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REVIEW PAPER

The Water Table: The Shifting Foundation of Life on Land

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Abstract Hyperarid, arid, and semi-arid lands represent over a third of the Earth's land surface, and are home to over 38 % of the increasing world population. Freshwater is a limiting resource on these lands, and withdrawal of groundwater substantially exceeds recharge. Withdrawals of groundwater for expanding agricultural and domestic use severely limit water availability for groundwater dependent ecosystems. We examine here, with emphasis on quantitative data, case histories of groundwater withdrawals at widely differing scales, on three continents, that range from the impact of a few wells, to the outcomes of total appropriation of flow in a major river system. The case histories provide a glimpse of the immense challenge of replacing groundwater resources once they are severely depleted, and put into sharp focus the question whether the magnitude of the current and future human, economic, and environmental consequences and costs of present practices of groundwater exploitation are adequately recognized.

Keywords Aquifer · Environmental impacts · Forest dieback · Groundwater dependent ecosystems · Water table

INTRODUCTION

Surface water and ground water are two manifestations of a single integrated resource (Winter et al. 1998). Groundwater that is actively exchanged with the Earth's surface water is referred to as 'renewable', while that accumulated over time, and not readily replenished, as 'nonrenewable'. Water stored beneath the land surface makes up ~2.5 % of Earth's water and is the largest unfrozen stock of fresh water. Fresh water in rivers, lakes, and soil pores amounts to much less than 1 % (Shiklomanov 1993). Foster and Chilton (2003) termed groundwater "the subterranean source of civilization," noting that "Springs, the surface manifestation of underground water, have played a fundamental role in human settlement and social development." Now, the inexorable growth in human appropriation of groundwater is a worldwide cause of concern (Alley et al. 1999; Gleick and Palaniappan 2010).

Groundwater is stored in aquifers in the uppermost portion of the Earth's crust. It moves slowly through the aquifers to areas of discharge at rates that range from <1 m per year to 30 cm or so per day (Alley et al. 1999). Days or thousands of years may separate the entry of water into an aquifer and its discharge to a spring, wetland, stream, river, or the sea. Discharge of groundwater from an aquifer will occur when the head in the aquifer is higher than the elevation of the water surface in the recipient body of water. During snowmelt or rainfall events, surface runoff provides the dominant water supply to streams, while the regular contribution of aquifer discharge is important to stream base-flow throughout the year. Generally, 20 % or less of precipitation contributes to aquifer recharge, the balance is runoff and evapotranspiration. If the water level in a body of surface water is above the water table in the aquifer, the direction of flow reverses as the surface water infiltrates permeable strata and contributes to groundwater recharge (e.g., Winter 1976).

Neglect of interaction of groundwater and surface water in the management of water resources ultimately leads to disastrous consequences. When the rate of systematic withdrawals by pumping from an aquifer exceeds the rate of recharge, the resulting water table decline leads to the gradual cessation of spring and stream flow, drying of wetlands, decreases in river flow, and losses of vegetation. Diminishing the flow of a river, the construction of massive dams and reservoirs, decreasing frequency of flood events, and pumping groundwater along its course, will lead to water table declines for hundreds of kilometers downstream with severe impact on the ecology of riparian zones (e.g., Sophocleous 2010; Zheng et al. 2010).

Theis (1940) emphasized "All water discharged by wells is balanced by a loss of water somewhere." Continued neglect of this fact is recognized as the root of the worldwide problem of groundwater depletion: "… the aggregate impact of millions of individual pumping decisions, while highly conditioned by the hydrogeological status of the pumped aquifers, is evident in falling groundwater tables and declining water quality" (Food and Agriculture Organization 2003).

Scarcity of water is the defining characteristic of hyperarid, arid, and semi-arid lands, which represent ~40 % of the continental land surface, and are home to >38 % of the world population (Reynolds 2007; Reynolds et al. 2007). The ratio between mean annual precipitation and potential evapotranspiration ranges from <0.05 for hyperarid to <0.45 for semi-arid lands (Le Houérou 1996). In 2000, these lands accounted for 39 % of the global yearly groundwater abstraction, but only 2 % of the global yearly groundwater recharge (Wada et al. 2010). The ecosystems of arid lands are subject to frequent droughts, and if not impacted by exploitative uses, have the resilience and adaptations required for recovery (Dregne 1983).

The composition, establishment, and survival of native vegetation on such lands depend on groundwater, and the precise depth of the water table dictates the spatial distribution of particular plants (e.g., Meinzer 1927; Le Maitre et al. 1999). It is not unusual to pump water from depths of hundreds of meters for human domestic or agricultural uses, but modest declines in the water table, causing little impact on supplies for such uses, may have catastrophic impacts on ecosystems. Obviously, extreme groundwater depletion impacts humans as well.

Case studies of groundwater declines are invaluable in linking the past and current practices of groundwater use to their near-term and long-term outcomes. They also raise a fundamental question. Is the magnitude of the future ecological, and societal consequences of diverse present practices, economic policies, and laws, adequately appreciated? To address that question, we explore the outcomes of different degrees of groundwater depletion at different scales on arid lands through some prominent examples drawn from the past 100 years. We conclude with a brief assessment of the hydrologic implications of increasing, widespread forest dieback.

The case histories incorporate insights provided by older literature, as well as ongoing research to provide long-term perspectives on the environmental changes in the areas examined. To the best of our knowledge, such a detailed case history approach to a broad synthesis of groundwater depletion and its environmental impact has not been attempted previously. A recent review assessing desertification noted the lack of reference situations: "Desertification is a matter of knowing how things were or should have been, compared to how they are today" (Verón et al. 2006).

