The International Scale of the Groundwater Issue 2

Michael N. Fienen and Muhammad Arshad

Abstract

Throughout history, and throughout the world, groundwater has been a major source of water for sustaining human life. Use of this resource has increased dramatically over the last century. In many areas of the world, the balance between human and ecosystem needs is difficult to maintain. Understanding the international scale of the groundwater issue requires metrics and analysis at a commensurate scale. Advances in remote sensing supplement older traditional direct measurement methods for understanding the magnitude of depletion, and all measurements motivate the need for common data standards to collect and share information. In addition to metrics of groundwater availability, four key international groundwater issues are depletion of water, degradation of water quality, the water-energy nexus, and transboundary water conflicts. This chapter is devoted to introducing these issues, which are also discussed in more detail in later chapters.

2.1 Introduction

Throughout history, groundwater has been a major source of water for sustaining human life. Because it is buffered from short-term variability in weather patterns, groundwater has often been considered a stable and reliable resource. With the advent of efficient pumps and rural electrification, global groundwater extraction increased from 312 km^3/year in the 1960s to 743 km^3/year in 2000 (Wada et al. 2010); approximately 70 % of this extraction is used for agriculture. About half of domestic human water consumption in urban areas is from groundwater

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M.N. Fienen (✉) • M. Arshad
US Geological Survey, Wisconsin Water Science Center, Middleton, 53562, Wisconsin, USA
e-mail: mnfienen@usgs.gov

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(Giordano 2009). With increased water use comes a related possibility of local, regional, and international conflict over groundwater resources.

Groundwater, surface water, humans, and ecosystems are all interconnected in ways that necessitate an integrated approach to management. To manage in this way requires an understanding not only of the component aspects of the problem but also of the components' interconnections. See Chap. 1 for a comprehensive list and description of the dimensions of an integrated approach. Determining the scope of these issues, a first dimension, is challenging on a global scale, primarily because groundwater systems themselves are not all connected, and each system has its own characteristics; thus, any measurements of a specific system reflect specific local conditions, making extrapolation from data-rich to data-poor regions problematic. In contrast to measurements of streams which can integrate information over an entire watershed, point measurements of groundwater conditions commonly reflect a smaller land area, requiring more measurements to evaluate a comparable region. Remote sensing techniques such as the Gravity Recovery and Climate Experiment (GRACE) satellite provide information over larger areas, but they also require site-specific calibration information and are more accurate for determining changes than for assessing conditions at a certain time. A realistic picture of global conditions, then, must be based on aggregation of data from a variety of widely distributed organizations, many of them local in focus. These data must also be used with modeling techniques to obtain estimates of groundwater conditions.

Once information from observations and models is assembled, metrics that allow comparison among regions can be developed to guide management. These metrics are typically based on water balance computations, which in turn are based on estimates of human extraction and returns, removal from storage, water required for ecosystem services, and natural replenishment. The management challenge then becomes making the difficult choices regarding the level of sustainability required, because the relationship of humans to groundwater resources differs from place to place.

Four key international groundwater issues are depletion of water, degradation of water quality (see also the devoted coverage in Chap. 15), the water-energy nexus (Chap. 4), and transboundary water conflicts (Chap. 6). In the context of these issues, technical challenges abound in attempting to understand and quantify current impacts and resources, even more so in attempting to plot a way forward. Yet, some advances in understanding are being made, and common threads of challenges related to scale, governance, and the need for integrated data also provide opportunities to impact multiple issues with each advance.

Depletion is a major groundwater issue, but the definition of depletion is not completely obvious and has changed over time. Dating back to 1915, concepts of *safe yield* in relation to groundwater were proposed. Originally, a balance was sought between groundwater extraction and replenishment by recharge such that extraction could continue in equilibrium. This early definition did not incorporate transient conditions, nor did it consider ecosystem impacts (as covered in Sect. 2.3, Chaps. 12 and 13). The concept of depletion has since evolved into one that acknowledges sustainability and integrated water management, but a true accounting of depletion also must embrace socioeconomic considerations (as covered in

Sect. 2.4, and Chaps. 20 and 21). Depletion is still typically measured by decreases in groundwater levels and decreases in baseflow or levels in connected surface water bodies and degradation in water quality.

Degradation of water quality falls into two broad categories (Chap. 14): that due to natural conditions and that due to anthropogenic causes. Both forms of degradation can result from human extraction of groundwater. Extraction or changes to recharge can alter groundwater flow directions or expose aquifer material to air, allowing for previously clean water to encounter natural contaminants such as radium, salt, arsenic, and fluoride and resulting in poor water quality and associated health impacts. On the other hand, chemical and biological contaminants emanating from industry and agriculture also cause water quality degradation.

As expounded in Chap. 4, the water-energy nexus is an integrative issue with feedbacks among water extraction, water quality, and energy production/consumption. Declining water levels due to extensive extraction lead to increased lift required by pumps, thereby increasing the amount of energy required for irrigation and domestic use. Exploration for new energy sources—for example, shale gas—also has the potential to create groundwater contamination from various activities associated with its production, such as during hydraulic fracturing and deep disposal of drilling fluids.

Transboundary aquifers (Chap. 6) have often been cited as potential hotspots of global conflict. Many aquifers are bounded by the borders of a single country so, whereas internal conflicts arise and can be substantial, they are less likely to be violent than conflicts between nations. Exceptions include the Nubian Aquifer in North Africa and aquifers in the Israel/Palestine region. Conflicts less intense than war nonetheless occur within nations at scales ranging from individual ranches to larger regions. Dire predictions of wars over groundwater resources have been made for many years, and although some violence has occurred, extraordinary cooperation has sometimes been motivated by mutual need for groundwater resources. Uncertainties related to groundwater resources—in contrast with surface water systems—may increase the likelihood of future conflicts.

In this chapter, we explore each of these integrated issues more deeply. We also discuss technologies and techniques for better understanding them. The goal is to highlight the need for integrated management and to set a conceptual framework for the discussion and potential solutions described in more detail throughout the book.

2.2 The Concept of Groundwater Depletion

When evaluating the international scale of the groundwater issue, it is important to establish what makes groundwater an issue in the first place. Understanding concepts of sustainability, safe yield, and depletion are central to this. These concepts guide definitions of where groundwater stresses are important.

A parallel evolution in thinking has occurred in the last 100 years regarding (1) the connections between surface water and groundwater and (2) the importance of water provided to ecosystems. Despite previous misconceptions of “safe yield” (for example, using calculations of recharge as a basis for allotting an amount of water that can be “safely” extracted from a groundwater basin), it has become more widely accepted that discharge to streams, springs, etc., is often the limiting water balance element. With regard to ecosystem services, the concept of “safe yield” has evolved to “sustainability,” augmenting consideration of undesirable economic impacts of depletion with the maintenance of discharge flows at levels that support ecosystem dependence on surface water and groundwater from aquifers.

