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Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States

S. Zektser · H. A. Loáiciga · J. T. Wolf

Abstract The southwestern United States—this paper's study region—is home to large urban centers and features a thriving agro-industrial economic sector. This region is also one of the driest in North America, with highly variable seasonal and inter-annual precipitation regimes and frequent droughts. The combination of a large demand for usable water and semi-arid climate has led to groundwater overdraft in many important aquifers of the region. Groundwater overdraft develops when long-term groundwater extraction exceeds aquifer recharge, producing declining trends in aquifer storage and hydraulic head. In conjunction with overdraft, declines in surface-water levels and streamflow, reduction or elimination of vegetation, land subsidence, and seawater intrusion are well documented in many aquifers of the southwestern United States. This work reviews case studies of groundwater overdraft in this region, focusing on its causes, consequences, and remedial methods applied to counter it.

Keywords Groundwater overdraft · Aquifer-stream interactions · Baseflow · Land subsidence

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Introduction

Groundwater is an important water-supply source worldwide. This is in part due to groundwater's widespread distribution and inherent properties that render it attractive. Groundwater, generally, contains micro and macro constituents essential for human health, it does not require expensive treatment, and it is relatively well protected from contamination. These factors account for a substantial increase in groundwater use in many countries since the beginning of the 20th century. Currently, groundwater is one of the main water sources in Austria, Belgium, Hungary, Germany, Denmark, Rumania, Switzerland, and the former Yugoslavia, where it accounts for more than 70% of the freshwater use (Zektser 2000). Most municipalities in Lithuania, Latvia, Estonia, Ukraine, Belorussia, Tadzhikistan, Armenia, and Georgia use groundwater. Groundwater meets 75% of the municipal water use, thus providing drinking water for more than one half of the USA's population (Zektser 2000). Groundwater use by municipalities worldwide has more than tripled since 1970, and it plays a substantial role in the water supply of China, India, Libya, Saudi Arabia, Tunisia, Yemen, and other Asian and African countries. Large-scale groundwater extraction may cause adverse environmental impacts on riverine ecosystems as described in Loáiciga and others (2000) because of groundwater's close linkages to biogeochemical cycles and ecological processes (Loáiciga 2003a, 2003b). Decreases in river runoff or spring flow, land subsidence, reduction or elimination of vegetation due to the lowering of water tables, and alteration of karst processes are common negative impacts brought about by intense groundwater extraction. Also, groundwater withdrawal may trigger the upwelling and inflow of highly mineralized, deep, groundwater into freshwater aquifers, and induce seawater intrusion into coastal areas. Considerable groundwater level rise caused by human action may result in flooding of civil infrastructure. Furthermore, changes in other

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environmental variables—precipitation, river runoff, for example—inevitably affect groundwater and its quality, closing a complex cycle of feedbacks posed by groundwater extraction and environmental change (Alley and others 2002; Loáiciga 2003c).

The formulation of principles guiding the rational use of groundwater and the prediction of the possible effects of groundwater withdrawal on the environment is a central objective of modern geoecological science (Loáiciga 2003a). It should be noted that methodology for studying groundwater-environment interactions, particularly under changing climatic conditions and population growth, is still in a developmental stage.

This article focuses on several of the most significant environmental impacts associated with large-scale groundwater extraction in aquifers of the southwestern United States, and on methods used to alleviate such impacts. Specifically, four impacts of groundwater extraction are considered in this article: streamflow reduction and decline of lake levels, reduction or elimination of vegetation, land subsidence, and seawater intrusion into coastal aquifers. The southwestern United States constitutes an excellent showcase for the study of groundwater-environmental feedbacks because of its (1) semi-arid and highly variable precipitation regime, (2) rapid population growth and expanding demand for potable and irrigation water; (3) diverse and vulnerable ecosystems intimately dependent on aquifer functioning, and (4) active monitoring and reporting of groundwater-environmental phenomena by governmental and private organizations. Figure 1 contains a generalized location map showing Arizona, California, New Mexico, and Texas. Case studies from these states are reviewed below.

Groundwater extraction and its impact on rivers and lakes

The Rio Grande and the aquifer in the City of Albuquerque, New Mexico

The Rio Grande runs north–south through the State of New Mexico in its long journey from its headwaters in the State Colorado to the Gulf of Mexico. Its streamflow is apportioned among the states of Colorado, New Mexico, and Texas by interstate compact, and between the United States and Mexico by international treaty. The streamflow is apportioned to meet specified target quantities in the twin cities of El Paso and Ciudad Juarez, on the Mexico–USA border.

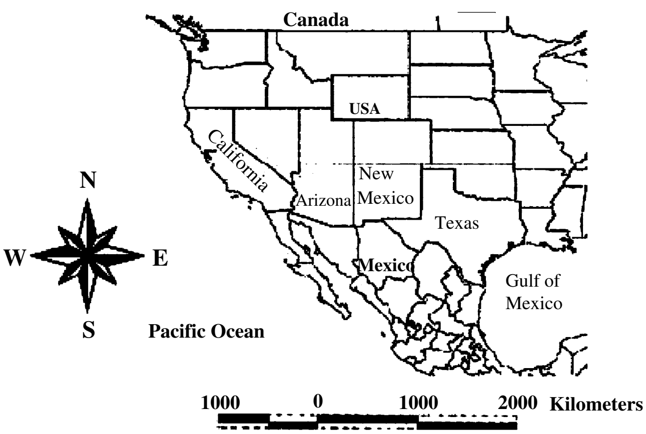

Fig. 1
General location map of the southwestern states (Arizona, California, New Mexico, and Texas)

