Towards Integrated Groundwater Management in China

18

Jie Liu and Chunmiao Zheng

Abstract

This chapter is intended to provide an overview of groundwater policy development in China, analyze the integration dimensions in current policy, identify the missing pieces and major challenges of integration in groundwater management, and offer suggestions towards more integrated groundwater management. The average groundwater recharge in China is about 880 billion m^3/year, 70 % of which is unevenly distributed in the south. Groundwater exploitation has doubled over the past three decades, and agriculture is the largest consumer at approximately 60 %. The exploitation of groundwater sustains a steady increase in agricultural production, but also brings about a multitude of eco-environmental problems. Since the founding of the People's Republic of China, the focus of groundwater work has changed from investigating and exploiting to managing and protecting groundwater, and the viewpoint that groundwater is a single natural resource has gradually given way to that regarding groundwater as an environmental element with multiple functions. Integrated considerations of groundwater quantity, quality and its eco-environmental effects have been reflected in several programs aimed at prevention and control of groundwater contamination and land subsidence. Integration of surface water and groundwater by managed aquifer recharge and water transfer projects has been implemented. In the future, improvement of the legislation system, strengthening of institutional control, building-up of professional management teams, and increasing stakeholder involvement and

J. Liu
Center for Water Research, College of Engineering, Peking University, Beijing, China

C. Zheng (✉)
School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen, China

Department of Geological Science, University of Alabama, Tuscaloosa, AL, USA
e-mail: czheng@ua.edu

A.J. Jakeman et al. (eds.), *Integrated Groundwater Management*,
DOI 10.1007/978-3-319-23576-9_18

public participation are all needed facets towards a more integrated groundwater management.

18.1 Introduction

As an important part of water resources, groundwater plays an essential role in securing domestic uses, supporting socioeconomic development and maintaining ecological balance. Especially in the arid and semi-arid northern and northwestern parts of China with relative limited surface water, groundwater is non-substitutable. Indeed, China's groundwater situation is very grim (see also Chap. 2). Many areas are experiencing storage depletion with the water table continually declining, which further induces geologic hazards such as land subsidence, karst collapse and sea water intrusion; groundwater quality degradation and contamination is also becoming severe (Qiu 2010; Zheng et al. 2010). The conventional emphasis of groundwater management studies usually includes engineering and technological measures, modeling approaches (Demetriou and Punthakey 1999; Barthel et al. 2008; Liu et al. 2008; Shu et al. 2012; Cao et al. 2013; Qin et al. 2013), and economic leverage (Yang and Zehnder 2007; Zhang et al. 2008; Wang et al. 2010a). However, comprehensive studies that integrate legislative and administrative dimensions have often been ignored. To ensure that scientists understand what kinds of knowledge are required by policy makers and how hydrological expertise can be translated into real actions, it is essential to have an understanding of the current groundwater management system in China.

The objective of this chapter is to depict how groundwater policy has been progressively implemented in China, the existing gaps between the current and integrated groundwater policy, and possible steps towards more integrated groundwater management. The present state of China's groundwater resources is first described, and the historical groundwater development and management is then reviewed. This is followed by analysis of the integration dimensions in current groundwater policy and the existing major integration challenges. Finally, the authors offer suggestions towards more integrated groundwater management in China. Considering the size of the nation and the severity of the groundwater situation in China, this study not only has practical significance for improving China's groundwater development and management, but also can provide important implications for global groundwater governance.

18.2 State of China's Groundwater Resources

18.2.1 Types of Groundwater Resources and the Distribution

Based on the occurrence of groundwater, China's aquifers can be divided into four major categories: (1) alluvial deposits in plains and basins; (2) groundwater in loess regions; (3) karstified limestone aquifers; and (4) bedrock aquifers in mountainous regions (Fig. 18.1).The first type is stored in porous and poorly consolidated sediments with an abundant amount of water, mainly distributed in alluvial plains, large river valleys, and the piedmont of inland basins. The total area is about 2.74 million km^2 and provides groundwater around 168.6 billion m^3/year, accounting for 46 % of the total exploitable groundwater. Groundwater in loess regions is a special type stored in unconsolidated sediments, mainly distributed in the loess plateau region in northern Shaanxi, southern Ningxia, western Shanxi and southeastern Gansu provinces. The total area is about 0.17 million km^2, with the total exploitable groundwater in the amount of 9.7 billion m^3/year, about 3 % of the nation's total exploitable groundwater. Karstified limestone aquifers occur in karst caves or fractures, with a total area of about 0.82 million km^2. The total exploitable groundwater resource of this type is about 87 billion m^3/year, accounting for 24 % of total exploitable groundwater resources. The bedrock aquifers mainly occur in the fractures of magmatic rocks, metamorphic rocks, and clastic rocks. The total area is about 5.75 million km^2, with total exploitable groundwater in the amount of 97 billion m^3/year, accounting for 27 % of the total exploitable groundwater resources (China's Groundwater Information Center 2014).

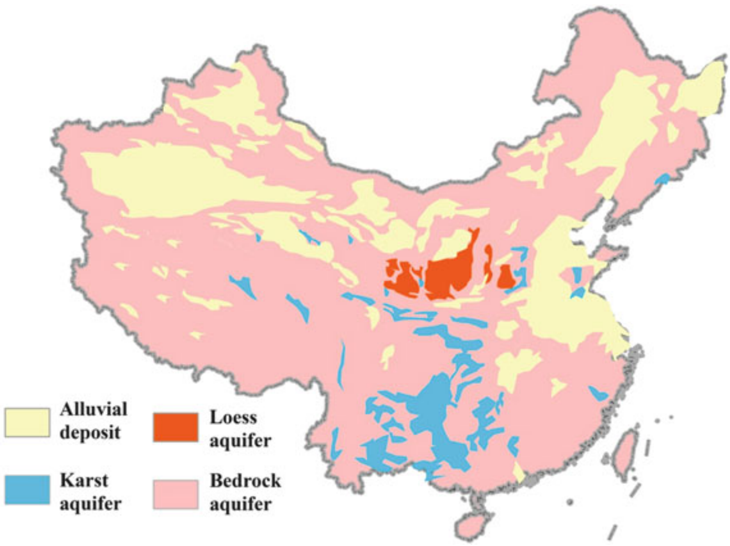

Fig. 18.1 China's major aquifer types and their spatial distribution

Fig. 18.2 Spatial distribution of groundwater resources in China (Data Source: The Ministry of Water Resources)

Table 18.1 Total amount and spatial distribution of China's groundwater resources (10^8 m^3)

Area	Total		Exploitable	
Nation-wide	8837		3527	
North	2743	31 %	1536	44 %
South	6094	69 %	1991	56 %
Plain area	2276	26 %	1561	44 %
Mountain area	6561	74 %	1966	56 %

According to the latest round (2000–2002) national groundwater resource assessment by the Ministry of Land and Resources, the average annual natural groundwater recharge in China is 884 billion m^3/year, accounting for nearly one-third of the nation's total water resources. The spatial distribution of groundwater resource in China is quite uneven. Nearly 70 % of its groundwater resource is in southern China (38 % of the country's total land area) while only 30 % is in northern China (62 % of the total land area). In general, the abundance of the groundwater resource decreases gradually from the southeast to the northwest (Fig. 18.2). Moreover, 74 % of the groundwater resource is in the mountainous areas and 26 % in plain areas, which adds difficulty and restriction in its exploitation and utilization (Table 18.1) (Zhang and Li 2004).

18.2.2 Groundwater Exploitation and Overdraft Issues

With fast economic development and population increase over the past three decades, groundwater exploitation in China has increased dramatically. Since the

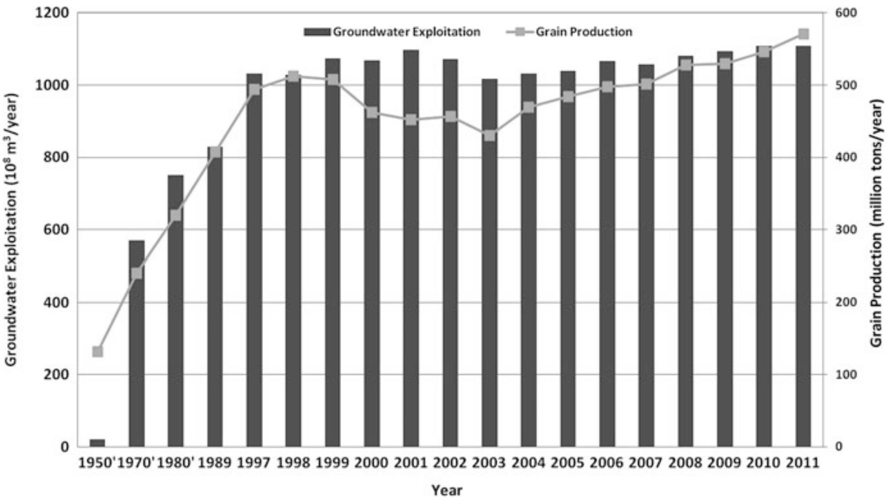

Fig. 18.3 Groundwater exploitation and total grain production from 1950s to 2011 in China (Data Source: The Ministry of Water Resources, China Statistical Yearbook)

1970s groundwater exploitation has grown at an average rate of 2.5 billion m^3/year. The total amount of groundwater exploitation was 57 billion m^3/year in the 1970s, 75 billion m^3/year in the 1980s, and reached 111 billion m^3 by 2011, accounting for more than 18 % of total water supply (Ministry of Water Resources 2011) (Fig. 18.3). Agricultural water use accounts for the largest percentage of the total groundwater use, although it has decreased from 88 % in the 1980s to 62 % in the late 1990s; industrial and municipal water use has increased from 12 % in the 1980s to 38 % in the late 1990s, and this trend will likely continue to keep pace with the acceleration of industrialization and urbanization.

Among the 657 cities in China, more than 400 (61 %) cities use groundwater as their major water supply. In rural areas of China, people generally use groundwater as their drinking water source, and 40 % of the total farmland is irrigated by groundwater. In northern regions, 65 % of domestic water, 50 % of industrial water and 33 % irrigated water come from groundwater (Ministry of Environment Protection 2011). The exploitation of groundwater has allowed a steady increase in grain production. Figure 18.3 shows the relationship between groundwater exploitation and total grain production in China from the 1950s to 2011. All those indicate that China's economic development and people's livelihoods depend greatly on groundwater.

With the increasing groundwater abstraction rate, most aquifers in northern China have been over-drafted, among which the entire Hebei Province, the aquifers in mega or middle-sized cities such as Beijing, Tianjin, Shenyang, Haerbin, Jinan, Taiyuan and Zhengzhou are all over-pumped. More than 100 regional groundwater cones of depression have been formed with total area exceeding 150,000 km^2. In the North China Plain, the cone of depression has spanned from Hebei to Beijing, Tianjin, Shandong, with the groundwater level in an area of 70,000 km^2 lower than sea level (Liu et al. 2001). The regional groundwater level decline has also impacted groundwater dependent ecosystems, such as the shrinking or disappearing of wetlands and degradation of vegetation coverage. Land subsidence occurred in more than 40 cities because of groundwater overdraft, among which Shanghai, Tianjin and Taiyuan have the maximum accumulative land subsidence over 2 m. In coastal areas such as Dalian, Qinhuangdao, Cangzhou, Qingdao, and Beihai, sea water intrusion has caused degradation of groundwater quality in a total area of nearly 1000 km^2, among which Shandong and Liaodong Peninsula are the most seriously affected. In addition, aquifer salinization has been caused by intensive irrigation in the North China Plain (Foster et al. 2004), the middle stream of the Yellow River and inland basins of northwestern China.

18.2.3 Groundwater Quality Issues

The overall quality of groundwater has deteriorated rapidly in recent years. According to the latest well sampling campaign in 2012 in nearly 200 cities and administrative regions by China's Ministry of Land and Resources, some 57.4 % of over 4,900 samples indicated groundwater of category IV or V – on a scale of I-V from the best to poorest quality (Ministry of Environmental Protection 1994, 2012). The spatial information of groundwater quality is shown in Fig. 18.4, from which it can be seen that groundwater contamination in Taihu basin, Liaohe basin, Haihe basin and Huaihe basin is the most severe, with 91 %, 85 %, 76 % and 68 %, respectively, of their total sampled areas with groundwater of category IV or V (Ministry of Environment Protection 2011).

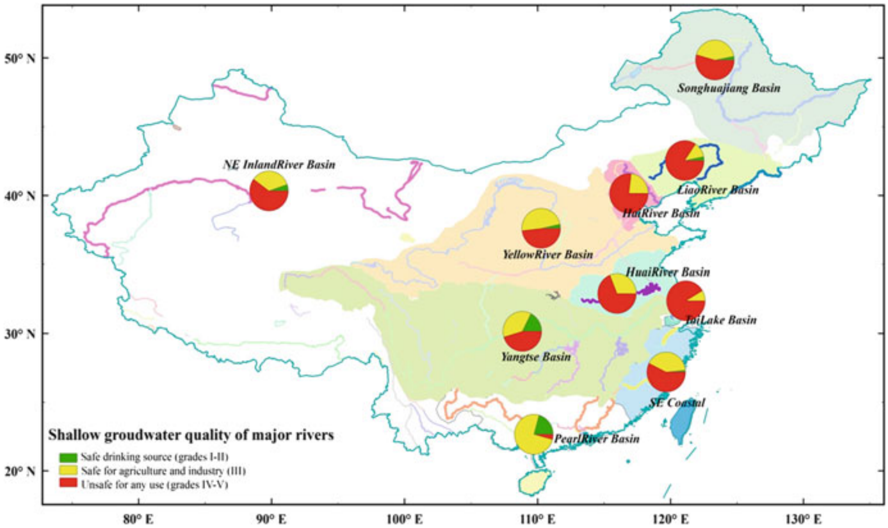

Fig. 18.4 Groundwater quality in major plains and basins of China. Categories I and II: good, category III: moderate, and categories IV and V: poor (Based on Tang et al. 2006)

China Geological Survey conducted an investigation and assessment of groundwater contamination in the North China Plain from 2006 to 2011. Based on 7,451 groundwater samples, shallow aquifers show more serious contamination than deep aquifers. The major pollutants include nitrates, heavy metals, and toxic organic compounds. The nitrate pollutant has a planar distribution surrounding villages and cities, and the major sources include unregulated disposal of polluted water from industries, and the overuse of fertilizer in agricultural activities. Pb, Cr and As are the major heavy metals with a high rate of exceeding environmental standards, and have a spotty or linear distribution pattern around cities and industries. The unregulated disposal of polluted water and poorly managed wastes are the major cause of heavy metal pollution. Toxic organic compounds have a low rate of exceeding standards but a high detection rate, mainly in shallow aquifers. The major source comes from the production, process, storage and use of those organic compounds by petrochemical industries (Zhang et al. 2012).

"It is estimated that 190 million Chinese fall ill and 60,000 die because of water pollution. According to the World Bank, such illnesses cost the government $23 billion a year, or 1 % of China's gross domestic product. And that doesn't factor in the impact on China's ecosystems and food supply" (Qiu 2011). The degradation of groundwater quality and groundwater contamination accidents also provokes socio-political unrest from the public. In the year of 2013, business owners in Shandong province were accused of disposing waste water through injection wells and contaminating shallow groundwater, which ignited a firestorm on the Internet (Zheng and Liu 2013).

18.3 Historical Perspectives on Groundwater Development and Management in China

China has a long history in utilizing groundwater resources. The earliest ancient well was found in Hemudu village of Yuyao, Zhejiang Province more than 5000 years ago (Liu 1987). Back to 2000 years ago, the Chinese began to use tube wells to exploit shallow groundwater. Systematic development of groundwater started after the founding of the People's Republic of China in 1949, and the development and management of groundwater in China has been closely related to the country's economic development. More than 60 years of groundwater development and management in China can be divided into the following five distinct stages (Ji and Wang 2009).

18.3.1 1949–1958: Initial Development

China's hydrogeological work was launched right after the People's Republic of China was founded in 1949, closely linked with the demands of the nation's reconstruction and socioeconomic development. During this stage, groundwater was managed as a type of geological resource by the Ministry of Geology back then (later changed to the Ministry of Geology and Mineral Resources, and now the Ministry of Land and Resources). The major task of this stage was to conduct hydrogeological investigations for the major industrial and urban construction projects. In 1956, a regional hydrogeological investigation was initiated in the main basins, such as the Chaidamu Basin in Qinghai Province, the Hexi Corridor in Gansu Province and the Yangtze River basin. Groundwater protection was mentioned for the first time in the "Interim Regulations on Mineral Resources Protection" (1956), which states that: hydrogeological investigations and reasonable extraction plans should be enforced to prevent groundwater resources from being damaged; and the relevant departments should adopt effective measures to prevent groundwater contamination from the discharged industrial, medical or municipal wastewater. The discipline of Hydrogeology has been set up since 1952 in colleges, and academic activities have been carried out since the late 1950s. At this stage, many working methods were learnt and adopted from the former Soviet Union.

18.3.2 1959–1978: Growth Period

Since 1959, hydrogeology has entered a growth period in China. Every province (autonomous region and municipality) built up their own hydrogeological and engineering geological teams. With the extensive development of agricultural activities and railway construction, hydrogeological investigations was conducted accordingly. Great progress was achieved in finding groundwater sources for areas with severe water shortage and endemic diseases. The academic and teaching activities also developed rapidly. In 1964, hydrogeological maps for the Huang-Huai-Hai (which means the Yellow River, Huai River and Hai River in Chinese) Plain and the Song-Liao Plain (at a scale of 1:1,000,000) were completed. The national hydrogeologic maps were compiled by the Institute of Hydrogeology and Engineering Geology in the late 1970s, which integrated the previous hydrogeological investigations in different plains and basins. In 1977, a geological survey team for karst areas was formed, whose name was then changed to the Institute of Karst Geology in 1979. In 1962, land subsidence appearing in Shanghai led to the concerns over geo-environmental issues and the study of environmental geology as an important subject followed. Rational groundwater development and protection to prevent groundwater level decline, quality deterioration, land subsidence and collapse have been studied in many large and middle cities and the North China Plain since then.

