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Groundwater: from mystery to management

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Abstract
Groundwater has been used for domestic and irrigation needs from time immemorial. Yet its nature and occurrence have always possessed a certain mystery because water below the land surface is invisible and relatively inaccessible. The influence of this mystery lingers in some tenets that govern groundwater law. With the birth of modern geology during the late nineteenth century, groundwater science became recognized in its own right. Over the past two centuries, groundwater has lost its shroud of mystery, and its scientific understanding has gradually grown hand-in-hand with its development for human use. Groundwater is a component of the hydrological cycle, vital for human sustenance. Its annual renewability from precipitation is limited, and its chemical quality is vulnerable to degradation by human action. In many parts of the world, groundwater extraction is known to greatly exceed its renewability. Consequently, its rational management to benefit present and future generations is a matter of deep concern for many nations. Groundwater management is a challenging venture, requiring an integration of scientific knowledge with communal will to adapt to constraints of a finite common resource. As scientists and policy makers grapple with the tasks of groundwater management, it is instructive to reflect on the evolution of groundwater knowledge from its initial phase of demystification at the beginning of the nineteenth century, through successive phases of technological conquest, scientific integration, discovery of unintended consequences and the present recognition of an imperative for judicious management. The following retrospective provides a broad context for unifying the technical contributions that make up this focus issue on groundwater resources, climate and vulnerability.

Keywords: groundwater history, groundwater law, groundwater policy, groundwater management, adaptive management

1. Introduction

At the beginning of the 21st century, concern exists worldwide for human sustenance on an Earth where finite water and land resources must be shared by humans and the environment. It is widely recognized that groundwater is a vital source of freshwater for communities around the world, and that this fragile natural resource is vulnerable to over-exploitation and chemical contamination, and constrained by climatic variability. Nations around the world are confronted with the difficult task of sustainable groundwater management (Morris *et al* 2003, Scheidleder *et al* 1999, Reilly *et al* 2008, Planning Commission 2007). This task is beset with challenges of science and technology, as well as of human behavior. There is much debate among scientists, social workers, policy makers and legislators on optimal groundwater management approaches.

Following Meinzer (1923), the term 'groundwater' is here restricted to water that occurs below the water table, entirely saturating the pores of geological materials. The zone between the land surface and the water table where water and air coexist

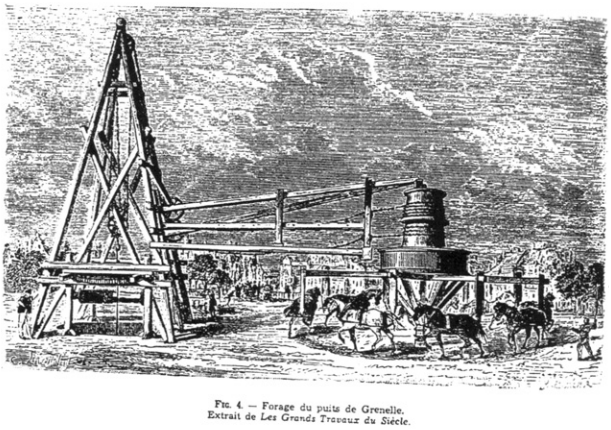

Figure 1. Cable-tool drilling of Grenelle well, Paris, *circa* 1840 (Barraqué *et al* 2008).

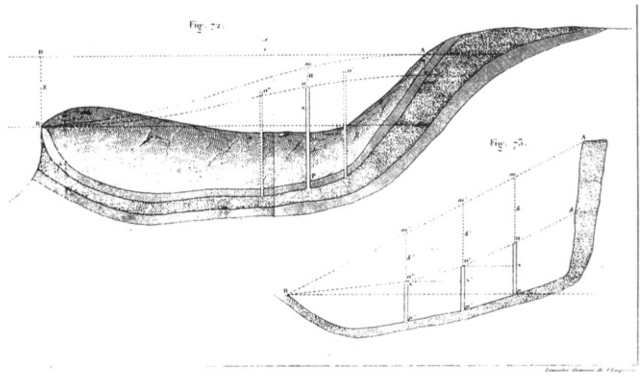

Figure 2. Dupuit's idealization of potentiometric profiles in an artesian aquifer (Dupuit 1863).

is referred to as the vadose zone, or the unsaturated zone. Water in this zone is referred to as soil water. Together, groundwater and soil water comprise subsurface water.

Groundwater is a remarkable natural phenomenon. Unlike surface water, groundwater cannot be readily observed. Consequently, groundwater was long considered to be mysterious or even occult in nature. This perception of mystery has historically influenced legal decisions relating to groundwater ownership and use (Acton v Blundell 1843). A rational understanding of the physical laws that describe groundwater has occurred only over the past century and a half. Simultaneously, groundwater has also been subjected to the influence of technological advances in pumps and power production. For these reasons, groundwater management is a multi-faceted task. Therefore, it is worthwhile to reflect on the different facets of groundwater as a natural phenomenon and as a vital natural resource. This work examines major developments in groundwater hydrology since the beginning of the nineteenth century. This history has been punctuated by periods with specific characteristics such as observation and discovery, technological conquest, scientific integration, unintended consequences and human adaptation. This historical overview provides a broad context within which the different technical contributions of this focus issue can be unified.