The Rio Grande traverses the City of Albuquerque and its underlying aquifer, which is pumped for municipal water supply. This aquifer is hydraulically connected to the Rio Grande, so that extracted groundwater reduces the river's streamflow even though the Rio Grande's streamflow is allocated in its totality. Furthermore, surface water rights in the Rio Grande are older than groundwater ones. For this reason, the former are senior to those of groundwater wells that deplete the river's streamflow. The preeminence of older water rights is consistent with New Mexico's doctrine of prior appropriation, under which—and subject to the beneficial use of water—first in time means first in (water) rights (DuMars and Minier 2004; Getches 1990). Groundwater extraction by the City of Albuquerque, therefore, created legal conflict because it diminished the Rio Grande's streamflow.

The State of New Mexico granted the City of Albuquerque conditional permits to extract groundwater. The permits obliged the city to reduce its Rio Grande surface-water consumption by an amount equal to the streamflow depletion caused by its permitted groundwater wells. Upon challenge by the City of Albuquerque, the New Mexico's Supreme Court affirmed the conditional permits in a landmark 1963 ruling that introduced a principle of conjunctive groundwater and surface-water management that was the first of its kind in the United States. According to this principle, the State of New Mexico limits new groundwater extractions to the amount of permitted surface-water rights held by the grantee, plus the amount of water the grantee returns directly to the river impacted by the groundwater extractions.

The Rio Grande's streamflow depletion by groundwater extraction in Albuquerque is of particular interest because of its role as a trendsetter in the realm of legal doctrines for conjunctive river-aquifer management. The associated technical discoveries associated with river-aquifer interactions in Albuquerque, in particular, and other parts of New Mexico, in general, are significant, also. For example the State of New Mexico has relied on the Glover-Balmer (1954) formula to estimate stream depletion by wells (see also, Sophocleous and others 1995). More recently, it has relied on numerical groundwater models to refine estimates of stream depletion. For example, a model by Kernodle and others (1995) predicted that by year 2020 between 44 to 63% of the groundwater extracted in the Albuquerque region will be streamflow depleted from the Rio Grande. At present, numerical models continue to be improved as new, more accurate, hydrogeological data are collected and interpreted. The models, whether empirical or numerical, are tools used to assist in granting new groundwater permits. The latter are governed by guidelines aimed at preventing depletion of the fully appropriated Rio Grande.

The San Marcos and Comal Springs, Texas

The San Marcos Springs, near the City of San Marcos, and the Comal Springs, near New Braunfels, Texas, are on the periphery of the Edwards Aquifer's discharge zone. The Edwards is the most productive aquifer in the southwestern United States. It provides water to New Braunfels, San Antonio, and San Marcos, to cite a few of the largest served cities, and supplies several irrigation districts and other groundwater users in a region encompassing about 16,000 km^2. Its karstic hydrogeology and the nature of its recharge-discharge dynamics have been described in Loáiciga and others (2000). The San Marcos Springs and Comal Springs sustain perennial streams and valuable aquatic ecosystems (Longley 1981). Ever-rising groundwater extraction in the Edwards Aquifer since the early 1900 s has, however, diminished spring flow and threatened dependent ecosystems. Springflow reduction has been particularly accentuated by recurrent droughts and increased groundwater extraction during drought. Rare, endemic, species that include plants (the Texas wild rice, *Zizania texana*), fish (the San Marcos gambusia, *Gambusia georgei*), and karst-dwellers (the Texas blind salamander, *Typhlomolge rathbuni*), among others, have seen their populations decline and become threatened with extinction (United States Fish and Wildlife Service 1996). Groundwater extraction has lowered water tables, negatively impacting habitat for invertebrate species endemic to the Edwards Aquifer's karstic formations and affecting processes of landscape change in the aquifer's region.
Figure 2 shows a time series of annual total spring flow (Comal Spring plus San Marcos Springs, plus other tributary spring flow emanating from the Edwards Aquifer) and annual groundwater extraction (pumping), both in 10^9 m^3/year, in the Edwards Aquifer from 1934 through 1995. It is seen in Fig. 2 that pumping exhibits a long-term increasing trend, explained by expanding urban and agricultural groundwater use. In the late 1980s and early 1990s groundwater pumping was curtailed occasionally by court orders issued to protect aquatic ecosystems threatened by reduced spring flow. The spring flow time series in Fig. 2 fluctuates wildly, a reflection of the highly variable nature of aquifer recharge. The latter has extreme inter-annual variability, which is compounded by drought, usually in association with the El Niño anomaly. In spite of the Edwards Aquifer's capacity to replenish itself during wet years, the combined incidence of protracted, multiyear, drought and accelerated pumping during dry periods (a situation that prevailed through most of the 1950s) has taken a toll on dependent aquatic ecosystems.
There has been a plethora of activity since the early1990s, in the legal realm as well as in the field, in search of solutions to the water supply and associated environmental impacts in the Edwards Aquifer region. Yet, the impetus to keep mining the high-quality and abundant Edwards Aquifer's groundwater is enormous. Alternative water supplies (such as surface-water reservoirs) are much more costly than the Edwards' groundwater. Water conservation is a viable option and inroads have been made in this respect. The latter, however, entails changes in the traditional patterns of water use, which are not always rapidly assimilated by the public. In view of these realities, the viability of threatened aquatic ecosystems in the Edwards Aquifer remains uncertain.

