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A glass half empty: Regions at risk due to groundwater depletion Reproduced from United Nations Environment Programme (UNEP) Global Environmental Alert Service (GEAS)

1. Why is this important?

The tiny fraction of freshwater not bound up in ice sheets and glaciers comprises only a very small fraction of total global water volume (about 0.79%) (Shiklomanov, 1993). Global use of that freshwater, however, has been growing at roughly twice the rate of global population for the past century (Shiklomanov, 1999; US Census Bureau, 2011) (Fig. 1). Even so, this volume of unfrozen freshwater is still more than adequate to meet all human needs. However, this essential resource, which is mostly stored as groundwater, is distributed quite unevenly around the globe. Furthermore, physical and economic constraints make it impractical in most cases to move great volumes of water from areas of surplus to areas of need (Gleick and Palaniappan, 2010). **Therefore regional scarcity has become a serious and growing problem, as rapidly growing populations in many areas rely on regional water supplies which are being depleted, degraded, and divided among more and more users (Gleick and Palaniappan, 2010). Alarmingly, aquifers in some of the world's major agricultural regions, including China, India and the United States—all of them crucial to the food security of 100 s of millions of people—are being exploited unsustainably.**

Mechanized pumping of groundwater makes it possible to improve crop production in many arid and semi-arid areas of the world but has also led to serious overexploitation of aquifers in many cases.

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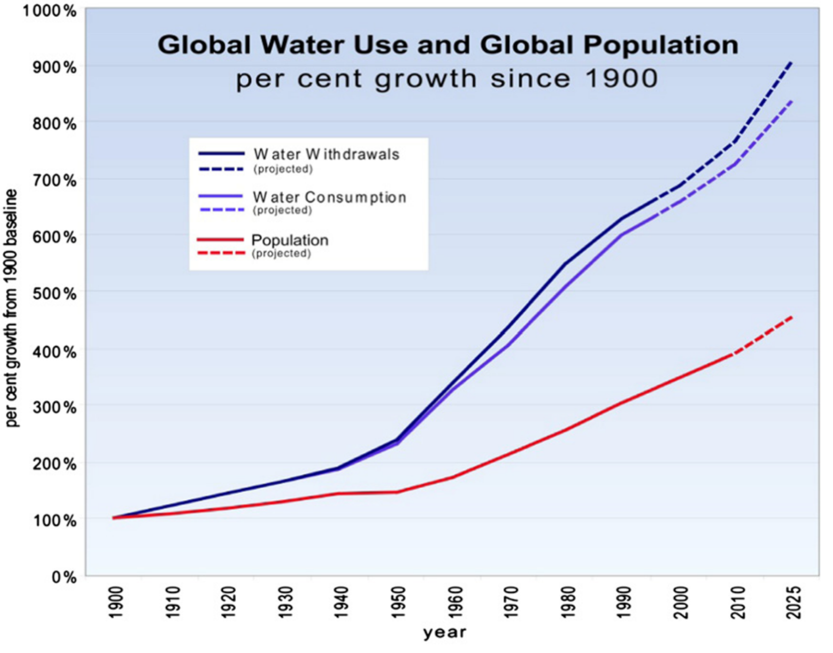

Fig. 1. Rate of growth in freshwater withdrawal and consumption has been even more rapid than global population growth. *Sources*: Shiklomanov (1999) and US Census Bureau, (2011).