18.3.3 1978–1998: Comprehensive Research and New Technologies

In the 1980s comprehensive investigation and mapping of hydrogeological conditions started, based on natural geographical units. The major achievements include the hydrogeological maps of the Yangtze River Basin and the Yellow River Basin. By the mid-1980s, the first round of national groundwater resources assessment had been completed (Zhang and Li 2004). Following that, the groundwater resource assessment in the northern karst region was conducted. In 1996, the regional hydrogeological survey of the entire country was completed, with two-thirds of the national territory at the scale of 1:200,000 and the rest at the scale of 1:1,000,000. New concepts and technologies in hydrogeological research and practice from western developed countries were introduced to China during this period; and some technologies such as drilling and geophysical technologies were also actively developed in China as well.

In 1988, the first comprehensive national Water Law was enacted. Before then there was no systematic management structure and no specific regulations or laws for groundwater. The only regulation directly related to groundwater resources is the Interim Regulations on Mineral Resources Protection enacted in 1956. Following the Water Law, Regulations on Water Pollution Prevention and Control in Drinking Water Source Protection Area, and Regulations on Urban Groundwater Development and Management were formulated in 1989 and 1993, respectively. The Mineral Resources Law was amended in 1986, and the specific rules for the Implementation of the Mineral Resource Law were formulated in 1994 (Department of Water Resources 2008). During this stage, the Ministry of Construction was in charge of urban groundwater management; the Ministry of Land and Resources was responsible for groundwater investigations; and groundwater quality management was under the jurisdiction of the Ministry of Environmental Protection.

18.3.4 1999–2008: Large-Scale Land and Resources Survey and Assessment

The second round of national groundwater resource and environmental assessment was conducted by the China Geology Survey (CGS) from 2000 to 2002. The CGS finished the regional hydrogeological survey in 11 major plains and basins in northern China (Fig. 18.5) and published a series of reports (Zhang and Li 2004). Groundwater recharge, runoff and discharge as well as their changes over the past 20 years were investigated. At the same time, geo-environmental issues related to groundwater such as land subsidence and seawater intrusion were also investigated comprehensively. A basin-scale digital groundwater information system was developed. Investigation of karst groundwater resources was conducted in eight provinces, including Yunnan, Guizhou, Guangxi, Hunan, Chongqing, Hubei, Guangdong, Sichuan, involving nearly 80 million people and a total area about 1 million km^2.

From 2005 groundwater quality investigations and assessments were conducted in the eastern plains, including Zhujiang Delta, Yangtz Delta, Huaihe River Basin and the North China Plain. Questions such as the state of the nation's groundwater, how the groundwater quality evolves over time, and how natural factors and human activities impact the quality of groundwater were addressed. The groundwater pollution investigation in the Pearl River Delta, Yangtze River Delta, the plains

Fig. 18.5 Regional hydrogeological surveys in major plains conducted by China Geological Survey (Data Source: China Geological Survey)

area of the Huaihe Basin, the North China Plain, the lower Liaohe Plain and the eastern plain with an area of 430,000 km^2 targeted inorganic to organic components. This provided important background information on groundwater quality for subsequent national groundwater pollution prevention and control efforts.

Groundwater exploration and exploitation in water-shortage and endemic areas was also been conducted. In the arid northwest region, and the so-called "red soil region" in the southwest, as well as areas with endemic diseases, the CGS carried out hydrogeological surveys and groundwater supply demonstration projects, and solved the drinking water supply problem for more than 20 million people.

The national monitoring network for the dynamic changes of groundwater level and quality has been under construction (Zhou et al. 2013). Currently, there are 24,417 groundwater monitoring stations, mainly distributed in the northern part of China. In the near future another 20,455 monitoring stations are planned to be constructed or reconstructed, which will cover 3,500,000 km^2 and dynamically monitor the groundwater level and quality changes of major plains, basins, karst areas and ecologically vulnerable areas. Figure 18.6 shows the density of monitoring stations in each province of China (China Groundwater Information Center 2014).

18.3.5 2009-Present: Attempt at Integrated Water Management

The integration dimensions of groundwater development and management have been considered to a greater extent during this stage. Back to 2000, the administrative management functions on groundwater resources of both the Ministry of

Fig. 18.6 National groundwater monitoring network in China (Data Source: China Institute of Geo-Environment Monitoring)

Construction (now the Ministry of Housing and Urban-rural Development) and the Ministry of Land and Resources have been moved to the Ministry of Water Resources. The Water Law was amended in 2002 to further strengthen the MWR's administrative power over groundwater. In 2011, the Plan of Groundwater Pollution Control and Remediation was issued, which was a joint effort of the Ministry of Environmental Protection, the Ministry of Water Resources, the Ministry of Land and Resources and the Ministry of Housing and Urban-rural Development. In 2012, the Land Subsidence Control Program (2011–2020) was launched by the Ministry of Land and Resources and the Ministry of Water Resources. Following those, the Working Plan of Groundwater Pollution Control and Remediation in the North China Plain was issued in 2013, which was also a joint effort by the Ministry of Environmental Protection, the Ministry of Water Resources, the Ministry of Land and Resources and the Ministry of Housing and Urban-rural Development. Integrated considerations of surface water and groundwater, water quantity and quality, groundwater exploitation and its subsequent consequences were reflected to some extent in the various programs mentioned above.

18.4 Analysis of the Integration in China's Groundwater Management

Although groundwater development and management in China has made great strides in the past decades, the outlook for groundwater management is still not optimistic. In major pumping areas like the North China Plain, groundwater overdraft is still severe. The average water table decline rate from 1980 to 1985 was about 0.5 m/year, slowed down in 1986–1995, but increased to more than 0.5 m/year from 1996 to 2008. The average annual groundwater storage depletion for the NCP is approximately 4 billion m^3 (Cao et al. 2013). The overdraft of groundwater caused further eco-environmental problems, such as land subsidence, sea water intrusion and groundwater quality deterioration. Based on groundwater sampling in the NCP by the China Geological Survey, 58 % of the samples showed poor quality (category IV or V). Land areas subsiding more than 200 mm extended 60,000 km^2, with the estimated economic loss at about 330 billion RMB.

The major challenges of integration in groundwater management come from both the defining characteristics of groundwater itself and the particular social, cultural and political contexts of China. Groundwater, by its very nature, has multi-functional characteristics: it is an important part of the hydrologic cycle and important resource; at the same time it occurs in geological media and is also a type of mineral resource. In addition, groundwater has environmental values, the quality of which significantly affects human health and ecosystems. As a common-pool resource, groundwater is easily appropriated simply by capturing it, and the negative externalities associated with its use as well as the difficulty to measure this invisible resource add to the complexity of groundwater management (Wijnen et al. 2012). Cooperation among users is promoted as a means of achieving better management, internalizing the damages of users' activities and reducing extractions (Esteban and Dinar 2011).

Through this historical review of groundwater development and management in China, it can be seen that "integration" has been gradually taking place in the nation's groundwater policies due to the increasing intensity of groundwater exploitation and its subsequent problems. The integration dimension has been reflected in the legal framework and the changes of the institutional system in charge of groundwater management, but challenges still exist.

18.4.1 Integration of Groundwater Quantity, Quality and Dependent Ecosystems

In the initial phase of groundwater development, the major task facing China was to identify groundwater sources by conducting hydrogeological investigations. With the fast exploitation of groundwater in the 1960s–1980s for agricultural activities and economic development, groundwater-related geo-environmental issues started to emerge. The land subsidence in Shanghai started from the 1960s, and initiated the concerns over environmental issues caused by groundwater overdraft. Environmental Geology became a major field of research and practice at that time aimed at the protection of groundwater from water table decline, quality deterioration, land subsidence and collapses, and seawater intrusion. In addition, changes in groundwater quantity and quality can adversely impact many ecosystems in China that rely on groundwater to survive.

Although the concerns over groundwater related environmental issues started in the 1960s, most of the work that has been done is scientific research in nature and has not been explicitly reflected in laws or regulations. In 2011, the State Council issued the National Plan for Groundwater Pollution Prevention and Control (2011–2020), which became an important official directive for groundwater quality management; in 2012, the National Plan for Land Subsidence Prevention and Control (2011–2020) was issued by the Ministry of Land and Resources and the Ministry of Water Resources, providing the official guidelines for the management of land subsidence. In this Plan, it is required to strictly restrict groundwater overdraft by controlling total groundwater pumping amount and the groundwater level. A water resources evaluation system is required if construction projects such as city construction and mining need to pump groundwater. The areas to limit or prohibit groundwater pumping need to be delineated. Based on the requirement of land subsidence control of a specific area, the goal of groundwater pumping control and reduction should be determined. At the same time, the construction of substitute water sources should be expedited to guarantee the requirement of domestic and industrial water uses.

In 2013, the Working Plan of Groundwater Pollution Prevention and Control in the North China Plain was issued to make specific provisions of groundwater protection in the NCP as a pilot study, and the Ministry of Environmental Protection, Ministry of Land and Resources, Ministry of Housing and Urban-rural Development, and Ministry of Water Resources were all involved. The working plan mandates that MEP constructs the monitoring network of groundwater quality and organizes routine groundwater quality monitoring, which should be linked up with the" National Groundwater Monitoring Project" implemented by the MLR and the MWR with all obtained information shared. The working plan is closely linked with the existing plans of water pollution prevention and control in the Haihe River Basin, the Yellow River Basin and other large river basins to manage surface water and groundwater quality jointly. The management of waste water outlets to rivers/lakes, water permits and environmental evaluation should be coordinated. The plan also mentions that the coordination of the relevant laws and regulations of groundwater pollution prevention and control should be enhanced, and that groundwater quality standards should be formulated and linked with the Standards for Drinking Water Quality. The enactment of regulations about the responsibility and compensation of groundwater contamination should be speeded up. Sound and diversified funding and financing mechanisms for groundwater remediation should be constructed with stakeholders, local and central government all involved. The responsibility of stakeholders and local governments is strengthened, and the executive leadership responsibility system is implemented, and therefore the groundwater pollution prevention and control is brought into the planning of local social and economic development. The MEP coordinates and supervises the implementation of the Working Plan in coordination with other relevant organizations such as the MLR, National Development and Reform Commission, Ministry of Finance, Ministry of Housing and Urban-rural Development, and the MWR.

18.4.2 Integration of Surface Water and Groundwater

"Integration of surface water and groundwater use" is explicitly mentioned in the Water Law, with the understanding that they are one single resource of the hydrologic cycle, but there are no specific and detailed regulations on how to integrate them. Most of the work related to integration of surface water and groundwater remains mainly at the technical level, such as characterizing the spatial and temporal connection of the major river-aquifer systems, and development of generic approaches/tools to identify and quantify the nature and extent of interaction between the surface and groundwater (Liu et al. 2014; Huang et al. 2012). However, the policy challenges have rarely been addressed; for example, how to integrate extraction limits in highly connected river-aquifer systems, and how to address groundwater extraction to meet environmental flow requirements of rivers. Substantial technical investigation and policy development are still needed towards integrated groundwater and surface water management.

Managed aquifer recharge (MAR) is one of the methods to integrate surface water and groundwater (see Chaps. 16 and 17). MAR uses excess runoff or reused urban waste water to recharge aquifers and offsets the decreased recharge that has been caused by reservoir construction or overdraft of groundwater. China has a long history in managed aquifer recharge. Dating back to the Qing Dynasty (1644–1911), people in the Huantai County of Shandong Province excavated subsurface channel-wells along the Wuhe River and used river water to recharge groundwater. Since the 1960s, cooling water and tap water were used to recharge groundwater to recover groundwater level in Shanghai as well as to prevent and control land subsidence. Before the 1990s the well-channel irrigation system was popularized in northern rural China with a combination of groundwater exploitation and recharge. In the 1990s, lots of facilities, such as underground reservoirs in coastal areas, were built to prevent sea water intrusion by groundwater recharge with surplus floods (Wang et al. 2010b). In the North China Plain, Xu et al. (2009) identified specific regions that could be targeted for MAR, all of which are alluvial fans in the piedmont of the Taihang Mountains, where regional recharge occurs (Currell et al. 2012). The South-to-North Water Transfer project has been under construction to transfer a billion cubic meters of surface water from southern China to northern China which is plagued by groundwater overdraft. This would be a good example to use surface water and groundwater conjunctively over a large spatial scale. With the transferred surface water satisfying parts of the water demands, groundwater can be conserved and protected to some extent.

18.4.3 Incompleteness of Legal Framework

The incompleteness in the current legal framework in China has limited the implementation of integrated groundwater management. Article 12 in the Water Law (issued in 1988 and amended in 2002) regulates the administrative system of water resources, which is to integrate watershed management with the management of administrative regions. The department of water administration under the State Council, that is, Ministry of Water Resources (MWR), is in charge of the integrated administration and supervision of water resources throughout the country. MWR establishes watershed management organizations for the major rivers and lakes, which perform the managing and supervising duties in their jurisdiction. The department of water administration under the local governments at or above the county level is responsible for the integrated management and supervision within their respective administrative regions.

Water planning is listed as an independent chapter (Article 14–19) in the Water Law to emphasize the importance of planning and its legal status. It is emphasized that integrated water planning should be done based on watersheds and regions, with the regional planning complying with watershed planning, and professional planning (such as flood control, irrigation, shipping, water supply, hydropower generation, and fisheries) complying with integrated planning (the overall arrangements of water exploitation, utilization, conservation and protection). The planning should be based on a comprehensive scientific survey and an investigation and assessment co-organized by the department of water administration at or above the county level in conjunction with the relevant departments at the same level.

Article 23 indicates that local governments at different levels should utilize surface water and groundwater conjunctively and make a rational and integrated exploitation of water based on the actual conditions of the local water resources. Article 36 mentions that groundwater abstraction should be strictly controlled in overdraft areas by the local government at and above county level. Scientific studies should be conducted and measures adopted if pumping groundwater in coastal areas in order to prevent land subsidence and sea water intrusion.

Although the Water Law has explicitly mentioned the “integration” issue in several of its articles, the legal regime is still far from complete and fails to capture important issues such as the necessity for integrated management and control of water quantity and quality. Article 32 mentions that the departments of water administration at or above the county level or watershed management organizations should evaluate the pollutant carrying capacity of a certain watershed and then provide suggestions of the total pollution discharge to the administrative department of environmental protection. The departments of water administration at or above the county level or watershed management organizations undertake the water quality monitoring task, and need to report to the administrative department of environmental protection. This segmentation in managing water quantity and quality will inevitably hinder the realization of integrated groundwater management.

18.4.4 Defective Institutional System

An integrated institutional system that is a good fit for the characteristics of groundwater resources has not been established in China. A coordinating organization is lacking and both segmentation and overlapping exist in the function of the major water management departments. Even though the amended Water Law indicates that the MWR has the right to govern water resources in an integrated fashion, including the protection and management of water resources, there is no further definition of what exactly the department is in charge of in the law. The multi-sectoral management system has caused undue overlaps, conflict of interests and additional complexity in solving problems (Department of Water Resources Management 2008). The Ministry of Land and Resources and its subordinate units take on the basic hydrogeological survey tasks and gather the basic geological data and information. In the meantime, the administrative function of groundwater management belongs to the Ministry of Water Resources, which is in charge of issuing groundwater abstraction permits and owns the information on groundwater utilization. The groundwater quality and pollution issue is under the jurisdiction of the Ministry of Environmental Protection. This has caused significant difficulties in data sharing and use, and prevented the hydrogeological surveys and groundwater contamination assessment to achieve the best outcomes.

Although watershed management organizations have been constructed and their legal status has been defined in the amended Water Law, the actual situation is that the management power of watershed management organizations is very limited. At present the major tasks of the watershed management organizations center on construction and management of river flood control systems and development of some ad hoc projects at the watershed scale, but they do not play a substantive role in the development and management of water resources, especially groundwater resources, at the watershed scale.

The current situation of water management authority has left "policy implementation . . . fragmented and disjointed" (Foster et al. 2004). Many local governments have been slow to embrace the laws and regulations; as a result enforcement of the laws varies widely among the localities. In addition, as an institutional setting, each administrative division has its own water resource management departments. A local bureau only reports to its corresponding local government, not the bureaus or ministry above it. A higher bureau has no mandatory power over the lower one (the broken arrows in Fig. 18.7 showing the indirect leadership). Furthermore, a bureau is financially supported by the local government whose budget mostly depends on its local GDP. All these tend to promote local protectionism which affects policy implementation, and also breaks the integrity and integration of watershed management (Saleth and Dinar 2000).

18.4.5 Lack of Information Sharing and Public Participation

As a public resource, groundwater governance cannot continue without public participation. In western countries such as the European Union and Australia, the system of public participation is specified in legal documents, and the public plays an important role in groundwater protection. In the United States, since the "Love Canal" incident and largely spurred by it, citizen groups have demanded more inclusion in decision processes that affect their communities, such as the cleanup of

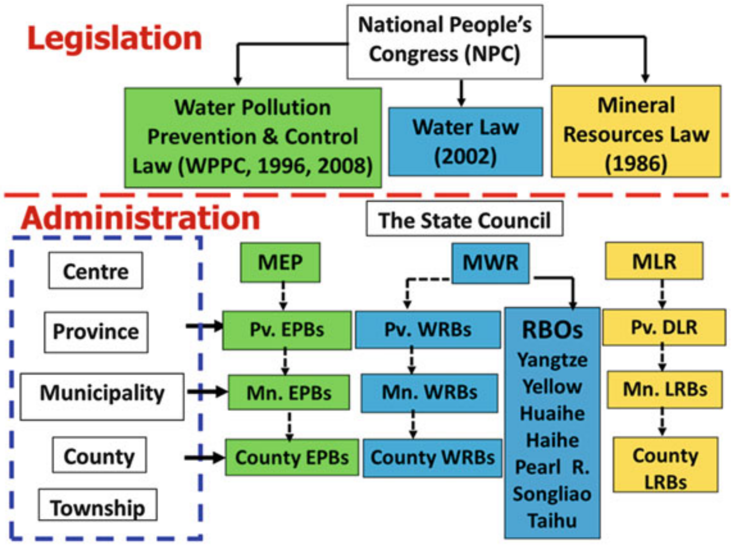

Fig. 18.7 Legislation, administrational and institutional system of groundwater management in China (Acronyms: *MWR* Ministry of Water Resources, *MEP* Ministry of Environmental Protection, *MLR* Ministry of Land and Resources, *WRB* Water Resources Bureau, *EPB* Environmental Protection Bureau, *DLR* Department of Land and Resources, *LRB* Land and Resources Bureau, *RBO* River Basin Organizations)
The *solid arrows* depict the political dependency
The *broken arrows* indicate indirect leadership – mainly professional guidance from higher-level authorities without any hierarchical subordination

Superfund sites. But in China the public participation system has not been defined in current groundwater-related laws and regulations. Public awareness of the importance of groundwater and the status of groundwater quantity and quality is lacking. One prerequisite for public participation is to have a transparent institutional structure and accessible information (Winalski 2009). Data publishing and information sharing should be promoted; education of the public regarding groundwater protection is needed. "Any law lacks teeth unless public involvement fostered by education and media coverage promotes and accelerates the implementation process as an external factor" (Beyer 2006).