DEVIL'S HOLE, NEVADA

Devil's Hole, in Death Valley National Park in Nevada, is home to a small population of pupfish (*Cyprinodon diabolis*). This species of pupfish evolved after it was isolated from its ancestral stock, perhaps over 100 000 years ago (Andersen and Deacon 2001), and occurs nowhere else in the world. Devil's Hole consists of a 16-ha tract that includes a deep limestone cavern at the bottom of which lies a pool, ~20 m long, 3 m wide, and >60 m deep. This pool is part of an 11 650 km^2 groundwater system that is recharged very slowly under modern climate conditions. Groundwater travel time from the Spring Mountains recharge area to Devils Hole is on the of the order of 2000 years (Winograd et al. 2006). Steep rock walls enclose three sides of the pool, and the fourth side has a sloping rock shelf on which algae grow. The pupfish population depends for its survival on access to this rock shelf that provides food and a critical spawning ground. The water level in the pool is measured relative to a copper washer placed above the shelf in 1962. Between 1962 and 1968 the average water level was 0.36 m below the marker. The top of the sloping shelf lay at ~1.0 m below the marker.

The Cappaerts' large ranch surrounds Devil's Hole. In 1968, the Cappaerts drilled several wells within 5 km of the pool and began pumping. Soon thereafter, the water level in Devil's Hole began to decline. The U.S. federal government filed a lawsuit to limit the amount the Cappaerts could pump to protect the pupfish. The Cappaerts and the State of Nevada argued that surface water and groundwater should be treated as distinct. In a landmark ruling, the U.S. Supreme Court declared that "The federal water rights were being depleted because, as the evidence showed, the "groundwater and surface water are physically interrelated as integral parts of the hydrologic cycle… the Cappaerts are causing the water level in Devil's Hole to drop by their heavy pumping," and permanently enjoined pumping of the ground water (U.S. Supreme Court 1976).

The Devil's Hole case highlights a little emphasized consequence of continuous local groundwater depletion. Over time, the water table decline will gradually spread through the area underlain by the same aquifer system. In this instance a critically endangered species was saved from certain extinction by an extraordinary set of circumstances. However, this seemingly unusual case may actually be representative rather than unique. Annual global groundwater withdrawals are currently about 1 000 000 km^3 (Shah et al. 2007), and the number of wells and boreholes, widely distributed around the globe, has grown by tens of millions. As a part of a great deal of the resulting obvious environmental impact, some known and some unobtrusive, yet-to-be-identified, endemic species may have already been driven into extinction by large and spreading water table declines—a form of unperceived collateral damage.

With the exponential growth in the number of wells, the phenomenon brought to the fore in the Devil's Hole case has become widely recognized, in another guise, as a commonplace cause of social inequity, where deeper, higher capacity boreholes in thick alluvial and sedimentary aquifers, deplete the local water table and essentially eliminate the access to water for users of shallower (cheaper) wells (Moench 2002; Foster and Chilton 2003; UNDP 2006).

Even though the interrelationship of groundwater and surface water is undeniable, both of these continue to be managed by different legal regimes. In California, Nebraska, and Texas, three of the largest groundwater-using states in the United States, state laws commonly allow withdrawals from an aquifer at a rate faster than the rate of recharge (Western Water Policy Review Advisory Commission 1998), and "most decisions regarding groundwater development, use, or protection are made with inadequate attention to the value of groundwater as a source of consumptive use and for the in situ services it provides" (NRC 1997).

OWENS VALLEY, CALIFORNIA

Owens Valley is a natural drainage basin surrounded on all sides by mountain ranges. The annual precipitation, ranging from 10 to 15 cm, falls on the valley floor mostly during the winter months. The abundant runoff from snow melt in the adjacent Sierra Nevada Mountains serves as the main source of water that each spring and summer flows into the valley and recharges the groundwater aquifers, thus maintaining a high water table. The Owens River and its tributaries drain the valley. The river terminates at Owens Lake. Prior to 1913, Owens Lake was over 6 m deep and covered more than 260 km^2 (Danskin 1998). A detailed early study of a portion of the Owens Valley provides a water table database that precedes large-scale water withdrawals (Lee 1912). At that time, alkali meadows covered about 14 165 ha of the Valley floor. The underlying water table was between 1 and 2.5 m beneath the surface, with an average annual variation of 1 m.

The arid to semi-arid conditions, the areas of highly saline soils, and the presence of a shallow water table, influence the nature and distribution of the native vegetation on the valley floor (see Table 3 in Danskin 1998). Much of the vegetation consists of xeric plant communities, primarily on lower alluvial fans. Many xeric species grow and flower in the spring, and then persist through the summer in a dormant state. "Facultative" phreatophytes, vegetation highly tolerant of salinity and alkalinity, predominate among the high groundwater alkaline scrub plants in areas where the water table ranges from 1 to 3 m below the surface. They subsist on soil moisture, but if necessary use water directly from the water table (Danskin 1998). The alkali meadows are a rare habitat and are classified as "very threatened" (Sawyer and Keeler-Wolf 1995).

By the end of the nineteenth century, about 400 km southwest from the Owens Valley, the city of Los Angeles was growing rapidly. Between 1880 and 1900, its population grew fivefold to 250 000 people, but continued growth depended on securing additional water supply. The water resources of the Owens River, including ground water in the Valley, estimated to be 45.6 km^3, were thought to be sufficient for the water needs of Los Angeles well into the future. Through purchases of land from 1905 to 1934, Los Angeles secured about 95 % of the water rights in the Owens Valley. In 1913, construction was completed on a 375-km long aqueduct connected to the Owens River to divert the surface water to Los Angeles. In 1970, to meet ever-growing demand, a second aqueduct was completed bringing the total export capacity to 0.7 km^3 year^{-1}. The additional water was obtained by using over 200 wells, distributed throughout the valley floor, to pump groundwater into the Owens River-aqueduct system. For 1970–2008, the average annual water export from Eastern Sierra to Los Angeles was $\sim$0.5 km^3 (LADWP 2009, pp. 2–33). The Owens Valley offers an unusually clear-cut opportunity to examine the environmental impacts of two stages of water withdrawal from the same area, separated in time by over 50 years, the first of which removed much of the river water, and the second which, in addition, depleted ground water at numerous widely distributed sites on the valley floor.