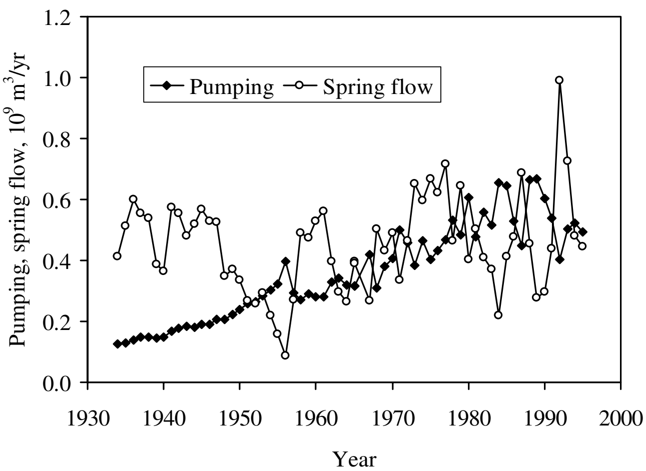

Fig. 2
Spring flow and groundwater pumping in the Edwards Aquifer, Texas (adapted from Loáiciga and others 2000)

Lake Merced, San Francisco, California

A common impact of groundwater extraction is the depletion of lake storage. This occurs when there is hydraulic connection between an aquifer subjected to groundwater overdraft and a lake. In this instance, several factors contribute to the decline in a lake's water level. These include the nature of the lake-aquifer interaction, the seasonal and long-term variations in precipitation, the mechanisms of aquifer recharge and how they are affected by aquifer overdraft, and the rate of groundwater extraction in wells adjacent to a lake or stream (Zektser 2000). Lake Merced, in San Francisco, California, is an interesting case involving deleterious impacts of human activities—including groundwater extraction—on storage depletion. Lake Merced's most important hydraulic connection is to the Westside Basin Aquifer. Evidence suggests that the height of the water table in the aquifer and the lake's water level are interdependent. Beginning in the second half of the 19th century, major modifications were made to Lake Merced. These modifications included the construction of two dams, several flumes and buildings, and the installation of pumps and pipelines. The use of the lake as a water source grew steadily through the first half of the 20th century. Eventually, however, alternative municipal water supplies were developed, and Lake Merced's role as a municipal water source ceased. Groundwater extraction, in particular, became a primary source for local golf courses, parks, and cemeteries. The regional water table dropped from 3 m above sea level in 1949 to 43 m below sea level in 1990 (Louie 2001). Lake Merced has lost half of its volume since 1989 and the environmental impacts of the lake's declining water level have been significant. The decline in Lake Merced's water level is a continuing source of scientific, legal and political contention. Action has been taken by conservation groups, who have filed an administrative petition with the State of California and several other local governmental agencies, asking that the lake's level be restored and maintained to at least 5.5 m above mean sea level, or 2.7 m above its current elevation. The San Francisco Water Department and California's Public Utilities Commission have called for a similar water-level restoration to provide a ten-day emergency water supply for the City of San Francisco (Stienstra 2001).

The main causes of Lake Merced's level decline are groundwater pumping and urbanization. The latter contributes mostly in the form of diversion of storm runoff. The vast majority of storm runoff is diverted to the city's combined sewer and storm water system, thus bypassing the aquifer without recharging it. As for the former, groundwater pumping, there is heated debate over its effect on the lake, a debate compounded by a complex hydrogeologic setting of the aquifer-lake system. Local golf courses, parks and cemeteries are major consumers of the aquifer's groundwater. Yet, representatives for several of the golf courses that extract groundwater from the Westside Basin Aquifer theorize that pumping is a minor contributor to Lake Merced's volumetric reduction when compared with drainage of storm water (Stienstra 2001). Evidently, a carefully monitored water-balance analysis of the lake-aquifer system is called for in this instance to better estimate the relative contributions of urbanization and groundwater extraction to Lake Merced's declining water level.

There are social and ecological ramifications to Lake Merced's receding volume. Regarding the social arena, the lake has lost much of its original aesthetical and recreational appeal. Fishing piers no longer reach the receding lake surface. In the ecological realm, the lake's trout population is in steady decline. While Lake Merced was once a major urban fishery, the trout's survival is now precarious. As for the fish that are caught, the low water level has led to high algal counts in parts of the lake, and this has contributed to a foul taste in these fish (Stienstra 2001).

Progress has been slow up to this point insofar as remedial action is concerned. There is consensus by the parties involved that storm water must be rerouted into Lake Merced. This measure, however, does not address the issue of groundwater extraction, and it may affect the quality of the lake's water. Conservation groups have requested that limits be set on groundwater pumping. Representatives of the golf courses, parks, and cemeteries in the area are reticent to reduce their groundwater extraction, however, which they consider to be a negligible contributor to the dewatering of Lake Merced (Stienstra 2001). To shed light onto this issue, a groundwater model was developed and implemented to simulate the local aquifer. Model simulations suggest that Lake Merced's level would increase 1.5 m if pumping were stopped (Brown and others 1997). These results suggest that a decrease in the rate of extraction would likely contribute to the partial restoration of the lake's storage.