1.1. *Growing global reliance on groundwater*

Intensive use of groundwater is a relatively recent phenomenon beginning in industrialized countries in the 1950s and reaching much of the developing world between 1970 and 1990 (Foster and Chilton, 2003). The development of cheaper drilling and pumping techniques has helped to make it an increasingly popular alternative to surface water for meeting the growing global demand (Foster and Chilton, 2003). Groundwater is generally of higher quality than surface water (Foster and Chilton, 2003; Zektser and Everett, 2004) and it is much less subject to seasonal or inter-annual variation making it more reliable than surface water sources. In contrast to large surface water development such as dams and reservoirs, groundwater infrastructure and development can be done in phases, as needed, thus scaling investment to current demand (Foster et al., 1998). Many cities have turned to groundwater for domestic and drinking water supply as surface water sources have become contaminated (Zektser and Everett, 2004). Almost half the global population now uses groundwater for their drinking water and an increasing proportion of agriculture relies on groundwater (Siebert et al., 2010). Across North Africa and in the Arabian Peninsula, enormous reserves of non-renewable groundwater have enabled large irrigation projects in the middle of the Sahara and Arabian Deserts (Al-Zahrani, 2009; Abdelrhem et al., 2009). In the Punjab of India and Pakistan—the heart of the 1970s' "Green Revolution"—groundwater, along with new crop varieties and improved inputs, has enabled enormous gains in agricultural productivity (Rodel et al., 2009).

1.2. *Problems caused by overexploitation*

In spite of the many successes of groundwater development around the globe there are very serious problems as well. In general these problems are the result of abstracting water faster than it is

replenished by rainfall and surface water flows (Custodio, 2002). Even when abstraction does not exceed recharge, it can alter complex aquifer system dynamics, decreasing spring and stream flow and degrading water quality (Custodio, 2002). In addition to undermining the sustainability of continued human uses, depletion of many aquifer systems in arid and semi-arid areas has been linked to diminished capacity for support of ecosystem functions and to environmental damage (Custodio, 2002; Esteban and Albiac, 2011). Such unsustainable overexploitation can generally be avoided with proper management incorporating understanding of the given resource and realistic use scenarios (Custodio, 2002) (Fig. 2).

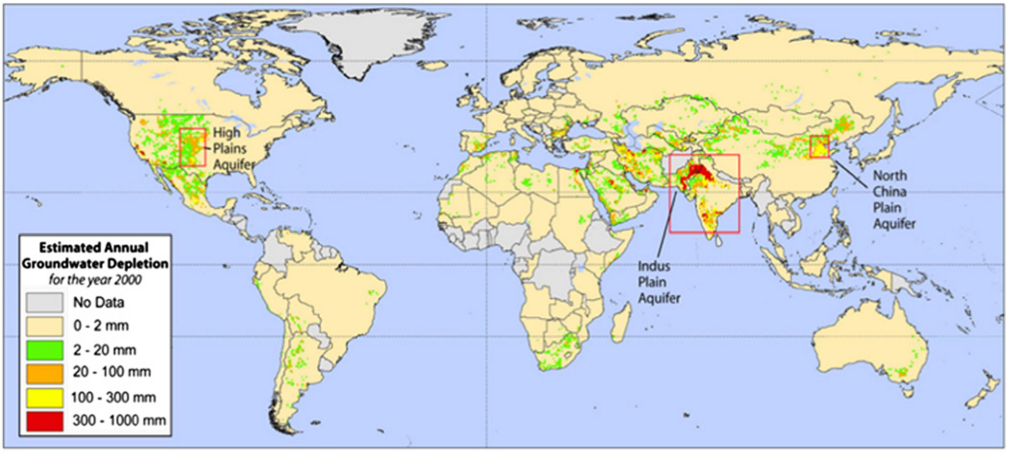

Fig. 2. By modeling groundwater abstraction and average groundwater recharge, Wada et al. (2010) have estimated groundwater depletion for most of the globe. West Asia, the central United States, northwestern India and northeastern China are among the areas showing the most serious groundwater depletions.
Source: Wada et al. (2010).

Groundwater overexploitation in many locations has already caused local or regional water tables to decline making continued water abstraction more difficult and expensive. Three of the most serious instances of overdraft occur in areas of intense irrigation in China, India and the central United States.

Several recent studies have identified the **Indus River plains aquifer**, underlying the India–Pakistan border, as having experienced some of the world's worst groundwater depletion (Rodel et al., 2009; Tiwari et al., 2009; Wada et al., 2010; Sidhu et al., 2010; Chatterjee and Purohit, 2009). The Indian Ministry of Water Resources classified a large proportion of northwestern India as "overexploited," with significant declines in the water table already being measured (Fig. 3) (Chatterjee and Purohit, 2009; Ministry of Water Resources, 2006). This finding is supported by satellite data showing changes in total water storage as inferred from gravity measurements, which estimated a decline of the water table (averaged across the states of Rajasthan, Punjab and Haryana and Delhi) at roughly one-third of a meter per year between 2002 and 2008 (Fig. 4) (Rodel et al., 2009). Some urban areas are reported to have experienced water table declines of up to 10 m in a single year (Shajan, 2004).