The diversion of the Owens River flow into the Los Angeles Aqueduct led to the transformation of its previous terminus, Owens Lake, into a playa. Through the early 1970s, groundwater levels and the acreage covered by native vegetation were similar to those observed between 1912 and 1921. After initiation of large-scale groundwater pumping, between 1970 and 1978, water levels in many wells in the valley declined, and by 1981, there was a loss of 20–100 % of the plant cover on about 10 520 ha of the alkali meadows (Danskin 1998). Partial reversal of large water table declines has resulted from an agreement reached in 1991, after more than 10 years of litigation to limit groundwater pumping and partially restore water table levels to those of 1980.

Current water withdrawals continue to result in intermittent declines in the water table to below the plant rooting zone, leading to continued transformation of plant communities in this ecosystem. When the groundwater pumping lowers the water table, the plants restricted to zones of shallow ground water are severely stressed. Superimposition of a drought from 1987 to 1992 led to a decline in the native vegetation, followed by widespread replacement by exotic non-phreatophytic annuals when the drought ended (Elmore et al. 2003). A fire in 2007 led to a similar outcome. A video presentation documenting the ongoing dramatic shift in the Owens Valley vegetation, is available online (Pritchett and Manning 2009).

Climatic and vegetation data on this region, from tree rings, lake cores, and pack-rat middens, that predate the anthropogenic intervention in the hydrologic cycle show that over the past 1000 years the region had regularly experienced 10- to 50-year droughts, but with little change in the vegetation communities. Recent studies in the Owens Valley also show little change in the vegetation where anthropogenic modification is minimal (Elmore et al. 2006).

HIGH PLAINS AQUIFER

Before the nineteenth century, tall-grass prairie grasslands covered an area greater than 565 000 km^2, stretching from Texas to Canada. The tall-grass prairie is now the most altered ecosystem in North America with less than 4 % remaining today. The rest has been converted to cropland, or other, less diverse vegetation. The mixed-grass and short-grass prairies also did not fare well (USGS Northern Prairie Wildlife Research Center 2006). Beginning with the advent in the mid-1800s of Euro-American homesteaders, the prairie was gradually transformed into farmland. Prior to 1930, dryland farming predominated in the High Plains. Deep plowing, soil harrowing, and dust mulching were used to prevent evaporation of scarce water. By the 1930s, continuous cropping, primarily by repeatedly planting the cropland in wheat, had depleted the humus that bound the soil. During 1931 to 1939, the High Plains were subjected to a severe drought. Multiple intense storms swept across the eroding fields. The winds blew away much of the pulverized soil as huge clouds of dust, and transformed the area to a “Dust Bowl.” By the 1940s, many High Plains areas had cumulatively lost more than 75 % of their original topsoil. The area encompassed by the Dust Bowl included much of the High Plains region (Putney 1937). To this day, the Dust Bowl is regarded as one of Earth’s greatest recorded environmental disasters.

The High Plains aquifer, one of the world’s largest and most extensively studied, underlies 461 000 km^2 in parts of eight states and includes the 347 000 km^2 Ogallala aquifer. The aquifer is generally unconfined and most of it underlies parts of three states: Nebraska has 65 % of the aquifer volume, Texas 12 %, and Kansas 10 %. The saturated thickness of the High Plains aquifer ranges from 365 m to less than 1 m (Miller and Appel 1997), and with a very slow recharge rate. Most of the water in this aquifer was recharged about 3400 to 15 600 years ago (Gurdak et al. 2009).

Irrigated agriculture expanded rapidly after World War II with the advent of powerful oil pumps capable of lifting ground water cheaply in large volumes, and with the development of efficient pivot irrigation systems (Fig. 1). These innovations ushered in the era of rapidly increasing withdrawals of ground water from the High Plains aquifer (Miller and Appel 1997; Sophocleous 2010). Irrigation enabled the area overlying the aquifer to become one of the major agricultural regions in the world, sustaining ~20 % of the irrigated acreage and using 30 % of all irrigation water pumped within the United States. The area accounts for ~19 % each of wheat and cotton, ~15 % of the corn, and ~18 % of the cattle production in the United States (Reilly et al. 2008). Pumping from numerous irrigation wells across the High Plains is the primary mechanism for groundwater discharge. Farmers began to use ground water for irrigation in the 1930s, to a much greater extent in the 1950s, and by 2002 the estimated irrigated acreage in the area overlying the High Plains aquifer reached over 55 000 km^2.

Total water in storage in the aquifer in 2009 was ~2.9 billion acre-feet, a decline of ~274 million acre-feet since 1950 (McGuire 2007). Mean annual precipitation, ranging from 0.4 m year^{-1} in the western part of the High Plains to about 0.7 m year^{-1} in the east, is the principal natural source of recharge to the aquifer. Evaporation rates measured from open-water surfaces in the High Plains range from 0.7 m year^{-1} in the north to 2.7 m year^{-1} in the south (Gutentag et al. 1984). Groundwater flows in the High Plains aquifer from west to east in response to the slope of the water table at an average rate of about 0.3 m per day and discharges naturally to streams and springs and directly to the atmosphere by evapotranspiration. Estimated recharge rates range from much less than 2.5 cm year^{-1} in parts of Texas to 15 cm year^{-1} in south-central Kansas (Gutentag et al. 1984). Consequently, there is little water available to recharge the aquifer. To give a specific example, in the year 2000, in Kansas the Ogallala aquifer yielded 2.96×10^9 m^3. The estimated average annual natural recharge to the Ogallala in Kansas is 0.89×10^9 m^3. Water levels declined in parts of the High Plains aquifer soon after the beginning of