Another restoration option for Lake Merced is to develop water supplies besides groundwater. One possibility is the reuse of treated municipal sewage to irrigate golf courses and parks. This would not raise public opposition because it is a well-accepted practice in California. There is, however, a significant financial hurdle. The cost of a sewage recycling plant is estimated to on the order of $ 4 million, not including the cost of installing a distribution system (Louie 2001). The search for solutions to restore the Lake Merced ecosystem continues as of this writing. The role that groundwater extraction might play in any restoration agreement remains uncertain given the vested interests governing its disposition.

Redwook Creek, California

The effect of groundwater extraction on streams is well exemplified by Redwood Creek, in northern California, whose streamflow has been significantly impaired, particularly during droughts. Intermittent spells of dry climate and groundwater extraction in the creek's tributary region have, at times, all but dried up the stream channel. The most significant impact of streamflow reduction has been on fish (salmonoid) populations. During the drought of 1988–1991, the length of stream habitat containing water decreased to about 23% of its historical average length. Streamflow depletion, shallow water, increased water temperature and reduced dissolved oxygen have threatened the native steelhead trout (*Oncorhynchus mykiss*) in Redwood Creek. For reference, the steelhead population had plummeted 89% below its historical level in 1994, following the drought of 1988–1991 and the concomitant surge in groundwater extraction (Smith 1994).

One obvious remedial action in Redwook Creek is the development of alternative water sources to alleviate groundwater extraction and maintain continuous and adequate streamflow during drought years. Another option is the introduction of hatchery-reared fish to revitalize the population (Smith 1994), although this might have undesirable and unforeseen effects on the genetic stock of the native salmonoid population, something that deserves further study before its implementation.

Groundwater extraction can sometimes increase streamflow. This situation may occur when groundwater originating in deep aquifers isolated from surface waters is used and discharged into stream channels (Zektser 2000). In this instance, the concern surrounding streamflow modification arises from potential changes in stream biochemistry and temperature, and from other potential negative impacts associated with modification of stream velocity, flooding of the riparian zone, and alteration of the water balance in water bodies receiving the streamflow.

Cosumnes River, California

When groundwater is extracted from an aquifer that is hydraulically connected to a stream, the effect on streamflow can be naturally alleviated if the stream is influent (that is, if it recharges the surrounding aquifer) during part of the year. This is the case in the Cosumnes River, which lies in the vicinity of the City of Sacramento, California. Although this region has experienced a drop in the water table to an elevation well below the river's thalweg, streamflow remains relatively abundant during the winter (wet) months (December through March). This is because the Cosumnes River is influent during this season, and, thus, the impact of groundwater extraction on streamflow is lessened. However, the stream is effluent (i.e., it receives baseflow from the underlying aquifer) during the dry season (June through October), and streamflow reduction and continuity are concerns regarding the fish populations of the Cosumnes River (Fleckenstein and others 2001).

Compared to the American River to the north and the Mokelumne River to the south, the Cosumnes River is relatively small, carrying an average annual volume of approximately 450 million m^3. Large-scale groundwater extraction by farmers along the banks of the Cosumnes River has caused the water table to decline to an elevation 17 m below its stream channel, thus depriving the river from baseflow nourishment during the dry season. At present, between 8 and 16 km of the Cosumnes River dry up towards the end of California's dry season (Glennon 2002). Such reduction of streamflow threatens the survival of the Chinook salmon (*Oncorhynchus tshawytscha*) that once thrived in this river. Historically, two to three million Chinook salmon per year spawned in the rivers of California's Central Valley (where the drainage basin of the Cosumnes River lies). Currently, that number is about 200,000. This decline is the result of groundwater extraction that has lengthened the period during which rivers in this region feature very low or negligible flow. While the onset of the wet season (in October) used to immediately produce runoff to the dry section of the Cosumnes River, storm runoff is now absorbed by the soil during a much longer period before saturation occurs. Consequently, Chinook salmon encounter insufficient streamflow as they start to migrate from the ocean through the river in an upstream direction in search of their natural spawning grounds in early autumn, even though the species only requires 18 cm of water to proceed up river (Glennon 2002).

Restoration is in progress for the Cosumnes River. A plan is in place to divert water from the American River and discharge it into the Cosumnes. In regards to conservation, a groundwater model developed at the University of California, Davis, suggests that an annual reduction in groundwater pumping of 234 million m^3 would be necessary to restore adequate flow to the river. Conservation of this magnitude is unlikely. On the contrary, future water demand in the region is expected to increase dramatically. The population in the Cosumnes River region, currently around five million inhabitants, is expected to double within the next twenty years as San Francisco Bay Area residents move into this region in search of affordable housing. Municipal groundwater overdraft in several nearby, fast-growing, cities has already created two major cones of depression encompassing the groundwater that is hydraulically connected to the Cosumnes River (Glennon 2002).

From an economic viewpoint, the industries most affected by streamflow reduction in the Cosumnes River are tourism and fishing. These have found allies among environmentally minded interest groups and citizens seeking to protect stream habitats in central California. Yet, restoration of the natural streamflow regime and salmon population in the Cosumnes River is still in its infancy.

Groundwater extraction and vegetation

Vegetation in semi-arid lands can be severely affected by the lowering of the water table, a phenomenon commonly caused by sustained drought and groundwater overdraft. This is particularly pertinent to phreatophytes, that is, plants that rely on groundwater for their subsistence. The depth to which a plant's roots extend is generally less than 5 m (Zektser 2000). Therefore, long-term decline of the water table can be acutely detrimental to vegetation. Two examples of groundwater extraction impacts on vegetation follow.

