallow root systems (<1 m).

Second, declining shallow water tables may reduce the amounts of salts and water wicked to the surface by capillary action, potentially altering the chemistry of surface soils in upland areas. Should surface salinity decrease, the species composition of the extensive phreatophytic-upland zone might change from salt-tolerant halophytes (e.g., *Sarcobatus vermiculatus)* to either low-salt-tolerant species such as *Chrysothamnus nauseosus* or salt-intolerant species (e.g., *Artemisia tridentata*) (Dodd and Donovan 1999).

In concert, the net effect would be shifts from halophytes dependent on capillary-fringe water to nonhalophytes dependent on ambient precipitation. For example, if groundwater declines below the extent of roots of phreatophytic halophytes such as *Allenrolfea occidentalis, Atriplex confertifolia*, *Sarcobatus vermiculatus*, and *Suaeda moquinii*, often several meters deep, these woody species, which presently characterize the landscape around the springs, would be replaced by shallower rooted nonhalophytes such as *Larrea tridentata* in southern spring areas, *Artemisia tridentata* in northern spring areas, and low-salt-tolerant *Chrysothamnus nauseosus* (Weber and Hanks 2006) in both areas. Plant communities with these species are common throughout the Mojave (southern) and Great Basin (northern) deserts, where soils are not saline. Potential conversion of halophytic to nonhalophytic species is not expected to occur with initial water table decline, but if groundwater withdrawal continues for an extended period such as a century or more based on anticipated groundwater extraction schedules, the transition may become apparent in that longer time frame. Much of the Great Basin Desert presently has extensive stands of nonhalophytic *Artemisia tridentata* and these might be expected to expand over time.

Hydrologic and Vegetation Changes at Representative Spring Locations

Three spring locations in Nevada, USA, studied for their potential response to groundwater decline, represent examples of different spring habitats found within the Great Basin and Mojave deserts. These are Spring Valley in east-central Nevada and Ash Meadows NWR and Lake Mead NRA in southern Nevada.

Spring Valley, White Pine County, Nevada, USA

Historic data show water table declines of 10–30 m or more during the latter half of the 20th century in east-central Nevada south of the Spring Valley study area (Leake and others 2000), while models based on Las Vegas groundwater withdrawal schedule suggest declines of $\geq$3 to 60 m in the water table in the Spring Valley area after several decades to a century of pumping. This level of decline in water table will greatly alter the spring vegetation and cause the vegetation composition bordering the outflow stream to change along a water-availability gradient (Table 1, Fig. 3).

Using a linear model on relationships between herbaceous community wetland indicator scores (WIS) and water table levels at Spring Valley (Model 1), we can project how the herbaceous plant communities might change in composition.

$$\begin{aligned}&\text{Model 1 : Herb WIS (Spring Valley : May} - \text{June)}\\&\quad = 0.786 + 1.085\ \text{Water Table Depth (August)}\\&\quad [n = 17,\ R^2 = 0.427,\ p \leq 0.01]\end{aligned}$$

Using the above model, we find that the WIS will increase by about 1 unit with each meter of decline in the water table. For example, a wetland/upland transition zone herbaceous community with a WIS of 2 at the Spring Valley study springs includes species of *Carex, Juncus, Puccinella, Sporobulus*, and *Distichlis.* Following a 2-m water level decline, this community might shift to one with a WIS of 4, equivalent to a phreatophytic-upland community vegetated by species such as those of *Descurainia, Distichlis*, and *Puccinellia* (Table 1). Although we could not produce a significant model for woody WIS change for Spring Valley because most woody species were upland species with low cover, a decline in the water table in this area would affect shallow rooted woody phreatophytes including "swamp cedar," an ecotype of Rocky Mountain juniper (*Juniperus scopulorum*) that thrives on a high water table and saline soils and is found in few places in the Great Basin Desert (Bostick and others 1975). In addition, if the salinity of the upland soil surface declines, woody upland species might shift from phreatophytic halophytes such as *Atriplex confertifolia* and *Sacrobatus vermiculatus* to woody nonhalophytes such as *Artemisia tridentata* (Table 1).

Water table declines would cause the Spring Valley spring flows to concomitantly decline and outflow streams to shorten, thereby gradually reducing the cover of wetland and wetland/upland transition vegetation as the outflow stream truncates. Most springs at Spring Valley presently have small discharge and limited outflow, and modeling by Schaefer and Harrill (1995), and others using their model, project future spring discharge declines for Spring Valley as well as other areas in eastern Nevada following several decades of groundwater extraction.

Ash Meadows Springs

Springs at Ash Meadows NWR are dependent on the local basin-fill aquifer, which is recharged by water from the deep aquifers to the north. Other sources of groundwater issuing from springs in Ash Meadows are from the Spring Mountains just north of Ash Meadows and Pahranagat Valley more than 100 km northeast (Fig. 2) (Winograd and Friedman 1972; Osmond and Cowart 1982). Although no more groundwater withdrawal will occur at Ash Meadows NWR, groundwater pumping from aquifers that support Ash Meadows springs could lower the shallow water table at Ash Meadows and/or reduce discharge at many of the springs. Modeling of earlier groundwater pumping in the area, a possible measure of future influences of groundwater use, indicates possible water table declines of <1 to >3 m and spring flow reduction by as much as 50% (Dudley and Larson 1976; Faunt and others 2004).