2. Observation and discovery

During the 16th and 17th centuries, the conceptual foundations of modern groundwater hydrology were laid when Palissy, Perrault and Marriot in France observationally established that natural flows in springs and base-flow in perennial rivers were fed by rainfall (Meinzer 1934, Narasimhan 2005). Early during the nineteenth century, these ideas came together, providing a rational approach to drilling deep artesian wells in the Paris Basin. Barely 50 years earlier, James Hutton in Scotland had put forward his theory of the earth system (Hutton 1788) ushering in a new era of interpreting earth processes in the context of unchanging physical laws. At the recommendation of François Arago of the French Academy of Sciences, drilling commenced on a well at Grenelle, about 90 km west of Paris. Arago estimated that water-bearing Albian sands, outcropping at higher elevations to the southeast and the northwest, would be intercepted under artesian conditions at a depth of 400 m. In actuality, however, the sands were pierced at a depth of over 600 m, with an artesian pressure of 1.2 MPa (12 bars or over 380 feet of water) at the land surface (Barraqué *et al* 2008). Figure 1 is an illustration of percussion drilling at Grenelle around 1840.

Soon thereafter, Darcy (1856) and Dupuit (1863) formally incorporated Arago's conceptualization into a framework of basin-wide groundwater motion in layered sedimentary systems, in which water moved from recharge areas at high elevations in the direction of decreasing hydraulic head. Over the following decades, this framework, in conjunction with Darcy's Law for steady motion of water in geological materials (Darcy 1856), set the stage for applying potential theory to analyze flow in groundwater systems. Seepage of water in soils and groundwater flow to wells were brought within the scope of quantitative analysis using partial differential equations. Figure 2 shows Dupuit's idealization of the potentiometric profile in an artesian aquifer sandwiched between two presumably impermeable confining layers. The lower figure also suggests dewatering associated with water level decline in the recharge area.

During the middle of the nineteenth century, the vast region west of the Mississippi in America began to be settled by immigrants from the east. Importing technological know-how from Europe, these settlers found ample scope for drilling artesian wells in the numerous sedimentary basins of the new land. By the end of the century, these groundwater systems were being systematically investigated by geologists of the newly formed United States Geological Survey. These studies expanded upon the artesian basin concept of Darcy and Dupuit by noting that no geological stratum is entirely impervious (Chamberlain 1885, Bredehoeft *et al* 1982), and that some leakage of water will occur through the seemingly impermeable layers that confine an artesian aquifer. Darton, who conducted detailed studies of the Dakota aquifer system, noted that hydraulic grade in the Great Plains east of the Black Hills in South Dakota was influenced by leakage of water upward through the 'so-called impermeable strata, especially

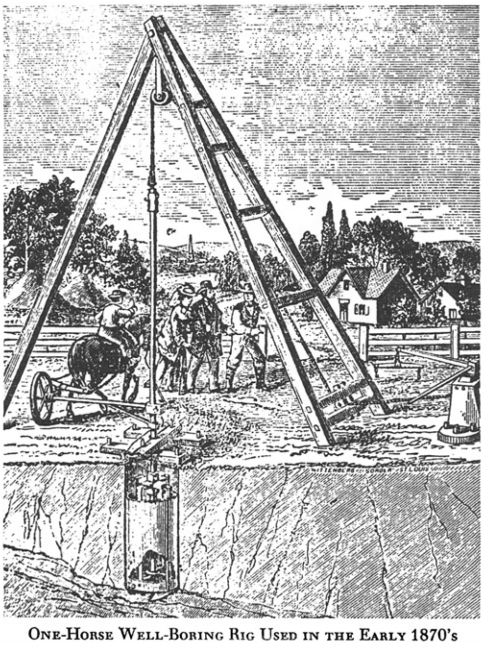

Figure 3. Horse-drawn well-boring rig used in California around 1870 (Freeman 1968).

Figure 4. Memorial to artesian wells of bygone days, Pixley, San Joaquin Valley, California (courtesy of Tulare County Historical Society).

when under great pressure' (Darton 1909, Bredehoeft *et al* 1982).

The collective contributions of Arago, Darcy and Dupuit, embellished by the observations of Chamberlain and Darton, have inspired the modern conceptual framework for an integrated understanding of three-dimensional groundwater flow patterns in groundwater basins, driven by precipitation recharge, gravity, and by evapotranspiration discharge.

3. Technological conquest

The presence of artesian conditions was a boon to the settlers of the arid American west. In California's Great Central Valley, for example, flowing wells (often producing in excess of 3800 m^3 (over a million gallons) of water per day) began playing a key role in irrigated agriculture, horticulture and municipal water supplies (Kahrl 1979). Figure 3 shows a horse-drawn boring machine in use in California around 1870.

By the end of the nineteenth century, continued production of water from a large number of wells led to a gradual decline and cessation of natural flows in many artesian basins. Figure 4 shows an epitaph to artesian wells from near Pixley in the San Joaquin Valley of California. Similar declines in artesian flows were experienced elsewhere in the United States, and in the artesian basins of France (Barraqué *et al* 2008).

With the cessation of natural flows, a need arose to lift water from below the land surface for irrigation and municipal uses. To this end, horizontal shaft centrifugal pumps began to be employed. Prior to the 1900s, these pumps were typically driven by steam engines. During the 1890s, California witnessed the first introduction of three-phase alternating current from hydroelectric power plants that ushered in the era of long-distance power transmission. Soon, steam engines gave way to electric motors that drove centrifugal pumps.

Centrifugal pumps, unfortunately, were limited to lifting water by suction from a maximum depth of about 8 m. As water levels declined due to continued production, water had to be lifted from greater depths. To achieve this, technology came up with a powerful invention, the multi-stage, vertical shaft, turbine pump, with the impellers submerged below the water level in the well. Water could now be lifted from depths of several hundred meters. In 1907, the first such unit was installed in Chino in San Bernadino County, California (Freeman 1968). The impeller assembly of an early turbine pump is shown in figure 5.

Along with the introduction of alternating current, and the concurrent growth in the petroleum industry, the onset of the twentieth century witnessed explosive growth in the drilling of water wells in sedimentary basins throughout the United States, and elsewhere in the world. Limited only by the energy costs of lifting water, turbine pumps enabled water extraction at rates far exceeding the rates of natural recharge. The revolutionary turbine pump had ushered in the era of groundwater overdraft, which forever changed the relationship between humans and groundwater.