Sonoran Desert Aquifers, Arizona

Chronic groundwater overdraft has been occurring since 1923 in the Pleistocene aquifers of the Sonoran Desert (which encompasses part of the southwestern USA and north-central Mexico). Groundwater serves a variety of purposes in this region, including municipal and agricultural uses, and landscape irrigation (primarily large golf courses). Almost all of the river valleys in Arizona's portion of the desert have been affected by a combination of groundwater pumping and water diversions. In the states which encompass the Sonoran Desert (parts of California, Arizona, New Mexico), groundwater levels have been declining at annual rates ranging between 0.3 and 3 m. As water tables drop, mesquite woodlands and riparian forests have retreated or died. "Desertification" of these forests and woodlands is a significant concern. Aquifer dewatering is exacerbated by ground fissuring caused by differential land subsidence(see section on land subsidence below), which is suspected of modifying runoff patterns that alter aquifer recharge and, ultimately, affect plant communities that rely on groundwater for their subsistence (Nabhan and Holdsworth 1998).

The goal of pertinent authorities in this affected region is to achieve groundwater extraction at the safe-yield level by 2025. Safe yield is that level of groundwater extraction that does not produce long-term reduction of groundwater storage relative to a level considered adequate from hydrogeologic and ecological viewpoints. Groundwater demand in this region, however, is expected to increase in the foreseeable future, and alternative water sources are scarce. There is hope that urban sprawl will reduce consumption as housing developments replace irrigated farmland, but there is no guarantee that the conversion to urban use will decrease overdraft in the long term. Most plans to reduce overdraft by way of an alternative water source involve diversions from the Colorado River. Yet, Colorado River diversions are already substantial, to the point that more than 100% of its average annual streamflow is legally appropriated among seven American states and Mexico. Therefore, it is unrealistic to count on it for greater future use (Nabhan and Holdsworth 1998).

The Owens River Valley, Inyo County, California

A well-publicized example of groundwater overdraft affecting the regional environment in general, and vegetation, in particular, is the Owens River Valley, in Inyo County, California (Reisner 1987; Stamon and others 2001). The Owens Valley is an inter-montane syncline east of the Sierra Nevada Mountains of California. Its climate is cool, due to its high elevation, and dry, due to the Sierra Nevada' rain shadow effect on the region. The Owens Valley receives an average annual precipitation of 14 cm, rendering its climate semi-arid with a moisture deficit during the dry season (May-September), when potential evapotranspiration exceeds natural moisture supply. The City of Los Angeles has been importing water from the Owens River Valley since 1913. This water was obtained by damming the Owens River and conveying its water to Los Angeles, actions that dried up Owens Lake, a natural water body formed in the closed basin that captures Owens River streamflow. In 1970, a second aqueduct was built by the City of Los Angeles to convey increased groundwater production from the Owens Valley. Groundwater extraction has lowered the water table and reduced water supply to native grasses, riparian habitats, and wetlands, adversely impacting habitat for migratory birds. Surface-water diversions from the Owens Rivers and the reduction of its streamflow by groundwater extraction have led to the drying of Owens Lake. Groundwater extraction in the Owens Valley has greatly reduced phreatophytic shrubs and grasses that depend heavily on subsurface water (Davis and others 1998).

Although it might seem that the health of wetlands, riparian habitats, and native grasses in the remote Owens Valley would be of concern primarily to conservationists, there is an industry at stake as well (Sanderson 2000). Tourism is the major industry in the Owens Valley. Therefore, environmental degradation stemming from the mining of its surface and groundwater resources could inflict a substantial economic loss to the local economy. In addition, vegetation reduction in the Owens Valley has created health hazards. As plants roots have died, the soil's erodibility has increased. Following the regional reduction of vegetation and the drying of Owens Lake, frequent gusty winds in the Owens Valley have been found to cause high concentrations of dust and particulate matter in air, which reduce visibility and increase human exposure to air pollutants. The communities of Ridgecrest and China Lake, located downwind from the now dry Owens Lake, have been particularly hard hit by the worsening air pollution. Environmental and economic worries have led to protracted legal battles involving Inyo County, the City of Los Angeles, and the State of California. Slow but meaningful progress is being made towards preventing further environmental degradation in the Owens Valley by groundwater extraction and surface-water diversions. This includes the setting of minimum allowable levels for the water table at selected locations, and restricting surface-water diversions so that Owens Lake begins to regain some of its lost volume. The long-term effects of these prevention and restoration efforts on the water resources and vegetation of the Owens Lake remain uncertain, although initial signs of recovery are encouraging.

Groundwater extraction and land subsidence

Land-surface subsidence is a well-known phenomenon associated with groundwater extraction (Domenico and Schwartz 1997). Subsidence occurs when the hydraulic head in an aquifer declines, thus reducing pore pressure and draining the pore space in an aquifer. With pore pressure reduced and pore water drained, the aquifer's mineral matrix takes a greater share of, or all, the geostatic stress. The effective stress on the aquifer's (rock) matrix increases and causes subsidence, or lowering of the ground surface. Subsidence results from reduction of the matrix's volume by mechanical compression and from pore-space reduction. Coarse-textured sediments, such as pebbles, gravel, and sands undergo relatively lower rates of compression and pore-space reduction (or consolidation) than fine-textured sediments (silts, clays), other things equal. Yet, subsidence of coarse-coarse textured aquifers is reversible and can be largely undone through artificial recharge. The latter is accomplished by injecting water into an aquifer to re-establish pore pressure in the aquifer. Subsidence in fine-textured aquifers, on the other hand, is usually inelastic (or plastic), and, therefore, irreversible partially or in its totality, so that original ground levels cannot be restored (Zektser 2000). In this second instance subsidence compounds itself by the fact that pore-space reduction decreases hydraulic conductivity, which reduces the rate of recharge to the aquifer in question inflicting a potentially permanent diminution in storage capacity (Chen and others 2002). Several examples of land subsidence caused by groundwater extraction follow.