Fig. 1 Variegated *green crop circles* cover what was once shortgrass prairie in southwestern Kansas. Image courtesy of NASA/GSFC/METI/ERSDAC/JAROS and the US/Japan ASTER Science Team. (http://earthobservatory.nasa.gov/IOTD/view.php?id=5772)

extensive irrigation using ground water, and, by 2007, water table declines ranged from 3 m to over 45 m. For Kansas, depending on the location, the aquifer will run dry in 25 to 200 years (Buchanan et al. 2009). The saturated thickness decline by over 50 % in some parts of the aquifer has in turn led to declines in the flows in many streams in the High Plains with attendant deterioration in riparian and aquatic ecosystems (Sophocleous 2010).

GROUNDWATER OVERDRAFTS IN PARTS OF ASIA

Collectively, India, Pakistan, Bangladesh, and North China use 380–400 km^3 of groundwater per year, an amount approaching half of the world's total annual groundwater withdrawals (Shah et al. 2007). Irrigated agriculture consumes over half of this water, and much of this agriculture is concentrated in parts of the Asian continent, including the entire Indo-Gangetic plains, that are arid or semi-arid with too little rainfall to provide natural recharge. Millions of farmers with small land holdings depend on groundwater for their livelihood.

In India, some 60 % of the irrigated area is served by groundwater wells. In the North China Plain, the area varies between 50 and 75 %. The number of tubewells is estimated to be 7.5 million in China (Shah 2006), 8.6 million in Bangladesh (UNICEF 2008), and 20 million in India (Wang et al. 2007). In India, about 0.8 million new tubewells are added every year. Shah (2006) commented that the "Groundwater socioecologies of South Asia and North China plains represent a veritable anarchy functioning on a colossal scale.” The three examples that follow examine recent data on groundwater depletion in these regions.

NORTH WESTERN INDIA

Measurement, at large basin scales, of the range, rate and amount of depletion of water resources, and the apportioning of the losses between surface water, soil moisture, and groundwater, only became possible with the launch of the Gravity Recovery And Climate Experiment (GRACE) in March 2002 (GRACE Tellus Gravity Recovery 2011). The GRACE satellites detect temporal changes in the Earth’s gravity field. Surface loads, such as continental water storage, contribute to the gravity field. Analysis of changes in the GRACE gravitational measurements allows extraction of the information on water mass variations (total water storage change) with time over large areas.

A GRACE analysis encompassed the Indian states of Rajasthan, Punjab, and Haryana (which includes India’s capital, New Delhi) (Rodell et al. 2009). The study area of 438 × 10^3 km^2 (Fig. 2) has a population of 114 million. It is underlain by the Indus River plain aquifer, a 560 000 km^2 unconfined-to-semiconfined porous alluvial formation. Only 28 % of the area is irrigated, but irrigation of crops such as rice accounts for 95 % of the water consumption. For the period from August 2002 to October 2008, GRACE data showed a net loss of water equivalent to 109 km^3 (the total groundwater depletion between 2001 and 2007 was estimated at -104 ± 40 km^3). For comparison, the capacity of Lake Mead, the largest reservoir in the United States (with a surface area of 640 km^2 and a maximum depth of 150 m) is 35 km^3. The mean rate of water table decline in the study area was calculated to be about 0.33 m $year^{-1}$. The local rates of water table decline varied considerably and were as large as 10 m $year^{-1}$ in some urban areas. These data indicate that during the study period the withdrawal rate, largely by irrigation water, exceeded the recharge rate by about 17.7 km^3 $year^{-1}$. Apparently, most of the groundwater withdrawn is subsequently lost from the region as a result of increases in run-off and/or evapotranspiration. Little variation in precipitation was observed during the study period, thus the groundwater depletion is occurring as a consequence of human consumption rather than natural climate variability. As a result of the water table declines, river flows have decreased, and saltwater intrusion in aquifers of coastal areas has increased (Kumar et al. 2005).

A second study examined a much larger region of 2.7 × 10^6 km^2 that includes the mountainous areas of Afghanistan and Pakistan, the Indus Basin (Pakistan–India), Ganga Basin (India–Nepal) and the Ganga–Brahmaputra Basin (China–Nepal–India–Bangladesh), home to 600 million people (Tiwari et al. 2009). For this much larger area, the groundwater loss was estimated as 54 ± 9 km^3 $year^{-1}$ corresponding to an ~10 cm $year^{-1}$ lowering of the water table.

To counter the groundwater depletion in western and southern India, the Government has developed a controversial mega-scale National River Linking Project, which proposes linkages of 30 rivers, 3000 storage structures, and 14 900 km of canals to shift water to western and southern India, as well as water from the Ganges and Brahmaputra to the Mahanadi basin, a major sedimentary deltaic basin located along the east coast of India (Kumar and Amarasinghe 2009).

NORTH CHINA PLAIN

The North China Plain, the largest wheat and maize producing area in China, where rainfall only averages about 200–400 mm $year^{-1}$, has a severe water shortage with a per capita water availability of ~750 m^3 $year^{-1}$, one-eleventh of the world average. Water scarcity is greatest in the Huang (Yellow)–Huai–Hai river basins (the 3-H basins). The area is home to ~35 % of China’s population, but has only 7.6 % of China’s naturally available water resources. In the ~319 000 km^2 Hai River basin, groundwater withdrawn from the aquifer accounted for ~67 % of the water usage. GRACE data on this area for the period from January 2003 to December 2006 indicate a lowering of the water table of ~20 cm $year^{-1}$, in good agreement with hydrological data from multi-point measurements of soil moisture and water table depth (no estimate of uncertainty for this value was provided; Moiwo et al. 2009).