18.5 Recommendations Towards More Integrated Groundwater Management in China

China's State Council warned in 2007 that by 2030 China's water use will reach or approach the total volume of exploitable water resources. The country will consume 750 billion m^3 of water per year by 2030, about 90 % of the total amount of usable water resources in the country (Qiu 2010). With changing climate and intensifying human activities, groundwater will continue to be used intensively in China, putting groundwater management under increasing stresses. The wide-ranging spatial and temporal scales of groundwater resources in China necessitate an integrated approach for exploitation and management. Implementing integrated groundwater management is a question of getting the "three pillars" right: (1) moving towards an enabling environment of appropriate legislation, policies and strategies; (2) putting in place the institutional framework through which policies can be implemented; and (3) setting up the management instruments required by these institutions to do their job (Water Partnership Program 2014). This has provided a general instruction for implementing integrated groundwater management in China.

Over the past 60 years, China has made great progress towards the integrated management of groundwater. However, there is still much work that needs to be done to continue the integration. Firstly, the legislation system should be improved. China still has no groundwater-specific laws and regulations, only with some provisions in general terms (the Water Law and the WPPC Law) regulating groundwater management. The overlapping of the WPPC Law and the Water Law leads to the confusion of institutional responsibilities of the MWR and the MEP as well as their local counterparts. In addition, the groundwater legal regime is far from complete and fails to capture important issues such as the necessity for integrated management and control of water quantity and quality. The formulation of specific "Groundwater Management Regulations" and the technical standards on groundwater development should be speeded up to enhance groundwater governance and protection in accordance with laws. The vague statutory language and general terms of the present laws and regulations also create obstacles to the implementation process, and need to be more clarified and specific.

Secondly, institutional reforms are needed to straighten out several critical relationships, including the relationship among different organizations with water-related jurisdiction, the relationship between the national and local governments, and the relationship between watershed based and administrative division based management approaches. The responsibilities, authorities and interests of each side should be clarified. Under the current institutional system, the management of water quantity and water quality is divided and is under the administration of the MWR and the MEP separately. A suggestion to resolve this separation is to construct an integrated water resources management system led by the MWR, and a supervision system on water environment protection led by the MEP. To improve watershed management, the relationship between watershed management organizations and the regional management authorities should be carefully defined. Different levels should be differentiated for the watershed management and regional management. In general, the institutional reforms involve the distribution of important resources and are closely related to the national political system. Information sharing and collaborations among those related organizations and at different levels are essential for integrated groundwater management.

Thirdly, it is urgently needed to set up the management instruments and build up professional management teams to guarantee the implementation of integrated groundwater management. Currently the MWR has led integrated water resources management, but for a long period the MWR has mainly managed surface water and lacks experience in managing groundwater. It is important to build up the capacity in managing groundwater, including the formation, distribution, transformation of groundwater and its interaction with surface water. A dynamic national groundwater monitoring network should be constructed with improved metering techniques to collect information and provide the scientific foundation for groundwater management. Data dissemination and access, and information sharing should also be greatly improved. In addition it is essential to improve participation of stakeholders and to enhance public awareness and education of groundwater utilization and problems.

Finally, China should rethink its economic development strategy, population policy, and food security policy. China has been attaching primary importance to the development of the economy in the past three decades. Environmental quality and ecosystem health have not been given sufficient consideration, although the situation has been improving recently. It is essential to integrate the eco-environmental factors into its sustainable development strategy. Agriculture is the largest groundwater consumer among the various water using sectors, and therefore how to optimize certain agricultural water use requirements without threatening the food security policy will be an important issue. With the population exceeding 1.3 billion, nearly 20 % of the world's population, China is facing unprecedented challenges in managing its limited water resources. In general, to manage China's groundwater resources effectively and sustainably, various aspects discussed in this chapter must be considered, including philosophical, legal, scientific and technological. This is a long-term goal that needs continuous and relentless efforts.

Acknowledgements The authors greatly appreciate the valuable comments by Jean-Daniel Rinaudo and Randy Hunt which have led to significant improvement of the presentation. The support for this work was provided by the National Natural Science Foundation of China (No. 41271032 and No. 91225301).

References

Barthel R, Jagelke J, Gotzinger J et al (2008) Aspects of choosing appropriate concepts for modeling groundwater resources in regional integrated water resources management – examples from the Neckar (Germany) and Oueme catchment (Benin). Phys Chem Earth 33:92–114

Beyer S (2006) Environmental law and policy in the people's Republic of China Chinese. JIL 5 (1):185–211

Cao G, Zheng C, Scanlon BR et al (2013) Use of flow modeling to assess sustainability of groundwater resources in the North China Plain. Water Resour Res 49:159–175. doi:10.1029/2012WR011899

China Ministry of Environmental Protection (1994) National quality standard for ground water (GB/T 14848–93)

China's Groundwater Information Center (2014) http://www.cigem.gov.cn. Accessed 20 Apr 2014

Demetriou C, Punthakey JF (1999) Evaluating sustainable groundwater management options using the MIKE SHE integrated hydrogeological modeling package. Environ Model Software 14:129–140

Department of Water Resources Management, the Ministry of Water Resources (2008) The collection of groundwater laws, regulations and standards. China Standard Press (in Chinese), Beijing

Esteban E, Dinar A (2011) Collective action and the commons: are cooperative groundwater institutions stable in the presence of environmental externalities? Water Science and Policy Center, Riverside

Foster S, Garduno H, Evans R et al (2004) Quaternary aquifer of the North China Plain – assessing and achieving groundwater resource sustainability. Hydrogeol J 12:81–93

Han D, Chen Z et al (2012) Sustainability of groundwater usage in northern China: dependence on palaeowaters and effects on water quality, quantity and ecosystem health. Hydrol Process. doi:10.1002/hyp.9208

Huang L, Zheng C, Liu J et al (2012) Application of distributed temperature sensing to study groundwater-surface water interactions in the Heihe river basin. Hydrogeol Eng Geol 39(2):6–11 (in Chinese)

Ji C, Wang Z (2009) Sixty years retrospect and prospect of China's hydrogeology and engineering geology. Paper presented at the 21st conference of committee of geological history, geological society of China, China University of Geosciences (Beijing), Beijing, Oct 2009

Liu Z (1987) Introduction of groundwater utilization in ancient China. Ground Water 3:186–187 (in Chinese)

Liu C, Yu J, Kendy E (2001) Groundwater exploitation and its impact on the environment in the North China Plain. Water Int 36(2):265–272

Liu J, Zheng C, Zheng L et al (2008) Ground water sustainability: methodology and application to the North China Plain. Ground Water 46:897–909

Liu C, Hu Y, Liu J et al (2014) Advances in the use of temperature data for study of surface water-groundwater interactions. Hydrogeol Eng Geol 41(5):5–10

Ministry of Environment Protection (2011) National pollution groundwater prevention plan (2011–2020). Index No. 000014672/2015-00539

Ministry of Environmental Protection (2012) China's Environmental Bulletin. Index No. 000014672/2015-00539

Ministry of Water Resources (2011) China Water Resources Bulletin (1997–2011). China Water Power Press, Beijing. ISBN 7508490797, 9787508490793

Qin H, Cao G, Kristensen M et al (2013) Integrated hydrological modeling of the North China Plain and implications for sustainable water management. Hydrol Earth Syst Sci 17:3759–3778

Qiu J (2010) China faces up to groundwater crisis. Nature 466:308

Qiu J (2011) China to spend billions cleaning up groundwater. Science 334:11

Saleth R, Dinar A (2000) Institutional changes in global water sector: trends, patterns, and implications. Water Policy 2:175–199

Shu Y, Villholth K, Jensen K et al (2012) Integrated hydrological modeling of the North China Plain: options for sustainable groundwater use in the alluvial plain of Mt. Taihang. J Hydrol 464–465:79–93

Tang K, Wu Y, Hou J (2006) Assessment of groundwater quality in China: groundwater quality and pollution analysis. Water Resour Prot 22(3):1–4 (in Chinese)

Wang J, Huang J, Zhang L et al (2010a) Water governance and water use efficiency: the five principles of WUA management and performance in China. J Am Water Resour Assoc 46(4): 665–685

Wang W, Sun X, Xu Y (2010b) Recent advances in managed aquifer recharge in China. 2010. In: International conference on challenges in environmental science and computer engineering, vol 2, pp 516–519. doi:10.1109/CESCE.2010.100

Water Partnership Program (2014) www.gwpforum.org. Accessed 20 Apr 2014

Wijnen M, Augeard B, Hiller B et al (2012) Managing the invisible – understanding and improving groundwater governance. Water Partnership Program. http://water.worldbank.org/sites/water.worldbank.org/files/publication/ESW_Managing-the-invisible.pdf. Accessed 20 Apr 2014

Winalski D (2009) Cleaner water in China? The implications of the amendments to China's law on the prevention and control of water pollution. J Environ Law Litig 24:181–202

Xu G, Liu L, Fei Y et al (2009) Research on the adjustment of groundwater storage in the North China Plain. Resour Sci 31:375–381 (in Chinese)

Yang H, Zehnder A (2007) "Virtual water": an unfolding concept in integrated water resources management. Water Resour Res 43:W12301. doi:10.1029/2007WR006048

Zhang Z, Li L (eds) (2004) Groundwater resources of China. SinoMaps Press, Beijing. ISBN 7-5031-3418-6

Zhang L, Wang J, Huang J et al (2008) Development of groundwater markets in China: a glimpse into progress to date. World Dev 36(4):706–726

Zhang Z, Fei Y, Guo C et al (2012) Regional groundwater contamination assessment in the North China Plain. J Jilin Univ (Earth Sci Ed) 42(5):1456–1461

Zheng C, Liu J (2013) China's "Love Canal" moment? Science 340:810

Zheng C, Liu J, Cao G et al (2010) Can China cope with its water crisis? – perspectives from the North China Plain. Ground Water 48(3):350–354

Zhou Y, Dong D, Liu J et al (2013) Upgrading a regional groundwater level monitoring network for Beijing Plain, China. Geosci Front 4:127–138

Social Science Contributions to Groundwater Governance

19

Allan Curtis, Michael Mitchell, and Emily Mendham

Abstract

All environments have been modified by human activity and those interactions produce "winners" and "losers". Improvements require changes in human behaviour, especially when these activities deny opportunities for future generations. However, changing human behaviour can be difficult to accomplish. We need to establish better ways to reach and implement sound decisions. For social researchers, a key assumption is that complex and difficult natural resource management (NRM) issues are often best addressed by engaging stakeholders in processes that involve dialogue, learning and action – that is, by engaging and building human and social capital. In this chapter we identify some of the social research principles and practices that will enhance groundwater governance. Social researchers have developed principles and approaches for effective stakeholder engagement, social impact assessment, collaborative approaches for NRM governance and changing the use and management of land and water by rural landholders. We conclude with a discussion of some of the challenges for social scientists contributing to larger integrated programs.

A. Curtis (✉) • E. Mendham
Graham Centre for Agricultural Innovation, Wagga Wagga, NSW, Australia

National Centre for Groundwater Research and Training, Flinders University, South Australia, PO Box 789, Albury, NSW 2640, Australia
e-mail: acurtis@csu.edu.au

M. Mitchell
Landscapes and Policy Hub, National Environmental Research Program, University of Tasmania, PO Box 789, Albury, NSW 2640, Australia

A.J. Jakeman et al. (eds.), *Integrated Groundwater Management*,
DOI 10.1007/978-3-319-23576-9_19

19.1 Introduction

Research to improve groundwater management is increasingly recognising the value of drawing on theory and methods from social research. In part, this trend reflects the increasing maturity of those disciplines; and builds on an acceptance that all environments have been modified by human activity and function as co-evolving social-ecological systems (SES), as discussed in Chap. 3. Improvements in environmental condition require changes in human behaviour, especially when these activities deny opportunities for future generations. However, changing human behaviour can be difficult to accomplish. Environmental management is complex because: cause and effect is often uncertain; effective intervention often requires substantial effort over a considerable period of time; it is often difficult to link an intervention with change in resource condition; and in many instances, no single actor is capable of addressing these issues on their own (Curtis and Lefroy 2010). That is, we are often dealing with "wicked problems" (Rittel and Webber 1973). Changing the behaviour of individuals and groups of people is necessary, but not always sufficient. It is also clear that land and water degradation frequently results from deficiencies in governance arrangements (Lockwood et al. 2009). We need to establish better ways to reach and implement sound decisions.

The introductory paragraph above sets out much of the rationale for a chapter that focuses on the social dimensions of groundwater governance. The chapter will provide a review of relevant literature in the social sciences with the aim of identifying the ways those disciplines can contribute to improved ground water governance.

19.2 Responding to Complexity and Uncertainty

For social researchers, a key assumption is that "wicked problems" are best addressed by engaging stakeholders in processes that involve dialogue, learning and action – that is, by engaging and building human and social capital. We deliberately distinguish 'engage and build' on the basis that we believe that all people possess inherent abilities and agency (ability to take action to meet their needs). By human capital we mean the skills and abilities of individuals (Castle 2002); and social capital refers to the social relations, networks, trust, norms and institutions (rules) that arise between people when they interact, and which can then lead to further benefits (Sobels et al. 2001). Social researchers typically support more inclusive approaches to Natural Resource Management (NRM) that move beyond government where decisions are largely influenced by markets and bureaucracies to governance where a wider set of actors and arrangements are embraced (Lockwood et al. 2010).

The social research team in Australia's National Centre for Groundwater Research and Training (NCGRT) recently completed a comprehensive review of social research focused on groundwater governance. That literature turned out to be a relatively small but expanding body of published work (Mitchell et al. 2011). Almost 300 potentially relevant publications were identified, sorted thematically and assessed for quality in terms of having sound theoretical underpinning and providing credible evidence to support key findings (Mitchell et al. 2012). Some of the ground breaking research identified included Ostrom's publications around the role of social norms in NRM governance that built on her doctoral thesis examining groundwater management in California (Ostrom 1965, 1990). In Australia, the work on justice principles by Syme and colleagues (e.g. Syme et al. 1999) is partly based on research involving reforms in groundwater allocations. This process also enabled the authors to identify some of the key social research principles and practices that will enhance groundwater governance; and identify future social research directions. Those topics are the main foci for this chapter. We will also reflect on our experiences as social researchers contributing to larger integrated research programs which we think are essential if "wicked problems" are to be addressed effectively.

19.3 Effective Community/Stakeholder Engagement

For political scientists, civic engagement is a fundamental right and responsibility of citizenship thought to enhance individual's sense of self and well-being. From the 1960s, public engagement became accepted practice with legislation in the USA mandating public involvement in all federal agency decision making (Stankey and Hendee 1975). Public participation was expected to provide an effective means of articulating and incorporating community values in decisions (Creighton 1983), legitimise planning outcomes, reduce conflict, provide feedback on program implementation and outcomes, contribute to community education and improve accountability of government (Daneke 1983; Grima 1983). Of course, the reality and outcomes were often very different. The public often perceived engagement as tokenistic because they thought decisions had already been made; existing inequalities were often entrenched because the privileged with better networks were more likely to be engaged; it was unlikely to be fully representative; those attempting to engage had little idea of how to do that effectively; and the expectation of resolving conflict was unrealistic and ill formed (Kweit and Kweit 1981; Priscoli 1983; Sewell and Phillips 1979; Stankey and Hendee 1975).

Those working in NRM often focus their engagement on local, place-based communities. The local scale can be appropriate for interventions that seek to address local manifestations of environmental problems and to do so by engaging and building human and social capital. However, that focus can also result in the marginalisation of others, including communities of practice, interest and identity (Harrington et al. 2008). There are also questions about the extent the concept of community is used by those with limited understanding or commitment to sound engagement principles and practices. For those operating at larger scales, stakeholder engagement might be a more appropriate conceptualisation of the task at hand.

We employ the term "stakeholder" to indicate the range of people who might participate, encompassing those who are influenced by a particular action, organisation or phenomenon, and those who influence that action, organisation or phenomenon (Freeman 1984). In the groundwater context, stakeholders can include scientists, policy makers, farmers, Indigenous people and environmental interests, and there are clear benefits from not excluding key actors (Knüppe and Pahl-Wostl 2011).

There is now abundant advice about how to implement participatory processes (Aslin and Brown 2002). Broad principles for effective stakeholder engagement include: ensure transparency about the purpose of engagement and the level of decision making offered; be inclusive of the range of stakeholders and empower the less advantaged to participate; and develop processes that enable participants to see other perspectives and, therefore, to act "reasonably" rather than "rationally" (Perlgut 1986).