As early as 1915, the term “safe yield” (Lee 1915) of a groundwater basin was used to define “the net annual supply which may be developed by pumping and Artesian flow without persistent lowering of the ground-water plane.” Subsequent work (Todd 1959) made a more general definition as “the amount of water which can be withdrawn from it annually without producing an undesired result.” Two important aspects of this definition warrant further scrutiny.

First, the specific source of water needs to be understood to evaluate whether withdrawals are balanced with sources. In Lee’s original definition, the entire water balance was considered, and it was acknowledged that often the source of water to pumping wells is the interception of discharge to surface water bodies rather than the collection of recharge. The early workers (Lee 1915) stated that “It is obvious that water permanently extracted from an underground reservoir, by wells or other means, reduces by an equal quantity the volume of water passing from the basin by way of natural channels.” Work by Theis (1940) and others also highlighted the importance of intercepted discharge to surface water or evapotranspiration as more significant than collection of recharge. However, over time, the importance of intercepted discharge was neglected and focus on balancing recharge with pumping became a popular definition of safe yield—including codification in legislation in some parts of the United States (Sophocleous 1997). This oversimplified concept has been called the “water budget myth” (Bredehoeft et al. 1982; Bredehoeft 1997; Sophocleous 1997).

Conservation of mass is a tenet of science, formally dating back to 1748 (Hockey et al. 2007), so the establishment of water budgets is a natural approach to assessing groundwater availability. Simply by accounting for inputs (through recharge and regional flow) and outputs (natural discharge to surface water, evapotranspiration, and anthropogenic extraction) and the change in storage, the amount of available groundwater can be established. Prior to pumping, the groundwater system is typically in dynamic equilibrium, with storage being constant and the sum of all inputs equal to the sum of all outputs. If a new stress acts on the system, either recharge must increase, discharge must decrease, or water must be removed from storage. It is uncommon for pumping to be accompanied by an increase in recharge from precipitation, so the change must result from some combination of a decrease in discharge or removal of water from storage. As water is removed from storage, the groundwater surface—the water table in unconfined aquifers or the potentiometric surface in confined aquifers—drops, which can increase the cost and difficulty of removing water through pumping. Through a dropping water surface, directly intercepted discharge, or a combination of those two effects, streams and springs can be reduced in flow or completely dried up. Removal of water from storage is referred to as "mining" or "overdraft," and some water is always mined before a new equilibrium is achieved after the addition of a stress such as human extraction through wells (Theis 1940). In the extreme, if all water is removed from storage, a groundwater basin could be, for practical purposes, depleted. A challenge for integrated groundwater management is to understand the sources of water where extraction is planned and to appropriately account for the deficiencies caused by extraction.

Second, in the 100 years since Lee's work, the concept of what is an undesired result has evolved significantly. Meinzer (1923), in the decade following Lee's work, in fact did not indicate specific undesired results, but rather defined safe yield as "…the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." At that time, as noted by Reilly and coworkers (Reilly et al. 2008), indoor plumbing was not widespread in the United States and the population was dispersed. It was natural, then, that the feasibility of future *human* consumption would guide concepts of preserving future use. Another widespread attitude of those times was that water flowing to springs or lost to evapotranspiration was "wasted" (Lee 1915). More recently, ecosystem health has been recognized as an important consideration for current and future use, and the dialogue has shifted from a concept of "safe yield" to one of "sustainability" (Alley and Leake 2004). Sustainable development was coined as part of the development that "…meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). This broad definition is meant to encompass not only the economic needs of future generations but also the health of the ecosystems they depend upon. When viewed in this framework, groundwater use must be balanced not only with the ability of an aquifer to continue supplying water to wells for human consumption but also with the capacity to maintain discharge to surface water, phreatophytic vegetation, and other habitats that make up the ecosystems surrounding and connected to the groundwater system.

It is clear that managing groundwater in a way that does not deplete the source of water or displace water from *all* dependent ecosystems—including humans—is a technical challenge. Some impact is inherent in the disruption of natural equilibrium through human activity—the challenge is to establish an agreed-upon acceptable level of disruption. Pierce et al. (2012) propose a continuum approach that balances socioeconomic, ecosystem, and sustainability constraints. Recently, Werner et al. (2013b) evaluated and ranked occurrences of mega storage depletion worldwide in terms of physical processes and the importance of the resource. Such nuances in definition and approach can pose challenges in coming to agreement among stakeholders (Llamas 2004), but the result of concurring on a definition and approach is much better management of the resource, tailored to the specific environmental and socioeconomic needs of a specific area. Giordano (2009) highlights this complexity noting that groundwater mining in Libya and Saudi Arabia, although unsustainable by most strict definitions, may provide socioeconomic benefit with little or no ecological impact that outweighs the downside of acknowledged depletion that is taking place.

By taking into account water quality, aquifer salinization (Chap. 16), risk of sea water intrusion, and subsidence issues, Konikow and Kendy (2005) described depletion as a physical process that renders reduction in the total or usable volume of the resource. Thus, depletion leads to consequences realized or perceived to be negative for the current and future use of the resource. Consequences of depletions such as salinization can be substantial, because it commonly is very time and resource expensive to bring a degraded aquifer back to its natural state. Further, some impacts—such as subsidence—can be irreversible (Zektser et al. 2005).

Today's nuanced understanding of differences in source from recharge, discharge, and storage is generally well documented and supported in the scientific literature. Yet, the water budget myth persists where science meets policy because it is much simpler to use a single metric—"recharge"—to regulate how much water may be extracted from an aquifer without undesired consequences without regard to the importance of timescale (Harou and Lund 2008). Many of the metrics available to document depletion must pass over these nuances to apply at a large scale and still rely on balancing recharge with human extraction—including metrics referred to in this chapter. Although the concept of sustainability has made its way into the dialogue through acknowledgement that ecological flows should be maintained, the recommended solution still often seems to be regulating pumping rates at less than or equal to recharge rates (ASCE 2004; Beck 2000).