The Quaternary aquifer that underlies the North China Plain is divided into a “shallow” aquifer and a “deep” aquifer. During the 1950s, the water table was 0–3 m beneath the land surface in most places. According to recent field studies, the maximum depth to water in the shallow aquifer exceeded 65 m, the water table was 10 m or deeper beneath more than 40 % of the entire plain, the maximum depth to water in the deep aquifer had reached 110 m, and the area where the hydraulic head is lower than the sea level covers more than 50 % of the entire plain (Zheng et al. 2010). A well-designed survey of groundwater withdrawal for irrigated agriculture by farmers at ~400 villages distributed widely on the North China Plain (Wang et al. 2007), revealed the spatial complexity that underlies the integrated assessments from the GRACE studies. Thirty-three percent of the villages extract groundwater only from shallow aquifers, 42 % only from deep aquifers, and the remaining 25 % from both. Presumably, for the villages that extract water only from deep aquifers, the shallow aquifers are exhausted or otherwise

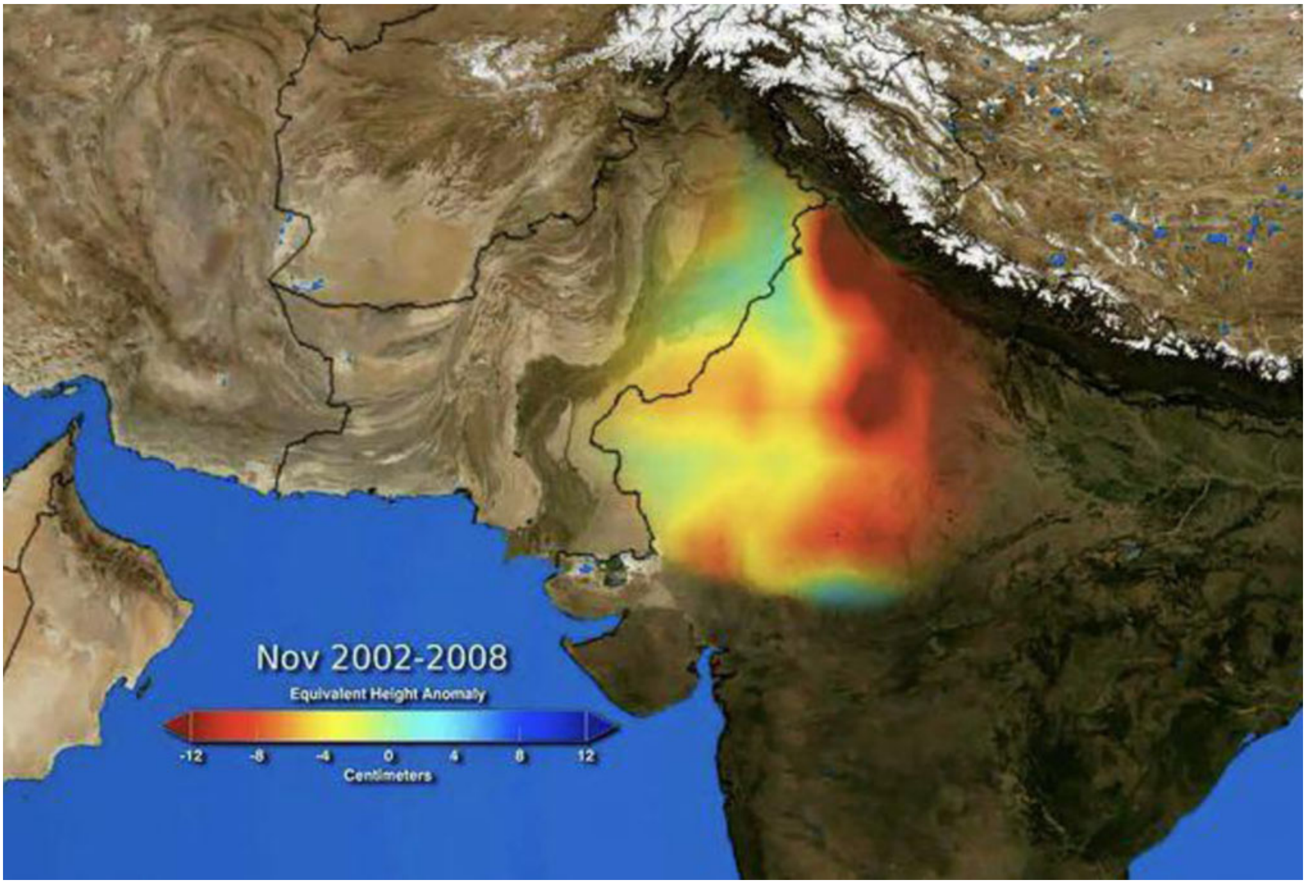

Fig. 2 Groundwater storage variation in northwestern India between 2002 and 2008, relative to the mean for the period, based on observations from NASA's Gravity Recovery and Climate Experiment (GRACE). The deviations from the mean are expressed as the height of an equivalent layer of water, ranging from −12 cm (*deep red*) to 12 cm (*dark blue*). Courtesy NASA/Trent Schindler and Matt Rodell (http://www.nasa.gov/topics/earth/features/india_water.html)

unsuitable. When the villages were divided into quartiles based on pumping from an average depth to water, the results were as follows: first quartile $\sim$4 m, second $\sim$9 m, third >30 m, and fourth >100 m. Deep cones of groundwater depletion are seen in aquifer areas that underlie major population centers, such as Beijing (Tamanyu et al. 2009). The pattern of local water table changes demonstrates the geological and spatial complexity of the aquifer systems that underlie the North China Plain, and indicates that the redistribution and recharge of water within these aquifers is very slow.