A reduced discharge will truncate plant communities dependent on the outflow stream, a response that will

Table 1 Herbaceous and woody plant species characteristic of community types at Spring Valley, Nevada, with wetland indicator status for each species and wetland indicator score range for each community type

	Wetland indicator status	Community type			
		Wetland, 1–2	Wetland/ upland transition, 2–3	Phreatophytic upland, 3–5	Upland, 3–5
Herbaceous species					
Berula erecta (Huds.) Coville	OBL	X			
Carex nebrascensis Dewey	OBL	X			
Eleocharis palustris (L.) Roemer & J.A. Schultes	OBL	X			
Eleocharis pauciflora (Lightf.) Link	OBL	X			
Nasturtium officinale Ait. f.	OBL	X			
Poa pratensis L.	FACU	X			
Juncus balticus Willd.	FACW	X	X		
Carex stenophylla Wahlenb.	UPL	X	X		
Sporobolus airoides (Torr.) Torr.	FAC		X	X	
Ivesia kingii S. Watts.	UPL		X	X	
Puccinellia lemmonii (Vasey) Scribn.	FAC		X	X	
Distichlis spicata (L.) Greene	FAC		X	X	X
Descurainia sophia (L.) Webb ex Prantl	UPL			X	X
Lappula redowskii (Hornem.) Greene	UPL				X
Woody species					
Rosa woodsii Lindl.	FAC		X		
Juniperus scopulorum Sarg.	UPL		X		
Artemisia tridentata Nutt.	UPL		X	X	X
Chrysothamnus albidus (M.E. Jones ex Gray) Greene	UPL			X	
Chrysothamnus nauseosus (Pallas ex Pursh) Britt	UPL			X	
Atriplex confertifolia (Torr. & Frem.) S. Wats.	UPL			X	X
Sarcobatus vermiculatus (Hook.) Torr.	UPL			X	X

Note. Wetland indicator status: OBL, obligate wetland; FACW, facultative wetland; FAC, facultative; FACU, facultative upland; UPL, upland

initially be more obvious at small springs. The decline in the water table will change the composition of the plant communities. For example, Model 2, based on May herbaceous plant community data from Ash Meadows, shows that with each 1-m decline in water table, the herbaceous community WIS will increase by about 1 unit (similar to patterns for Spring Valley).

$$\text{Model 2 : Herb WIS (Ash Meadows : May)}$$
$$= 1.697 + 1.061 \text{ Water Table Depth (May)}$$
$$[n = 21,\ R^2 = 0.325,\ p \leq 0.01]$$

Consequently, a decline of $\geq$2 m may shift herbaceous vegetation outside the outflow stream area from wetland/ upland transition to upland, that is, from one including species of *Anemopsis, Eleocharis, Juncus, Phragmites* and *Sporobolus* to one characterized by species of *Distichlis* and *Descaurainia* (Table 2). Several rare, endemic herbaceous species associated with springs and outflow streams in Ash Meadows NWR may be threatened by changes in shallow water tables and reduced outflows (Morefield 2001). These include *Centaurium namophilum* Revel, Bro. & Beatley, *Grindelia fraxinopratensis* Reveal & Beatley, and *Cordylanthus tecopensis* Munz & Roos.

For woody plant communities (Model 3) it would take a decline of $\sim$2 m to increase the woody community WIS by 1 unit. Consequently, woody vegetation bordering the wetland outflow area may be more resistant to water table decline. However, it appears that change will occur as woody species respond to declining water tables. For example, using Model 3, a woody community with a WIS of $\sim$3 is associated with a water table depth of $\sim$1 m, whereas a woody community with a WIS of 5 is associated with a water table of $\sim$4.4 m.

$$\text{Model 3 : Woody WIS (Ash Meadows)}$$
$$= 2.490 + 0.576 \text{ Water Table Depth(August)}$$
$$[n = 21,\ R^2 = 0.317,\ p \leq 0.01]$$

Recognizing that wetland status rankings apply more to wetland than upland species, it is notable that the compositional shift between a WIS of 3 and a WIS of 5

Table 2 Herbaceous and woody plant species characteristic of community types at Ash Meadows NWR, with wetland indicator status for each species and wetland indicator score range for each community type