2.3 Groundwater Depletion Globally

Groundwater demands for consumptive and environmental uses are expected to grow, while supplies will remain constrained by unsustainable use of the aquifers. In the last five decades, economic gains from groundwater use have been substantial, but they have been realized at high social and environmental costs (Custodio 2002; Birol et al. 2010). Groundwater levels in many places have already dropped and are further dropping in response to excessive extraction. Adverse effects of overdraft have been observed in many places in the forms of reduced flows in streams and wetlands, stream-aquifer disconnection, water quality degradation through intrusion of saline or poor-quality surface or groundwater, reduced availability of groundwater for consumptive uses, land and aquifer subsidence, and increased costs of pumping. Recent studies have also quantified the contribution of groundwater depletion to sea level rise, accounting for as much as 13 % in recent years (Konikow 2011; Wada et al. 2012)

2.3.1 Global Estimates of Groundwater Extraction

Giordano (2009) reported global groundwater extraction in excess of 650 km^3 per year (Fig. 2.1), with India, the United States, China, Pakistan, Iran, Mexico,

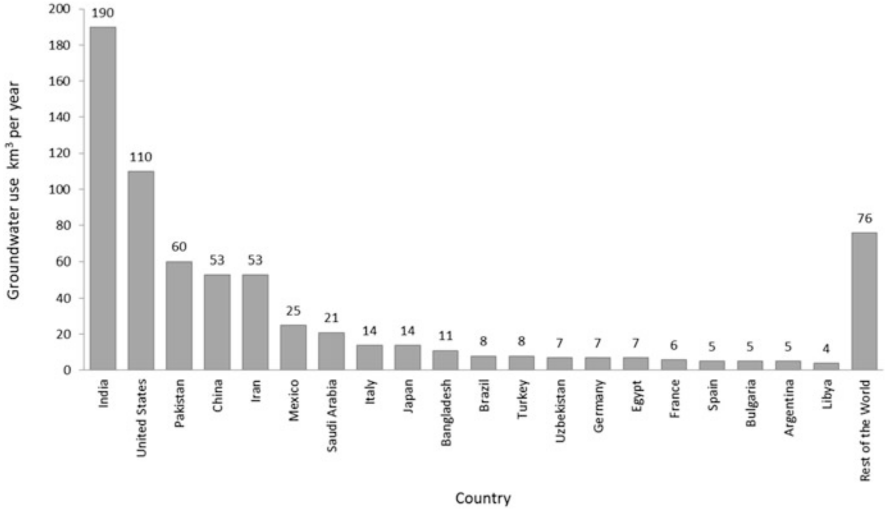

Fig. 2.1 Groundwater use by country, in cubic kilometers per year (Adapted from Giordano (2009))

and Saudi Arabia collectively accounting for 75 % of the global annual water extraction.

The GRACE analysis reports an approximate doubling of global groundwater extraction between 1960 and 2000. From 1960 to 2000, global groundwater annual extraction increased from 312 km^3 in 1960 to 734 km^3 in 2000. Major hot spots of depletion were observed in arid and semiarid parts of the world, mainly resulting from high population density, heavy reliance on groundwater, little and highly variable rainfall that generates quick runoff, and low rates of natural recharge. For subhumid and arid parts of the world Wada et al. (2010), prepared a global map of groundwater depletion by calculating the difference between global groundwater recharge and groundwater extraction for the year 2000. Hot spots of groundwater depletion were reported in the northwest of India, northeast of China, northeast of Pakistan, and in the High Plains and California Central Valley aquifers in the United States. Other countries where depletion was significant included parts of Iran, central Yemen, and southern Spain. The total global groundwater depletion in those areas was reported as 283 (±40) km^3 per year (Wada et al. 2010). Using an index based approach, Werner et al. (2013b) reported mega storage depletion cases around the world from more than 50 published sources. The largest depletion indices were reported for China, Spain, and the United States.

2.3.2 Global Depletion Examples

Depletion is typically measured by decreases in groundwater levels and decreases in baseflow in surface water bodies that are connected to aquifers. Regions where depletion has been significant as quantified through the best available scientific information include south and central parts of Asia, north China, the Middle East and North Africa, North America, parts of Australia, and many localized areas in southern Europe. In the United States, about 700–800 km^3 of groundwater has been depleted from aquifers in the last 100 years (Konikow and Kendy 2005). In the Fuyang River Basin in the North China Plain, the water surface has dropped from 8 to 50 m during 1967–2000 (Shah et al. 2000). In India, consumptive uses are depleting the groundwater reserves of Rajasthan, Punjab, and Haryana at a rate of or 17.7 ± 4.5 km^3/year. Similarly, a volume of 143.6 km^3 of groundwater was depleted during the period 2003 and 2009 in the in the north-central Middle East, including portions of the Tigris and Euphrates River Basins and western Iran (Voss et al. 2013).

Next we provide an overview of the major depletion examples; the cases discussed are representative and not an exhaustive inventory of the global depletion cases. More details of the global depletion cases can found in Konikow (2011), Morris et al. (2003), Wada et al. (2010) and Werner et al. (2013b).

2.3.2.1 High Plains Aquifer, United States

In the United States, 60 % of irrigation relies on groundwater. The High Plains (HP) aquifer is one of the largest freshwater groundwater systems in the world, covering eight states and encompassing over 450,000 km^2 in area. The HP aquifer is the most intensively used aquifer in the United States, responsible for nearly one-third of the total groundwater extraction, and it provides drinking water to nearly 2.3 million people residing within in the boundaries and vicinity of the aquifer system (Dennehy et al. 2002). Groundwater is considered as the major economic driver for the HP region, known as the “breadbasket of the United States” and annually contributing US $35 billion of the US $300 billion in national total agricultural production in 2007 (Scanlon et al. 2012a).

On the basis of groundwater monitoring data from 1950 to 2007 from 3600 wells, Scanlon et al. (2012a) estimated that 330 km^3 of groundwater was depleted from the HP aquifers. This storage decline in the HP aquifer accounts for nearly 36 % of the total groundwater depleted in the United States during 1900–2008 (Scanlon et al. 2012b). If the depletion were assumed to be uniform throughout the HP aquifer, the corresponding drop in water surface over the entire HP region would be 4 m.

The effects of depletion in terms of water surface decline are highly variable spatially. For example, recent groundwater monitoring from GRACE, (Scanlon et al. 2012d) indicates almost negligible depletion and water surface decline in the northern HP (Nebraska, 0.3 m), concurrent with much greater decline in the water surface in the central HP (Kansas, 7 m) and the southern HP (Texas, 11 m). In localized pockets of the southern HP and large areas of Kansas and Texas, a decline of more than 30 m was observed over 17,000 km^2, where the ratio of the rates of extraction to natural recharge was found to be 10 and greater. Large variation in the depletion is primarily due to a decrease in natural recharge from north to south but partially due to the amount of water pumped from the aquifer. A common view of the HP aquifer is that it contains old water that has been mined and depleted continuously since 1950s. Groundwater age dating indicates that some of the fossil water in the central and south HP aquifer was recharged as long ago as 13,000 years. Policy implemented to control groundwater use in the HP is described in Chap. 21.