Community self-regulation of groundwater, such as treated in Chap. 9, exemplifies the "citizen control" end of Arnstein's (1969) ladder of citizen participation. However, Arnstein's typology has been criticised for idealising "citizen control", potentially disparaging a wider range of participation approaches that might be appropriate in different contexts (Collins and Ison 2009; Ross et al. 2002). Baldwin (2008), for example, investigated an irrigation community's effort to initiate a system of co-management of groundwater with government through a water planning process in the Lockyer Valley of southern Queensland, Australia. She concluded that groundwater management should draw on values-based rules developed by stakeholders to reflect Ostrom's principles for improving self-governance of common pool resources, but that these should be enforced by government. Taylor et al. (2009) also concluded that government authorities should maintain a role in groundwater management.

In the groundwater literature there are examples where stakeholders have been engaged in planning through participatory modelling (Martínez-Santos et al. 2008), agent-based modelling (Zellner 2008), integrated assessment modelling (Letcher and Jakeman 2003) or cooperative modelling (Tidwell and van den Brink 2008). Henriksen and Barlebo (2008) and more recently Ticehurst et al. (2011) assess the use of Bayesian Networks (BNs) as a tool to enable stakeholder engagement in policy implementation and evaluation. They have also been used as a tool to integrate local ecological knowledge with scientific-based knowledge (Liedloff et al. 2013). BNs are particularly suited to participatory processes because stakeholders are engaged in processes to establish a common language and a shared understanding of causality. In this sense the use of BNs contributes to a process of social learning (Reed et al. 2010; Schusler et al. 2003). The largely hidden and complex nature of groundwater governance provides an ideal context for engagement that embraces social learning.

19.4 Social Impact Assessment

Changes in access to water resources have been a key element of government responses to environmental degradation and water scarcity. In relation to groundwater, these reforms have included reductions in groundwater entitlements and annual allocations, the introduction of trading in groundwater, and changes in rules to allow for the "banking" of surplus water in aquifers for later recovery and use (Contor 2009; Schlager 2006; Thompson et al. 2009). Of course, these changes have the potential to have substantial impacts on stakeholders, including irrigators, industries dependent on irrigation and the nearby towns and cities.

Social impact assessment (SIA) explores how particular events or policies affect people's way of life, their culture and their community (Vanclay and Esteves 2011). SIA may draw on economic assessments, but emphasises the non-monetary effects of an intervention. SIA uses a range of social science disciplines to anticipate the consequences of proposed actions compared to a "no change" scenario. While there are limits to the capacity of the social sciences to predict impacts, plausible scenarios can be constructed, including by drawing on experience with similar interventions in other contexts.

Australian researchers have been at the forefront of developing solid theoretical foundations for SIA (Howitt 1989; Syme and Nancarrow 2006; Syme et al. 1999; Vanclay and Esteves 2011). An important aspect of SIA is the identification of social groups which may be impacted in both negative and positive ways (winners and losers), in particular in relation to individual and community well-being. Amongst other things, SIA examines the unequal distribution of benefits and costs; changes in power structures; implications for family life, health and education; and effects on community cohesion and local organisations. SIA considers impacts on basic human needs (e.g. food, shelter, health, education, work), but extends to consider all of the key aspects of contemporary life in a particular society (e.g. access to banking services; recreation opportunities and infrastructure; quality of information and communication technology; aspirations for the future, including for family succession and education of children).

SIA provides policy makers with a process for identifying and working through issues with stakeholders. A key assumption is that SIA will enable stakeholders (including governments and communities) to identify strategies to mitigate impacts and to monitor impacts over time. Public engagement is a fundamental part of SIA. While there are likely to be benefits from engagement through an SIA in terms of providing a sound information base, clarifying issues, articulating values (i.e. what is important), identifying alternatives and clarifying tradeoffs, and enhancing agency credibility and reducing conflict, these outcomes cannot be assumed. These objectives are reflected in the steps that an SIA typically involves (Vanclay and Esteves 2011).

Public engagement can be costly, requires expertise and, in the case of contentious issues, takes some time (from a few months to years). The scale and duration of the SIA will depend on an initial assessment of the extent of likely impacts (e.g. minimal/substantial/transformational), the extent that the intervention will be contentious and the time/resources available.

Despite the potential of SIA, there is always the concern that governments will offer to undertake SIA to placate disgruntled stakeholders and that SIA will occur after a decision has been made. This has largely been the case so far in the past decade with the major water reform process in Australia (Baldwin et al. 2009).

Notwithstanding those remarks, there are international examples where social researchers have been able to make recommendations that have been empowering and proactive (Howitt 1989; Vanclay and Esteves 2011). Of course, social researchers can examine the social impacts of interventions without undertaking a formal SIA. Budds (2009) was able to expose the extent a hydrological assessment undertaken by a contractor for a Chilean government agency enabled wealthier and better educated farmers upstream to secure groundwater allocation rights, including substantial additional amounts of water. Those additional allocations came at the expense of the majority of groundwater users who were peasants located downstream. Apparently, modelling by the contracting agency had failed to consider the widespread illegal use of groundwater, an amount that was estimated to be almost twice that of actual legal extractions. The illegal groundwater use was predominantly by peasant farmers.

Syme et al. (1999) focused on the concepts of fairness and justice as part of their research examining water reform processes, and employed rigorous empirical research to explore these ideas. These authors developed a set of fairness principles and a fairness heuristic that can be used to assess the justice of such decisions. Syme et al. (1999) found that the public considered both distributional and procedural justice when deciding whether water allocation processes were fair. Additionally, they concluded that most of the community assessed fairness as both situational – relating to specific water allocation decisions and each community's unique context; and universal – relating to overarching principles, such as a community's rights to have a say in allocation decisions, adherence to principles of procedural justice in the decision-making process, and rights of the environment. These topics have been pursued through subsequent studies by Lukasiewicz et al. (2013).

19.5 Collaborative Approaches to Groundwater Governance

Governance involves the interactions between social structures, processes and traditions that determine how power in society influences how decisions are made, how responsibilities are exercised and who has a say in all of this (Lockwood et al. 2010). The shift to governance reflects an approach to decision making that moves beyond markets and bureaucracies to be inclusive of a wider set of actors and arrangements (Lockwood et al. 2010). For Mukherji and Shah (2005) "groundwater governance" implied a shift from expert-driven processes derived from the "mathematical model-building exercises" of hydrologists and "the formulation and implementation of groundwater laws" by water managers. In part, the move towards governance reflects the need to establish better ways to reach and implement sound decisions. But groundwater governance has its own challenges, including those related to incomplete property rights, compliance with rules when the resource is largely invisible, lack of knowledge about the interconnections with surface and groundwater, the impact of groundwater use at considerable distance from where extraction occurs (Bolin et al. 2008), and conflicting interpretations over sustainable use of groundwater (Shriver and Peaden 2009; Weber et al. 2011) derived in part from the problematic construct of sustainable yield (Richardson et al. 2011; Seward et al. 2006).

There is increased interest in exploring the potential for community self-regulation of groundwater given the trend to devolve responsibilities away from centralised authorities (Chap. 9; Wilder and Lankao 2006), problems associated with privatisation (Bluemling et al. 2010), and the difficulties government agencies face in regulating groundwater use and preventing over extraction (van Steenbergen 2006). Defined as the "collective management of groundwater by water users" (López-Gunn 2003; Wester et al. 2011), the concept is also referred to as local, community-based and/or participatory management (Sandoval 2004; van Steenbergen 2006; Yamamoto 2008). In Gujarat, India, for example, government agencies in partnership with local non-governmental organisations have nurtured the development of farmer cooperatives and other credible local organisations (Tewari and Khanna 2005). Drawing on examples from developing economies, van Steenbergen (2006) concluded that informal norms based on moral imperatives (or "injunctive" social norms) have been the most effective means to limit the negative consequences of excessive private development of groundwater resources. Others have examined the difficulties that can be faced when authorities attempt to promote self-regulation of groundwater (López-Gunn and Cortina 2006; Mustafa and Qazi 2007; Wester et al. 2011).

Our review of the literature suggests that self-regulation is most effective when it evolves through collective action, building on the strength of existing social capital. Ross and Martinez-Santos (2010) confirmed Ostrom's (1990) conclusion that self-regulation is more likely to work for smaller scale groundwater systems than larger ones. Existing literature has little to say about how to build and engage community capacity for self-organisation. Yet there is a body of research exploring attributes of social capital that could provide researchers examining groundwater management with a rich pool of theory and research tools to draw upon. For example, de Vos and van Tatenhove (2011) described the evolution of trust relationships between fishers and government through the development of co-management arrangements in the Netherlands. In their evaluation of regional NRM governance in Australia, Lockwood et al. (2010) identified seven governance principles and provided a set of examples of how the elements of each principle could be evaluated.

19.6 Influencing the Use and Management of Land and Water by Rural Landholders

In developed and developing economies rural landholders are key stakeholders in groundwater governance. Groundwater access and the quality of that water are often critical factors influencing human wellbeing (e.g. food security, incomes, employment and health). The land use and management actions of rural landholders also influence the integrity of aquifers and in turn, the condition of key environmental assets. However, groundwater research has focused mostly on the resource, rather than the actors who use and manage the resource (Hammani et al. 2009). Bekkar et al. (2009), Kuehne et al. (2008) and Albrecht (1990, 1995) are some of the small set of researchers who have explored the links between landholder behaviour and influences on landholder adoption in the groundwater context.

Engaging rural landholders in practice change is complex and difficult, not least because there is a potentially large set of factors (personal, societal) influencing their decisions (Mazur et al. 2013; Pannell et al. 2006); and these vary according to each technology, each landholder, each farming context and over time (Curtis and Mendham 2011). Figure 19.1 provides a useful framework for those attempting to identify the most relevant factors in any context. Even the concept of adoption is problematic. For example, when does a trial of a new practice become a change that represents adoption/implementation?

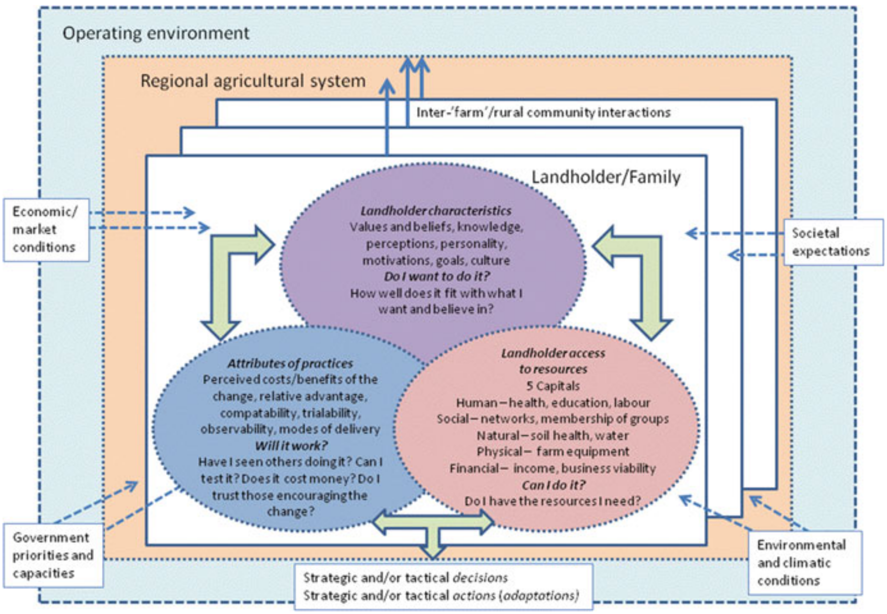

Fig. 19.1 Understanding landholder decision making (Adapted from Mazur et al. 2008)

Personal engagement with individual landholders can be very effective. However, personal engagement is not always possible or necessary and it may be sufficient to develop a suite of policy instruments from across the "five P's: prescription, penalty, persuasion, property rights (and markets) and payment that meet the diverse needs of landholders (Salzman 2005).

The selection of policy instruments should be based on an assessment of the extent we are confident in the science underpinning decisions about "where we are headed and how to get there" (Curtis and Lefroy 2010); the adoptability of the technology (landuse or management practice); and the relative costs of different approaches, including transaction costs (Pannell 2011).

Where we are reasonably confident about the appropriateness of the outcomes we are seeking and the science that links the proposed intervention and desired outcomes, we can apply best-practice recommendations. If that is the case, we then need to make an assessment of the adoptability of those practices by rural landholders. For example, if awareness, knowledge or management skills are the issue, then activities that address those issues are appropriate. If the issue is lack of confidence in a recommended practice, perhaps because elements of the technology might be unproven or complex, then activities to trial those practices in the local area might be appropriate. If the issue is that the change involves considerable expense and appears to offer limited financial returns to landholders, then some form of cost-sharing between government and private landholders might be appropriate. Of course, even the implementation of best practices should be undertaken within an adaptive management framework.

We live in an increasingly modified environment. Having accepted that reality, it makes little sense to base NRM around the objective of restoring the environment to "pristine" condition. We must also recognise that concepts such as "pristine," "safe" or "sustainable yield" are human constructs that are changing over time (Alley and Leake 2004; Pierce et al. 2013).

A way forward is to bring stakeholders together to negotiate desired condition outcomes for specific environmental assets or systems (e.g. a water catchment) and for these condition targets to be the basis for developing and adapting strategies to move towards more desirable futures (Curtis and Lefroy 2010).

Rural landholders would be a key stakeholder in these processes and would be actively engaged in the dialogue, learning and action (not just on their property) that would occur in such an iterative process. The literature around resilience thinking and social learning provides important theoretical foundations and much practical guidance for those contemplating this type of engagement with rural landholders.

While improved environmental condition or health is the desired outcome of NRM interventions, considerable focus will be on engaging and building human and social capital that underpin much of the capacity of any community to respond to the challenges of sustainability. These concepts were introduced earlier and we expand those explanations here. Human capital embraces the attributes of a population, its training and skills, health and cultural diversity. Social capital refers to the attributes of relationships established in a community that enables participants to act together more effectively. These attributes include the structural social capital of networks and partnerships; and the cognitive social capital of trust, norms, institutional arrangements and reciprocal relationships that predispose people to cooperative behaviour and reduce transaction costs (Sobels et al. 2001). A focus on developing positive social norms is one strategy that can be used to influence adoption of new practices (Minato et al. 2010). Of course, if changes in human and social capital are part of our intermediate objectives as we strive to achieve our environmental condition targets, we must develop measures to evaluate those outcomes.

There is a trend in social research focused on environmental behaviour to draw on Values–Beliefs–Norms (personal) (VBN) theory (Stern et al. 1999). Our view is that this and related theories arising from the Theory of Planned Behaviour (Ajzen 1991) are adequate for explaining the conservation behaviours of the general public, but do not adequately account for the larger set of factors influencing decisions by rural landholders (Pannell et al. 2006). These additional factors include attributes of specific practices; government interventions to influence landholder decisions; global commodity prices; and the existence/development of social norms through local organizations [refer to Fig. 19.1]. It is also important to note that while values, beliefs and personal norms (VBN) may mediate or moderate some of these other factors, it is difficult to change these attributes in the short or medium term. At the same time, we know from research that interventions that focus on engaging and building human and social capital, including through one-to-one extension, involvement in short courses and participation in field days have positive effects on adoption (Curtis and Mendham 2011). An additional layer of complexity is emerging as a result of the trend to non-farmer (by occupation) rural landholders, and a substantial cohort of absentee owners (Mendham and Curtis 2010).

19.7 Conclusions

19.7.1 Future Research

Drawing on our review, our knowledge of the more expansive social research contributions to NRM, and our understanding of the groundwater context, we have identified a number of research topics that could be pursued by social researchers in order to achieve more integrated groundwater management. Sustainable yield remains a problematic concept for groundwater managers and scientists. Social researchers could make an important contribution here by describing, explaining, and perhaps assisting in reconciling the different ways stakeholders define or interpret "sustainable yield" and how those different interpretations affect their attitudes and behaviours, and in turn, policy and management.

The contemporary proliferation of coal seam gas (CSG) developments in Australia, Canada, the United States and elsewhere, which has the potential to impact negatively on aquifer integrity and water quality, also provides a context to examine stakeholder perceptions of risk and trust. A key issue and one of considerable theoretical interest would be the nature of any relationships between risk interpretation and trust and their influence on the social acceptability of CSG by different stakeholders. While there is an established body of research into the social acceptability of carbon capture and storage (e.g. van Alphen et al. 2007) and risk perceptions associated with groundwater contamination (e.g. Vandermoere and Vanderstraeten 2014), research into stakeholder perceptions of risks associated with CSG is in its infancy (Jacquet 2009; Shackley et al. 2006). Given the scale of public controversy over CSG mining, we believe there is considerable scope to inform those policy debates by investigating how CSG risks are interpreted and communicated.

Theoretical constructs and frameworks associated with justice, collective action, trust and social norms can be explored further as researchers contribute to efforts to undertake social impact assessment processes, develop improved collaborative management and community self-regulation, and identify interventions designed to influence landholder behaviour. In this way, developments in theory will be underpinned by practice.

19.7.2 Social Scientists Contributing to Integrated Research

Working as social researchers contributing to multi-disciplinary and interdisciplinary research programs has had many benefits. Regular and structured interactions with scientists have increased our understanding of ecology and hydrogeology and the assumed links between property management and environmental condition outcomes. As part of research teams we have found it easier to access informants and data layers held by spatial scientists. There have also been benefits in terms of being exposed to different perspectives and approaches that have led to improved problem definition and the interpretation of results. These interactions improved the efficiency of the research process, the quality of research outcomes and the extent research has influenced policy and management.

At the same time, our experience has been mixed in that offers to engage with other disciplines have often been ignored. That has typically occurred at the start when research priorities are being developed and resources allocated. Our experience has been that over time, most researchers develop an appreciation of the relevance of social research and the capacity of the social sciences to contribute to integrated approaches. So, it is critical for social researchers to be engaged from the outset in problem definition and setting research priorities. It is also important for social researchers to articulate what they see as the cutting-edge social research rather than being considered as service providers who can support the tasks of stakeholder engagement or social impact assessment. Of course, social researchers must be open to offers to contribute to these research teams and to explain and justify their research approaches.