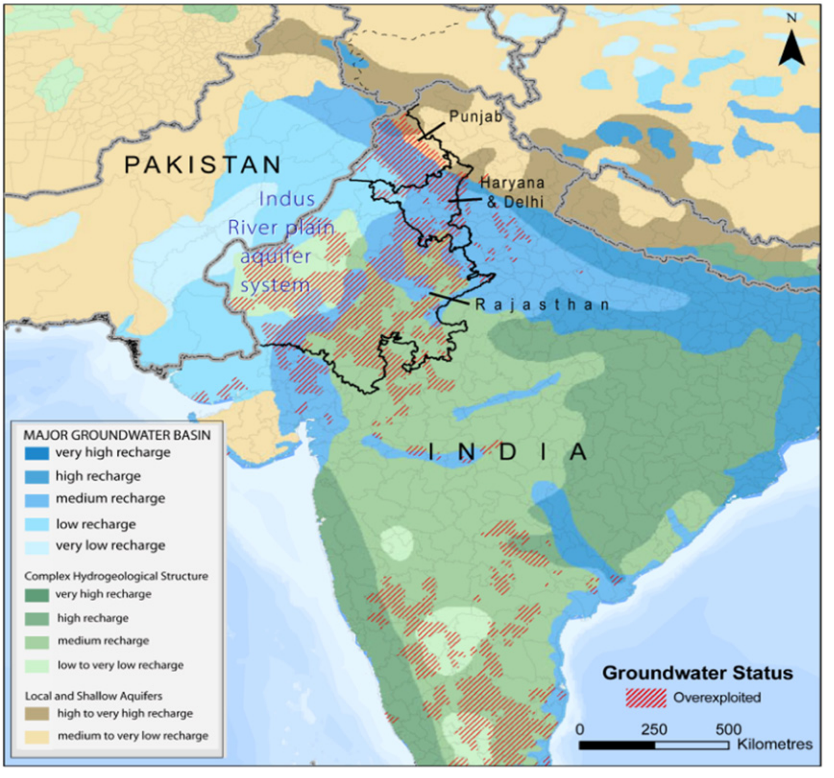

Fig. 3. Indian government estimates show areas where groundwater is being overexploited (red hatching). The greatest concentration is in the states of Punjab, Rajasthan and Haryana and Delhi over the Indus Plains aquifer system.
Sources: WHYMAP (2008), Ministry of Water Resources, India 2006; Redrawn: UNEP GRID Sioux Falls.

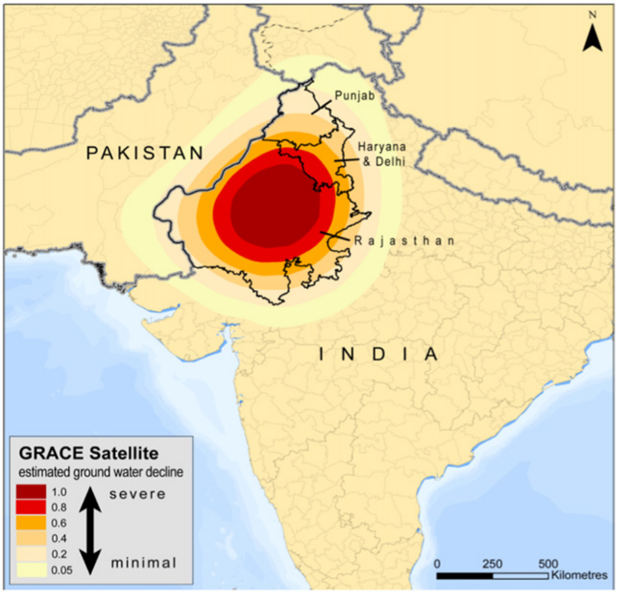

Fig. 4. Rodel et al. (2009) used the GRACE gravity sensing satellite to estimate the change in groundwater storage in northern India. They found the most severe depletion centered over the same three states that Indian Government data had also found to be depleting groundwater.
Source: Rodel et al. (2009); Redrawn: UNEP GRID Sioux Falls.