	Wetland indicator status	Community type			
		Wetland, 1–2	Wetland/ upland transition, 2–3	Phreatophytic upland, 3–5	Upland, 4–5
Herbaceous species					
Scirpus americanus Pers.	OBL	X			
Typha domingensis Pers.	OBL	X			
Anemopsis californica (Nutt.) Hook. & Arn.	OBL	X	X		
Eleocharis rostellata (Torr.) Torr.	OBL	X	X		
Lythrum californicum Torr. & Gray	OBL	X	X		
Juncus mexicanus Willd. ex J.A. & J.H. Schultes	FACW	X	X		
Muhlenbergia asperifolia (Nees & Meyen ex Trin.) Parodi	FACW	X	X		
Carex praegracilis W. Boott	FACW		X		
Nitrophila occidentalis (Moq.) S. Wats.	FACW		X		
Phragmites australis (Cav.) Trin. ex Steud.	FACW		X		
Sporobolus airoides (Torr.) Torr.	FAC		X	X	
Iva acerosa (Nutt.) R.C. Jackson	FACU		X	X	
Distichlis spicata (L.) Greene	FAC		X	X	
Thelypodium integrifolium (Nutt.) Endl. ex Walp.	FAC			X	
Descaurainia spp.	UPL			X	
Woody species					
Salix exigua Nutt.	OBL		X		
Salix gooddingii Ball	FACW		X		
Tamarix ramosissima Ledeb.	FACW		X		
Fraxinus velutina Torr.	FACW		X		
Prosopis pubescens Benth.	FAC		X		
Baccharis emoryi Gray	FACW		X	X	
Pluchea sericea (Nutt.) Coville	FACW		X	X	
Atriplex lentiformis (Torr.) S. Wats.	FAC		X	X	
Prosopis glandulosa Torr.	FAC		X	X	
Suaeda moquinii (Torr.) Greene	FAC		X	X	X
Allenrolfea occidentalis (S. Wats.) Kuntze	FACW			X	
Atriplex confertifolia (Torr. & Frem.) S. Wats.	UPL			X	
Chrysothamnus nauseosus (Pallas ex Pursh) Britt	UPL			X	
Lycium pallidum Miers	UPL			X	
Isocoma acradenia (Greene) Greene	FACU			X	X
Larrea tridentata (Sesse & Moc. ex DC) Coville	UPL				X

Note. Wetland indicator status: OBL, obligate wetland; FACW, facultative wetland; FAC, facultative; FACU, facultative upland; UPL, upland

is equivalent to a shift in a community with primarily facultative and facultative upland species including, for example, *Atriplex confertifolia, Prosopis pubescens* and *Suaeda moquinii* to a community with facultative upland and upland plants with species such as *Atriplex confertifolia, Lycium pallidum, Chrysothamnus nauseosus*, and *Larrea tridentata* (Table 2). Several of these woody species, although not considered to be species associated with wetlands, still had an affinity to wetland or near-wetland areas at the Ash Meadows springs. A possible decline in soil salinity resulting from water table decline might result in an upland woody community composed of species of *Larrea, Chrysothamnus*, and possibly *Fraxinus velutina* rather than halophytes such as species of *Atriplex* and *Suaeda.*

Lake Mead, Nevada Springs

Groundwater that sustains flow in springs in Lake Mead NRA is mostly derived from local precipitation, which recharges a local carbonate aquifer and shallow basin-fill aquifers, which in turn support springs (Pohlmann and others 1998). Consequently, shallow water tables in the Lake Mead area may vary temporally in response to local, mountain precipitation and have greater seasonal fluctuations than those at Spring Valley or Ash Meadows. The other source of water for some large springs at Lake Mead NRA is a subregional groundwater flow system (Prudic and others 1995). This aquifer is being considered for urban use, which, if developed, may directly influence spring discharge and associated shallow groundwater in Lake Mead NRA.

We have developed WIS models for Lake Mead NRA spring areas. The herbaceous WIS model (Model 4) indicates that a decline in the water table of $\sim$0.75 m will increase the herbaceous WIS by 1 unit. It would take a decline of $\sim$1.5 m to make a major shift in species composition from a wetland/upland transition to an upland herbaceous plant community. This would include a shift from species of *Anemopsis, Phragmites*, and *Sporobolus* to a monospecific community of *Distichlis spicata* (Table 3).

$$\begin{aligned}&\text{Model 4 : Herb WIS (Lake Mead)}\\&\quad = 1.014 + 1.328\ \text{Water Table Depth (August)}\\&\quad [n = 19,\ R^2 = 0.366,\ p \le 0.01]\end{aligned}$$

The woody WIS model (Model 5) shows that it would take a decline in the water table similar to that for the herbaceous decline to shift the woody community by 1 WIS unit, that is, a decline of $\sim$0.80 m.

$$\begin{aligned}&\text{Model 5 : Woody WIS (Lake Mead)}\\&\quad = 1.652 + 1.238\ \text{Water Table Depth (August)}\\&\quad [n = 19,\ R^2 = 0.500,\ p \le 0.001]\end{aligned}$$

A decline of $\sim$1.5 m would also shift the woody plant community from wetland/upland transition with mostly facultative wetland and facultative plants such as species of *Baccharis, Pluchea, Prosopis*, and *Tamarix* to phreatophytic upland with a possible mixture of facultative wetland and upland plants, for example, species of *Pluchea, Prosopis, Atriplex*, and *Suaeda* (Table 3). The overlap of species indicates that the shift in woody

Table 3 Herbaceous and woody plant species characteristic of community types at Lake Mead NRA, with wetland indicator status for each species and wetland indicator score range for each community type