19.8 Summarised Points

1. *Difficult or 'wicked' natural resource management (NRM) issues are often best addressed by engaging stakeholders in processes that involve dialogue, learning and action to build and engage social and human capital.*
2. *Human and social capital underpins much of the capacity of any community to respond to the challenges of sustainability.*
3. *Principles and practices developed by social researchers that will enhance groundwater governance include: approaches for effective stakeholder engagement, social impact assessment, collaborative approaches for NRM governance and changing the use and management of land and water by rural landholders.*
4. *When conducting integrated research, it is critical for social researchers to be engaged from the outset in problem definition and setting research priorities.*

References

Ajzen I (1991) The theory of planned behavior. Organ Behav Hum Decis Process 50(2):179–211. doi:10.1016/0749-5978(91)90020-T

Albrecht DE (1990) The adaptations of farmers in an era of declining groundwater supplies. South Rural Sociol 7:46–62

Albrecht DE (1995) A comparison of the views of farmers and the nonfarm public regarding resource use the case of Texas groundwater. South J Rural Sociol 11(1):1–15

Alley WM, Leake SA (2004) The journey from safe yield to sustainability. Ground Water 42 (1):12–16. doi:10.1111/j.1745-6584.2004.tb02446.x

Arnstein S (1969) A ladder of citizen participation. J Am Inst Plann 35(4):216–224. doi:10.1080/01944366908977225

Aslin H, Brown V (2002) Terms of engagement: a toolkit for community engagement for the Murray-Darling Basin. Bureau of Rural Sciences, Canberra. http://adl.brs.gov.au/brsShop/html/brs_prod_90000002788.html. Accessed 30 July 2011

Baldwin C (2008) Rules for the magic pudding: managing Lockyer groundwater. Soc Altern 27 (3):26–31

Baldwin C, O'Keefe VO, Hamstead M (2009) Reclaiming the balance: social and economic assessment – lessons learned after ten years of water reforms in Australia. Australas J Environ Manag 16(2):70–83

Bekkar Y, Kuper M, Errahj M et al (2009) On the difficulty of managing an invisible resource: farmers' strategies and perceptions of groundwater use, field evidence from Morocco. Irrig Drain 58(S3):S252–S263. doi:10.1002/ird.527

Bluemling B, Pahl-Wostl C, Yang H et al (2010) Implications of stakeholder constellations for the implementation of irrigation rules at jointly used wells: cases from the North China Plain, China. Soc Nat Resour 23(6):557–572. doi:10.1080/08941920903376998

Bolin B, Collins T, Darby K (2008) Fate of the Verde: water, environmental conflict, and the politics of scale in Arizona's central highlands. Geoforum 39(3):1494–1511. doi:10.1016/j.geoforum.2008.02.003

Budds J (2009) Contested H_2O: science, policy and politics in water resources management in Chile. Geoforum 40(3):418–430. doi:10.1016/j.geoforum.2008.12.008

Castle EN (2002) Social capital: an interdisciplinary concept. Rural Sociol 67(3):331–349

Collins K, Ison R (2009) Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. Environ Policy Gov 19(6):358–373. doi:10.1002/eet.523

Contor BA (2009) Groundwater banking in aquifers that interact with surface water: aquifer response functions and double-entry accounting. J Am Water Resour Assoc 45 (6):1465–1474. doi:10.1111/j.1752-1688.2009.00378.x

Creighton JL (1983) The use of values: public participation in the planning process. In: Daneke GA, Garcia MW, Priscoli JD (eds) Public involvement and social impact assessment. Westview Press, Boulder, pp 143–160

Curtis A, Lefroy EC (2010) Beyond threat- and asset-based approaches to natural resource management in Australia. Aust J Environ Manag 17(3):6–13

Curtis AL, Mendham E (2011) Bridging the gap between policy and management of natural resources. In: Vanclay F, Pannell DJ (eds) Changing land management: adoption of new practices by rural landholders. CSIRO Publishing, Collingwood, pp 153–176

Daneke A (1983) Public involvement: what, why, and how. In: Daneke GA, Garcia MW, Priscoli JD (eds) Public involvement and social impact assessment. Westview Press, Boulder, pp 11–34

de Vos BI, van Tatenhove JPM (2011) Trust relationships between fishers and government: new challenges for the co-management arrangements in the Dutch flatfish industry. Mar Policy 35 (2):218–225. doi:10.1016/j.marpol.2010.10.002

Freeman RE (1984) Strategic management: a stakeholder approach. Pitman, Boston

Grima AP (1983) Analyzing public inputs to environmental planning: a summary and discussion of public involvement in Great Lakes management. In: Daneke GA, Garcia MW, Priscoli JD (eds) Public involvement and social impact assessment. Westview Press, Boulder, pp 111–119

Hammani A, Hartani T, Kuper M et al (2009) Paving the way for groundwater management: transforming information for crafting management rules. Irrig Drain 58(S3):S240–S251. doi:10.1002/ird.521

Harrington C, Curtis A, Black R (2008) Locating communities in natural resource management. J Environ Policy Plan 10(2):199–215

Henriksen HJ, Barlebo HC (2008) Reflections on the use of Bayesian belief networks for adaptive management. J Environ Manage 88(4):1025–1036. doi:10.1016/j.jenvman.2007.05.009

Howitt R (1989) Social impact assessment and resource development: issues from the Australian experience. Aust Geogr 20(2):153–166. doi:10.1080/00049188908702987

Jacquet J (2009) Energy boomtowns and natural gas: implications for Marcellus Shale local governments and rural communities. NERCRD Rural Development paper no. 43, Northeast Regional Center for Rural Development, Pennsylvania State University, University Park

Knüppe K, Pahl-Wostl C (2011) A framework for the analysis of governance structures applying to groundwater resources and the requirements for the sustainable management of associated ecosystem services. Water Resour Manag 25(13):3387–3411. doi:10.1007/s11269-011-9861-7

Kuehne G, Bjornlund H, Cheers B (2008) Identifying common traits among Australian irrigators using cluster analysis. Water Sci Technol 58(3):587–595. doi:10.2166/wst.2008.681

Kweit MG, Kweit RW (1981) Implementing citizen participation in a bureaucratic society. Praeger, New York

Letcher R, Jakeman A (2003) Application of an adaptive method for integrated assessment of water allocation issues in the Namoi River catchment. Australia. Integr Assess 4(2):73–89

Liedloff AC, Woodward EL, Harrington GA et al (2013) Integrating indigenous ecological and scientific hydro-geological knowledge using a Bayesian Network in the context of water resource development. J Hydrol 499:177–187. doi:10.1016/j.jhydrol.2013.06.051
Lockwood M, Davidson J, Stratford E et al (2009) Multi-level environmental governance: lessons from Australia for natural resource management. Aust Geogr 40(2):169–186
Lockwood M, Davidson J, Curtis A et al (2010) Governance principles for natural resource management. Soc Nat Resour 23(10):986–1001. doi:10.1080/08941920802178214
López-Gunn E (2003) The role of collective action in water governance: a comparative study of groundwater user associations in La Mancha aquifers (Spain). Water Int 28(3):367–378. doi:10.1080/02508060308691711
López-Gunn E, Cortina L (2006) Is self-regulation a myth? Case study on Spanish groundwater user associations and the role of higher-level authorities. Hydrogeol J 14(3):361–379. doi:10.1007/s10040-005-0014-z
Lukasiewicz A, Syme GJ, Bowmer KH et al (2013) Is the environment getting its fair share? An analysis of the Australian water reform process using a social justice framework. Soc Justice Res 26:231–252
Martínez-Santos P, Llamas MR, Martínez-Alfaro PE (2008) Vulnerability assessment of groundwater resources: a modelling-based approach to the Mancha Occidental aquifer, Spain. Environ Model Software 23(9):1145–1162. doi:10.1016/j.envsoft.2007.12.003
Mazur N, Curtis A, Thwaites R et al (2008) Rural landholder adaptation to climate change: social research perspectives. Landscape Logic Research report no. 5, University of Tasmania, Hobart. http://athene.riv.csu.edu.au/~acurtis/reports/No%205_P2_Mazur_climate%20change.pdf
Mazur N, Curtis A, Rogers M (2013) Do you see what I see? Rural landholders' belief in climate change. Soc Nat Resour 26(1):75–85. doi:10.1080/08941920.2012.686650
Mendham E, Curtis A (2010) Taking over the reins: trends and impacts of changes in rural property ownership. Soc Nat Resour 23(7):653–668. doi:10.1080/08941920801998893
Minato W, Curtis A, Allan C (2010) Social norms and natural resource management in a changing rural community. J Environ Policy Plan 12(4):381–403. doi:10.1080/1523908X.2010.531084
Mitchell M, Curtis A, Sharp E et al (2011) Social research to improve groundwater governance: Literature review. ILWS report no. 66, Institute for Land, Water and Society, Charles Sturt University, Albury. http://www.csu.edu.au/research/ilws/research/reports2011.htm
Mitchell M, Curtis A, Sharp E et al (2012) Directions for social research to underpin improved groundwater management. J Hydrol 448–449:223–231. doi:10.1016/j.jhydrol.2012.04.056
Mukherji A, Shah T (2005) Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeol J 13(1):328–345. doi:10.1007/s10040-005-0434-9
Mustafa D, Qazi MU (2007) Transition from karez to tubewell irrigation: development, modernization, and social capital in Balochistan, Pakistan. World Dev 35(10):1796–1813. doi:10.1016/j.worlddev.2007.06.002
Ostrom E (1965) Public entrepreneurship: a case study in ground water basin management. Dissertation, University of California, Los Angeles
Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Cambridge University Press, Cambridge
Pannell D (2011) Policy perspectives on changing land management. In: Pannell D, Vanclay F (eds) Changing land management: adoption of new practices by rural landholders. CSIRO Publishing, Melbourne, pp 177–187
Pannell DJ, Marshall GR, Barr N et al (2006) Understanding and promoting adoption of conservation technologies by rural landholders. Aust J Exp Agric 46(11):1407–1424
Perlgut D (1986) Introduction. In: Sarkissian W, Perlgut D, Ballard E (eds) The community participation handbook: resources for public involvement in the planning process. Impact Press, Roseville, pp 1–6
Pierce SA, Sharp JM, Guillaume JA et al (2013) Aquifer-yield continuum as a guide and typology for science-based groundwater management. Hydrogeol J 21(2):331–340. doi:10.1007/s10040-012-0910-y

Priscoli JD (1983) The citizen advisory group as an integrative tool in regional water resources planning. In: Daneke GA, Garcia MW, Priscoli JD (eds) Public involvement and social impact assessment. Westview Press, Boulder, pp 79–87

Reed MS, Evely AC, Cundill G et al (2010) What is social learning? Ecol Soc 5(4):r1. [online] URL: http://www.ecologyandsociety.org/vol15/iss4/resp1/

Richardson S, Evans R, Harrington G (2011) Connecting science and engagement: setting groundwater extraction limits using a stakeholder-led decision-making process. In: Connell D, Grafton RQ (eds) Basin futures: water reform in the Murray-Darling Basin. ANU e-press, Canberra, pp 351–366

Rittel HWJ, Webber MM (1973) Dilemmas in a general theory of planning. Policy Sci 4 (2):155–169. doi:10.1007/BF01405730

Ross A, Martinez-Santos P (2010) The challenge of groundwater governance: case studies from Spain and Australia. Reg Environ Chang 10(4):293–310. doi:10.1007/s10113-009-0086-8

Ross H, Buchy M, Proctor W (2002) Laying down the ladder: a typology of public participation in Australian natural resource management. Aust J Environ Manag 9(4):205–217

Salzman J (2005) Creating markets for ecosystem services: notes from the field. N Y Univ Law Rev 80:870–961

Sandoval R (2004) A participatory approach to integrated aquifer management: the case of Guanajuato State, Mexico. Hydrogeol J 12(1):6–13. doi:10.1007/s10040-003-0311-3

Schlager E (2006) Challenges of governing groundwater in U.S. western states. Hydrogeol J 14 (3):350–360. doi:10.1007/s10040-005-0012-1

Schusler TM, Decker DJ, Pfeffer MJ (2003) Social learning for collaborative natural resource management. Soc Nat Resour 16(4):309–326. doi:10.1080/08941920390178874

Seward P, Xu Y, Brendonck L (2006) Sustainable groundwater use, the capture principle, and adaptive management. Water SA 32(4):473–482

Sewell WRD, Phillips SD (1979) Models for the evaluation of public participation programs. Nat Resour J 19:337–358

Shackley S, Mander S, Reiche A (2006) Public perceptions of underground coal gasification in the United Kingdom. Energ Policy 34(18):3423–3433. doi:10.1016/j.enpol.2005.07.010

Shriver TE, Peaden C (2009) Frame disputes in a natural resource controversy: the case of the Arbuckle Simpson Aquifer in south-central Oklahoma. Soc Nat Resour 22(2):143–157. doi:10.1080/08941920801973789

Sobels J, Curtis A, Lockie S (2001) The role of Landcare group networks in rural Australia: exploring the contribution of social capital. J Rural Stud 17(3):265–276. doi:10.1016/S0743-0167(01)00003-1

Stankey GH, Hendee JC (1975) Applied social research can improve public participation in resource decision making. Rural Sociol 40(1):67–74

Stern PC, Dietz T, Abel T et al (1999) A value-belief-norm theory of support for social movements: the case of environmentalism. Hum Ecol Rev 6(2):81–97

Syme GJ, Nancarrow BE (2006) Achieving sustainability and fairness in water reform: a Western Australian case study. Water Int 31(1):23–30. doi:10.1080/02508060608691911

Syme GJ, Nancarrow BE, McCreddin JA (1999) Defining the components of fairness in the allocation of water to environmental and human uses. J Environ Manage 57(1):51–70. doi:10.1006/jema.1999.0282

Taylor B, de Loe R, Kreutzwiser R et al (2009) Local groundwater management studies in Ontario, Canada: a case for retaining a role for the state in community-based water research. Aust J Water Resour 13(1):69–80

Tewari DD, Khanna S (2005) Building and energizing water institutions: a case study of irrigation management transfer in Gujarat. J Environ Syst 31(3):201–221. doi:10.2190/ES.31.3.a

Thompson CL, Supalla RJ, Martin DL et al (2009) Evidence supporting cap and trade as a groundwater policy option for reducing irrigation consumptive use. J Am Water Resour Assoc 45(6):1508–1518. doi:10.1111/j.1752-1688.2009.00384.x

Ticehurst JL, Curtis A, Merritt WS (2011) Using Bayesian Networks to complement conventional analyses to explore landholder management of native vegetation. Environ Model Software 26:52–65

Tidwell VC, van den Brink C (2008) Cooperative modeling: linking science, communication, and ground water planning. Ground Water 46(2):174–182. doi:10.1111/j.1745-6584.2007.00394.x

van Alphen K, van Voorst tot Voorst Q, Hekkert MP et al (2007) Societal acceptance of carbon capture and storage technologies. Energ Policy 35(8):4368–4380. doi:10.1016/j.enpol.2007.03.006

van Steenbergen F (2006) Promoting local management in groundwater. Hydrogeol J 14 (3):380–391. doi:10.1007/s10040-005-0015-y

Vanclay F, Esteves AM (eds) (2011) New directions in social impact assessment. Edward Elgar, Cheltenham

Vandermoere F, Vanderstraeten R (2014) Back and forward to the future: an explorative study of public responses to urban groundwater contamination. J Environ Plan Manag 57(5):720–732. doi:10.1080/09640568.2013.763773

Weber EP, Memon A, Painter B (2011) Science, society, and water resources in New Zealand: recognizing and overcoming a societal impasse. J Environ Policy Plan 13(1):49–69. doi:10.1080/1523908x.2011.564414

Wester P, Sandoval R, Hoogesteger J (2011) Assessment of the development of aquifer management councils (COTAS) for sustainable groundwater management in Guanajuato, Mexico. Hydrogeol J 19(4):889–899. doi:10.1007/s10040-011-0733-2

Wilder M, Lankao PR (2006) Paradoxes of decentralization: water reform and social implications in Mexico. World Dev 34(11):1977–1995. doi:10.1016/j.worlddev.2005.11.026

Yamamoto S (2008) Groundwater management in rice terraces: a case study of a lakeside community in Shiga Prefecture, Japan. Local Environ 13(5):449–460. doi:10.1080/13549830701809775

Zellner ML (2008) Embracing complexity and uncertainty: the potential of agent-based modeling for environmental planning and policy. Plan Theory Pract 9(4):437–457. doi:10.1080/14649350802481470

20 Lessons to Be Learned from Groundwater Trading in Australia and the United States

Sarah Ann Wheeler, Karina Schoengold, and Henning Bjornlund

Abstract

This chapter provides an overview of the issues and challenges facing policy makers intending to establish groundwater markets. It studies in detail two developed countries that have introduced groundwater trading and have some experience in its implementation—Australia and the United States of America—and draws out lessons from these countries that need to be considered for the development of groundwater markets around the world. The key lessons that this chapter stresses are: the importance of establishing institutions and regulations; investing in high quality economic and scientific research; that opportunities arise from crises; and that social concerns are not always the most important considerations to be aware of for efficient and effective groundwater markets.

20.1 Groundwater Global Over Extraction and Shortage

Globally, groundwater extraction is the outcome of decisions by organisations and individuals; there is little control or planning involved with its management. Groundwater withdrawals supply a large percentage of the world's population. It accounts for about 50 % of global drinking water and 43 % of global irrigation (van der Gun 2012). As detailed in Chap. 2, its overuse is associated with several

S.A. Wheeler (✉)
Global Food Studies, University of Adelaide, Adelaide, SA, Australia
e-mail: sarah.wheeler@adelaide.edu.au

K. Schoengold
Agricultural Economics and School of Natural Resources, University of Nebraska, Lincoln, NE, USA

H. Bjornlund
School of Commerce, University of South Australia, Adelaide, SA 5000, Australia

A.J. Jakeman et al. (eds.), *Integrated Groundwater Management*,
DOI 10.1007/978-3-319-23576-9_20

negative externalities including: water drawdown and groundwater depletion; land subsidence; loss of biodiversity; reduced dilution and assimilation of contaminants; increased salinity; pollution; and seawater intrusion into coastal aquifers (Moreaux and Reynaud 2004; Goesch et al. 2007). In some of the world's most important food producing regions, such as Punjabi in India, Northern Plains in China and the Ogallala aquifer in the United States, over extraction has now reached levels where it is apparent that it will not be possible in the longer term to support irrigation at current levels (Shah 2009). It is thus a major threat to food security.