2.3.2.2 Northwestern India

India has become the largest consumer of groundwater at the global scale with an estimated total annual consumption of 230 km^3 per year, or about one-fourth of the total global groundwater extraction annually. The annual replenishable groundwater resources of India are estimated as 433 km^3, with net availability of 399 km^3 (Chatterjee and Purohit 2009). India's apparent groundwater surplus can be misleading because of large variation across regions in terms of groundwater availability and extraction, as well as natural recharge. This imbalance of pumping and natural recharge has placed several aquifers in a state of overexploitation and many under semicritical and critical categories (Rodell et al. 2009).

In comparison to the only 20 million ha of land irrigated with surface storage, the irrigated area fed by groundwater now exceeds 45 million ha. Production returns from groundwater irrigation are almost twice those of surface water irrigation because of high reliability and cheaper access. About 70 % of India's agricultural production is generated through use of groundwater (Fishman et al. 2011). The economic value of groundwater irrigation in India in 2002 was estimated at US $8 billion per year (World Bank 2010). Groundwater is a primary source of drinking water supplies for rural villages and a growing number of urban areas. A major portion (85 %) of rural drinking water supply comes from groundwater.

The exploitation of groundwater in many states of India has expanded over the last five decades through installation of millions of irrigation wells (Shah 2009). And the scale of resource exploitation has accelerated in the last two decades. The number of tubewells was less than a million in 1980, jumped to 8 million in the mid-1990s, and exceeded 15 million by 2010 (Shah et al. 2012). In addition to cheaper pumps and low well installation costs, electric power subsidies to farms have played a pivotal role in the phenomenal growth of tubewells and overexploitation of groundwater in 16 major states of India. The flat power tariff reduced the marginal cost of pumping groundwater to near zero (Shah et al. 2012).

Because of the heavy reliance on groundwater for consumptive uses in India, the resource is now approaching its critical limit in some states. The national groundwater assessment in 2004 indicated one-third of India's aquifers fall in the overexploited, semicritical, or critical categories (Rodell et al. 2009). An increasing number of aquifers in northwestern India have reached unsustainable levels of exploitation. In the northern state of Punjab, groundwater in 75 % of the aquifers is overdrawn; in the western Rajasthan state, the corresponding fraction is 60 % (Rodell et al. 2009; World Bank 2010). The potential social and economic consequences of groundwater depletion are serious because aquifer depletion is concentrated in densely populated and economically productive areas. The implications can be serious for achieving food security and sustaining economic growth and environmental quality.

2.3.2.3 Northeastern China

In China, significant shifts toward groundwater dependency have occurred over the last 50 years (see Chap. 19 for a comprehensive overview of Integrated Groundwater Management in China). The installation and use of tubewells across China has increased dramatically, from 150,000 in 1965 in all of China to 4.7 million by the end of 2003 (Wang et al. 2007). In many parts of the country, groundwater levels have been falling at astonishing rates, often more than one to tens of meters per year. Overdraft occurs in more than 164 locations across 24 of China's 31 provinces, affecting more than 180,000 km^2 (Werner et al. 2013b).

Aquifers of the North China Plain (NCP) play a central role in China's food production. The region supplies nearly half of China's wheat and one-third of other cereal grains. The NCP covers 320,000 km^2 and is home to more than 200 million people. In the NCP, groundwater overexploitation for agricultural, industrial, and urban uses began in the early 1970s and became a serious problem after the 1980s with more intensive groundwater extraction. The negative impacts of overexploitation became evident during the 1990s in many parts of the NCP with rapid declines in water levels in both unconfined and confined aquifers. Cones of depression in the potentiometric surface have developed and expanded, with decreases in storage causing subsidence and water quality degradation associated with water surface declines. Groundwater depletion has led to seawater intrusion into the freshwater aquifer system; for example, in the coastal plain of Laizhou city, lateral sea water intrusion into the fresh aquifer system has increased from 50 m per year in 1976 to more than 404.5 m per year in 1988 (Changming et al. 2001). Groundwater depletion has salinized 44 % of the total area between the coastal plain and the city. The Chinese government has implemented a series of water-saving initiatives such as water efficiency in irrigation techniques, water pricing and groundwater licensing, and similar measures. However, the lack of information on volumetric groundwater extraction and limited groundwater monitoring networks make groundwater management challenging.

2.3.2.4 Middle East and North Africa (MENA)

From the standpoint of declining water availability, the Middle East and North Africa (MENA) region is considered by many to be the most water-scarce region of the world. The MENA countries possess annual renewable water resources of 1274 m^3 per capita—the lowest in the world—making the region the most water stressed globally by this metric. MENA is home to about 6 % of the world's population, consisting of 22 countries with 381 million people. And the population is projected to reach nearly 700 million by 2050 (Droogers et al. 2012). Population densities in MENA are largest where irrigation systems are present, including the Nile Delta in Egypt, the central part of Iraq, and Iran (Abu Zeid 2006).

Countries and small territories in the MENA region such as Bahrain, the Gaza Strip, Kuwait, Libya, Oman, Qatar, Saudi Arabia, the United Arab Emirates (UAE), and Yemen have few renewable water resources and heavily rely on groundwater and desalination for most of their supply. The region has some 2800 desalination plants that produce about 10 km^3 of freshwater annually, representing about 38 % of global desalination capacity.

Other countries in MENA such as Egypt, Iraq, Iran, Jordan, Lebanon, the West Bank, Sudan, and Syria get much of their water from river systems but at the same time depend on groundwater for supplemental use. Aquifers in MENA contain both renewable and fossil water. Many countries in the region are depleting groundwater at a rate that exceeds recharge. For example, the ratio of annual groundwater extraction to the estimated recharge exceeds 3.5 in Egypt, is about 8 in Libya, and is 9.54 in Saudi Arabia (Michel et al. 2012). GRACE data (Voss et al. 2013) show that a volume of 143.6 km^3 of groundwater was depleted during the period 2003–2009 in the north-central Middle East, including portions of the Tigris and Euphrates River Basins and western Iran.

In Chap. 24 of this book, the scale of the groundwater-dependent economy in Algeria, Morocco, and Tunisia is discussed. These three countries in North Africa have a high reliance on groundwater for irrigated agriculture, with more than 1.75 million ha of farmland and probably more than 500,000 farm holdings. Algeria's 88 %, Tunisia's 64 %, and Morocco's 42 % of irrigated land rely on groundwater resources. The official figures reported in Chap. 24 indicate that more than half the aquifers in Algeria and Morocco and about one-quarter of the aquifers in Tunisia are overexploited.