	Wetland indicator status	Community type			
		Wetland, 1–2	Wetland/ upland transition, 2–3	Phreatophytic upland, 3–5	Upland, 3–5
Herbaceous species					
Eleocharis rostellata (Torr.) Torr.	OBL	X			
Scirpus americanus Pers.	OBL	X			
Juncus mexicanus Willd. ex J.A. & J.H. Schultes	FACW	X			
Solidago confinis Gray	FACW	X			
Anemopsis californica (Nutt.) Hook. & Arn.	OBL	X	X		
Phragmites australis (Cav.) Trin. ex Steud.	FACW	X	X		
Sporobolus airoides (Torr.) Torr.	FAC		X	X	
Distichlis spicata (L.) Greene	FAC		X	X	
Woody species					
Baccharis salicifolia (Ruiz & Pavon) Pers.	FACW		X		
Populus fremontii S. Wats.	FACW		X		
Tamarix ramosissima Ledeb.	FACW		X		
Prosopis pubescens Benth.	FAC		X		
Allenrolfea occidentalis (S. Wats.) Kuntze	FACW		X	X	
Pluchea sericea (Nutt.) Coville	FACW		X	X	
Isocoma acradenia (Greene) Greene	FACU		X	X	
Prosopis glandulosa Torr.	FAC		X	X	X
Suaeda moquinii (Torr.) Greene	FAC			X	
Atriplex confertifolia (Torr. & Frem.) S. Wats.	UPL			X	
Encelia farinosa Gray ex Torr.	UPL				X
Larrea tridentata (Sesse & Moc. ex DC) Coville	UPL				X

Note. Wetland indicator status: OBL, obligate wetland; FACW, facultative wetland; FAC, facultative; FACU, facultative upland; UPL, upland community composition may not be great and that species classified as facultative or upland, for example, may have overlapping environmental tolerances. However, a greater decline in the water table might, over time, also reduce surface salinity and drive the upland areas around the springs to a nonphreatophytic, nonhalophytic woody community characterized by *Larrea tridentata, Encelia farinose*, and possibly *Prosopis* spp. (Table 3).

A reduced discharge at the Lake Mead NRA springs will have consequences similar to those projected for Ash Meadows NWR. Table 3 shows wetland species that may be impacted by a reduction or loss of discharge.

Discussion

Historic and recent studies of groundwater withdrawal document decline of local and regional water tables throughout much of eastern and southern Nevada, USA. Many of these are located in urban or agricultural areas where spring flows have terminated (Pavleko and others 1999). The magnitude of the decline varies spatially but potential for additional water table decline is real if expanding human activities increasingly use groundwater.

Projection of actual consequences of water table decline is dependent on how much and where the water is harvested. In our analysis of the impacts of potential future groundwater withdrawal from regional and shallow basin-fill aquifers in the Great Basin and Mojave deserts of the United States, we have speculated on vegetation responses to water table decline based on our studies of species–water table relationships. These aquifers are primary drivers of spring hydrology and thus alteration of these aquifers and their associated water tables is also expected to alter surface flows (Fiero and Maxey 1970; Dudley and Larson 1976; Burk and others 2005) and soil moisture near springs in this arid region of North America.

Our present understanding of potential impacts of groundwater withdrawals from supporting aquifers on water tables at desert spring ecosystems has been informed primarily by groundwater models, increasingly an important tool, although historic data are also important inputs. Hydraulic models using potential future or known past levels of groundwater pumping have projected potential changes in water tables in different regional aquifers (Schaefer and Harrill 1995; Faunt and others 2004). However, few models project changes in spring discharge, a key linkage to understanding effects of groundwater withdrawal. Quantification of the relationship between reduced flow and length of outflow stream is also missing and, along with impacts on spring discharge, an important area of desert spring research.

As regional groundwater pumping drives reductions in spring discharge and local water tables, it will modify vegetation in the spring area (Perkins and others 1984; Sorenson and others 1991). Our projections of truncation of the lateral and longitudinal extent of the wetland and wetland/upland transition areas, declines in areal cover of hydrophytic vegetation, and composition shifts toward drought-tolerant species have been documented globally for other wetland and riparian ecosystems affected by dewatering (Stromberg and others 1996; Fairfax and Fensham 2003; Cooper and others 2006; Earmus and others 2006; Elmore and others 2006; MacKay 2006). Spatial patterns of soil water quality (salinity, in particular) also may change in response to reduced spring discharge and shallow water table decline resulting from groundwater withdrawal. In the wetland and wetland/upland transition zones along the outflow stream, halophyte cover might increase where less water is available to dilute saline soils. In the phreatophytic-upland zone, reductions in soil salinity, a response to reduced capillary rise of salts from the declining shallow water table, may drive shifts toward nonhalophytes. Increased salinity at the ground surface is a common consequence of elevated water tables created by agricultural irrigation in semi-arid and Mediterranean climate regions; western and southeastern Australia are examples (Cramer and Hobbs 2002; Dogramaci 2004). Solutions to the salinity problem and reclamation of saline areas for agriculture often include lowering of the shallow water table (Nulsen and Henschke 1981; Norman 1995; Anderies 2005). Thus, reduced surface salinity may be an expected response of regional groundwater withdrawal for urban expansion in the Great Basin and Mojave deserts. One caveat to this projection is that many of the saline soils in these deserts have existed for millennia, thus changes resulting from percolation of salts into the soil following rain events will be long-term. However, many desert areas with nonhalophytic plant species (e.g., *Larrea* in the Sonoran Desert in North America) have a petrocalcic horizon (caliche) several decimeters deep, a result of salt leached from the surface over time (McAuliffe 1994).