The San Joaquin Valley, California

Land subsidence is a process that may take place over a wide range of temporal scales, from almost instantaneous ground settlement to very slow rates of ground-level drop that become appreciable over decadal time scales. Yet, impacts associated with subsidence can be substantial in either case. Those include flooding of sunken land and damage to civil infrastructure (Zektser 2000). In the San Joaquin Valley, California, land-subsidence rates are some of the largest recorded. Subsidence reached 9 m in some areas of the San Joaquin Valley by 1970 after nearly half a century of groundwater extraction (Bertoldi and others 1991). About 1.5 million ha of land are under irrigation in the San Joaquin Valley, and half of this area has experienced subsidence (Zektser 2000). The remedy implemented to cope with subsidence is to extract less groundwater from the valley's aquifer. To counter the loss of groundwater, surface waters are diverted from the delta of the Sacramento and San Joaquin rivers, and from the

San Joaquin, Kings, Kern, and Feather rivers for irrigation. This remedy is precarious, however, because of the high streamflow variability and frequent droughts in California (Bertoldi and others 1991).

The environmental risks posed by groundwater extraction and the vagaries of the regional climate have led to ingenious approaches for conjunctive surface water-groundwater management. The most widely used one is called groundwater banking, a scheme whereby carefully calculated amounts of streamflow are diverted during wet years and recharged in vast alluvial aquifers. The recharged groundwater is kept underground, with minimal losses, and extracted and used during dry periods.

Subsidence in the Gulf Coast, Texas

In the Texas Gulf Coast area, 244,900 ha of land have subsided an average 30 cm since 1943. Most of the subsidence has occurred near Galveston Bay. Subsidence-related problems in Galveston Bay have been temporary flooding, permanent inundation, volumetric expansion of saturated clayey sediments, and structural damage. The estimated cost and property value losses were $32 million annually by 1975 (Jones and Larson 1975). Also, according to the Galveston Bay National Estuary Program, there has been a net loss of 9960 ha of estuarine bay marshes due to subsidence followed by regional landward advance of the ocean.

Cities of San Francisco and Los Angeles, California

Land subsidence caused by groundwater extraction has been as large as 2.4 m in the environs of the San Francisco Bay, which necessitated the construction of levies to avoid landward influx of seawater. Ground-level subsidence in reclaimed lands neighboring the San Francisco Bay has also been caused by the removal of native vegetation. This has exposed organic soils to accelerated conversion of their carbon-rich matrix to gas by aerobic and anaerobic decay processes, thus causing a loss of soil mass, and, with it, a drop in ground level.

In the vicinity of the City of Los Angeles, land subsidence occurred at an annual rate of 0.7 m over several decades. The subsidence was caused by oil and gas extraction and by groundwater pumping (Zektser 2000).

Land subsidence in Arizona

Subsidence was first detected in the lower Santa Cruz basin, Arizona, in 1948, where it reached 4.5 m by 1985. Large-scale groundwater extraction has lowered the water table by as much as 150 m in various parts of Arizona. Two such areas are southwest of Casa Grande near Stanfield, and south of Chandler near Chandler Heights. Subsidence has affected an estimated 808,000 ha in Arizona (Gelt 1992).

Differential subsidence and fissuring

Another concern regarding land subsidence is ground fissuring. Measured fissure length ranges from tens of meters to over 10 km, with depth and width reaching hundreds of meters and up to 3 m in some cases, respectively. In the Sonoran Desert, for example, 1 m of land subsidence has caused 1-km long fissures (Nabhan and Holdsworth 1998). Fissures are produced by differential settlement in subsiding lands. Fissures can adversely affect overland runoff, aquifer recharge, and cause structural damage. Irrigation ditches and canals might be broken as land settles, leveled fields can become unleveled, and groundwater wells may collapse in subsiding aquifers (Gelt 1992). Evidently, land subsidence can inflict considerable structural and economic losses. Severe damage to civil infrastructure, public and private, has been documented throughout the western United States.

Mitigation of land subsidence in Houston, Texas

Land subsidence in parts of Houston, Texas, had reached 4 m by 1975, causing the flooding of coastal lands by seawater. Since 1976, however, State authorities have implemented measures to limit groundwater extraction in vulnerable regions and to mitigate land subsidence by means of artificial recharge. These measures reversed subsidence considerably. The success in Houston is largely due to State-sponsored, long-term, monitoring and research of land subsidence, and to the implementation of well-thought out control and abatement measures (Zektser 2000).

Groundwater extraction and seawater intrusion

Seawater intrusion occurs in coastal aquifers subjected to groundwater extraction. The latter lowers the hydraulic head in coastal aquifers and triggers inland migration of saline water. This invariably leads to difficult-to-reverse contamination of freshwater aquifers. Two of the most notable cases in California involve coastal aquifers in Los Angeles and Monterey counties.