The extraction of groundwater during the twentieth century was mainly for irrigation. Given the increasing impact of climate change on surface water availability, it is likely the pressure on groundwater will increase in the future (van der Gun 2012). The Brundtland report in 1987 increased the awareness that there had been over-allocation of water reserves and that groundwater was being drained more quickly than it could be replenished. This led to the emergence of the concept of 'safe yields', which set upper limits on the available water for use without depleting storage. However, this did not protect the interests of other users of water, notably the environment (Richardson et al. 2011).

20.1.1 Groundwater Features

Aquifers are recharged by rainwater, snow melt and returns from irrigated agriculture. Sometimes water moves considerable distances underground. Aquifers can be depleted if more water is extracted than the annual recharge. For several decades, aquifers in arid and semi-arid regions have been stressed with a growing gap between extraction and recharge. This has direct economic impacts because of increased pumping costs for consumptive users and water degradation and ecosystem damage (Esteban and Albiac 2012). Stocks of groundwater in aquifers are often larger than surface water stocks. This makes them important buffers during prolonged dry spells where, with reduced surface water availability and increased demand, groundwater use typically increases during droughts (van der Gun 2012; Goesch et al. 2007).

Groundwater management is more challenging than surface water management because it is less visible and recharge is more difficult to measure than stream inflows. Also, the hydraulic interconnectedness between different aquifers and between aquifers and surface water is still not fully understood in many regions. Groundwater is much more poorly monitored relative to surface water. It is only in recent years that authorities in many countries have started to require meters to be installed and monitored on bores (i.e., wells). For example, in Australia, by 2007 only 20–40 % of major groundwater users were monitored (Goesch et al. 2007).

Another feature of groundwater is its 'shared water' component; that is, the interconnectedness of aquifers and streams. Shared water is that component that feeds into a stream or river from an aquifer (gaining stream) or that discharges into an aquifer from a river (losing stream). In some areas, a single river can gain and lose water (Goesch et al. 2007). Some ecosystems, such as wetlands, small streams, rivers, and lakes, are fed by aquifers (Esteban and Albiac 2012).

Managing the quality of groundwater also poses a challenge, as problems such as salinity are common (Chap. 15). The susceptibility to quality pollution depends on the properties of the soil, climatic conditions, location of aquifers and factors such as rainfall frequency. The type of cropping, as well as fertilizer and pesticide application, also influence the risk of pollution. Short duration crops lead to greater levels of leaching (Arthukorala and Wilson 2012). Further, certain irrigation practices, failure to dispose of waste water properly and land clearing can all decrease groundwater quality (NWC 2012).

To understand groundwater use, a model of groundwater flow systems is required, including its sources and the spatial nature of natural and induced or imposed recharge and discharge. Quantifying recharge from all sources is difficult, as is determining the amount of water extracted. Thus where overuse is suspected, regular measurement is essential (Athukorala and Wilson 2012).

20.2 Groundwater Policy Frameworks

In the 1990s there was a shift in thinking about water within the international community. It was generally recognised that the possibilities of increasing water supplies had ended and there should be a shift in focus to managing water demand and reallocation. The global document Agenda 21, emerging from the Rio Convention in 1992, reflected this thinking and its main elements for dealing with water shortage included the notions that:

- users should pay the full cost of water;
- water markets should be established;
- the community should be involved in the decision making process
- water use should be more efficient; and
- the environment must be recognized as a legitimate stakeholder (Sitarz 1993).

Strategies must be found to more purposefully allocate water in ways that respond to competing demands, promote sustainability, prevent environmental damage and generate economic efficiency. In general, existing diversions can be reallocated or reduced through an administrative reallocation of water rights, information approaches or market-oriented policy approaches (Bennett 2008). Government managed 'command and control' approaches can be unpopular, while market based instruments are frequently regarded as politically neutral, and as an efficient means of managing water under conditions of scarcity (Skurray et al. 2013). However, many countries are heavily influenced by political influences which means second-best policy approaches are often chosen when first-best policies are available (for example, see Crase (2011) for a discussion of the Australian water situation). Markets, by contrast, allow for voluntary action informed by price signals and market forces.

20.2.1 Water Market Conditions

Before the establishment of water markets in any area, four broad elements are needed to drive efficient use and outcomes. These are:

- A fixed limit to resource availability (set consumptive pool) that is ideally: (i) credible and based on accurate science; (ii) monitored and enforced; and (iii) consistent with sustainable levels of extraction;
- Users are provided with secure property rights in the form of an access entitlement to a share of that consumptive pool;
- These shares, and the water allocated to them each season, are tradeable under low transaction costs and entry/exit barrier conditions, such that ownership, control and use can change over time; and
- Prices for these shares and allocations that take into account externality costs to third-parties are established in a market that uses the value placed on water use by a large pool of well-informed buyers and sellers (NWC 2011; Bjornlund et al. 2013; Loch et al. 2013).

For groundwater markets in particular, there need to be well-defined rights with limited groundwater use allocations and monitoring of groundwater extraction by all users. These rights and allocation levels need to be based on a good understanding of the hydrogeology of a groundwater area, groundwater mobility and its sustainable yield, along with knowledge of dependent ecosystems and the way the aquifer responds to extraction. However, caution needs to be taken that property rights to water can be reduced when necessary for environmental or climate purposes, or due to uncertainty about watershed hydrology. It has been proposed that sustainable yield be managed by defining lower and upper bounds for water table levels and monitor them (Anderson and Snyder 1997). Entrenching property rights in water can be problematic. Firstly, there is the issue of dozer and sleeper rights (e.g. unused or unutilized water rights). For example, establishing water markets in Australia activated many unused licences, and reduced the water left in the river. Secondly, enshrining property rights holds dangers if there is incomplete knowledge of riverine ecosystems and future environmental needs for water (Crase et al. 2004; Young 2014).

20.2.2 Difficulties in Establishing Groundwater Markets

Bauer (1997) argues that establishing markets in water resources is difficult. Water markets are not natural or self-maintaining. Further, the institutional frameworks, the political and economic conditions, as well as geographic context are important influences on market function. Regulation is necessary to prevent third party effects and externalities. Despite the need to clearly define property rights, some aspects of water resources are inherently public goods and represent collective interests. Government oversight is also very important for markets to work effectively, particularly in relation to assessing trade applications, monitoring and reporting on the state of ground and surface water resources and market performance, revising trading rules as appropriate and ensuring water management plans are adequate (GHD et al. 2011). However, markets are embedded in institutions which can either facilitate or impede their optimal functioning. High transaction costs can be a significant disincentive to trade and they are likely to be particularly relevant when establishing new markets since they involve a change from historical systems of water management. Such costs can arise from the transaction itself or they can be generated by the institutional factors that are necessary in enabling trade (Skurray et al. 2013; Garrick et al. 2009).

20.2.2.1 Property Right Issues

The characteristics of groundwater and surface water and their interaction differ in ways that lead to various challenges in defining property rights to each type of resource. These differences also affect the complexities involved in developing water markets.

With surface water, movement across boundaries can be difficult to control. Moreover simultaneous and sequential users of water make exclusion difficult and create numerous interdependencies. Thus, multiple parties can be affected by surface water trading. Also, in some countries, individuals do not own water; it is owned by the state and held in trust for individual citizens, creating a legal impediment to developing property rights. There is also a chronological hierarchy in claims to water (similar to the framework of high, medium and low security water rights used in countries such as Australia) which may not be correlated to the value of its use (Brewer et al. 2008).

Surface water markets also depend on conveyance opportunities and the absence of canals, or rivers, to move water can decrease arbitrage opportunities. Markets tend to be local because of regulation between different states and the cost of transporting water over long distances (Brewer et al. 2008). It is essential that market boundaries are clearly defined; this relates to physical boundaries as well as volumetric ones. Finally, Crase et al. (2004) suggest that efficiency improvements may not return water to the environment unless there are institutional mechanisms to direct saved water to environmental flows.

In contrast, groundwater aquifers have many of the characteristics of a common property resource where the location of the user is important. Early work on groundwater management (e.g., Gisser and Sanchez 1980; Gisser 1983) modelled groundwater as a spatially homogeneous common property resource (i.e., the "bathtub" model), where one individual's groundwater use immediately affected all other users equally. More recent work (e.g., Brozović et al. 2010) shows that while groundwater aquifers have some characteristics of a common property resource, the impact of one individual's use on other users varies over space and time from one aquifer to another, depending on hydrological characteristics. This distinction is important for the appropriate definition of property rights and the region where trading is permitted. It is important for policymakers to first set the total level of groundwater use rights for an aquifer to a sustainable level, then the important task is the distribution of those rights over the aquifer.

Given the inherent and manifold difficulties in specifying property rights in groundwater, greater specification of rights and their conditions seems a tempting option. However, greater specification decreases the ease of transferability of rights. The greater the degree of specification, the thinner the market and the less benefits it will generate. The alternative to extensive specification of property rights is introducing other measures to prevent environmental and other third party effects (Skurray et al. 2013).

Aquifers can vary markedly in terms of their hydrogeological properties, with consequent variation in the ease of extracting water, the capacity for recharge, the difficulty of specifying property rights and the external costs associated with accessing groundwater from them. Therefore, it may be difficult to expect management regimes to be applied to a number of different aquifers. Furthermore, management regimes are often embedded in administrative jurisdictions that do not necessarily align with the boundaries of aquifers. Decision making must therefore address and integrate interconnected natural systems. A further element of flexibility relates to the temporal variation in aquifer 'behaviour'. Responsiveness to changing conditions should override a reliance on rigidly applied and upheld regulations (Skurray et al. 2013).

The physical differences between surface water and groundwater systems also affect the ease of monitoring water use. Well-defined property rights that are quantifiable and can be monitored are essential for a water market. Surface water systems are more likely to have (but note this is far from certain) a well-developed infrastructure of rivers and canals that make quantifying water use relatively straightforward. Water flows can be measured at each point of diversion to determine water use by individuals or communities. By contrast, groundwater is generally extracted through a network of individual wells, which are interconnected horizontally depending on geology. Quantifying water use can require installing flow meters at each well and collecting information on actual water use. Quantifying use also can be estimated by a range of various models. While the monitoring technology is readily available to collect this information for groundwater use, the cost of doing so is higher for groundwater than for surface water systems. The higher monitoring cost is one reason that many areas have been slower to limit groundwater than surface water. In addition, the interconnectedness of groundwater and surface water adds to the complexity of establishing property rights. Property rights to surface water and groundwater need to be coordinated to incorporate the physical connection between the two resources.

20.2.2.2 Externalities

Due to the common pool ownership of aquifers, and the unique physical properties of aquifers, externalities are easily created. Because of the spatially-dynamic nature of groundwater flow, the extent of various externalities depends on the quantity, location and time of extraction and the strategic behaviour of users. In a competitive and unregulated setting, the temporal and spatial profile of external effects results in inefficient pricing and misallocation; users take too much, too quickly and from what may be considered the wrong locations (e.g. closer to surface water rivers). Individual users of groundwater have, in the absence of regulation or other incentives, little reason to consider the increased pumping costs for other users as a result of the extraction they undertake (Katic and Grafton 2012). Nor is there much incentive to consider future costs associated with reduced stock. Finally, they have little reason to consider the impact of their activities on surface water, where groundwater extractions can decrease the amount of surface water available (Goesch et al. 2007). Regulation is needed. Groundwater is not used optimally by individuals who do not internalize the part of the extraction costs and environmental externalities in their pumping decisions. Extraction by one user will deplete the water supply and, because users believe competitors will not conserve water, there is little incentive to protect the storage. This is a significant reason for market failure and highlights the need for institutional arrangements. A key issue is therefore whether markets are capable of achieving balanced inter-temporal allocation of resources (Esteban and Albiac 2012).

20.3 Actual Groundwater Trade

Notwithstanding the complexity of the physical influences on groundwater, its use is also inextricably linked with socio-economic, legal, institutional and political systems. There are several drivers of groundwater access and use: other water sources; demographic and socio-economic factors; science and technological innovation; policies, laws and financial conditions; climate variability and market changes (changed demand, changed renewal, availability of other sources) (van der Gun 2012).

Surface water markets around the world occur mainly in semiarid areas and include: United States (mostly in the western states), Chile (Limarí River Valley), Australia (Murray-Darling Basin), Spain, Canada (South Saskatchewan River Basin), South Africa, China, Brazil, Mexico and Tanzania (Loch et al. 2013; Wheeler et al. 2014). All water markets can be hampered by political, technical, social and administrative factors. However, markets in groundwater face some particular challenges, including the three dimensional nature of aquifers, boundary uncertainties, water quality variation and local drawdown impacts. Groundwater markets are less common than surface water markets but some exist in Australia (Skurray et al. 2013; Skurray and Pannell 2010), China (Zhang et al. 2008; Wang et al. 2007), Oman (Zekri and Al-Marshudi 2008; Al-Marshudi 2007), the Indian Subcontinent (Meinzen-Dick 1998; Shah 1993; Easter et al. 1998) and the United States (Colby 2000; Colby and Bush 1987; Anderson and Snyder 1997; Griffin 1998).

The specific details of markets can vary by location. For example, in China, Oman, and India groundwater trading typically occurs when water is sold and transported to be used on non-adjacent land. In Australia and the United States groundwater trading generally involves selling the right to pump water from a shared aquifer. However, some of the major groundwater transfers in the US have taken place by purchasing water farms and pumping the water to distant cities, especially in Arizona, with detrimental impact on exporting regions This distant pumping has also taken place in California and Texas (Colby and Bush 1987; Anderson and Snyder 1997). The Omani and Indian/Pakistan groundwater markets provide some interesting insights on groundwater opportunities and problems. A brief discussion is provided in Box 20.1.

Box 20.1: Examples of Groundwater Markets in Developing Countries

India and Pakistan

Informal groundwater markets have developed in India and Pakistan where irrigation water is supplied from deep tubewells which are costly to install (Meinzen-Dick 1998; Shah 1993; Easter et al. 1998). This excludes small farmers from accessing water. However, many of them can buy water from large farmers with excess capacity. There are various arrangements for payment: (i) the buyer pays an agreed amount or works for the larger farm in exchange for water; (ii) two-way share farming: one party supplies the water, the other the land and labour and all share net profits; (iii) three-way share farming: one party supplies the water, another the land and the third the labour and all share net profits.

These groundwater markets increase availability and reliability of water supplies; but the ability to sell water, combined with subsidized electricity prices, encourages over-extraction of groundwater. This results in increased pumping costs, elimination of use of shallow wells, and increased saline aquifers.

Oman

A unique groundwater market has developed in Oman within the falaj irrigation systems (Zekri and Al-Marshudi 2008; Al-Marshudi 2007; Bjornlund and Bjornlund 2010). There are 1,000 year old underground water mobilization systems tapping water from the top of mountain aquifers and transporting it by gravity-driven tunnels and canals to villages and fields (with domestic use given first priority). The system can only tap the aquifer's overflow, and access is granted in flow time only; hence access is correspondingly reduced in times of shortage. In most systems, the majority of water is controlled by the village community and semi-public charity organizations, such as the mosques. Many farmers are dependent on buying water access either on a weekly or annual basis. The proceeds from the weekly auctions are used to pay for the administration and maintenance of the falaj system, while the water controlled by semi-public organizations is sold annually and the proceeds go towards community activities. Many of the systems are currently under threat due to external encroachment on this communal resource (e.g. farmers have sunk tube wells into aquifers supplying the falaj systems).

The remainder of this paper studies in detail two of the most advanced countries in the world in terms of groundwater trading: Australia and the United States.

20.3.1 Australia

In Australia, groundwater has typically been: (i) unmetered; (ii) provided free or at low prices; and (iii) 'managed' by management plans, which have not properly considered the connectivity between surface and groundwater (NWC 2012). Groundwater use almost doubled between 1983/4 and 1996/7, but this average masks a tripling in the states of New South Wales, Victoria and Western Australia (where much of Perth's drinking water supply comes from groundwater). Under the National Water Initiative (NWI), Australian governments are committed to:

- improving knowledge of ground-surface water connectivity;
- returning all over-allocated systems to sustainable levels of extraction;
- improving understanding of what is a sustainable extraction rate; and
- improving understanding of the relationship between groundwater and groundwater dependent ecosystems (NWC 2008).

The National Groundwater Action Plan, arising from the 2007 evaluation of progress of the NWI, seeks to take the actions needed to achieve these outcomes. The National Water Commission (NWC) concluded in 2008 that ongoing use of groundwater for consumptive use from 'stressed' aquifers and connected systems is an 'unacceptable risk'. They then developed a set of principles to guide subsequent action (NWC 2008). Developing water markets in groundwater was one such consideration, though there were many considerations that needed addressing first (Goesch et al. 2007).

In 2004–05, ABS (2006) estimated that groundwater access entitlements accounted for 146,185 (or 65 %) of all water access entitlements and 6,998 GL of water allocated in Australia. As at June 2012, NWC (2013) suggested there were 81,719 groundwater entitlements issued, covering about 6,600 GLs (the majority are in New South Wales, followed by Western Australia, Victoria, Queensland and South Australia) (Table 20.1).