To increase our predictive capacity, increased understanding is needed on hydrologic thresholds for vegetation change. Although vegetation change will occur along a continuum from wetland to upland, it will occur as tolerance levels with respect to soil moisture reduction, and water table depth or seasonal fluctuation of the water table are exceeded for the dominant plant taxa that occupy different zones at or near the spring. Community-wide spatial gradient studies have clarified some relationships, but knowledge of water depth tolerance ranges for dominant taxa of the different zones of the springs should be refined through experimental manipulation of water levels (Naumburg and others 2005), population-focused studies along spatial hydrologic gradients (Groeneveld and Or 1994), and monitoring studies.

Table 4 Consequences of hydrological changes at Great Basin and Mojave Desert springs: comparison of large and small springs

Change	Primary consequences	Secondary consequences	Large spring change	Small spring change
Groundwater decline	Reduced discharge	Reduced outflow length and width	Potential great loss of wetland and wetland/upland transition communities	Small loss of wetland and wetland/upland transition communities
	Lowered capillary fringe	Wetland to wetland/upland transition or wetland/upland transition to upland shift	Extensive loss of wetland area	Small loss of wetland area
		Reduced "wicking" of salts by capillarity	Upland shift from halophytes to nonhalophytes	Upland shift to nonhalophytes
Discharge + or –	Outflow stream length change	Altered extent of wetland/upland transition community	Potential great change in wetland/upland transition community	Small change in wetland/upland transition community
	Wetted area width change	Altered extent of wetlands	Potential extensive wetland area change	Small wetland area change, but a high percentage of total
Discharge terminated	No pool or outflow stream	Loss of wetlands and wetland/upland transition Communities	Conversion from wetland to upland species and community	Conversion to upland species and communities

The response of the vegetation at the desert springs to regional groundwater pumping will vary as a function of many factors including spring size, soil traits at the spring, rate and magnitude of expected groundwater decline, magnitude of change in spring discharge, and degree of dependence on spring discharge on local vs. regional groundwater sources (Table 4). Of the springs we examined, one set was highly influenced by local hydrology and on the fringe of the potential impact zone from urban groundwater pumping, another was in the groundwater flow path of possible pumping locations, and another was located within a high groundwater withdrawal impact zone. Regional maps of the distributions of desert springs, overlaid on maps of expected groundwater declines in relation to anticipated pumping locations, would be a helpful regional planning tool.

Using our conceptual model (Fig. 1), we show the many hydrologic relationships and linkages to soils and plant communities that need to be understood to be able to make definitive statements about the magnitude of hydrologic change that will lead to changes in spring-associated vegetation. Using the model, one can also identify the pathways of influence following changes in one or more of the hydrological factors, for example, the deep carbonate aquifer, and which spring ecosystem functions and plant communities might be altered. Although the conceptual model can be used to guide identification of important attributes to study, on-site monitoring will be critical for detecting impacts. Plans are in place to monitor local hydrologic conditions at several desert spring sites because in 2006 when the Department of the Interior withdrew its protests of the SNWA groundwater withdrawal proposal for Spring Valley, it stipulated extensive and intensive hydrologic monitoring and management programs.

In addition to abiotic monitoring to achieve ecological sustainability of the spring areas through appropriate water management, we emphasize the importance of directly monitoring measures of ecosystem function for which biotic response is one metric (Earmus and others 2006; Lake and Bond 2007). Biotic monitoring has been planned in other arid locations where off-site groundwater depletion affects are a concern, and these, along with our studies, might be used for guidance (Stromberg and others 2006). Vegetation data, often used for resource management decisions, are recommended for evaluating disturbance at desert springs (Fleishman and others 2006). Vegetation monitoring also has been highly ranked by several of the U.S. National Park Service Inventory and Monitoring Networks, as vegetation combined with other indicators provides key data on ecosystem health. Long-term vegetation monitoring data are capable of providing early warning signs of impending changes in ecosystem processes. Vegetation also integrates information on geology, soils, hydrology, and climate (Fig. 1) and thus sampling of plant communities can provide sensitive metrics for assessing ecological changes over time at different spatial scales. To ensure that scientific information is appropriate for policy and management (MacKay 2006), it is important that monitoring and analysis be designed to test for magnitudes of change in vegetation rather than just existence of change (Morrison 2007), a phenomenon that can occur under disturbance and/or nondisturbance conditions.