Los Angeles County, California

One third of the water used by coastal cities in Los Angeles County—whose population is close to 10 million—is groundwater. Not surprisingly, severe overdraft has been documented in the county's aquifers, where the hydraulic head has fallen below sea level at many locations. Saline intrusion into its coastal aquifers has occurred since the 1920s (Edwards and others 2002). The primary method used to control seawater intrusion in Los Angeles County has been the injection of freshwater along the coast to create hydraulic barriers. These hydraulic barriers are created by a series of injection wells strategically located to halt and push back plumes of advancing saline water. The barriers are not infallible, however, due to the complex hydrogeology of the coastal region, where sea waters intrude through unknown subterranean passages (Edwards and others 2002). Injection, in addition, is costly. Two of the three barriers created in Los Angeles County required the importation of nearly 7.4 million m^3 of water between 1996 and 1997. A third barrier, the West Coast Basin Barrier Project, imported over 13.6 million m^3 of water and used over 7 million m^3 of recycled water for injection purposes.

Another method used to control seawater intrusion into Los Angeles County's overdrafted aquifers is enhanced storm runoff recharge. The County has used water-conservation facilities that are adjacent to stream channels and in soft-bottom channels to permit storm runoff to infiltrate into underlying aquifers for later pumping. These facilities are located where soils are most permeable and hydraulically connected to the recharged aquifers. This approach is, in fact, one variant of groundwater banking, in this case used for aquifer restoration rather than water supply.

Monterey County, California

Seawater intrusion has occurred in coastal aquifers of Monterey County since the mid 20th century. There, State of California and County agencies have resorted to the reduction of groundwater overdraft to manage seawater intrusion. To this end, freshwater has been imported from northern California and local sewage has been treated and reused for crop irrigation. Approximately 4,900 ha of farm land in Monterey County are currently irrigated with recycled sewage. Recycled sewage, however, has not been trouble free. Specifically, growers have expressed concern over high levels of sodium, chloride, total dissolved solids (TDS), and sodium-adsorption ratio (SAR) in reused sewage. Upgrades were made to the sewage treatment plant; yet, many growers have expressed dissatisfaction with the quality of recycled sewage being used to irrigate crops. An analysis of the recycled sewage conducted by researchers of the University of California at Davis found that soil permeability has not been negatively impacted. On the other hand, the yield and quality of sensitive crops, such as strawberries, may be have been reduced by the sodium and chloride concentrations in recycled sewage.

Another finding regarding the use of recycled sewage is that the presence of nitrogen and phosphorous in it has raised the yields of other—nonsensitive—crops. Among those are celery, broccoli, and cauliflower, whose yields grew by as much as twenty percent (Lieberman 2003). In addition to these conflicting results associated with the use of recycled sewage for irrigation, other issues have arisen. First, recycled water is relatively expensive, costing about \$0.22/m^3 while the cost of groundwater extraction and application is about \$0.06/m^3 (Lieberman 2003). Secondly, negative public perception towards crops irrigated with recycled sewage is difficult to overcome. This is a disincentive to the use of recycled sewage on the part of growers. On the other hand, they are not required to inform the public about the use of recycled water in food labels. With the specter of widespread saline contamination of Monterey County's coastal aquifers looming in the background, irrigation with recycled sewage remains an attractive alternative to large-scale groundwater extraction.

The seawater intrusion phenomenon has been well researched, and the methods of its containment and abatement have been in practice in California for several decades. It is still a pressing problem, however, hence the continuing studies and control measures being conducted by regional, State, and federal agencies throughout California. The high level of concern stems from the fact that seawater intrusion affects vital freshwater resources and the environment, and, with them, California's profitable agricultural sector.

Discussion and conclusion

This article has presented an overview of environmental impacts of large-scale groundwater extraction and associated overdraft. Case studies from various regions of the southwestern United States illustrated key principles governing cause-effect relationships of intense groundwater withdrawal.

This survey focused on four major impacts associated with groundwater extraction and overdraft:

- Reduction of streamflow and lake levels
- Reduction or elimination of vegetation
- Land subsidence
- Seawater intrusion

It was shown in this work that the listed impact categories share several commonalities, besides the well-established role of the hydrogeologic setting on groundwater dynamics and quality. Those are:

- The paramount role of the seasonal and inter-annual precipitation variability, and, in particular, of drought incidence
- The importance of the social context in which groundwater extraction takes place. Specifically, (1) population expansion, (2) economic activity, specially agricultural production, and (3) the extent of civil infrastructure vulnerable to groundwater extraction;
- The complexity of groundwater-environmental relationships and feedbacks, which makes it dicult to foresee the extent of probable negative effects of large-scale and long-term groundwater extraction.

Much has been learned about groundwater extraction-environmental feedbacks from long-term groundwater extraction in the southwestern United States. This has given impetus to the enactment of environmental regulations and to the evolution of groundwater rights and management in this region. This survey of large-scale groundwater extraction and of its key environmental impacts contributes to a growing body of evidence on the complexity of groundwater-environment interactions. It is another call for pursuing the search of sustainable ways to use the groundwater resource.