By the 1920s, the impacts of the turbine pump became manifest in the form of declining well productivity, lowering water levels and escalating pumping costs. An early documentation of the impact of overdraft on the productivity of wells in the Santa Clara Valley of California is shown in figure 6. As can be seen, well productivity declined by 86% over a period of two decades (Tibbetts and Kiefer 1921). Other consequences of this overdraft soon emerged. In 1933, routine geodesic surveys revealed that the land had subsided by as much as 1.2 m at San Jose, in the heart of the Santa Clara Valley (Rappleye 1933). Elsewhere in California, overdraft

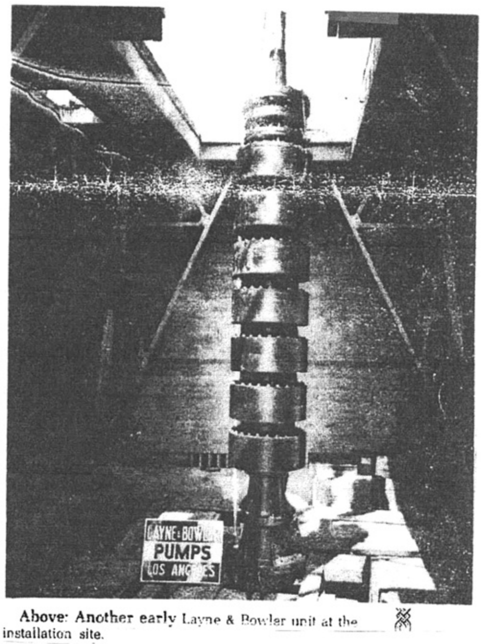

Figure 5. Multi-stage impeller assembly of an early deep-well turbine pump (courtesy of Pentair Inc.).

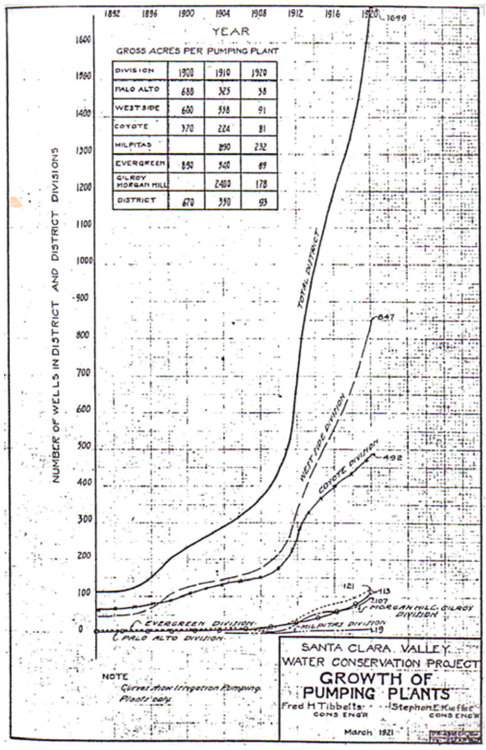

Figure 6. In the Santa Clara Valley of California, rapid increase in the number of pumped wells for irrigation of orchards led to well-productivity declines of 86% between 1900 and 1920 (Tibbetts and Kiefer 1921, Plate 7).

of groundwater from coastal aquifers, and the accompanying decline in groundwater levels, had led to landward intrusion of saltwater in freshwater aquifers (Division of Water Resources 1933).

Despite these indications of adverse environmental consequences, the first half of the twentieth century witnessed impressive growth in groundwater development around the world, aided by developments in drilling techniques, pumping technology and availability of electric motors and diesel engines to drive the pumps and lift water. At least in the short term, it appeared as though the technological conquest of groundwater was successful and permanent.

4. Scientific integration

In an atmosphere of vigorous developments in geology, hydrology, civil engineering, soil science, petroleum engineering and other branches of earth sciences, the first half of the twentieth century witnessed the emergence of groundwater hydrology as an identifiable discipline within the earth sciences. Oscar Meinzer (1923) of the US Geological Survey synthesized accumulating field evidence and historical developments to establish groundwater hydrology as a discipline in its own right, and elaborated on the relationships between plants and groundwater (Meinzer 1927).

A major development during the 1920s was the recognition that groundwater systems are inherently time-variant or transient, and that the steady-state assumption of Darcy and Dupuit was only a useful approximation. The importance of time in the understanding of groundwater systems was first pointed out by Meinzer (1928), based on studies of the Dakota aquifer system. Field observations had shown unequivocally that declining water levels (or hydraulic heads) in artesian wells were associated with the removal of groundwater from storage. Meinzer hypothesized that decreases in storage occurred in a deep water-saturated aquifer through a small decrease in porosity and a small expansion of water in response to declining water pressure. The mechanical explanation for the relationship between change in water pressure and change in porosity had been advanced by Terzaghi (1923), who devoted attention to deformation of clays and associated ground settlement due to water drainage. A decade later, Theis (1935) showed how groundwater flow problems involving time-dependent changes in water level and storage could be analyzed using partial differential equations. Soon thereafter, Jacob (1946) initiated the application of mathematical analysis to the study of leaky artesian aquifers involving inter-formational flow between aquifers and adjoining clay layers, as postulated earlier by Darton (1909).

Because of the coexistence of air, the physical processes governing movement of water in the unsaturated zone overlying the water table differ significantly from those governing groundwater movement. Buckingham (1907) showed that water movement in the vadose zone could be mathematically treated in a manner similar to Darcy's Law by introducing the concept of capillary potential. The device for physically measuring capillary potential (the tensiometer) was first introduced by Gardner *et al* (1922). These two developments enabled a unified mathematical analysis of groundwater and soil water.