2.3.2.5 Australia

Groundwater resources are of great socioeconomic and environmental significance for Australia. The Great Artesian Basin (GAB) is the largest groundwater aquifer system in Australia and underlies 22 % of the Australian continent. The GAB includes considerable areas of the states of Queensland, New South Wales, the Northern Territory, and South Australia. Limited available information on the potential of the GAB resource indicates that nearly 60,000 km^3 of water is contained in the GAB. Groundwater in Australia is pumped mainly from unconfined aquifers, and there is increasing concern regarding the potential impact of groundwater depletion on the sustainability of the resource.

Because of limited and highly variable surface water availability, groundwater use for irrigation has substantially increased in Australia. From the National Land and Water Resources Audit (2001), Khan (2008) reported a 90 % increase in groundwater use across Australia between 1985 and 2000. At present, the volumes of water pumped from aquifers are much greater than natural recharge (Nevill 2009). In many parts of Australia, overdraft from the aquifers is resulting in falling groundwater levels in the shallow unconfined systems and decreasing groundwater pressures in the deep confined and semiconfined systems (MDBA 2012). Many aquifers in the Murray Darling Basin in particular are showing negative socioeconomic and environmental effects as a result of overdraft from aquifers. In many coastal aquifers, saline seawater has intruded to the fresh groundwater aquifers; thus, degradation of groundwater quality is further undermining use of the already scarce resource. A detailed account of saltwater intrusion in Australia and elsewhere is provided in Chap. 16.

2.3.2.6 Techniques for Assessing Groundwater Depletion

Data assimilation of water level fluctuation is the most direct and simplest method to estimate the volume of water depleted from an aquifer. The technique integrates head changes over the aquifer area and multiplies the obtained area by a representative aquifer storage factor to yield an estimate of storage depletion. Major challenges confronted by this simple technique are to establish large-scale monitoring networks and to collect water level data over large areas at regular time intervals. Maintaining a large-scale groundwater data base and keeping the data updated are costly and complex tasks. Community data integration—such as the Incorporated Research Institutions for Seismology (IRIS 2013)—combines centralized data serving with common data standards. Although Aquastat (FAO 2013) is an example of serving water information internationally, it does not include seamless data integration as does IRIS and has limited data on the spatial distribution of groundwater storage and water levels. Particularly in developing countries, advances in data integration will enable managers and researchers to work with more complete information to assess and manage groundwater resources. See Chap. 27 which is devoted to advances in integrated data management.

Even with the great advances in other techniques discussed in the following paragraphs, personal communication with various governmental agencies and ministries remains the most robust and definitive method of assessing groundwater levels and, thus, depletion. Efforts at personal communication can run up against cultural and language barriers—including the desire of some governments to treat water data as strategic and secret (Voss et al. 2013)—and can be very tedious and time consuming. Without organizing community efforts and common data standards, compiling data on the regional scale often requires many late-night phone calls and individual persistence (Fan Y (2013), Personal Communication). Such long-term individual effort can lead to a snapshot in time on conditions at the continental scale (Gleeson et al. 2011) and the global scale (Fan et al. 2013); but without a time series, depletion values cannot be easily obtained. This challenge is less acute for aquifers that fall under a single government's management authority but is exacerbated in transboundary aquifers.

In the United States and Canada, efforts have been made to adopt the Groundwater Markup Language (GWML, (Boisvert and Brodaric 2011)) to unify data among agencies and organizations within both countries. The First Groundwater Interoperability Experiment (Open Geospatial Consortium Inc. 2011) worked toward harmonizing groundwater data across the border between the two nations. In the Second Groundwater Interoperability Experiment (Open Geospatial Consortium Inc. 2013), Australia and Europe are joining the effort. This progress represents steps down a path toward consolidating data and enabling evaluation of conditions on a global scale, but large gaps of information still remain for many areas (Fan et al. 2013).

Even though direct regional groundwater depletion estimates can be integrated to provide global depletion estimates, groundwater data collection and data interpretation are subject to a high level of inconsistencies across countries and regions.

When groundwater data are of questionable quality, information generated through such data tends to be less reliable. This is why the magnitude of depletion is imperfectly assessed and poorly documented at the global scale (Giordano 2009). The water balance approach uses a number of scientific methods to estimate and account for various types of recharge and discharge processes to estimate groundwater storage differences and depletion over specific periods. Numerical simulation models based on water balance calculations have been helpful to estimate net groundwater removed from an aquifer. But the accuracy of the model to predict depletion depends on the quality of hydrogeological data provided as input to the model. Recent advances in the development of three-dimensional hydrogeological models have made it possible to provide better representation of the aquifers, underlying geological formations, and the processes that link the groundwater system both to surface water in general and ecological processes specifically. Examples include HydroGeoSphere (Therrien et al. 2012), GSFLOW (Markstrom et al. 2008), and MIKE SHE (DHI Software 2012). Three-dimensional modeling enables more detailed estimates of depletion and impact on surface water, but it remains limited by the data. At the continental and global scales, models of recharge processes and groundwater flow are typically data-driven, with relatively simple treatment of the physics integrated over coarse grids (Cao et al. 2013; Fan et al. 2013; Scanlon et al. 2006; Wood et al. 2011).

In practice, direct measurement of groundwater depletion at the global scale is imperfect. The imperfections arise because of insufficient groundwater monitoring data networks and inconsistent data collection and reporting standards. Another challenge arises when the depletion process is viewed from multiple dimensions, leading to different definitions of the depletion process and its estimation. Recently, satellite-based GRACE has been able to more confidently measure the changes in groundwater storage over large regions. GRACE measurements are made by measurement of the Earth's gravity, detected from the distance between two coordinated satellites that are generally separated by about 220 km (Tapley et al. 2004). Small changes in gravity on short timescales are generally a function of changes in water storage (underground, on the surface, and in the atmosphere), so quantification of gravity changes can be converted to estimates of water storage changes (Ramillien et al. 2008). Parsing of water content among groundwater, snow, the atmosphere, and surface water requires some processing that differs for various locations and scales (Scanlon et al. 2012c; Longuevergne et al. 2010). Although not a replacement for direct measurement of groundwater storage, GRACE observations have the potential to extend estimates of storage over time, although only back as far as the 2002 launch of the GRACE satellites. Rates of storage depletion in important groundwater-stressed regions have been made using GRACE, including the High Plains of the United States (Scanlon et al. 2012a), India (Rodell et al. 2009), and the Tigris, Euphrates, western Iran region in MENA (Voss et al. 2013).

2.4 Contamination of Groundwater

Water in nature, on the surface or underground, is never free from impurities and typically contains many dissolved and suspended constituents (salts, other inorganic and organic chemicals, sediments, and microorganisms). Contamination of a water body or an aquifer occurs when the concentration of one or more substances increase to a level such that the resulting water quality undermines the use of resource and, in some instances, becomes a hazard to the environment and a risk to human, animal, or plant life (Morris et al. 2003). The principal causes of groundwater contamination due to human activity can be classed as agricultural, industrial, and urban (Foster et al. 2002). Human activity can add salts, chemicals, and microorganisms (pathogens) that affect quality of groundwater.