References

Alley WM, Healy RW, LaBaugh JW, Reilly TE (2002) Flow and storage in groundwater systems. Science 295:1985–1990

Bertoldi GL, Johnston RH, Evenson KD (1991) Groundwater in the Central Valley, California, a summary report. U.S. Geological Survey Professional Paper 1401A. U.S. Geological Survey, Sacramento, California http://water.usgs.gov/pubs/circ/circ1182/pdf/06sanjoaquinvalley.pdf
Brown N, Pezzetti T, Carlson F, Dumas L (1997) San Francisco groundwater master plan technical memorandum TM-18. CH2MHill, San Francisco, California
Chen C, Pei S, Jiao JJ (2002) Land subsidence caused by groundwater exploitation in Suzhou City, China. Hydrogeol J 11:275–287
Davis FW, Stoms DM, Hollander DA, Thomas KA, Stine PA, Odion D, Borchert MI, Thorne, JH, Gray MV, Walker RE, Warner K, Graae J (1998) The California gap analysis project-final report. University of California, Santa Barbara, California http://www.biogeog.ucsb.edu/projects/gap/gap_rep.html
Domenico PA, Schwartz FW (1997) Physical and chemical hydrogeology. 2nd edn. Wiley, New York
DuMars CT, Minier JD (2004) The evolution of groundwater rights and groundwater management in New Mexico and the western United States. Hydrogeol J 12(1):40–51
Edwards BD, Evans KR (2002) Saltwater intrusion in Los Angeles area coastal aquifers: the marine connection. U.S. Geological Survey Fact Sheet 030–02, San Diego, California http://geopubs.wr.usgs.gov/fact-sheet/sf030–02/index.html
Fleckenstein J, Suzuki E, Fogg G (2001) Local and regional scale investigation of groundwater surface-water interaction in an over-grafted groundwater basin. Hydrologic Sciences Program, University of California, Davis, California
Gelt J (1992) Land subsidence, earth fissures, change Arizona's landscape. Arroyo 6(2):7–15
Getches DH (1990) Water Law, 2nd edn. West, St. Paul, Minnesota
Glennon R (2002) A matter of inches for salmon in peril on the Cosumnes. In: Water Follies:_Groundwater Pumping and the Fate of America's Fresh Waters. Island Press, New York
Glover RE, Balmer GG (1954) River depletion resulting from pumping near a well. Transactions of the American Geophysical Union, 35(3):468-470
Jones LL, Larson J (1975) Economic effects of land subsidence due to excessive groundwater withdrawal in the Texas Gulf Coast area. Technical Report No. 67, Texas Water Resources Institute, Texas A&M University, College Station, Texas
Kernodle JM, McAda DP, Thorn CR (1995) Simulation of groundwater flow in the Albuquerque-Belen Basin, New Mexico. U.S. Geological Survey Water-Resources Investigations Report 86–4194, Reston, Virginia
Lieberman L (2003) Recycled wastewater used to irrigate crops in California. In: The vegetable grower's news. Great American, Boston, Massachusetts
Loáiciga HA (2003a) Sustainable groundwater exploitation. Int Geol Rev 44(12):1115–1121
Loáiciga HA (2003b) Groundwater mining. In: Stewart BA, Howell, TA (eds) Encyclopedia of Water Sciences, Dekker, New York, pp 345–349
Loáiciga HA (2003c) Climate change and groundwater. Ann Assoc Am Geograph 93(1):30–41
Loáiciga HA, Maidment D, Valdes JB (2000) Climate-change impacts in a regional karst aquifer, Texas, USA. J Hydrol 227:173–194
Longley G (1981) The Edwards' aquifer: Earth's most diverse groundwater ecosystem. Int J Speleol 11:123–128
Louie C (2001) Salt water: a threat after a century of pumping. San Mateo County Times. March 18, 2, San Mateo, California
Nabhan PG, Holdsworth AR (1998) State of the Sonoran desert biome: uniqueness, biodiversity, threats and the adequacy of protection in the Sonoran bioregion. Wildlands Project. University of Arizona, Tucson, Arizona http://alic.arid.arizona.edu/sonoran/documents/nabhan/dbgroundwater.html
Reisner M (1987) Cadillac Desert: the American west and its disappearing water. Penguin, New York
Sanderson RE (2000) Draft Environmental Impact Report/Environmental Impact Statement, Lower Owens River Project, Inyo County, California. U.S. Environmental Protection Agency, San Francisco, California http://www.inyowater.org/Annual_-Reports/1998-1999/veg.htm
Smith JJ (1994) The effect of drought and pumping on steelhead and coho in Redwood Creek from July to October 1994. Department of Biological Sciences, San Jose State University, San Jose, California
Sophocleous M, Koussis A, Martin JL, Perkins SP (1995) Evaluation of simplified stream-aquifer depletion models for water rights administration. Groundwater 33:579–588
Stamon CL, Nishikawa T, Martin P (2001) Water supply in the Mojave River groundwater basin, 1931–99, and the benefits of artificial recharge. U.S. Geological Survey Water fact sheet 122–01, U.S. Geological Survey, San Diego, California http://water.usgs.gov/pubs/FS/fs-122–01
Stienstra T (2001) Lake Merced's troubled waters: action taken to stop overpumping at Lake. San Francisco Gate, 3–4, San Francisco, California http://www.lakemerced.org/press/stienstra/stienstra013001.html
U.S. Fish and Wildlife Service (1996) San Marcos and Comal Springs and associated ecosystems (revised) recovery plan. Ecological Services Station, U.S. Fish and Wildlife Service, Austin, Texas
Zektser IS (2000) Groundwater and the environment: applications for the global community. Lewis, Boca Raton, Florida