Contemporaneously, substantial progress was being made in chemically analyzing groundwater and interpreting chemical data in terms of the geological environment. Chebotarev (1955a, 1955b, 1955c) noted that the anionic content of groundwater revealed much about the chemical processes to which the moving groundwater is subject. By the early 1960s, the field of hydrogeochemistry had advanced to the point of establishing that groundwater undergoes predictable chemical transformations as it migrates from oxygen-rich areas of recharge to oxygen-deficient areas of discharge, intimately interacting with the host geological materials (Hem 1959, Garrels 1960). Thus, the pattern of water quality variations over a groundwater basin, the distribution of soils and plants, and the mineralogical make-up of geological formations were all recognized to be dynamically interrelated.

The concept of regional, basin-wide groundwater movement was given a rigorous hydrodynamical explanation by Hubbert (1940), who defined a groundwater potential and interpreted Darcy's Law in terms of a balance between impelling and resistive forces. Our modern conceptualization of a groundwater basin as a transient three-dimensional system, driven by climate and gravity, crystallized during the early 1960s through the contributions of Back (1960, hydrogeochemistry), Toth (1962, topographic control) and Meyboom (1962, role of heterogeneity). A longitudinally symmetric intermontane groundwater basin with areas of recharge and discharge is shown in figure 7. The groundwater profile in a two-layered groundwater system of the Canadian Prairies, as inferred from field observations, is given in figure 8. Flow in the upper, poorly permeable glacial till is dominantly vertical, while flow in the underlying permeable sandstones is mainly horizontal.

Of the total annual precipitation falling on the Earth's land surface, 61–66% has been estimated to return to the atmosphere as evapotranspiration and is unavailable for human use (Shiklomanov 1997). For example, if we choose annual evapotranspiration to be 65% over the continents (Brutsaert 2005), the remaining 35% comprises surface water runoff and subsurface infiltration. Part of the subsurface infiltration returns to sustain base-flow in streams, while another part is returned to the atmosphere as evapotranspiration. Giving consideration to these, it may be reasonably assumed that, of the 35% excess of total precipitation over evapotranspiration, about two-thirds constitutes surface runoff while the remainder constitutes recharge to the groundwater reservoir below the water table. That is, total precipitation may be partitioned into 65% evapotranspiration, 25% surface runoff and 10% groundwater recharge, or equivalently, annually renewable groundwater resource. Clearly, these are imprecise estimates. Yet, they provide a useful conceptual picture of the relative magnitudes of the components of the annual water budget over land. This rough estimate of 10% groundwater renewability is constrained by climatic uncertainty in annual precipitation. Thus, the quantity of renewable groundwater will vary from year to year around this average.

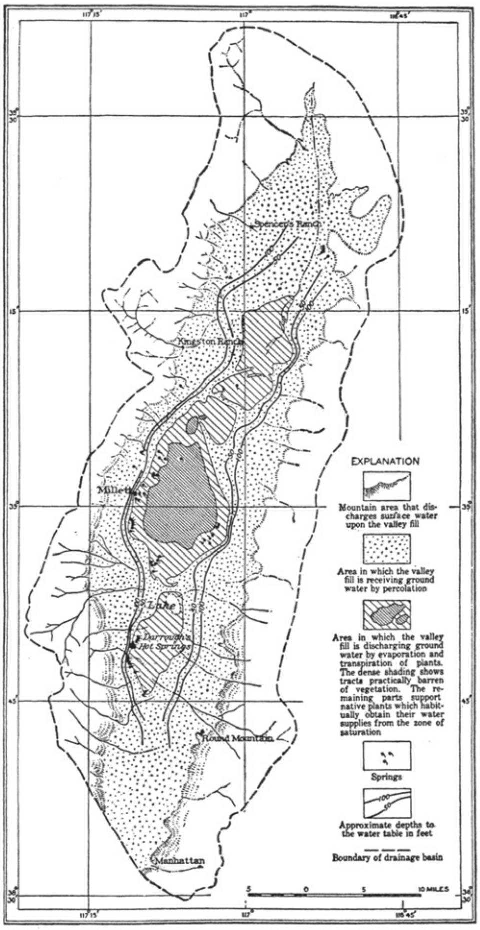

Figure 7. Northern drainage basin of Big Smokey Valley, Nevada showing areas of recharge (stippled) and discharge (hatched). Dense hatching indicates areas barren of vegetation due to excessive salt accumulation, surrounded by a zone of native phreatophytes (Meinzer 1942 p 415).

5. Unintended consequences

Despite indications of undesirable consequences of intensive groundwater production such as land subsidence and seawater intrusion, the first half of the twentieth century witnessed enormous growth in groundwater development for municipal, irrigation and industrial purposes. Impressive strides were made in groundwater exploration, drilling methods, well construction techniques and the mathematical theory of aquifer hydraulics. Until the 1960s, groundwater hydrologists were mostly concerned with exploring and developing hitherto undeveloped sources of groundwater and efficiently extracting the resource.

The publication of the book *Silent Spring* by biologist Rachel Carson in 1962 launched a vigorous environmental movement in the United States, drawing attention to adverse impacts of toxic pesticides on wildlife habitat. Soon, groundwater became an integral part of this environmental movement because groundwater accounts for over half of the freshwater needs of the United States. Inevitably, attention of groundwater professionals began to shift from production to protection of water quality, conservation and management.