Since the 1950s, population and area under irrigation have grown dramatically in all three states and the proportion of irrigation relying on groundwater has grown still faster (Narayanamoorthy, 2006). The unsustainable rate of abstraction is a serious threat to future agricultural productivity and domestic water supply for a population which is expected to reach 130 million people for these states by 2015 (Rodel et al., 2009; SEDAC, 2010).

In the west-central United States, **the High Plains Aquifer** is heavily exploited for large-scale irrigation in one of the world's major agricultural regions (McGuire, 2004). Irrigated agriculture here uses roughly 30 percent of the total of all groundwater used for irrigation in the United States and accounts for 27 percent of all irrigated land in the country (Strassberg et al., 2009). The growth in total area irrigated over the aquifer grew by over 650 percent between 1949 and 1971, but had generally leveled off by 1980 (McGuire, 2004). By 1980, average water levels had dropped by just under four meters and as of 2009 by over 4.2 m across the entire aquifer relative to pre-development levels (Luckey et al., 1981; McGuire, 2011). The average aquifer level declined the most in Texas (McGuire, 2011), with large parts of several counties experiencing declines of over 45 m (Fig. 5) (McGuire, 2011). A 2010 study estimated that depletion of groundwater in the Texas Central High Plains area of the aquifer was ten times the rate of recharge (Scanlon et al., 2010). The drop in water levels began impacting the viability of agriculture regionally before 1980 (Luckey et al., 1981).

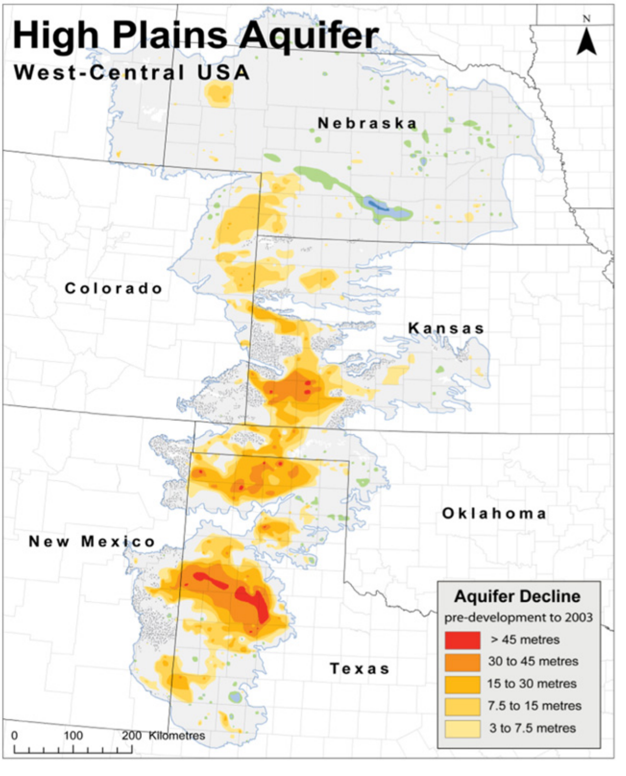

Fig. 5. High Plains Aquifer in the central United States has been heavily exploited for irrigation since the 1940s. Large parts of several counties in Texas have seen the water table decline by over 45 m relative to pre-development levels.
Source: McGuire (2004); Redrawn: UNEP GRID Sioux Falls.