This section provides an overview of major issues and concerns related to contamination of groundwater. See Chaps. 15 and 16 for a more detailed discussed of water quality.

Here, the significance of the widespread groundwater contamination problem is highlighted with relevant examples. Three groundwater contamination examples and their effects are summarily discussed: (i) land and aquifer salinization, (ii) contamination due to chemicals, and (iii) contamination due to microorganisms.

2.4.1 Land and Aquifer Salinization

Salinization of land and water is a widespread phenomenon that is an issue in more than 100 countries, including China, India, and the United States. Current global estimates indicate that over 1 billion ha are affected by various degrees of soil salinization (Shahid 2013). Globally 45 million ha (18 %) of the total 230 million ha of irrigated land are negatively affected by irrigation-related salinity (Ghassemi et al. 1995), which can result from a high water table, poor drainage conditions, and use of saline-brackish water for irrigation with insufficient drainage.

The Indus Basin of Pakistan is an example of a region severely affected by land and aquifer salinization problems that resulted from continuous irrigation without sufficient drainage. It is estimated that out of the total 16.3 million ha of irrigated land in Pakistan, about 6.2 million ha (38 %) have become waterlogged, with water table levels of <1.5 m below the surface; additionally, 2.3 million ha (14 %) have become saline, with soil ECe (soil saturated extract) >4 dS/m (Kahlown and Azam 2002).

Detail beyond the following overview of land and aquifer salinization process is given in Chap. 16.

2.4.1.1 Land Salinization

Salinization is a characteristic of soil and water which relates to their water-soluble salt content. Such salts predominantly include sodium chloride, but sulfates, carbonates, and magnesium may also be present. A saline soil is one which contains sufficient soluble salts to adversely affect plant growth and crop production. Waterlogging and salinity have been persistent problems in many irrigation regions of the world. Irrigation water normally contains salts in the range of 300–500 mg/l (IWMI 2007). A simple calculation shows that, in the absence of effective leaching, an annual irrigation of 1000 mm with good quality irrigation water and with salt content as low as 300 mg/l adds 300 kg of salts per hectare of irrigated land in a single year. Rainwater, which is considered a source of pure water, can also become a source of salt addition to aquifers and land. Raindrops, during their brief residence in the atmosphere, dissolve carbon dioxide to form a weak carbonic acid. During infiltration, the weak carbonic acid reacts with minerals and rocks in the soil to dissolve them more readily to become a source of salt in aquifers (Hillel 2000). Changes in properties of soil and water lead to the development of an environment which deteriorates soil and water quality.

Waterlogging, another major problem in irrigated land, is the saturation of soil particles with water that results from the rising of the water table due to over-irrigation, seepage, or inadequate drainage. Salinization, however, is a process that increases the concentration of salts in water or soil beyond a threshold limit; that is, mean electircal conductivity in the root zone (EC_e) in excess of 4 deci-siemens per meter (dS/m) at 25 °C (Hillel 2000). The processes of waterlogging and salinization, although different in their characteristics, usually occur together and adversely affect water quality and crop yield.

2.4.1.2 Aquifer Salinization

Mixing of saline water with freshwater is a frequent cause of aquifer salinization in many coastal regions (Werner et al. 2013a). Coastal aquifers are more vulnerable to groundwater extraction because of high population densities and predicted sea-level rise (Ferguson and Gleeson 2012). Coastal areas are the most densely populated areas in the world, with 8 of the 10 largest cities of the world located at coastlines. Nearly half of the world's population resides in coastal areas (Post 2005), and coastal aquifers provide a water source for more than one billion people.

In most cases, coastal aquifers are hydraulically connected to seawater. Under natural conditions, the hydraulic gradient (in part, a function of the density variation of the seawater and freshwater systems) maintains net water flow from the freshwater aquifer toward the sea. However, the gradient is usually small, and any excessive groundwater pumping can alter the hydraulic balance and allow seawater to enter and replace the freshwater pumped out from the aquifer (Werner et al. 2013a). The quality of groundwater aquifers can also be adversely affected by pumping if interlink connections exist between brackish or saline water. Additionally, a low rate of natural groundwater recharge in combination with sea-level rise can introduce and accelerate movement of saltwater into freshwater aquifers, although Ferguson and Gleeson (2012) found that the impact of groundwater extraction on coastal aquifers was more significant than the impact of sea-level rise or changes in groundwater recharge.

The overall impact of saline water intrusion highly depends on the amount of extraction and natural groundwater recharge. Incorrect positioning of well fields can accelerate the problem. Climate change is expected to exacerbate many water resource problems, but the impact of seawater intrusion may be much more serious and widespread because many areas with moderate population densities and water demand are expected to experience saltwater intrusion.

Seawater intrusion has affected groundwater quality in major coastal irrigation regions around the globe where pumping has destabilized the hydraulic equilibrium of the aquifers. Coastal regions such as Queensland in Australia, Florida in the United States, the southern Atlantic coastline of Spain, and Lebanon are among the most highly visible and notable cases where saltwater has intruded into coastal aquifers. Other problem areas in the United States include Cape May County in New Jersey and in Monterey and Orange Counties in California (Barlow and Reichard 2010). Similarly, in the western State of Sonora in Mexico, seawater has intruded approximately 20–25 km inland, forcing the closure of irrigation wells. Likewise in Cyprus, Egypt and Israel, exploitation of groundwater resources for irrigation has lowered aquifers' hydraulic heads to allow seawater intrusion.

In the Burdekin coastal region of Queensland, Australia, more than 1800 wells are currently used for irrigation. The large volumes of groundwater extracted have at times lowered the regional water surfaces and made it challenging to control seawater intrusion (Narayan et al. 2007). To confront long droughts, future use of groundwater is likely to increase in Australia. This growing use of groundwater will stress the aquifers already in deficit. Thus, saltwater intrusion will likely become more challenging because of the extensive coastlines where the majority of the population resides.

2.4.2 Groundwater Contamination Due to Chemicals

Fertilizers, pesticides, and salts contained in irrigation water can be major agricultural contaminants. Excessive irrigation drives water from the root zone of crops to the groundwater below (Chowdary et al. 2005), carrying with them applied fertilizers and pesticides and their component nitrogen compounds, phosphorus, potassium and other minerals and chemical compounds (Langwaldt and Puhakka 2000). Because of the widespread areal extent of these contaminants, they are often referred to as "nonpoint-source" contaminants.