The potential consequences of steadily declining water tables may include the drying out of rivers, streams, springs, and lakes, land subsidence, loss of wetlands, saltwater intrusion (much of the very deep groundwater is saline), and contamination of aquifers by pollutants. All such adverse outcomes are represented on the North China Plain. The annual runoff of the Haihe River, the major river in the North China Plain, has decreased threefold since the 1950s, and more than 4000 km of the river channels have dried up. Wetlands have shrunk from 10 000 km^2 in the 1970s to less than 2000 km^2 at present (Zheng et al., 2010).

TARIM RIVER, XINJIANG

The Tarim River and its tributaries typify allogeneous river systems (systems fed from wet mountainous regions that flow across arid or semi-arid land). This case study illustrates the cumulative consequences of upstream groundwater pumping, withdrawals of surface water from the river itself as well as from its tributaries, and the construction of dams. Similar outcomes of surface water and groundwater depletion in other such systems are seen for the Colorado, Ganges, Indus, Nile, and Yellow Rivers that now flow to the sea only intermittently or not at all, and for the Amu Daria and Syr Daria that no longer adequately replenish the Aral Sea (Meybeck 2003).

The $\sim$337 000 km^2 Taklimakan Desert is one of the largest deserts in the world. The vegetation in this extreme desert with an annual precipitation of <70 mm is very largely confined to exogenous water resources or aquifers (Bruelheide et al. 2010). The internally draining 1300-km long Tarim River flows through the Taklimakan Desert. Its headwaters have their source in alpine glaciers and snowpack at elevations of 2800–3500 m (Feng et al. 2001). Relative to other such basins, the Tarim Basin receives a low amount of runoff from the surrounding mountains (Viviroli et al. 2007). The lower reaches of the river from Qiala to Taitema Lake (see Fig. 2 in Hou et al. 2007) are referred to as the "Green Corridor," because of the vegetation communities that formerly covered a strip 5–10 km wide along the river and included wetlands near the terminal, Taitema Lake. The riparian communities are simple and in the main consist of a dominant deciduous tree species, the Euphrates poplar *Populus euphratica*, some woody shrubs (*Tamarix ramosissima*, *T. hispida*, *Halimodendron halodendron*), and about a dozen herbs (Bruelheide et al. 2010).

Annual precipitation in the lower reaches of the Tarim River is <25 mm, whereas annual evaporation can be as high as 1500 mm. Surprisingly, water can be reached at depths of 5–10 m in deepest dune valleys throughout the Taklimakan desert. In the late Pleistocene, the Tarim Basin was a giant lake fed by glacial meltwater. Paleohydrological data indicate that during the "Little Ice Age" there was a prolonged wet environment in Tarim Basin, spanning AD 1400–1850. During this period, the river discharge within the basin increased, surface area of terminal lakes in the desert area expanded, lake levels rose, and groundwater recharge increased (Liu et al. 2011). Cones of the deep-rooted *Tamarix* spp., which mark locations of accessible groundwater, occupy ~15 % of the area throughout the Taklimakan desert. The *Tamarix* cones are coppice dunes of alternating layers of sand and leaf litter accumulated around *Tamarix* spp. clumps. Older cones date back to a thousand years or more (Xia et al. 2004).

From 1950 to 1990, increased withdrawal of ground water for large-scale expansion of agriculture resulted in substantial reduction of the streamflow in the Tarim River. Between 1965 and 1995, as ground water used for farming contributed an increasing proportion of the recharge in the lower reaches of the river, the salt content of the shallow groundwater doubled, reaching 5–16 g L^{-1} in 1995 (Feng et al. 2001). Construction of the Daxihaizi Reservoir in 1972 resulted in the disappearance of surface water in the lower 321 km portion of the river, the drying up of Taitema Lake, and, within 30 years, to a drop in the water table along the river from a range of 3–5 m to a range of 8–12 m.

The rapid decrease in river flow and its ultimate cessation led to a cascade of environmental impacts. The desert riparian vegetation in the lower reaches of the Tarim River gradually withered and died. Annual and shallow rooted perennials were almost all gone by 1980, and the deep-rooted perennial vegetation has been gradually declining. By 2010, the area of the *P. euphratica* forests decreased by over 85 % (Huang and Pang 2010). What remains, going from the river outwards for less than a kilometer, are patches of *Populus* sp., mixed *Populus* sp. and *Tamarix* spp., and *Tamarix* spp. (Hou et al. 2007). The loss of vegetative cover has exposed the land surface to the full force of the winds. The winds have produced frequent sandstorm events leading to significant land desertification, with a gradual increase of the areas of shifting sands and decreases of fixed dunes.

Attempts to restore the "Green Corridor" were initiated in 2000. Yingsu, 60 km downstream of Daxihaizi Reservoir, was chosen as the site to monitor the progress of the restoration effort. The small remnants of the vegetation were in patches of *Populus* sp.-dominated forest closest to the dry riverbed, further out an occasional belt of mixed *Populus/Tamarix* forest about 100-m wide, beyond that a belt of *Tamarix* some 100–150 m wide (Hou et al. 2007). The water table thresholds for plant stress, established for the "Green Corridor" vegetation (Hou et al. 2007), were −3.5 m for grass, −4.5 m for *Populus* spp., and −5 m for *Tamarix* spp. The average precipitation in the Lower Tarim River area is ~40 mm year^{-1} and the potential evaporation is 2590 mm year^{-1}.