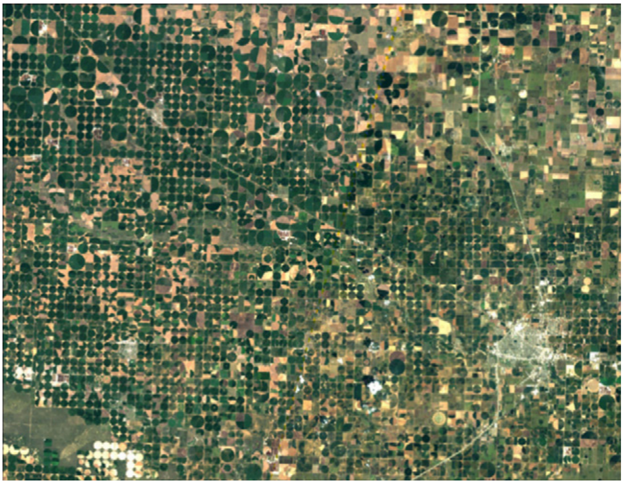

Fig. 6. Landsat (August, 2010) image shows intense concentration of center pivot irrigation in Castro, Swisher, Lamb and Hale Counties of Texas coincides with some of the worst aquifer depletion on the High Plains Aquifer in the central United States.

The **North China Plain aquifer** system, another of the world's most overexploited groundwater resources, gets over 70 percent of its total water supply from groundwater (Liu et al., 2011). Introduction of mechanized groundwater irrigation to this semi-arid region in the 1960s enabled dramatic increases in agricultural production (Kendy et al., 2003). A part of that gain was the result of adopting a double-cropping system that grows wheat in winter and maize in summer, but also increases water demand during the dry winter months (Qiu, 2010). Population has grown significantly over the past 25 years and the number of people living in the counties directly over the aquifer will be approaching 100 million by 2015 (SEDAC, 2010) (Fig. 6).

A significant proportion of the shallow aquifer has seen water levels drop by 20 m since 1960 with some small areas experiencing declines of over 40 m (Fig. 7) (Foster and Garduno, 2004). The deeper, semi-confined aquifer, which has very little recharge, has declined by more than 40 m across much of its extent (Foster and Garduno, 2004). The lowered water table is already increasing the cost of abstraction and threatens the viability of local agricultural production (Foster and Garduno, 2004). In addition, the high rates of pumping create risk of salinization from coastal saltwater intrusion and from brackish water layers within the aquifer (Foster and Garduno, 2004).

Similar overexploitation is occurring in many Middle Eastern and North African countries with Yemen, Oman and Iran among the most often cited examples. Several of Iran's key aquifers have declined between 13 and 20 m in recent decades (Motagh et al., 2008). The rapidly growing populations in many parts of this mostly arid region rely heavily on irrigated agriculture, much of it using groundwater (UN Data, 2010; Shah et al., 2007).

Salinization often occurs in coastal aquifers where overexploitation of groundwater can stimulate recharge from more saline waters within the groundwater system and seriously degrade water quality (Steyl and Dennis, 2010; Custodio, 2002). Several areas in North Africa have experienced this type of seawater intrusion, including Tunisia, Libya and the Nile Delta (Steyl and Dennis, 2010).

Excessive withdrawal of water from some aquifers has led to significant land subsidence. This is of particular concern in urban areas where the damage can be substantial. A study in Mexico's Toluca Valley estimated areas of subsidence up to two meters between 1952 and 2009 (Calderhead et al., 2011).