Industrial wastes contain a wide variety of heavy metals and solvents. A recent study by Dwivedi and Vankar (2014) reported contamination of groundwater potentially from industrial sources (tanning, textile, and several others) in the Kanpur-Unnao district of India. Concentrations of cadmium, cobalt, chromium, copper, mercury, nickel, lead, tin, and zinc were found to exceed the maximum permissible limit. When chemical releases occur at specific facilities, they are referred to as "point-source" contaminants.

The accidental spillage and leakage of industrial chemicals can also cause serious groundwater contamination (Foster and Chilton 2003a). Subsurface releases of MTBE (methyl tertiary-butyl ether) can be a source of groundwater contamination. MTBE is a gasoline fuel additive that can leak from gasoline underground storage tanks and contaminate aquifers and wells. In the United States alone, releases of gasoline fuels has been reported at more than 250,000 sites, putting over 9000 municipal water supply wells at risk of contamination with MTBE (Einarson and Mackay 2001). Synthetic microorganic compounds also known as emerging organic contaminants (EOCs) are another and new source of groundwater contamination reported across Europe and many other parts of the world (Lapworth et al. 2012). EOCs are used for a range of industrial purposes including food preservation, pharmaceuticals, and healthcare products (Lapworth et al. 2012). Public health and environmental impacts of EOCs in groundwater are currently under-researched areas.

Arsenic and nitrate are two major contaminants with serious public health impacts. High concentrations of arsenic in groundwater have been recognized as a major public health concern in several countries and often are the result of natural conditions rather than human activity. The contamination of groundwater by arsenic in Bangladesh has been called the largest poisoning of a human population in history (Smith et al. 2000). An estimated 36 million people in the Bengal Delta alone (Bangladesh and India) are at risk of drinking arsenic-contaminated water (Nordstrom 2002). Long term exposure of arsenic in drinking water and its impacts on human health are documented in Ng et al. (2003). Geochemical processes in the presence of oxygen dissolve arsenopyrite [FeAsS], leading to increased concentrations of dissolved arsenic in groundwater. Oxidation can be a major driver to mobilize arsenic already present in aquifer rocks and can be promoted as a result of recharge by oxygenated waters or through lowering of the groundwater surface by excessive pumping (Nordstrom 2002). Chemical reactions among nitrate, iron, and oxygen can also increase mobilization of arsenic in aquifers (Höhn et al. 2006). The incidence of high concentrations of arsenic in drinking water is significant in Asian countries. The problem was initially detected in Bangladesh, India, and China. Most recently, the problem has been reported in Myanmar, Cambodia, parts of Europe, the United States, and Australia. A global summary of arsenic contamination of groundwater is available in Ravenscroft et al. (2011) and Mukherjee et al. (2006).

Nitrate contamination of groundwater is a widespread and global problem both in developed and developing nations. Excessive application of commercial fertilizers or animal waste and inadequate waste disposal of municipal and animal waste are associated with this problem. High concentration of nitrate in municipal groundwater (10–50 mg/l) is considered a public health hazard. Nitrate contamination of groundwater due to agrochemicals has become a serious problem in China and India (Foster and Chilton 2003b). A detailed review of nitrate contamination of groundwater and its health impact is available in Spalding and Exner (1993) and Canter (1996).

2.4.3 Groundwater Contamination Due to Microorganisms

Microbial contamination of groundwater can be caused by inadequate protection of aquifers against release of sewage effluent into groundwater. Contamination of groundwater can occur via many pathways, such as from urban landfills in proximity to natural groundwater recharge sites, rural on-site sanitation facilities, leaking septic tanks and sewers, and waste from farm animals. The concentration of many harmful microorganisms attenuates (naturally reduces) when water passes through the unsaturated zone; however, the degree of pathogen removal depends on the type of soil, level of contamination, and type of contaminant. Natural attenuation generally is most effective in the unsaturated zone, especially in the top soil layers where biological activity is greatest (Morris et al. 2003).

Several viral and bacterial pathogens present in human and animal waste contaminate groundwater and cause human health problems. In 2012, more than 500,000 diarrhea deaths were estimated to be caused by microbially contaminated drinking water (Prüss-Ustün et al. 2014). Baldursson and Karanis (2011) give a comprehensive review of worldwide waterborne disease outbreaks that occurred and were documented between 2004 and 2010. Similarly, a recent study based on a systematic review by Ngure et al. (2014) provides a global assessment of drinking-water microbial contamination. All incidence of waterborne diseases cannot be attributed to groundwater, because microbial contamination of water can occur in surface water bodies and in distribution pipes. However, a significant fraction of waterborne disease outbreaks may be associated with groundwater, given that more than 50 % of population worldwide meet their primary drinking needs from groundwater that may be contaminated at some stage (Macler and Merkle 2000).

2.5 The Water-Energy Nexus

Water and energy are inextricably linked in many important ways and this issue is covered in more detail in Chap. 4. Water is used in the generation of energy, and energy is required for the movement and treatment of water. This linkage results in multiple management challenges.

The movement of water requires a significant portion of all energy generated worldwide. In California (United States), 19 % of all electrical energy produced is used for water-related conveyance and treatment (Navigant Consulting Inc. 2006)—nearly 2 % of all electrical energy in California is used for groundwater extraction through pumping (GEI Consultants/Navigant Consulting Inc 2010). Such energy requirements account also for significant contributions to greenhouse gas emissions, estimated as 0.6 % of China’s emissions (Wang et al. 2012) and 4–6 % of India’s emissions (Shah et al. 2012). These energy requirements increase with the distance the water must be lifted (depth to water) and decrease with pump efficiency. Hence, declining water levels will increase energy requirements for groundwater pumping unless offset by increased pump efficiency. This increased energy demand for pumping is exacerbated in India by government subsidies for electrical power for the purpose of groundwater extraction (Badiani et al. 2012)

In addition to energy use for water movement and treatment, groundwater plays an important role in the generation of energy—particularly the production of alternative energy such as biofuels (Gerbens-Leenes and Hoekstra 2012; Dominguez-Faus et al. 2009). Significant water is used both in the growing of feedstock to create ethanol and in the distillation of the feedstock into fuel. In the United States, governmental mandates require that ethanol from corn (maize) will continue into the future (Dominguez-Faus et al. 2009), although a wide range of water footprint calculations suggest that efficiencies may be found that could reduce groundwater extraction needs for irrigation and distillation (Gerbens-Leenes and Hoekstra 2012; Dominguez-Faus et al. 2009). Other alternative energy technologies can have surprising energy implications. Concentrated solar power generation on a large scale in desert environments can require large amounts of water for cooling and washing (Woody 2009; McKinnon 2010). In the United States, the National Research Council (2012) has also studied production of biofuel from algae, raising questions about sustainability.