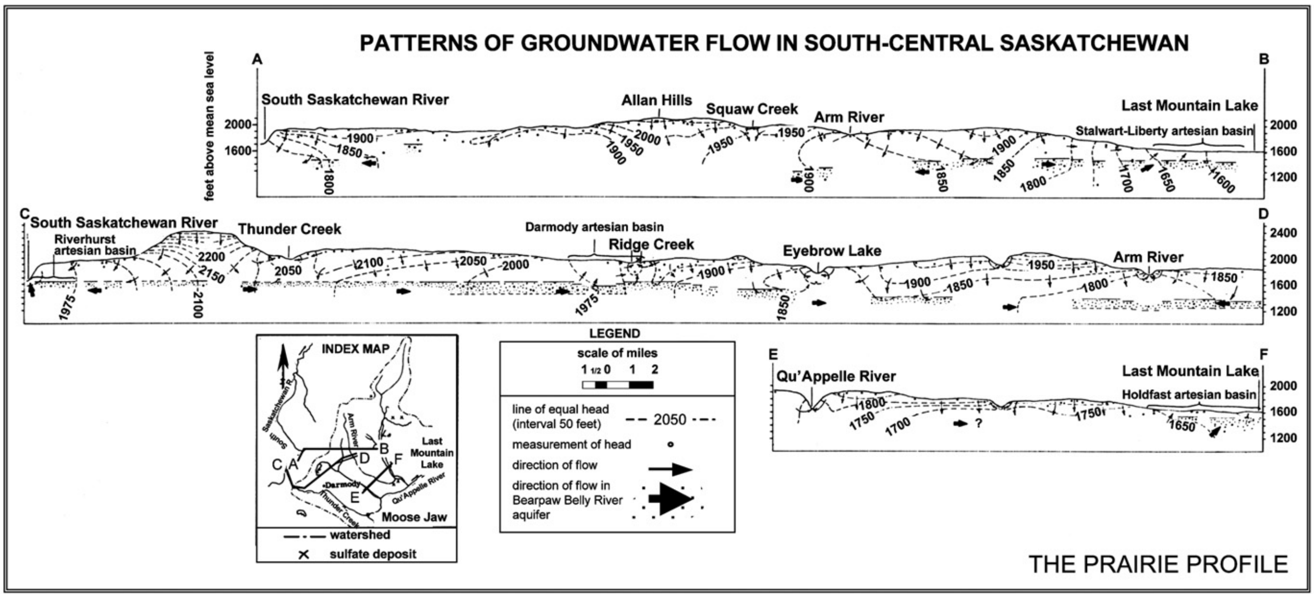

Figure 8. Patterns of groundwater flow in the Canadian Prairies. Regional flow pattern is governed by undulations in topography as well as permeability contrasts between the poorly permeable glacial till and the underlying, permeable sediments (Meyboom 1962).

For convenience, adverse impacts of groundwater development may divided into two categories: depletion or degradation of the groundwater resource, and environmental or ecological consequences.

5.1. Resource depletion

5.1.1. Physical principles. Within the groundwater reservoir, water is stored in the pore spaces of geological materials that it fills (or saturates). We shall use 'depletion' to denote a reduction in the quantity of water stored. If the depleted water has no prospects of being replaced in the foreseeable future, the action may be termed groundwater mining, and the abstracted water is referred to as non-renewable groundwater. In addition to these two concepts, a third concept, namely 'lost storage', is important and is described below.

Depletion can occur in different ways. In unconfined aquifers that immediately underlie the water table, depletion occurs as water physically drains from the pores when the water table falls, with porosity practically remaining unchanged. The process may be described as desaturation of pores. In such aquifers, if the same quantity of water that had drained from the pores is replaced, the water table will regain its original position. Thus, the space available for groundwater storage does not change, as long as enough water is available to fill the pores. In the case of unconfined aquifers, groundwater mining and non-renewability imply that existing climatic conditions cannot be expected to replace the abstracted groundwater in the foreseeable future. The most spectacular example of groundwater mining is the Great Man-Made River project of Libya, which pumps groundwater from the Nubian aquifer underlying the interior Sahara desert and transports it to coastal cities in the north via a 1900 km pipeline (Encyclopedia Britannica 2009).

In underlying confined aquifers, separated from the water table by confining layers, water does not physically drain from the pores because the pores always remain saturated with water. Whereas pore space available for water accumulation remains unchanged in an unconfined aquifer, in a confined aquifer change in groundwater storage occurs largely because of a decrease in pore volume. We say 'largely' because a small portion of the change in storage is accounted for by a slight expansion of water (Meinzer 1928). As water pressure falls in a confined aquifer, porosity decreases by a small amount and an equivalent volume of water (0.001%–0.01% of bulk volume) is released from storage. Generally, pressure can be restored to its original state by putting the same volume of water back into the system. When this is possible, the geologic material is said to be 'elastic'. However, when the geological material is subjected to unprecedented declines in water pressure (tens of meters of water level decline), it will behave in a 'non-elastic' fashion. That is, a greater reduction in porosity will occur when water pressure declines by a certain amount than when the pressure is restored to the original condition. Under such non-elastic deformation, a certain amount of porosity (groundwater storage) will be permanently lost (lost storage) when groundwater is extracted at rates causing large declines in water pressure.

Groundwater resource depletion is 'water-limiting' in the case of unconfined aquifers. That is, available groundwater storage space remains unchanged, provided enough water is available to replace water that has been removed. In the case of confined aquifer systems that are prone to inelastic behavior, depletion is 'space-limited' in the sense that some storage space will be permanently lost if production causes unprecedented pressure decline. The change in porosity of a formation per unit change in water pressure is variously referred to as 'compressibility' or 'specific storage'. Under elastic conditions, specific storage is a small number, varying generally from 0.000 01 in sandy materials to perhaps 0.001 in clayey materials. Under unprecedented pressure declines,

Table 1. Comparison of depletion of groundwater storage of five large basins in the United States.