The restoration process consisted of 12 water releases from the Daxihaizi Reservoir starting in May 2000 with the final one in September 2006 (see Table II in Hao et al. 2010). Starting with the sixth flow in March 2003, the water reached Lake Taitema. The average flow through the study site was $3.07 \times 10^8\ \text{m}^3\ \text{year}^{-1}$. In the 1950s, the average flow past the Kala station (upstream of the Daxihaizi Reservoir) was $13.3 \times 10^8\ \text{m}^3\ \text{year}^{-1}$ (Feng et al. 2001). These data suggest that relative to 1950s flows, the average water flow in the Tarim River below Daxihaizi Reservoir attained between 2000 and 2006 was some fourfold lower than the historic flows of the 1950s.

The water table depth required to recreate the historic diversity and extent of vegetation along the lower reaches of the Tarim River is ~5 m or less. The area of water table rise brought about by the water releases that meets this criterion is narrow, within 200 m or less from the riverbed, and narrows further downstream. The water table rise did not reach the remnants of the "Green Corridor" ecosystem at 1000–1500 m, which continue to diminish (Huang and Pang 2010). Substantial continuing water releases would be needed to increase width of the "Green Corridor" and sustain the recovery process (Ye et al. 2009). However, the water releases were discontinued in 2008 because the main stream of the Tarim River showed an increasingly negative runoff trend. While climate change led to an increase in the surface runoff in the headstreams of the Tarim River, quantitative assessments showed that local anthropogenic activities since the 1970s led to a decrease of the water volume diverted into the main stream of the Tarim River Basin, a negative trend which became more prominent in the 2000s. The human impacts reflect population growth with attendant increases in activities such as agricultural irrigation and reservoir construction, with resulting decrease the surface runoff in the mainstream.

MURRAY–DARLING BASIN

“Australia is the driest inhabited continent on Earth and in many parts of the country – including the Murray–Darling Basin (MDB) – water for rural and urban use is comparatively scarce and is a most valuable resource” (CSIRO 2008). The combined Murray–Darling drainage basin has an area of 1.3 million km^2 and encompasses Australia’s largest river system. This drainage basin represents 14 % of the total area of Australia and is its most important agricultural area.

In the latter half of nineteenth century, massive clearing of forests and woodlands in the MDB was driven in part by the need to accommodate rising numbers of sheep, which increased in New South Wales between 1860 and 1890 from 5 to 63 million. The grazing of sheep and cattle on the natural grasslands, and the introduction of foreign plants, and weeds, transformed the vegetation in the affected areas of the MDB. On the grazed pastures, the tall summer-growing grasses on the original perennial grasslands, were replaced by largely unpalatable perennial species, annual species including legumes, and less desirable weedy plants. Other perturbations included the introduction and rapid spread of rabbits (*Oryctolagus cuniculus*), and of prickly pear (*Opuntia* spp). Additional stress was superimposed by the devastating “Federation” drought, caused by low-rainfall from 1895 through 1902 (Murray–Darling Basin Authority 2010). Consequently, the types and patterns of vegetation that had evolved in response to the historical precipitation regime and/or access to groundwater were already largely altered by the beginning of the twentieth century.

Subsequent intensive water resource development in the MDB has reduced the average annual stream flow at the mouth of the Murray River by 61 % and increased the cease-to-flow periods from 1 % of the time under the historical climate conditions to 41 % of the time (CSIRO 2008). Much decreased river water flows have resulted in numerous adverse outcomes for the riparian and wetland vegetation, for fish breeding habitat, and in declining water quality. In 1991, the low flows, drought, and elevated phosphate concentrations in the Darling River, led to a potentially toxicogenic cyanobacterial bloom of *Anabaena circinalis* that extended for more than 1000 km.

In Australia’s largest extant river red gum (*Eucalyptus camaldulensis*) forest, the 65 000 ha Barmah-Millewa Forest on the eastern reaches of the Murray River, the frequency of medium size floods has been drastically reduced. About 70 % of river red gum stands on the Murray River flood plain are in poor condition with higher mortality than at other sites in the region (Cunningham et al. 2007). In 1965, a red river gum plantation trial was established in the Barmah-Millewa Forest and has been carefully monitored and studied since that time (Horner et al. 2009). This ongoing forest management experiment has yielded uniquely valuable information. The effective root zone of river red gums in Barmah-Millewa Forest extends to a depth of 9 m. From 1987 to 1998, the water table was relatively constant at a depth of ~12.5 m. From 1998 onwards, there was a decrease of nearly 0.25 m year^{-1} in water table depth, by 2007 the water table was >15 m deep. The decline coincided with a dramatic increase in the mortality in high-density stands suggesting that the reduction in water table depth played a fundamental role in driving the observed pattern of mortality. Decreased river flow (Cunningham et al. 2007) and change in flood frequency, drought, increasing high levels of groundwater withdrawal, increased maximum temperatures, and a rainfall deficit, all contributed to the decline in the water table during an exacerbated drought from about 2001 through 2010 (Horner et al. 2009).

Total water storage data from GRACE (Leblanc et al. 2009) showed an accumulated reduction of ~130 mm equivalent water depth across the basin between August 2002 and December 2006, an estimated total water loss of ~140 ± 54 km^3, equivalent to four times the maximum capacity (~35 km^3) of Lake Mead. There was high correlation between GRACE data and the observed groundwater variations. The GRACE data substantiated the persistent reduction in groundwater storage in the MDB, with groundwater levels still declining 6 years after the onset of the drought. It is noteworthy that of the total water lost between 2002 and 2006, ~83 % was ground water, 14 % was soil moisture, and only 3 % was surface water (Leblanc et al. 2009). Climate projections predict a temperature rise of 1–5 °C by the year 2100 (CSIRO 2007; Cai and Cowan 2008), which would exacerbate these changes.

The *Water Act 2007*, passed by the Australian Parliament, established the Murray–Darling Basin Authority to develop and implement new Basin-wide water planning and management arrangements, including enforceable limits on the withdrawal of water (Murray–Darling Basin Authority 2010). A proposed Basin Plan was released in late November 2011.