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References

Anderies JM (2005) Minimal models and agroecological policy at the regional scale: An application to salinity problems in southeastern Australia. Region Environ Change 5:1–17

Belcher WR (ed.) (2004) Death Valley regional ground-water flow system, Nevada and California—hydrologic framework and transient ground-water flow model. U.S. Geological Survey Scientific Investigations Report 2004–5205. U.S. Geological Survey, Reston, VA

Bostick VB, Niles WE, McClellan WA, Oakes EH, Wilbanks JR (1975) Inventory of natural landmarks of the Great Basin. Compiled for the National Park Service. University of Nevada, Las Vegas

Brussard PF, Charlet DA, and Dobkin D (1999) The Great Basin-Mojave desert region. In Mac MJ, Opler PA, Puckett-Haecker CE, and Doran PD (eds). The status and trends of the nation’s biological resources. U.S. Department of the Interior, U.S. Geological Survey, Reston, VA

Burk N, Bishop C, and Lowe M (2005) Wetlands in Tooele Valley, Utah—an evaluation of threats posed by ground-water development and drought. Special Study 117. Utah Geological Survey

Caldwell MM, Richards JH (1989) Hydraulic life: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia 79:1–5

Canadell J, Jackson RB, Ehleringer JB, Mooney HA, Sala OE, Schulze E-D (1996) Maximum rooting depth of vegetation types at the global scale. Oecologia 108:583–595

Castelli RM, Chambers JC, Tausch RJ (2000) Soil-plant relations along a soil-water gradient in Great Basin riparian meadows. Wetlands 20:251–266

Cooper DJ, D’Amico DR, Scott ML (2003) Physiological and morphological response patterns of *Populus deltoides* to alluvial groundwater pumping. Environ Manage 31:215–226

Cooper DJ, Sanderson JS, Stannard DI, Groeneveld DP (2006) Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community. J Hydrol 325:21–34

Cramer VA, Hobbs RJ (2002) Ecological consequences of altered hydrological regimes in fragmented ecosystems in southern Australia: impacts and possible management responses. Austral Ecol 27:546–564

Danielopol DL, Griebler C, Gunatilaka A, Notenboom J (2003) Present state and future prospects for groundwater ecosystems. Environ Conserv 30:104–130

Davis JC (1993) The hydrology and plant community relations of Canelo Hills Cienega, an emergent wetland in southwestern Arizona. M.S. thesis. University of Arizona, Tucson

Deacon JE, Williams AE, Williams CD, Williams JE (2007) Fueling population growth in Las Vegas: how large-scale groundwater withdrawal could burn regional biodiversity. BioScience 57:688–698

Dettinger MD (1969) Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development. Summary of findings, 1965–66. Report 1. University of Nevada, Desert Research Institute, Las Vegas

Dettinger MD, Harrill JR, Schmidt DL, Hess JW (1995) Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development, southern Nevada and adjacent parts of California, Arizona, and Utah. U.S. Geological Survey Water-Resource Investigation Report 91–4146. U.S. Geological Survey, Reston, VA

Dodd GL, Donovan LA (1999) Water potential and ionic effects on germination and seedling growth of two cold desert shrubs. Am J Bot 86:1146–1153

Dogramaci S (2004) A review of groundwater pumping to manage dryland salinity in Western Australia. Department of Environment, Salinity and Land Use Impacts Series Report No. SLUI 25, Perth, Australia

Dudley WW Jr., Larson JD (1976) Effects of irrigation pumping on desert pupfish habitats in Ash Meadows, Nye County, Nevada. U.S. Geological Survey Professional Paper 927. U.S. Geological Survey, Reston, VA

Dunham JB, Minckley WL (1998) Allozymic variation in desert pupfish from natural and artificial habitats: genetic conservation in fluctuating populations. Biol Conserv 84:7–15

Durbin TJ, Bond LD (1998) FEMFLOW3D: a finite-element program for simulation of three-dimensional aquifers, Version 1.0. U.S. Geological Survey Open File Report 97–810. U.S. Geological Survey, Reston, VA

Eamus D, Froend R (2006) Groundwater-dependent ecosystems: the where, what and why of GDEs. Austral J Bot 54:91–96

Eamus D, Froend R, Loomes R, Hose G, Murray B (2006) A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Austral J Bot 54:97–114

Elmore AJ, Mustard JF, Manning SJ (2003) Regional patterns of plant community responses to changes in water: Owens Valley,California. Ecol Appl 13:443–460

Elmore AJ, Manning SJ, Mustard JF, Craine JM (2006) Decline in alkali meadow vegetation cover in California: the effects of groundwater extraction and drought. J Appl Ecol 43:770–779

Fairfax RJ, Fensham RJ (2003) Great Artesian Basin springs in southern Queensland 1911–2000. Mem Queensland Mus 49:285–293

Faunt CC, Blainey JB, Hill MC, D’Agnese FA, O’Brien GM (2004) Transient numerical model. In: Belcher WR (ed.), Death Valley regional ground-water flow system, Nevada and California—hydrologic framework and transient ground-water flow model. U.S. Geological Survey Scientific Investigations Report 2004–5205. U.S. Geological Survey, Reston, VA. pp 257–352