Basin	Type	Area (km^2)	Period	Volume withdrawn (km^3) Total	Pore volume lost	Lost pore volume as % of total withdrawal
Dakota Aquifer System[a]	Confined	171 000	1880–1980 (100 years)	19.7	14.9	76
Atlantic Coastal Plain[a]	Confined	44 000	1891–1980 (89 years)	4.5	3.5	78
San Joaquin Valley[b]	Confined	9730	1925–1970 (45 years)	?	17.2	80 (?)
South Central Arizona[b]	Unconfined	8070	1915–1973 (58 years)	80.2	Negligible	Negligible
High Plains, Ogallala Aquifer[c]	Unconfined	443 000	1949–1997 (48 years)	243	Negligible	Negligible

[a]Konikow and Neuzil (2007); [b]Holzer (1979); [c]McGuire *et al* (2003).

specific storage may be greater by a factor of 10 or more compared to these values for elastic conditions (Konikow and Neuzil 2007). Thus, for repeated storage and recovery of groundwater, one has to rely on the storage space associated with elastic storage. Depletion associated with lost porosity is thus a one-time benefit.

Given these physical principles, it is worthwhile to examine the consequences of groundwater being a component of the hydrological cycle. Groundwater gets recharged by seasonal precipitation, and is discharged throughout the year through sustaining base-flow of streams, transpiration by phreatophytes and evaporation via the vadose zone. Because of these interactions, groundwater storage is continuously changing, diurnally, seasonally and progressively over longer timescales. A major portion of groundwater, extending to considerable depths beneath the water table, represents water that has accumulated over centuries or millennia or longer. On the other hand, a small portion of the water represents transient storage or storage that is changing in response to seasonal changes in precipitation. From the perspective of human needs, transient storage may be considered to be ‘renewable groundwater’, while water that has accumulated over centuries to millennia is ‘non-renewable’ storage. Clearly, storage that is lost permanently due to inelastic properties of geological materials is non-renewable storage.

5.1.2. Observational evidence. Large-scale groundwater abstraction leading to non-renewable groundwater storage can be attributed to the invention of the deep-well turbine pump, introduced in the United States during the first decade of the twentieth century. Data on groundwater extraction, water level declines and storage depletion on the timescale of a century are now forthcoming from the records and publications of the United States Geological Survey. Because of the uniqueness of these data and the remarkable insights they provide, a brief summary is pertinent.

Groundwater depletion data from five large groundwater basins in the United States are summarized in table 1. Of the five, three (Dakota sandstone, Atlantic Coastal Plains, San Joaquin Valley) constitute confined aquifer systems. In these, storage depletion includes a permanent loss of about 80% of storage space due to non-elastic deformation. The remaining two (South Central Arizona, High Plains Aquifer) constitute unconfined systems in which permanent water declines of several tens of meters have occurred over periods of decades. There is little likelihood that the storage depletion will be compensated by natural recharge in the foreseeable future. Clearly, groundwater has been mined from all these major groundwater basins, far in excess of renewability.

5.2. Environmental and ecological impacts

Intensive groundwater development in sedimentary basins can lead to different types of environmental impacts: land subsidence, seawater intrusion, base-flow reduction in perennial streams and deterioration of ecosystems.

Land subsidence due to groundwater pumping from confined aquifers was first discovered in the Santa Clara Valley, California in 1931 (Rappleye 1933). Meinzer (1937) suggested for the first time that the observed subsidence was a manifestation of volume reduction of strata from which water had been expelled as a result of groundwater pumping. Since then, land subsidence associated with groundwater overdraft has been reported from many parts of the world: Venice, Italy (Gambolati and Freeze 1973); Osaka, Japan, and Mexico City, Mexico (Poland and Davis 1969).

In aquifers of coastal sedimentary basins, regional motion of fresh groundwater is towards the sea, being driven by the high groundwater elevations of recharge areas. Close to the coast, the less dense fresh groundwater floats on the denser seawater. Because of poor mixing, the interface between freshwater and seawater remains fairly well defined. In a coastal area where there is very little groundwater development, the position of the seawater interface represents a balance between seaward forces of regional groundwater motion and landward forces of tidal fluctuations. If, because of groundwater production, water levels are drawn down significantly in wells in coastal aquifers, the resulting decrease in seaward forces will cause the seawater interface to migrate landward, causing deterioration in groundwater quality. Seawater intrusion caused by groundwater production has been documented widely from many parts of the world (Morris *et al* 2003).

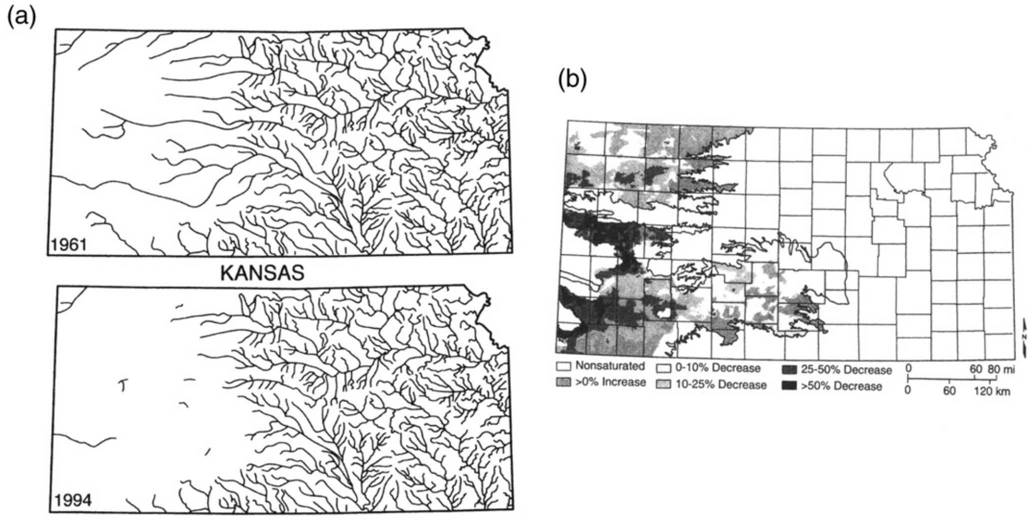

Figure 9. Impact of overdraft from the High Plains Aquifer on drainage pattern in western Kansas. (a) Drainage patterns of 1961 and 1994 and (b) decrease in unconfined aquifer thickness since onset of development through 1996 (Sophocleous 2000; composite of figures 2 and 9).