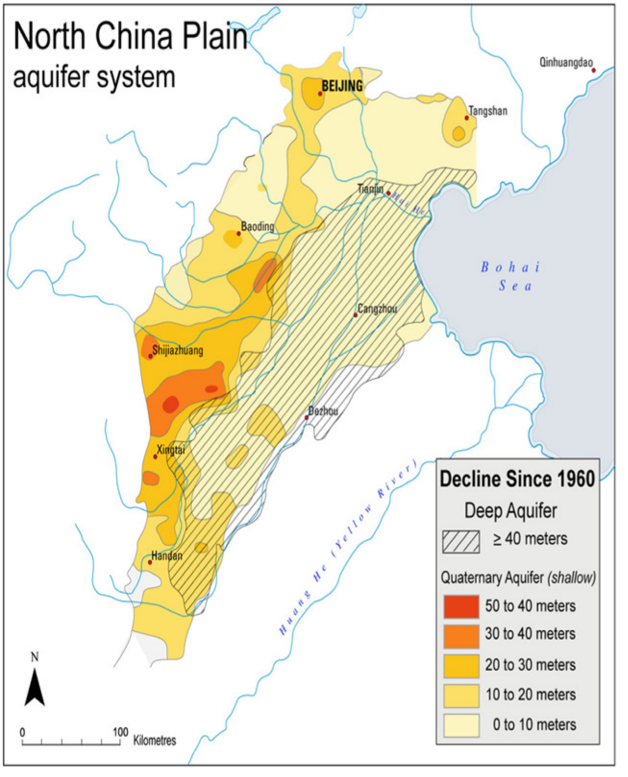

Fig. 7. Intensive irrigation over the North China Plain aquifer system has seriously lowered the water table in both the shallow quaternary aquifer and the semi-confined deep aquifer. The water table has dropped by over 40 m in parts of the shallow aquifer and much of the deep aquifer since 1960.
Source: Foster and Garduno (2004); Redrawn: UNEP GRID Sioux Falls.

On the Southern Yangtze Delta in China, subsidence from over abstraction of as much as three meters has caused cracking of buildings and failure of buried pipelines (Zhang et al., 2008).

Declining water tables can reduce stream flow, affect water quality in wetlands and lakes, dry up wetlands, diminish the capacity of rivers to dilute inflowing pollutants and change areas of groundwater discharge to areas of groundwater recharge (Zektser and Everett, 2004; Sophocleous, 2001). These changes can directly eliminate or degrade habitat and result in loss of biodiversity, and can indirectly cause repercussions throughout aquatic and terrestrial ecosystems (Sophocleous, 2001).

1.3. *The current state of understanding and management*

In spite of a growing global reliance on groundwater, there are still large uncertainties about the volume, distribution, recharge and withdrawal of the planet's groundwater resources (Siebert et al., 2010). Various estimates of total global groundwater storage disagree by more than an order of magnitude, (Jones, 2011; Nace, 1971). Historically, most global estimates of groundwater recharge have been built upon data collected at national and sub-national scales, which may be estimated by different methods and based upon differing definitions and which are often out of date (Siebert et al., 2010; Jones, 2011; Döll and Fiedler, 2008). International efforts to improve compatibility and completeness of global groundwater data have made some progress in developing international

standards for data collection (Jones, 2011). Recent estimates of global groundwater recharge have used sophisticated hydrological models which have the advantage of consistency across national boundaries but remain difficult to validate (Wada et al., 2010; Döll and Fiedler, 2008).

However, in many respects groundwater management is inherently local or regional, based around regional stocks and flows of water and regional demand and use practices. While groundwater resources have interactions at much broader scales, the aquifer scale is the most commonly used for management and study and captures most of the important flow information of recharge, use and discharge as is relevant to management decisions (Van der Gun et al., 2011). Adequate data and a good working model of the flows in aquifer systems are essential for maintaining sustainable use and avoiding damage to long-term functions of the system (Foster and Chilton, 2003; Custodio, 2002; Wang et al., 2007). Even when good data and well-designed models are available, uncertainty can be considerable due to the complexity of groundwater systems and the difficulty in defining variables such as future rainfall, land use and surface flows (Custodio, 2002). The uncertainty that already exists in global climate model (GCM) projections is compounded by downscaling to the scale of individual aquifer systems (Allen et al., 2009; Chen et al., 2011; Beven, 2011) making any projections regarding specific groundwater systems under climate change still more uncertain (Beven, 2011) and largely speculative. In spite of these limitations, better data, ongoing monitoring and improved modeling of aquifer systems are the basis upon which sustainable management of groundwater resources can be developed (Konikow and Kendy, 2005).

Even as hydrogeological understanding of many groundwater systems has improved and even when sustainable-use can be reasonably well defined, effective management of groundwater remains elusive (Esteban and Albiac, 2011; Konikow and Kendy, 2005). Groundwater is a common-pool resource where users see little personal motivation to limit use when they have no expectation that others would do the same; i.e. groundwater is subject to the concept of "the tragedy of the commons" (Hardin, 1968).