Fenelon JM, and Moreo MT (2002) Trend analysis of ground-water levels and spring discharge in the Yucca Mountain region, Nevada and California, 1960–2000. U.S. Geological Survey Water-Resources Investigations Report 02–4178. U.S. Geological Survey, Reston, VA

Fiero GW, Maxey GB (1970) Hydrogeology of the Devil’s Hole area, Ash Meadows, Nevada. Publication 44009. Desert Research Institute, Water Resources Center, Las Vegas, NV

Fleishman E, Murphy DD, Sada DW (2006) Effects of environmental heterogeneity and disturbance on the native and non-native flora of desert springs. Biol Invas 8:1091–1101

Freckman DW, Virginia RA (1989) Plant-feeding nematodes in deep-rooting desert ecosystems. Ecology 70:1665–1678

Gibbens RP, Lenz JM (2001) Root systems of some Chihuahuan Desert plants. J Arid Environ 49:221–263

Grimm NB, Chacon A, Dahm CN, Hostetler SW, Lind OT, Starkweather PL, Wurtsbaugh WW (1997) Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: the basin and range, American Southwest, and Mexicò. Hydrol Process 11:1023–1041

Groeneveld DP, Or D (1994) Water-table induced shrub-herbaceous ecotone: hydrologic management implications. Water Resources Bull 30:911–920

Grootjans AP, Vandiggelen R, Wassen MJ, Wiersinga WA (1988) The effects of drainage on groundwater quality and plant-species distribution in stream valley meadows. Vegetation 75:37–48

Hartle RT, Fernandez GCJ, Nowak RS (2006) Horizontal and vertical zones of influence for root systems of four major Mojave Desert shrubs. J Arid Environ 64:586–603

Hendrickson DA, Minckley WL (1985) Cienegas—vanishing climax communities of the American Southwest. Desert Plants 6:103–175

Horton JL, Clark JL (2001) Water table decline alters growth and survival of *Salix goodingii* and *Tamarix chinensis* seedlings. Forest Ecol Manage 140:239–247

Hunt CB (1974) Natural regions of the United States and Canada. W. H. Freeman, San Francisco, CA

Jackson RD, Allen-Diaz B (2006) Spring-fed wetlands and riparian communities respond differently to altered grazing intensity. J Appl Ecol 43:485–498

Laczniak RJ, Cole JC, Sawyer DA, Trudeau DA (1996) Summary of hydrogeologic controls on ground-water flow at the Nevada Test Site, Nye County, Nevada. U.S. Geological Survey Water Resources Investigations Report 96–4109. U.S. Geological Survey, Reston, VA

Lake PS, Bond NR (2007) Australian futures: freshwater ecosystems and human water usage. Futures 39:288–305

Leake SA, Konieczki AD, Rees JAH (2000) Desert basins of the Southwest. U.S. Geological Survey Fact Sheet 086–00. U.S. Geological Survey, Reston, VA

MacKay H (2006) Protection and management of groundwater-dependent ecosystems: emerging challenges and potential approaches for policy and management. Austral J Bot 54:231–237

McAuliffe JR (1994) Landscape evolution, soil formation, and ecological patterns and processes in Sonoran Desert Bajadas. Ecol Monogr 64:111–148

Minckley WL, Deacon JE eds (1991) Battle against extinction: native fish management in the America West. University of Arizona Press, Tucson

Morefield JD, ed. (2001) Nevada rare plant atlas. Compiled for the U.S. Department of the Interior, Fish and Wildlife Service, Portland, Oregon, and Reno, Nevada. Nevada Natural Heritage Program, Carson City

Morrison LW (2007) Assessing the reliability of ecological monitoring data: power analysis and alternative approaches. Nat Areas J 27:83–91

Mudd GM (2000) Mound springs of the Great Artesian Basin in South Australia: a case study from Olympic Dam. Environ Geol 39:463–476

Munch Z, Conrad J (2007) Remote sensing and GIS based determination of groundwater-dependent ecosystems in the Western Cape, South Africa. Hydrogeol J 15:19–28

Naumburg E, Mata-Gonzales R, Hunter RG, Mclendon T, Martin DW (2005) Phreatophytic vegetation and groundwater fluctuations: a review of current research and application of ecosystem response modeling with an emphasis on Great Basin vegetation. Environ Manage 35:726–740

Nilsen ET, Sharifi MR, Rundel PW, Jarrell WM, Virginia RA (1983) Diurnal and seasonal water relations of the desert phreatophyte *Prosopis glandulosa* (honey mesquite) in the Sonoran Desert of California. Ecology 64:1381–1393

Norman CP (1995) Effect of groundwater pump management on reclaiming salinized land in the Goulburn Valley, Victoria. Austral J Exp Agr 35:215–222

Nulsen RA, Henschke CJ (1981) Groundwater systems associated with secondary salinity in Western Australia. Agr Water Manage 4:173–186

Osmond JK, Cowart JB (1982) Groundwater. In: Ivanovich M, Harmon RS (eds). Uranium-series disequilibrium: applications to environmental problems. Clarendon Press, Oxford. pp 202–245