In recent years, unconventional drilling for shale gas and coal bed methane—particularly in the United States, China, and Australia—has increased dramatically (Vidic et al. 2013; Moore 2012). Improvements in the accuracy of horizontal well drilling, coupled with hydraulic fracturing, have made it practical to extract methane from thin, deep and tight strata. These advantages, coupled with increasing energy demand, have resulted in massive expansion of exploitation of these unconventional gas reserves. Hydraulic fracturing uses a focused large amount of water for short periods of time, resulting in competition with other water users—particularly in arid regions like the Eagle Ford Formation in Texas (United States). Hydraulic fracturing also uses a variety of chemical additives in the process. Some water contaminated with these additives returns as flowback water and must be disposed of, leading to a potential groundwater contamination source (Vidic et al. 2013). One concern is that methane liberated by the hydraulic fracturing process and additive chemicals could migrate to shallow aquifers or the surface. A recent study (Myers 2012) attempted to address this issue and prompted discussion and criticism (Saiers and Barth 2012; Myers 2013; Cohen et al. 2013), highlighting the level of uncertainty about the degree and nature of potential contamination from this activity. Further research in the field and through modeling is necessary for understanding of the depth and breadth of potential groundwater impacts to catch up with the rapid increase in development of unconventional gas resources (Jackson et al. 2013).

2.6 Transboundary Water Conflict

Most of the literature discussing transboundary water conflict has focused on surface water. Groundwater conflict has received less attention. However, owing to both “uncertainty in defining ground water flow…[and]…uncertainty of the hydraulic connection between groundwater and surface water" (Jarvis et al. 2005) and combined with increasing water usage needs—particularly for agricultural irrigation (Llamas and Martinez-Santos 2005)—it seems that serious conflict over transboundary groundwater resources may be inevitable. This condition is exacerbated by a lack of regulation and management of groundwater, which is often blamed on the same uncertainties surrounding the quantity and dynamics of groundwater at the regional scale (Llamas and Martinez-Santos 2005; Jarvis et al. 2005; Puri 2003). Several conceptual models can apply to transboundary aquifers, including cases where the source of water to the aquifer is in one country but the main demand is in another (for example, Eckstein and Eckstein 2005). Transboundary aquifers meeting these definitions number as many as 408 (UN-IGRAC 2012). Using analysis similar to the groundwater footprint (Gleeson et al. 2012), Wada and Heinrich (2013) performed a quantitative assessment of water stress (considering recharge, extraction, and environmental flows) for the 408 identified transboundary aquifers and determined that 8 % of them are stressed by human consumption. They point out, however, that many of these transboundary aquifers are found in geopolitically charged areas such as the Arabian Peninsula, the United States—Mexico border, and India and Pakistan.

In one example of this type, the Ceylanpinar aquifer spans the border between Turkey and Syria, with recharge in the Turkish headwaters and the majority of discharge in the Ras al-Ain Springs in Syria (Oeztan and Axelrod 2011). Data availability is asymmetric, with much more information available about conditions in the aquifer in Turkey than in Syria. Nonetheless, Oeztan and Axelrod (2011) modeled the aquifer to try to calculate sustainable extraction rates based on discharge from the springs. Mutually beneficial organic agriculture along the border that previously was unfarmable due to extensive placement of landmines is proposed but would first depend on cooperation with respect to hydrogeologic and water use information. Joint management to prevent overdepletion requires collaboration, which may be at odds with other priorities of neighboring countries, but this example shows it can have positive outcomes.

Beyond water quantity, water quality concerns can arise when contaminants enter an aquifer under a different governance than that of the users of the aquifer; for example, such as bordering northeastern Greece (Vryzas et al. 2012) and Russia (Zektser 2012). Similar challenges as facing depletion problems are encountered in managing water quality. The parallel challenges of establishing responsibility for contamination and finding the motivation to remediate it can present opportunities for constructive collaboration but also may heighten tension in some areas.

In modern times (1948–present), no full-scale declarations or acts of war have been attributed to the tension related to the use of transboundary water (De Stefano et al. 2010). This is contrary to predictions stemming from at least the 1980s onward that major wars—particularly in the Middle East—would be fought over water because of stress over increasing demand for water resources due to increasing population, climate change, and depletion of water sources (see Cooley (1984) and Starr (1991), for example). It is still possible for this to happen, and indeed tensions and local violence have been attributed to water conflict, but thus far full-scale war has not resulted with the exception of the war between Sumerian city-states Lagash and Umma in 2500 BCE (Wolf 1998). Although a somewhat controversial notion, it has been argued that interactions among states involving water more often, of necessity, lead to cooperation than conflict (De Stefano et al. 2010; Wolf 2007).

In summary, transboundary aquifers present many challenges in integrated management. The connection between surface water and groundwater are all the more important because the source of water and the water's users (human or ecological) may be in different countries. Data sharing and integration are more challenging across national borders but are extremely important to reduce the uncertainties surrounding integrated management. An additional challenge is that protection of water resources in one country may depend on the actions taken in another country. This binding together for a common purpose provides the opportunity for cooperation but may also devolve into conflict. For these reasons, active management and communication are key to managing water resources across boundaries.

2.7 Conclusion

The issues outlined in this chapter highlight both the challenges and promise of the groundwater issue internationally. The growing importance of groundwater supply combined with the challenges in its characterization and measurement make management difficult. Yet, advances in data analysis, remote sensing, and modeling at regional to continental scales provide some hope for more informed planning, which may ultimately lead to sustainable and responsible management.

Depletion of groundwater—a precious resource for agriculture, ecosystem services, and domestic supply—has the potential to cause significant interruption of societal and ecological functions. The uncertainties inherent in managing a resource that is generally unseen create challenges in management and can lead to conflict among interests vying for the resource—because proving who is responsible for stresses and impacts is a challenge.

Advances in remote sensing (such as the GRACE satellite), data management, and numerical modeling provide hope of reducing the uncertainty of evaluating the magnitude and locations of depletion and degradation of groundwater resources. None of the technical and managerial issues raised in this chapter can be properly considered on its own. The water budget myth implied a simple balance between recharge and availability, but over the past century we have learned that the interconnections among groundwater-dependent ecosystems, human needs, and the groundwater system are deep and elaborate. Only an integrated approach to water management—viewing the components of the system together with competing needs—can maintain sustainability for future generations and a robust environment. Integration is also critical to manage the connections between seemingly disparate sectors of society and economics. As mentioned previously, the connection between electrical prices and agricultural pumping is an important consideration in India. The desire to mitigate climate change (see Chap. 5 for this issue) through alternative energy production can have a ripple effect of consequences on water resources, particularly in the case of biofuels. Agricultural policy beyond water use restrictions has important implications on water quality as it relates to chemical use and to salinization of soil and water. Even the stability of relationships among nations can hinge on proper water management.

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