It is well recognized that base-flow in streams during non-rainy seasons is sustained by groundwater seepage. If the water table is lowered significantly due to groundwater production, it will cause a reduction in base-flow. In turn, reduction in base-flow has an impact on the riparian habitat. This linkage between groundwater production and base-flow reduction is well illustrated in the state of Kansas (area, 210 630 km^2). The large aquifer system known variously as the High Plains Aquifer, or the Ogallala Aquifer, underlies the western half of Kansas. The unconfined aquifer system has been subjected to intense groundwater development starting from the early 1960s, which led to water table declines of as much as 30 m by the 1990s (McGuire *et al* 2003). The impact of this water table decline (and associated saturated thickness of the aquifer) on the drainage pattern of Kansas is shown in figure 9. Many streams of the western half of the state that existed in 1961 disappeared by 1994. Obviously, the disappearance of these streams must seriously influence the associated riparian habitats.

5.3. Chemical contamination

In addition to overdraft, groundwater systems are particularly vulnerable to chemical contamination. Once contaminated, it is extremely difficult, if not impossible, to decontaminate them. The second half of the twentieth century has witnessed documentation of chemical contamination in shallow as well as deep groundwater systems due to various human activities such as seepage from landfills, agriculture, dairy farms, mine wastes, industrial effluents and septic tanks in rural areas (Morris *et al* 2003). Contamination from heavy metals and organic chemicals used as pesticides pose special public health concerns because these contaminants can be toxic even in such small quantities as parts per billion (Scheidleder *et al* 1999).

In combination, groundwater overdraft and chemical degradation lead to an overall decrease in the total available groundwater resource. Consequently, larger societal interest requires that this resource be managed judiciously and equitably.

6. Attitudes, ownership and law

The focus of civil law, with its roots in Roman law, has historically been on private ownership of property. During the sixth century AD, Roman jurists, assigned the task of codifying law by Emperor Justinian of Byzantium, were influenced by the Greek philosophy of reason (Birks and Mcleod 1987). They recognized that water, the air and the sea are vital needs for all humans and are governed by immutable physical laws. In contrast, human laws are subject to change with time. They deemed it unreasonable that these vital natural elements could be owned by individuals as private property. Accordingly, they divided material things into two categories, namely, those that could be owned as private property, and those that belonged to all. Thus, private property came within the domain of *jus civile* (or civil law), while vital natural elements came under *jus gentium* (or law of all peoples). The philosophy of *jus gentium* influenced the Magna Carta of thirteenth century England, and subsequently evolved into the doctrine of public trust that is generally accepted by western European countries and the United States as the guiding tenet for water ownership and management (Narasimhan 2008).

Starting from the 17th century, public ownership of water, as a consequence of the public trust doctrine (and, more broadly, *jus gentium*) has been well established in Spain, France, The Netherlands and England in Europe, and in the United States (Narasimhan 2008). However, an important constraint has been that public trust was restricted to surface waters and tidal lands on the coast. The ownership of groundwater within public trust was not clearly addressed. This lack of clarity with regard to groundwater did not cause much practical concerns prior to the turn of the twentieth century because humans were unable to extract large volumes of groundwater. The technological revolution of the turbine pump dramatically changed the situation.

As described in section 2 above, groundwater science began taking shape only during the first half of the nineteenth century. Not surprisingly, contemporary judicial opinions on groundwater ownership were based on the notion that groundwater was an occult, mysterious phenomenon not amenable to rational understanding (Acton v Blundell 1843). The general assumption was that all groundwater beneath the land belonged to the overlying land owner.

The thorny issue of groundwater ownership began demanding serious attention at the beginning of the twentieth century with the introduction of the deep-well turbine pump in California. Within a decade, productivity of wells declined alarmingly with concomitant decline in water levels. Mutual interference among wells producing from the same aquifer became clearly noticeable, and groundwater ownership litigation could no longer be addressed without quantitative scientific analysis. Thus, beginning in the twentieth century, judicial decisions began giving credence to scientific understanding of groundwater (Katz v Walkinshaw 1903). Groundwater was not anymore a mysterious phenomenon.

At present, the legal status of groundwater, especially in the arid western part of the United States, remains ambiguous. Although scientific knowledge clearly shows that surface water and groundwater are intimately interconnected, and that they have to be managed together, the legal status of groundwater is not the same as that of surface water. The latter is subject to public trust, while the former is not. The reason for this dichotomy is historical. During the nineteenth century, the immigrants settling a vast new land of the American west were granted legal rights to specified quantities of groundwater without scientific basis. Such rights continue to this day. Understandably, land owners enjoying the rights are unwilling to relinquish them.

At the beginning of the twentieth century, when disputes arose between neighboring land owners when well productivity declined during times of drought, the prevalent concept of absolute rights of the overlying land owner was supplanted by the principle of correlative rights (Katz v Walkinshaw 1903). Accordingly, overlying landowners proportionately share the burden of diminished yield.