HYDROLOGIC IMPLICATIONS OF WIDESPREAD FOREST DIEBACK

The importance of forest watersheds, particularly in arid regions, as sources of fresh water, both for runoff and for ground water, has long been understood. In 1879, John Wesley Powell described vividly the dire consequences of the destruction of forests: "It is well known that, under the modifying influences of man, the streams of any region redeemed from the wilderness are changed in many important characteristics. In times of flood their volumes are excessively increased and their powers of destruction multiplied. In seasons of drought, some streams that were perennial before man modified the surface of the country become entirely dry (Powell 1879)." In the United States, more than 50 % of fresh water originates from forested areas.

Snow, representing large amounts of water supply, accumulates in high-elevation forests during the winter, and the snowmelt is released gradually, sustaining downstream water flows throughout the dry seasons. Compared to grasslands or agricultural lands, root systems of many forest trees are more extensive and deeper. Deep roots have the capacity to transfer deep soil water by upward hydraulic redistribution into shallow layers when leaf stomata are closed, or to transfer water from shallow to deep soil layers following rainfall by the same means after extended periods of drought. Hydraulic redistribution allows recharge of ground water to occur much more quickly than by percolation or capillary forces alone (Caldwell et al. 1998) and enhances the efficiency of roots in all parts of the soil profile. This mechanism is particularly important in increasing the ability of plants to transpire during the dry season (Lee et al. 2005).

In the mid-1980s, in the western United States, frequency of large forest fires and the length of the wildfire season increased suddenly and markedly. These changes were strongly associated with an ~2 °C increase in spring and summer temperatures and an earlier spring snowmelt (Westerling et al. 2006). Over the past 25 years, forests worldwide have been subjected to "stress complexes," combinations of biotic and abiotic stresses, that have led to an increasing number of large-scale forest dieback events (Ryan et al. 2008; Breshears et al. 2009; Carnicer et al. 2011). Typically, stress complexes involve some combination of drought, insects and/or fungi, and fire (McKenzie et al. 2009). A growing body of evidence indicates that global warming and the resulting increased aridity, are "conditioning factors" for these dieback events. Many species of trees, exposed to protracted water stress by a combination of drought and warmer temperatures, maintain themselves as long as possible by upward hydraulic redistribution of ground water through their deep roots. When the groundwater level recedes beyond the reach of the deep roots, the trees are severely weakened (Breshears et al. 2009). The ability of forests to survive more extreme drought events and warmer temperatures, associated with increased evapotranspiration, is uncertain, raising serious concerns about future of forests, as well as freshwater supplies. Already, the reduced snowpack and earlier snowmelt require modification of current water management infrastructure.

CONCLUSION

In 1997, hydrogeologist Marios Sophocleous argued that a nuanced definition of sustainable yield with respect to ground water withdrawals needs to address the sustainability of the system—not just the trees, but the whole forest; not just the fish, but the aquatic food chain; not just the ground water, but the running streams, wetlands, and all the plants and animals that depend on it (Sophocleous 1997).

Unfortunately, as illustrated here, such a holistic sustainable yield definition does not govern the management of current freshwater resources. As briefly summarized below, the findings documented in the case studies, conform to expectations from the current knowledge of hydrology:

1. Ground water and surface water are physically connected (Devil's Hole).
2. Dramatic vegetation change or loss occurs when water tables decline below the plant rooting zone (Owens Valley, Tarim River, Murray–Darling Basin).
3. Groundwater withdrawal for irrigation can significantly lower the water table even in massive aquifers with slow recharge (High Plains Aquifer, North Western India, North China Plain, Tarim River, Murray–Darling Basin, Owens Valley).
4. River flows decline or cease with water table declines (Owens Valley, North Western India, North China Plain, Tarim River, Murray–Darling Basin).

These case histories of interacting ground and surface water withdrawals in drylands on three continents, all document clearly substantial ecosystem damage, most frequently due to the massive conversion of lands to uses fully dependent on replacing natural hydrological regimes by irrigation at the expense of steadily declining water tables. Prior to irrigation, some of the impacted lands had already undergone large-scale conversion of native grasslands and forests to grazing and agricultural use, in some instances 50–150 years ago.

"Provisioning of water to water-stressed regions for human needs is routinely done at the expense of ecosystems, both aquatic and terrestrial (Carpenter et al. 2011).” Nor does widespread change appear to be imminent. “In parts of India, groundwater overextraction and quality decline have been recognized since the 1970s. With a few possible exceptions, little has been done to regulate groundwater extraction or control degradation of the resource base. This is also the case across Latin America and Africa and in countries as diverse as China, Spain, and the western USA. This situation is, in fact, mirrored across much of the globe” (Moench, 2007).

Examples that support the above assertions are abundant worldwide. To cite one, a strictly utilitarian view on groundwater use is implicit in the current, actively pursued objective of the Chinese central and local governments to convert unused land (“wasteland”) to irrigated agricultural land. Wasteland encompasses wetlands, forest, grassland, and desert (Yuling 2009). Unsurprisingly, according to the Government of China, “over 40% of the land area is adversely affected by grassland degradation, the loss of soil fertility and the loss of natural forest. This area increased from a rate of an additional 1800 km^2 yr^{-1} being degraded in the 1980s, to 3436 km^2 yr^{-1} being lost in the late 1990s. The most affected areas are the Loess Plateau and the vast Western Region” (cited in UN 2011).

Continuing substantial population growth in drylands, and alarming levels of groundwater pollution (Qiu 2011), are increasing costly challenges to freshwater security. The current human, economic, and environmental costs and consequences of excessive groundwater exploitation underscore our vital reliance on this foundation for life on land.

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