2. Major findings and implications

Groundwater overexploitation—defined as use that leads to ongoing water table drawdown, water quality degradation, increasing cost of abstraction or ecological damage (Custodio, 2002)—has become a serious problem in many of the world's semi-arid and arid environments (Wada et al., 2010; Konikow and Kendy 2005; Pandey et al., 2011; Shah et al., 2000; Giordano, 2009). The lowering of water tables increases the difficulty and cost of abstracting water and threatens the viability of irrigated agriculture and in turn the food security of these regions. Projected population growth, irrigation expansion and economic growth is expected to create increasing groundwater demand in the coming decades (Wada et al., 2010). Great uncertainty remains in the understanding of what impact future climate change could have on groundwater resources, particularly at the local and regional scale where most management considerations are addressed (Chen et al., 2011; Beven, 2011). However, the growing global reliance on groundwater makes it increasingly important that we better understand existing groundwater systems upon which a large proportion of the world's population is dependent, and that we manage this most fundamental of resources sustainably.

It is widely stated in the groundwater literature that there is a need for better data regarding existing groundwater resources—including their recharge, use and discharge rates—to support management of this increasingly important resource (Foster and Chilton, 2003; Döll and Fiedler, 2008; Konikow and Kendy, 2005; Pandey et al., 2011; Custodio, 2000; Shah et al., 2000). New technologies such as the GRACE satellite may eventually provide some of this data as well. In addition, research regarding the behavior of aquifer recharge under changing land use, changing climate and changing surface water patterns will help improve groundwater management (Allen et al., 2009; Taylor et al., 2011; Bellot et al., 2001).

More efficient technologies such as this drip irrigation of lettuce in Argentina may help to reduce the pressure on groundwater demand.

Reduced demand through regulation, economic incentives and improved technologies may lessen the pressure on overtaxed aquifers (Shah et al., 2000). There may also be gains through augmenting aquifer recharge with rainwater harvesting, managing surface water use to enhance recharge and engineered artificial recharge (Shah et al., 2000) To a limited extent, trade in "virtual water" or water embedded in products may alleviate water stress in some regions (Chapagain and Hoekstra, 2008). In some settings, joint management of surface water and groundwater can help make the most of limited renewable water resources. One example of this type of strategy is to draw down aquifer levels during dry months, creating additional storage capacity for recharge during wet months (Shah et al., 2007). In some cases, wastewater can be deliberately infiltrated into groundwater. This both augments groundwater levels and provides at least partial filtration and treatment of wastewater (Shah et al., 2007). Agriculture is the largest user of groundwater, thus, increased efficiency through improved irrigation techniques such as drip and sprinkler systems, use of pipe transport rather than open furrows, mulching to mitigate water loss and water-efficient crop varieties has the potential to reduce water demand (Shah et al., 2007).

The groundwater literature makes some recommendations regarding the role institutional reforms might play in furthering sustainable use of groundwater. Among the recommendations is shifting the orientation of national water agencies from a "supply-development" perspective to a "resource-custodian" perspective (Foster and Chilton, 2003; Shah et al., 2007). It is also suggested that in some cases, collective action—in effect stakeholder management—can be a way to overcome the common pool resource challenge (Giordano, 2009). Cooperative management of aquifers shared by two or more countries is a relatively recent development (Eckstein, 2010). A few examples of multi-national arrangements to meet these challenges exist—such as in the case of the Nubian Sandstone Aquifer in North Africa and the Genevese Aquifer on the France-Switzerland border (Eckstein, 2010). The common pool nature of groundwater makes it particularly important that countries come to a common understanding to avoid the "tragedy of the commons" played out at an international scale (Chermak et al., 2005). Management of groundwater can often take place indirectly and unintentionally; for example, through agricultural policy, energy policy or economic development policy. Giordano (2009) gives an example of development and energy policy in India where a simplified flat rate on electricity used for irrigation inadvertently removed much of the incentive for efficient water use. Overuse of water and loss of revenue has persuaded the government of India to try changing back to a metered system Giordano (2009).

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