While the legal status of groundwater still remains subject to litigation in the United States, many local communities have successfully taken control of groundwater within their jurisdiction and implemented integrated surface water and groundwater management. Examples include the Santa Clara Valley Water District, which supplies water to Silicon Valley (Reymers and Hemmeter 2001), and the Orange County Water District (OCWD 1993), both in California.

Outside of the United States, many countries have moved towards articulating, in their constitutions, the importance of water and the necessity to share it among all segments of the population. South Africa (South Africa 2006), New Zealand (New Zealand 2006) and Spain (Costejà *et al* 2002) are examples. The basic premise is that surface water, groundwater and ecosystems are interconnected components of the hydrological cycle. The Water Framework Directive of the European Union (European Commission 2000) has taken a unified view of surface water and groundwater, and has required that water law and policy be guided by an unifying framework of river basins. All the 27 member countries are required to prepare position papers on groundwater issues specific to their countries within the context of basin-wide water management so that due action can be initiated to ensure that all water within the Union attains good ecological status by 2015.

7. Where we are

Groundwater is no longer a mysterious phenomenon. We know it to be a component of the hydrological cycle, subject to well-established physical laws. It is a finite resource, vital for the survival of humans and other living things. Of the total quantity of freshwater stored in the groundwater reservoir, a small portion (less than ten per cent of annual precipitation) is replenished annually through recharge by precipitation. The remainder, accumulated over long time periods, may be considered non-renewable.

Only over the past 50 years or so have we begun to recognize that any diminution in the availability of groundwater can have a profound impact on human welfare. Reduced groundwater availability can occur either due to water extraction at rates exceeding annual renewability, or due to degradation of its quality that makes it unsafe for human consumption. There is serious concern among developed as well as developing nations that water in general, and groundwater in particular, cannot be expected to sustain arbitrarily high rates of economic, technological and population growth indefinitely into the future. Even maintaining stable conditions at the present levels or at very small rates of growth, groundwater has to be managed rationally and judiciously.

Meanwhile, the aforesaid concerns are compounded by the new and unexpected discovery of global warming. Concerns about global warming have begun to attract serious attention only over the past two decades. Regardless of whether it is caused by human action or not, there is compelling evidence that the Earth's climate is experiencing a warming trend. Global warming has direct implications on groundwater through the hydrological cycle. Changing patterns of precipitation and evapotranspiration will inevitably modify basin-wide groundwater flow patterns through changes in recharge–discharge relationships. Such modifications of groundwater flow patterns will occur on varying timescales and will have to be addressed on a site-specific basis. Nevertheless, there is one direct impact of global warming on groundwater that can be readily foreseen. This relates to coastal groundwater basins. If the sea level were to rise even by a few meters because of climate change, coastal aquifer systems around the world would become vulnerable to significant water quality degradation due to saltwater intrusion.

It is beyond dispute that groundwater management has to be based on scientific knowledge. However, science can only provide information on how the resource will respond to various developmental strategies. Optimal strategies that will result in maximum benefit to all segments of society and the environment must be based on social values that lie beyond the scope of science. Thus, science and management policy are inexorably interwoven.

Science cannot create groundwater. It can, through sophisticated instruments, continuously observe the response of groundwater systems to climatic changes and human activities, foresee changes in the availability of resource (quantity as well as quality) and guide sustainable resource use. Here, sustainability implies stable availability of the resource for present and future generations. The challenge to science is twofold. First, because of the difficulty of accessing geological formations below the land surface, and the complexities of earth structure, characterizing the attributes of groundwater systems in sufficient detail to reasonably quantify its expected behavior is beset with imprecision. Second, climate, which is the primary force driving groundwater systems, changes in unpredictable ways. Under the circumstances, the best that science can do is to continuously observe groundwater systems in adequate detail so as to monitor how the system is responding, whether it is being unduly depleted, how water quality is changing and whether associated ecosystems are impacted. Ongoing, consistent monitored information provides the basis for management choices.

The human challenge is to formulate and implement laws, statutes and policies that translate scientific knowledge into adaptive human behavior. Democracy is currently the preferred form of self-governance around the world. Commonly, democracy is associated with individual rights to basic needs of clean water, as well as the rights to accumulate personal property and wealth. In a finite Earth where demand for water outstrips available freshwater supplies, rights of individuals have to be balanced by collective responsibilities. Such a balance requires that groundwater is managed and equitably shared among all segments of society. In formulating laws, policies and statutes to ensure a balance between rights and responsibilities democratic institutions are facing tremendous challenges. Water is a source of economic and political power. Consequently, achieving a balanced path between rights and responsibilities is difficult.

In a thoughtful reflection on Earth resources, time and man, von Engelhardt *et al* (1975) stated,

> ‘Mankind is on the threshold of a transition from a brief interlude of exponential growth to a much longer period characterized by rates of change so slow as to be regarded essentially as a period of nongrowth. Although the impending period of transition to very low growth rates poses no insuperable physical or biological difficulties, those aspects of our current economic and social thinking which are based on the premise that current rates of growth can be sustained indefinitely must be revised. Failure to respond promptly and rationally to these impending changes could lead to a global ecological crisis in which human beings will be the main victims’.

Although this observation was made in the general context of Earth resources, it is equally applicable to groundwater. It is encouraging to note that there has been a gradual move in the United States, Europe and elsewhere towards implementing statutes and policies that would ensure scientific management of groundwater in conjunction with surface water. Much remains to be done to establish the scientific institutions needed for sustained monitoring of groundwater systems in adequate detail to facilitate rational management. Human behavior under stress is hard to predict. Hopefully, democracy will, in the future, evolve beyond rights into responsibilities, and pave the way for enlightened groundwater management. When that happens, the ‘*jus gentium*’ vision of the sixth century Roman jurists will have been attained.

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