Table 20.1 Groundwater entitlements on issue at 30 June 2012

Jurisdiction	Number	Volume (GL)
New South Wales (NSW)	47,835	2,056
Queensland (Qld)	8,153	1,008
Victoria (Vic)	8,956	950
Western Australia (WA)	11,400	1,713
South Australia (SA)	4,911	620
Tasmania (Tas)	0	0
Northern Territory (NT)	232	125
Australian Capital Territory (ACT)	262	76
Total	**81,719**	**6,596**

Source: NWC (2013)

Table 20.2 Groundwater entitlement and allocation trading in 2011–12

	Qld	*NSW*	*Vic*	*SA*	*WA*	*NT*	*Tas*	*ACT*
Entitlement (no)	0	208	304	202	68	0	0	0
Entitlement volume (ML)	0	84,377	35,325	15,725	11,004	0	0	0
Allocation (no)	62	134	97	41	29	0	0	0
Allocation volume (ML)	3,688	26,972	7,524	2,147	4,255	0	0	0

Source: NWC (2013)

Groundwater entitlement trading made up only about 12 % of total trade in Australia in 2011–12 (NWC 2013). The number and volume of entitlement and allocation trade is shown in Table 20.2.

20.3.1.1 Murray-Darling Basin (MDB) Groundwater Trade

In the MDB, most surface and groundwaters are hydraulically linked; meaning that overuse of surface water will deplete aquifers, while increased groundwater extraction will adversely affect the supply of surface water. Groundwater comprises about 15 % of irrigation water in the MDB, but this can increase to over 70 % in some catchments in extended dry conditions (Richardson et al. 2011).

As of 2012, annual groundwater extractions from the MDB were 1,744 GL per annum. However, the MDB Plan allows for an increase up to a total of 4,340 GLs annually. Of this increase, 760 GL is due to be extracted from aquifers that need to have extractions reduced or capped. In some areas of the MDB, extraction exceeds recharge capacity with poor long term outcomes for groundwater levels (Wentworth Group of Concerned Scientists 2012).

Policies and guidelines for sustainable groundwater extraction are currently being developed. In the past, an extraction limit was defined as part of a technical process and then announced via a water plan. This has worked reasonably well, but has led to some tensions. These tensions were mainly about the over-extraction of groundwater because of a development imperative, unchecked by knowledge of the ecological needs served by, and dependent on, groundwater (Richardson et al. 2011).

In some areas people use groundwater in dry periods to augment the supplies they receive from surface water (NWC 2011). Groundwater trade is permitted in New South Wales, South Australia, Victoria, the Northern Territory and Western Australia. However only a small amount of trade has occurred (e.g. Tables 20.2, 20.3, and 20.4).

Table 20.4 indicates that groundwater and unregulated trade only made up 2 % of total MDB water allocation trade in 2011–12, while Table 20.3 shows it made up 14 % of total MDB water entitlement trade. Overall, groundwater trading within the southern MDB increased significantly during the 2000s from 2–5 % of total groundwater use to 10–20 % (NWC 2010).

One of the first active groundwater markets was in the Northern Adelaide Plains, where urban encroachments into market gardening areas left many ground water

Table 20.3 Australian water trade volumes

(GL) in 2011–12	Water entitlements
MDB regulated	1,065
MDB unregulated and groundwater	153
Other water systems	218
Australia total	1,437

Source: Adapted from data in NWC (2013)

Table 20.4 Water allocation trading volumes (GL), Australia, 2007–08 to 2011–12

	2007–08	*2008–09*	*2009–10*	*2010–11*	*2011–12*
MDB Regulated	1,376	1,663	2,118	3,340	4,127
MDB Unregulated and groundwater	17	290	183	76	89
MDB total	1,393	1,953	2,301	3,417	4,216
Other water systems	201	205	194	77	81
Total Australia	1,594	2,158	2,495	3,493	4,297

Source: NWC (2013)

licenses unused. Trading was allowed to enable this water to move to remaining market gardeners. However, this caused water extraction to concentrate withdrawal in the most productive region and after only 4 years of trading a large cone of depression developed in this area. This resulted in the introduction of zones and trade limitation between some zones (Boyd and Brumley 2004).

Access to groundwater for irrigation is governed by entitlement and is usually separate from land and other property rights. Generally, each entitlement specifies the volume that irrigators can extract in a given year. But some entitlements specify daily pumping rates, while others specify additional volumes that can be withdrawn during droughts. Extraction in some areas is not sustainable. Sustainability is formulated by assessing extractions against sustainable yield. There is variation in the definition of sustainable yield. The National Groundwater Committee defines it as an extraction regime that allows acceptable levels of stress and protects economic, social and environmental values. This recognizes the trade-offs between competing uses (Goesch et al. 2007).

In the Namoi groundwater area in NSW, there is well developed trading in groundwater because of several initiatives. Firstly, over-allocation was addressed. This has allowed the setting of total extraction limits, with annual allocations announced at the beginning of the year. The key elements of successful trading activity in NSW are:

- high demand for groundwater;
- water sharing plans for aquifers based on sound scientific knowledge;
- access to perpetual licenses for users;
- transparent trading rules;
- efficient approval processes; and
- a system for metering and monitoring is in place (NWC 2011).

Table 20.5 Groundwater and surface water allocation trade volumes, Namoi, 2006–07 to 2011–12 (ML)

	2006–07	2007–08	2008–09	2009–10	2010–11	2011–12
Groundwater allocation trade	12,155	12,543	10,210	9,102	6,096	3,997
Surface water allocation trade	n.a.	5,598	12,581	12,151	17,516	23,462

Source: NWC (2013)

Table 20.5 illustrates the trade in groundwater and surface water allocations over the past 6 years. It highlights that groundwater trade was highest in the drought years of 2006–07 and 2007–08, while surface water trade is higher in years of higher rainfall (and higher water allocations).

Groundwater trade is comparatively much less developed in Victoria than in NSW. There seem to be a number of reasons for the under-developed trade in Victoria: (1) historical reliance on bulk water supply provider systems; (2) some groundwater regions are not fully allocated; (3) incomplete resource planning; and (4) underdeveloped market rules and institutions. In Victoria, just less than half of the groundwater management units are considered over-allocated, while 12 % are considered less than 50 % allocated. Within under-allocated units, new licenses are being issued and there is little incentive for trade. Furthermore, many 'sleeper' licenses have been issued. This would limit trade even in over-allocated areas, as many current licence holders already have the capacity to expand. However, there is compelling evidence that groundwater levels are declining in Victoria. Therefore, if increasing groundwater extraction continues, the predicted consequences of climate change eventuate and there is lack of recharge following drought, demand for trade should increase (NWC 2011).

A second barrier to trade in Victoria is lack of planning for management of groundwater resources. In areas designated as Water Supply Protection areas, trading in or out is not permitted until a management plan for the area has been developed. There have been delays in developing such plans because of lack of knowledge about aquifers and sustainable yields (again due to historical reliance on surface water systems and a lack of development on groundwater). In other areas, where trade in groundwater has been developed, or has the potential for such development, caps need to be set to ensure the volume that can be taken from a given groundwater management area in a given period is established. This requires defining the boundaries of the area so that they align with the hydrogeological boundaries of the aquifer and ensure that the boundaries of groundwater and surface water align. Without this consistent establishment of boundaries, it is difficult to properly manage the asset. There are a number of administrative barriers to groundwater trade in Victoria. These include unbundled licenses, licenses that are of short duration, lack of clarity about the basis for reducing seasonal allocations and complex and restrictive trading rules (NWC 2011).

20.3.1.2 Western Australia

In 2011–12, there were over 11,000 ML of groundwater entitlements traded nationally and 4,255 ML of these groundwater allocations were traded in Western Australia (NWC 2013). In the Gnangara aquifer of Western Australia, the legal rights associated with a 10 year licence for a volume of groundwater are significantly attenuated because unused portions of water may be reclaimed by the relevant Minister. Rights can also be ‘amended’ by the Minister in order to protect third parties. In addition, the Government can amend a license if the reason for the use of water is not appropriate. Further, licences are time limited and do not represent an unconditionally owned asset. There are up to 80 conditions that relate to well depth, monitoring, infrastructure, reporting and time of use requirements (Skurray et al. 2013). Thus the property rights entailed by having a licence for Gnangara groundwater is administratively restricted, purpose limited, and time limited with conditional rights that are vulnerable to cancellation or amendment. While it might be argued that the Government control of certain aspects of water rights is a means to guarantee sustainable management of the resource, this has not proved to be the case. The current arrangements do not meet the NWI’s guidelines for the creation of effective markets, despite the fact that the WA government is a signatory to the agreement. Transfers of water can only be made to a person who either owns, or occupies, the land on which the water will be used, or they must have written permission from the land owner to use the land for activities which are deemed appropriate under the conditions of the water licence. These significantly constrain the transferability of licences. The process for applying to transfer water is cumbersome, expensive and does not adequately maintain confidentiality. Moreover, even where transfers are approved by the Minister’s office, they can be overridden by local regulations (Skurray et al. 2013).

20.3.2 United States of America (US)

Of critical importance in understanding the existence and potential for groundwater trading in the United States is the fact that water law is generally determined at the state level, as opposed to the federal level. There are some exceptions (e.g. the Endangered Species Act, which trumps state-level decisions when the habitat of an endangered species is at risk, or compacts that regulate interstate rivers such as the Colorado River). However, most groundwater law, including the rights structure, regulation, and the potential for groundwater trading varies by state and some states have further devolved groundwater management to regions, counties, or basins. For example, Texas groundwater law has historically given landowners an absolute right to use groundwater below the land, while Nebraska law is defined by “reasonable use” and “correlative” rights, which mean that groundwater users are expected to manage the resource jointly and restrictions affect all users equally.

The Edwards Aquifer in Texas has implemented regulation that restricts groundwater use and allows trading but the changes are not comprehensive across the state. In fact, in 2011 the Texas Legislature passed a bill that upheld the interpretation that landowners that are not in the Edwards Aquifer management area have "a vested ownership interest in and right to produce groundwater below the surface" (Eckhardt 2013). Kansas and Idaho use appropriative rights for groundwater so that groundwater is managed based on a "first in time, first in right" basis. Arizona regulates groundwater use based on a state law that requires an assured water supply for users (Megdal 2012), while California has little groundwater regulation at the state level, but allows local areas to develop more restrictions (Hanak 2003; Jacobs 2006).

States in the western parts of the US enshrined the environment's right to water under common law doctrines. However, given that these regulatory and administrative regimes are implemented by individual states, the result is very uneven in terms of the amount of reform achieved in each jurisdiction. Increasingly, private entities have engaged in buying or leasing high security water for the environment. As this activity has increased, so too has monitoring, scrutiny of transfer and enforcement of regulations (Garrick et al. 2009). While most of the purchases of water for environmental benefits have been for surface water, there are some cases where protecting environmental quality also helps groundwater resources. For example, protecting natural wetlands such as the playa system in the Southern High Plains has environmental benefits via the provision of important habitat and also helps recharge groundwater aquifers (Bolen et al. 1989).

Another important distinction between surface and groundwater rights is the incentive to use water. While the details vary by state, western states in the United States generally use the prior appropriation system for surface water. Under prior appropriation, failure to continue using water can result in rights being lost; this is a disincentive to using less water and those who save water often see it forfeited to others. This creates a situation in which there are rewards for using a lot of water to grow low value crops. California eliminated this disincentive with a regulation that allowed water saved to be sold, leased or transferred (Brewer et al. 2008). However, Garrick et al. (2009) suggests that the prior appropriation doctrine establishes an implicit cap on the amount of water available, which has been an incentive to the development of trading. In contrast, groundwater rights are more frequently determined on the basis of land ownership and are less likely to be subject to a "use it or lose it" clause.[1] While this reduces the incentive for overuse, it fails to provide the implicit cap on available water.

Brewer et al. (2008) found in their review of surface water markets in the US that:

1. Agriculture is the origin for many of the transactions;
2. The annual flow of water traded and the amount of water committed for transfer show different patterns;

[1] This varies by state. In some states (e.g., Idaho, Montana) groundwater rights are based on prior appropriation and can be lost if unused. Other states (e.g., Arizona, California, Nebraska, and Texas) base rights on land ownership, making it difficult to lose a right if the land or pumping right is not sold.

3. Number of trade transactions is increasing (mainly accounted for by agriculture-to-urban trades);
4. Sales and multi-year leases are growing, while 1 year leases are not;
5. Arizona, Texas and California are among the top four states on any measure of trading;
6. Agriculture -to-urban trades account for most permanent trades on committed trade measures, while agriculture -to- agriculture trades account for most of the annual leases;
7. In comparing sales and leases across a number of US western states, prices varied more across states than across sectors and this differential reflects differences in demand and supply characteristics, transaction type, transaction costs and regulatory restrictions that prevent arbitrage across states. Sales are more common than leases of water (because of the greater security they provide) and this is reflected in increasing sales prices while those for leases have declined relatively; and
8. Finally, the price data reveal that urban users pay considerably more for water than agricultural users.

In contrast to surface water, in most places groundwater rights are not quantified; that is, there is no legal right for users to withdraw a specific amount of water. Thus there is a general right for all those who are located above the aquifer to pump from it. Basins where the rights to groundwater are specified are located primarily in urban areas. They usually charge pumping fees and manage recharge programs. The development of clearly defined and limited property rights to groundwater is a necessary condition for further development of groundwater trading.

20.3.2.1 California

While surface water markets were introduced in California in the late 1970s, the factors leading to their expansion in the 1990s were severe drought and government mandated environmental flows. Trade was initially spurred by dry years, but has persisted since the return of normal precipitation. In its early stages, most transfers were short term trades such as 1 year leases, but the percentage of longer term leases and permanent sales has increased. The proportion of sales has fluctuated but the trend in longer term leases is sustained. Since the late 1980s, the percentage of water bought or leased for cities and the environment has continued to increase relative to other uses (Hanak and Stryjewski 2012). However, there is some indication that overall trade has slowed in recent years (Hanak and Stryjewski 2012).

California provides an interesting example of water regulation and trading, with surface water laws clearly defined and a thriving surface water market, while groundwater regulation and associated trading is extremely limited and very little data exist. While groundwater management is improving in the state overall, it is still largely a voluntary system and groundwater regulations are primarily determined at a local level (Hanak and Stryjewski 2012). Groundwater is an important source of 'wet water' in California and groundwater transfers are subject to less oversight by the state than surface water since the state's water code does not cover groundwater (Hanak and Stryjewski 2012). Historically this meant that there was little regulation over groundwater use. This was highlighted after many surface water irrigators sold their water rights to the state in the drought of the late 1980s and early 1990s, only to respond by pumping groundwater as a substitute. This trend has not changed and the same pattern of irrigators substituting groundwater for limited surface water availability was also seen in the late 2000s (Famiglietti et al. 2011).

Groundwater banking has emerged as an important tool in California's water management, which involves the deliberate storage of surface water in aquifers during wet years (Hanak 2005). Since 2000, the state has been making active attempts to facilitate groundwater storage, which is part of the strategy to encourage conjunctive use of water as part of a diversification process (Hanak and Stryjewski 2012). The term "groundwater banking" is a misnomer: while a useful tool for managing water, in most parts of the state it is really a conjunctive management system although the details are case-specific. For example, some districts that use groundwater are purchasing surface water to augment local aquifers for local use. In other cases, municipalities are purchasing storage space in existing aquifers to store surface water. Groundwater banking describes the practice of storing surface water in natural or created aquifers during wet periods to save the water for dry periods. There are many benefits of groundwater banking for overall water management. It is a relatively cost-effective way to bolster water supplies especially in drought times. It also will help mitigate the loss of seasonal storage provided historically by the Sierra Nevada snowpack, which is expected because of climate change. Groundwater banking has become common in California (Hanak and Stryjewski 2012) and in Arizona (Megdal 2012) but typically does not actually involve the transfer of existing (i.e. natural) groundwater. However, any transfer of the banked water is often limited by local ordinances, limiting the benefits of water trading (Hanak and Stryjewski 2012).

There is a history of aquifers being drained, with adverse consequences for other users in California. This background helps to explain the development of local ordinances and the contemporary resistance to groundwater export from local communities. Many of the local ordinances restrict the export of groundwater. These ordinances are a significant deterrent to groundwater trade, which in many areas make groundwater transfers more difficult than surface water trades (Hanak 2003; Hanak and Stryjewski 2012). The efficiency of the approvals process for handling transfers is an important determinant of benefits of a market. Some counties place restrictions on groundwater exports and limitations on groundwater substitution transfers, while some aim to restrict groundwater banking with non-local parties. There are no state level 'no injury' groundwater protection statutes that can regulate groundwater (Hanak and Stryjewski 2012). In addition, there is local resistance to recent attempts by the state to collect information on groundwater use and groundwater levels. Without such information it is nearly impossible to develop a well-managed system of regulated groundwater rights that can facilitate groundwater trading.

In summary, California provides an interesting example that shows strong differences in the approach to developing trade in groundwater versus surface water. However, despite the growing maturity of the surface water market, overall trade has been declining since 2003, despite some drought years since 2000. A number of factors appear to explain the reduction in surface water trade. New pumping restrictions since 2007 have impeded north to south and east to west transfers around the Delta. Aspects of the approval process have also impeded transfers (Hanak and Stryjewski 2012). At the same time, county ordinances have limited groundwater transfers. These transfers are subject to environmental strictures over and above those related to the ‘no injury’ to environmental flows. In both surface and groundwater, recent high commodity prices are associated with a reluctance to lease/sell water. Finally, the existence of different kinds of water rights with separate approval processes has dampened the market. Overall, developing a more robust groundwater market will require additional restrictions to limit groundwater use and well-defined property rights that are streamlined across different counties.

20.3.2.2 Nebraska

Nebraska has developed a system where groundwater law is developed at the state level but administered and managed at a local level. Groundwater law follows a system of correlative rights, which means that all groundwater users have equal rights to use the resource. The state is divided into 23 natural resource districts, or NRDs. The NRD boundaries are determined by watersheds and each NRD has responsibility for managing natural resources such as groundwater and soil. Each NRD has substantial autonomy in choosing how to interpret and apply any state groundwater laws, and they frequently impose additional regulations above state limits. In contrast, surface water use is managed by the state using a prior appropriation system.