Pavleko MT, Wood DB, Laczniak RJ (1999) Las Vegas, Nevada. In: Galloway DL, Jones DR, Ingebritsen SE (eds). Land subsidence in the United States. U.S. Geological Survey Circular 1182. U.S. Geological Survey, Reston, VA. pp 49–64

Perkins DJ, Carlsen BN, Fredstrom M, Miller RH, Rofer CM, Ruggerone GT, Zimmerman CS (1984) The effects of groundwater pumping on natural spring communities in Owens Valley. In: Warner RE, Hendrix KM (eds). California riparian systems; ecology, conservation, and productive management. University of California Press, Berkeley. pp 515–527

Plume RW (1996) Hydrogeologic framework of the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409. U.S. Geological Survey, Reston, VA

Pohlmann KF, Campagna DJ, Chapman JB, Earman S (1998) Investigation of the origin of springs in the Lake Mead National Recreation Area. Publication 41161. Desert Research Institute, Las Vegas, NV

Pringle CM (2000) Threats to U.S. public lands from cumulative hydrologic alterations outside of their boundaries. Ecol Appl 10:971–989

Pringle CM (2001) Hydrological connectivity and the management of biological reserves: a global perspective. Ecol Appl 11:981–998

Prudic DE, Harrill JR, Burbey TJ (1995) Conceptual evaluation of regions ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah and adjacent states. U.S. Geological Survey Professional Paper 1409-D. U.S. Geological Survey, Reston, VA

Reynolds TD, Fraley L Jr (1989) Root profiles of some native and exotic plant species in southeastern Idaho. Environ Exp Bot 29:241–248

Richards JH, Caldwell MM (1987) Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. Oecologia 73:486–489

Robinson TW (1958) Phreatophytes. U.S. Geological Survey Water Supply Paper 1423. U.S. Geological Survey, Reston, VA

Schaefer DH, Harrill JR (1995) Simulated effects of proposed groundwater pumping in 17 basins of east-central and southern Nevada. USGS Water-Resources Investigations 95–4173. U.S. Geological Survey, Reston, VA

Schultz BW (2001) Exent of vegetated wetlands at Owens Dry Lake, California, USA, between 1977 and 1992. J Arid Environ 48:69–87

Scott ML, Shafroth PB, Auble GT (1999) Responses of riparian cottonwoods to alluvial water table declines. Environ Manage 23:347–358

Shafroth PB, Friedman JM, Ischinger LS (1995) Effects of salinity on establishment of *Populus fremontii* (cottonwood) and *Tamarix ramosissima* (saltcedar) in southwestern United-States. Great Basin Nat 55:58–65

Shafroth PB, Stromberg JC, Patten DT (2000) Woody riparian vegetation responses to different alluvial water table regimes. West North Am Nat 60:66–76

Shepard WD (1993) Desert Springs—both rare and endangered. Aquat Conserv Mar Freshwat Ecosyst 3:351–359

Sorenson SK, Dileanis PD, Branson FA (1991) Soil water and vegetation responses to precipitation and changes in depth to

groundwater in Owens Valley, California. USGS Water-Supply Paper 2370-G. U.S. Geological Survey, Reston, VA
Stromberg JC, Tress JA, Wilkens SD, Clark SD (1992) Response of velvet mesquite to groundwater decline. J Arid Environ 23:45–58
Stromberg JC, Tiller R, Richter B (1996) Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecol Appl 6:113–131
Stromberg JC, Lite SJ, Rychener TJ, Levick LR, Dixon MD, Watts JM (2006) Status of the riparian ecosystem in the Upper San Pedro River, Arizona: application of an assessment model. Environ Monitor Assess 115:145–173
Thomas JM, Welch AH, Dettinger MD (1996) Geochemistry and isotopic hydrology of representative aquifers in the Great Basin region of Nevada, Utah and adjacent states. U.S. Geological Survey, Reston, VA
Tiner RW (2003) Geographically isolated wetlands of the United States. Wetlands 23:494–516
Tumbusch ML, Plume RW (2006) Hydrogeologic framework and groundwater in basin-fill deposits in the Diamond Valley flow system, central Nevada. U.S. Geological Survey Scientific Investigations Report 2006–5249. U.S. Geological Survey, Reston, VA
USFWS (1997) National list of vascular plant species that occur in wetlands: 1996 national summary. Ecology section, National Wetlands Inventory. U.S. Fish and Wildlife Service
USGS (1997) Groundwater atlas of the United States—segment 1 California Nevada. U.S. Geological Survey, Reston, VA
Weber DJ, Hanks J (2006) Salt tolerant plants from the Great Basin region of the United States. In: Khan MA, Weber DJ (eds). Ecophysiology of high salinity tolerant plants. Springer, Dordrecht, Netherlands. pp 69–106
Winograd IJ, Friedman I (1972) Deuterium as a tracer of groundwater flow, southern Great Basin, Nevada and California. Geol Soc Am Bull 83:3691–3708
Winter TC (1988) A conceptual-framework for assessing cumulative impacts on the hydrology of nontidal wetlands. Environ Manage 12:605–620