Unlike states such as California that rely primarily on surface water,[2] groundwater is the major source of water for Nebraska, providing approximately 85 % of total water used (Kenny et al. 2009). Historically surface water and groundwater law in the state were separate. However, legal changes since the mid-1990s have provided legal recognition to the many hydraulically-connected surface and groundwater systems in the state. Much of the state’s groundwater is connected to surface water basins, including the Platte River Basin and the Republican River Basin. A law passed in 2004 (Legislative Bill 962) requires many of the NRDs to cooperatively develop integrated management plans (IMPs) to specify how hydraulically connected groundwater and surface water will be jointly managed. One outcome of this change is that groundwater wells need to be certified, registered, and metered in much of the state. In addition to metering, many NRDs have set groundwater allocations for each well, establishing binding property rights for groundwater users. This combination of factors has allowed some of the NRDs to

[2] Approximately 80 % of total water use in California is from surface water (Kenny et al 2009).

permit groundwater trading to be used to improve the economic efficiency of groundwater use. However, variation exists between the approaches used by different NRDs:

Upper Republican Natural Resource District (URNRD): The URNRD was an early adopter of groundwater regulation. This primarily rural district, located in southwest Nebraska, initially required all irrigation wells to install flow meters in 1979. Use restrictions were also implemented in the same year, although the initial allocation levels were sufficiently high that users were not constrained. Allocations are determined for a multi-year period (typically for 5 years) and the allocations have gradually decreased. Initial water allocations were set at 5,610 m^3/year/hectare and current allocations are 3,315 m^3/year/hectare (RRB 2013). The expansion of acres is controlled, setting a cap on total water use. The allocation rights are allocated to each field based on the size of the field. Given the binding allocations and history of monitoring, the URNRD is well-suited for groundwater trading.

In the URNRD, an irrigator can transfer part of his/her water allocation to another irrigator if the water will be used within a confined geographical region (9,324 hectares). This constraint has advantages and disadvantages. The advantages are that it reduces regional economic impacts associated with the transfer of groundwater and can reduce the chance of cones of depression, where groundwater pumping is concentrated in a small area. Disadvantages accrue from limiting potential trading partners, reducing the potential economic benefits of trade. Relative to surface water, groundwater transfers have few technical impediments since the right to pump is transferred as opposed to the wet water. One impediment to groundwater transfers has been high transaction costs. There is no mechanism to help prospective buyers and sellers find trade partners. In addition to formally transferring allocation, the URNRD also allows an irrigator to combine the pumping rights to all of his/her land in a limited geographical area. This creates a defined set of fields (referred to as a "pool"). Total groundwater use is limited for the pool of fields, but the irrigator can choose how to distribute the total allocation between fields. This allows flexibility to move water from one field to another due to differences in soil type or crop choice. Many producers use pools to help manage their water allocation, and this suggests that reducing the transaction costs for formal trading would lead to more trades and greater economic benefits. In a recent analysis, Juchems (2013) found that indicators of profitability such as soil type, depth to groundwater, and pumping capacity are strong indicators of the direction of trade in both formal trades and within-pool transfers.

Lower Republican Natural Resource District (LRNRD): As with the URNRD, the LRNRD establishes multi-year groundwater allocations for irrigators. Due to changes in state law, the NRD began metering and limiting groundwater allocations in 2005. Unlike the URNRD, transfers of groundwater allocation are not permitted. Research suggests that modifying the rules to allow groundwater transfers would have economic benefits, and would allow the NRD to reduce overall groundwater use at a very low cost (Palazzo and Brozović 2014).

Central Platte Natural Resource District (CPNRD): The motivation for improved water management is different in the Platte River Basin than in the Republican River Basin. Both are interstate rivers and restrictions on hydraulically connected groundwater in the Republican River Basin have been necessary to provide enough water to Kansas (the downstream state). In contrast, restrictions on hydraulically connected groundwater in the Platte River Basin are designed to improve instream flow for endangered species. A series of interstate agreements and legislative changes between 1997 and 2006 led to the current restrictions and water management plan for the CPNRD.

The CPNRD has developed a number of tools to help groundwater users manage their water allocation. First, the CPNRD allows groundwater users to transfer (trade) the right to pump groundwater to another location. Transfers are permitted between the NRD and other NRDs as long as the transfer is approved (CPNRD 2012). The permitting process is designed to ensure that any transfer does not lead to additional depletion from the river. As seen in the URNRD, one-to-one transfers can have high transaction costs due to the difficulty of finding a trading partner. In addition to one-to-one transfers, the CPNRD has developed a water bank. To date most of the water bank activities have been permanent buyouts of irrigated land (both groundwater and surface water). However, the water bank has been designed to also permit some flexibility, with individual producers able to purchase water. While the program is still fairly new, the centralized system is expected to lead to lower transaction costs, more trades, and higher economic benefits from water use.

While each of the 23 NRDs differs in their approach to managing groundwater, these three examples highlight some of the groundwater trading activities that are already occurring. Jointly, these three case studies show evidence that there is demand for transfers and flexibility when it is permitted. The URNRD, which is fairly restrictive with formal transfers, had approximately 40 transfers during the 2005–2011 period (Juchems 2013). Transfers within a pool of fields are extremely common. The CPNRD has a more established system for transfers, and has approved many transfers. Thus, a key lesson from these experiences is that even with high transaction costs, there are economic benefits from groundwater transfers. While local control of groundwater resources is politically important across the state, the differences between districts illustrate how economic efficiency may be improved by relaxing constraints on groundwater trading and reducing transaction costs. Transferring the right to pump water, instead of moving water, reduces transportation costs but without oversight may lead to the problem of more intensive pumping in a small area, resulting in cones of depression.

20.3.2.3 Edwards Aquifer (Texas)

Texas has historically had a rule of capture for groundwater, where a landowner has the right to use groundwater below his or her land. While some of the state still operates under a ‘rule of capture’, the Edwards Aquifer in south-central Texas provides an example of groundwater management that includes some restrictions on use and permits groundwater trading. Motivated by threats to endangered species’ habitat that depend on aquifer flow, the Texas legislature passed Senate Bill 1477 (SB 1477, known as the Edwards Aquifer Authority Act) in 1993 (Boadu et al. 2007). SB 1477 changed the water rights structure for groundwater users, created a permit system that gave a right to use a specified quantity of water, and created the Edwards Aquifer Authority (EAA). While some initial rights were allocated in the late 1990s, many water users felt the allocation was unjust, leading to extensive litigation (Colby 2000). A series of legal challenges delayed the assigning of most water rights until 2001 and 2002, when the legal authority of the EAA to restrict groundwater use was upheld by the Texas Supreme Court (Eckhardt 2013). Legal challenges have continued to lengthen the process of regulating the Edwards Aquifer, reducing the benefits of water permits and trading, and increasing stress on endangered species.

An analysis of the *potential* changes due to the regulation in SB 1477 finds that without regulation, low water flow will significantly affect habitat for endangered species (Gillig et al. 2004; Boadu et al. 2007). A recent analysis of proposed legislative changes has compared expected water flows and economic benefits with and without regulation and water markets. Results show that under regulation, flows are higher without water markets but that regulated water markets are necessary for habitat needs and that the economic loss due to regulation is reduced when trading is permitted (Gillig et al. 2004; Boadu et al. 2007). Results also show that unregulated groundwater use is expected to lead to insufficient water flow for endangered species.

The experience in the Edwards Aquifer shows that legal battles can reduce the benefits of water trading and regulation. In 2013, almost 20 years after the initial legislation to regulate groundwater and create tradable permits was passed, the expected benefits have still not been realized.

20.4 Lessons Learned from Groundwater Trade in Australia and the US

There are a number of lessons that can be learned from this review of groundwater trade in Australian and the US. They include:

1. ***Institutions matter:*** While there are physical limits on the operation of groundwater markets, in Australia it appears that institutional barriers are as significant an impediment to trade as hydrogeological factors. While groundwater trading is permitted everywhere, only in a few states is there much market activity and there are few trades relative to the number of entitlements held; this is largely because trades are concentrated in particular areas. There is no consistency about whether products are unbundled across states (NWC 2011). Variation in the

rules established by Nebraska's different NRDs affects the frequency and feasibility of groundwater trading. The legal institutions involved in the management of the Edwards Aquifer in Texas have played a role in impeding the development of a viable water market.

2. ***Science matters:*** Before groundwater markets can be established, it is critical to understand and specify the boundaries of a groundwater management system. Groundwater systems should be based on physical aquifers, have clearly defined boundaries based on hydrogeological features. Interactions between surface water and groundwater need to be understood and incorporated, as well as the water quality of the system and the social and environmental externalities. Entitlement and extraction limits must be as accurate as possible, as should processes for changing long term entitlement and extraction limits, determining allocation limits and restricting extractions during periods of shortage (GHD et al. 2011).
3. ***A crisis can be an opportunity:*** Several examples of successful restructuring of water rights and the development of water trading are due to necessity. For example, a major impetus for the development and expansion of surface water markets in both Australia and California was a multi-year drought in the late 1980s and early 1990s (Bjornlund and McKay 2000; Hanak 2003). In California, where statewide groundwater legislation does not exist, courts have adjudicated radical changes to groundwater rights, management and trading in examples of severe stress, such as in the Tehachapi Basin and Mojace Basin north of Los Angeles (Anderson and Snyder 1997). Interstate legal conflicts in Nebraska led to legislative changes in the joint management of hydraulically connected surface and groundwater.
4. ***Economics matters:*** As well as the need to put proper institutions in place, there is a need for economics in groundwater management. There is a need to consider how many users there are in a management area, the value to be gained from trading groundwater, and the costs involved in establishing a market. A properly established market will grow in trade over time, and optimal water prices achieve efficient management by balancing benefits and costs across users and across time (Hansen 2012). Rural water users in the western USA have typically paid only for conveyancing and pumping cost of water, not its scarcity value. Markets will allow the movement of water to high value users.
5. ***Society's concerns do not always matter:*** Although policy needs to be concerned with social externalities from water markets, it is not something that should always be considered for designing efficient groundwater markets. This is where other policy needs to be put in place to address those rural social concerns; water markets should not be used as a second-best tool to address their problems. There have been a myriad of concerns about equity, low income impacts, rural community depopulation and the belief that water is a public good that have led commentators to imply that water should not be commodified (NWC 2012). However, setting water prices artificially low will result in inefficient pumping and consumption, and not allowing water markets to develop will deny rural users a valuable adaptation and risk measure (Hansen 2012).

Finally, the most important point that needs elaborating upon is that flexibility matters. Flexibility in institutions, in policy, in scientific and social science research is needed to continually deal with changes in the environment, the climate and in rural conditions. There is an element of path dependence that has resulted in the way institutions in each country are established and policy prescriptions for a variety of environmental and water scarcity problems are made. In California, water marketing and groundwater banking are essential tools for helping water users to manage their scarce water resources more efficiently and sustainably. The continual development of such tools augments the ability to cope with future droughts (Hanak and Stryjewski 2012). In Australia, the decision to institute water markets, the setting of the initial Cap on water use and the inability to recognise that this would activate many unused water rights by such water owners selling their water, has led to the situation in the 2000s where governments are buying back billions of dollars of surface water entitlements in the MDB. By significantly increasing the demand for water entitlements (and paying what is perceived to be higher prices for water), this has also activated many farmers selling their surface water, and increasingly turning to their groundwater entitlements to support their farm production. It is predicted that this growth in groundwater use is unsustainable in the MDB. Such a situation highlights the importance of history, and of how various policy decisions play a part in creating further externalities down the line. It also highlights that policy needs to be flexible to deal with unintended externalities that have resulted from previous attempts to solve water issues.

Acknowledgements We are grateful for the research assistance of Jane Edwards in helping to prepare this manuscript. This research was supported by an ARC Discovery project DP140103946 and ARC Future Fellowship FT140100773.

References

ABS (Australian Bureau of Statistics) (2006) Water account Australia: 2004–05. Australian Bureau of Statistics, Canberra

Al-Marshudi A (2007) The falaj irrigation system and water allocation markets in Northern Oman. Agric Water Manage 91:71–77

Anderson T, Snyder P (1997) Water markets: priming the invisible pump. Cato Institute, Washington, DC

Athukorala W, Wilson C (2012) Groundwater overuse and farm-level technical inefficiency: evidence from Sri Lanka. Hydrogeol J 20:893–905

Bauer C (1997) Bringing water markets down to earth: the political economy of water rights in Chile, 1976–95. World Dev 25:639–656

Bennett J (2008) Defining and managing environmental flows: inputs from society. Econ Papers 27:167–183

Bjornlund V, Bjornlund H (2010) Sustainable irrigation: a historical perspective. In: Bjornlund H (ed) Incentives and instruments for sustainable irrigation. WIT Press, Southampton, pp p13–p24

Bjornlund H, McKay J (2000) Are water markets achieving a more sustainable water use? In: Proceedings from the Xth world water conference, Melbourne, 11–17 Mar

Bjornlund H, Wheeler S, Rossini P (2013) Water Markets and Their Environmental, Social and Economic Impact in Australia. In: Maestu J (ed) Water Trading and Global Water Scarcity: International Perspectives. RFF Press, Abingdon, pp 68–93

Boadu FO, McCarl B, Gillig D (2007) Empirical investigation of institutional change in groundwater management in Texas: the Edwards Aquifer case. An Nat Resour J 47:117–163

Bolen E, Smith M, Schramm H (1989) Playa lakes: prairie wetlands of the southern high plains. BioScience 39:615–623

Boyd T, Brumley J (2004) Optimising sustainable use of groundwater: a challenge for science and water markets. In: Paper presented at the 1st international conference on sustainability engineering and science, Auckland, 6–9 July 2004. Available at www.thesustainabilitysociety.org.nz. Accessed 4 July 2013

Brewer J, Glennon R, Ker A et al (2008) Water markets in the west: prices, trading and contractual forms. Econ Inq 46:91–112

Brozović N, Sunding D, Zilberman D (2010) On the spatial nature of the groundwater pumping externality. Res Energy Econ 32:154–164

Colby B (2000) Cap-and-trade policy challenges: a tale of three markets. Land Econ 4:638–658

Colby S, Bush D (1987) Water markets in theory and practice. Market transfer. Water values and public policy. Studies in water policy and management. Westview Press, Colorado

Crase L (2011) The fallout to the guide to the proposed basin plan. Aust J Publ Admin 70:84–93

Crase L, Pagan P, Dollery B (2004) Water markets as a vehicle for reforming water resource allocation in the Murray-Darling Basin. Water Resour Res 40:1–10

CPNRD (Central Platte Natural Resource District) (2012) Integrated management plan. http://www.cpnrd.org/IMP%20Final.pdf. Accessed 5 May 2013

Easter K, Dinar A, Rosengrant M (1998) The performance of water markets: transaction costs, interjurisdictional barriers and institutional options. In: Just R, Netanyahu S (eds) Conflict and cooperation on trans-boundary water resources. Kluwer, Boston, pp 299–313

Eckhardt G (2013) The Edwards Aquifer website. http://www.edwardsaquifer.net/rules.html. Accessed 3 July 2013

Esteban E, Albiac J (2012) The problem of sustainable groundwater management: the case of La Mancha aquifers, Spain. Hydrogeol J 20:851–863

Famiglietti J, Lo M, Ho S et al (2011) Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys Res Lett 38:L03403. doi:10.1029/2010GL046442

Garrick D, Siebentritt M, Alyward B et al (2009) Water markets and freshwater ecosystem services: policy reform and implementation in the Columbia and Murray-Darling Basins. Ecol Econ 69:366–379

GHD et al (2011) A framework for managing and developing groundwater trading. Waterlines report. National Water Commission, Canberra. http://archive.nwc.gov.au/__data/assets/pdf_file/0019/10378/52_framework3.pdf. Accessed 10 May 2014

Gillig D, McCarl B, Jones L et al (2004) Economic efficiency and cost implications of habitat conservation: an example in the context of the Edwards Aquifer region. Water Resour Res. doi:10.1029/2003WR002749

Gisser M (1983) Groundwater: focusing on the real issue. J Polit Econ 91:1001–1027
Gisser M, Sanchez D (1980) Competition versus optimal control in groundwater pumping. Water Resour Res 16:638–642
Goesch T, Hone S, Gooday P (2007) Groundwater management: issues affecting the efficient allocation of groundwater. Aust Commod 14:200–211
Griffin R (1998) The application of water market doctrines in Texas. In: Easter K, Rosengrant M, Dinar A (eds) Markets for water. Potential and performance. Kluwer, Boston, pp 51–64
Hanak E (2003) Who should be allowed to sell water in California? Third-party issues and the water market. Public Policy Institute of California, San Francisco
Hanak E (2005) Stopping the drain: third-party responses to California's water market. Contemp Econ Policy 23:59–77
Hanak E, Stryjewski E (2012) California's water markets, by the numbers: update 2012. Public Policy Institute of California, San Francisco
Hansen J (2012) The economics of optimal groundwater management in Southwestern USA. Hydrogeol J 20:865–877
Jacobs N (2006) California: groundwater management, conjunctive use and water banking. West Water Law Policy Rep 10:122–125
Juchems E (2013) Predicting groundwater trading participation in the Upper Republican River Natural Resource District. Masters Dissertation, University of Nebraska-Lincoln
Katic P, Grafton R (2012) Economic and spatial modelling of groundwater extraction. Hydrogeol J 20:831–834
Kenny J, Barber N, Hutson S et al (2009) Estimated use of water in the United States in 2005. U.S. Geological Survey Circular, Reston, 1344
Loch A, Wheeler S, Bjornlund H et al (2013) The role of water markets in climate change adaptation. National Climate Change Adaptation Research Facility, Gold Coast
Megdal S (2012) Arizona groundwater management. The water report. http://www.cwi.colostate.edu/southplatte/files/TWR_AZGroundWaterManagement.pdf. Accessed 10 May 2014
Meinzen-Dick R (1998) Groundwater markets in Pakistan: institutional development and productivity impacts. In: Easter K, Rosengrant M, Dinar A (eds) Markets for water–potential and performance. Kluwer, Boston, pp p207–p222
Moreaux M, Reynaud A (2004) Optimal joint management of a coastal aquifer and a substitute resource. Water Resour Res 40:W06S18. doi:10.1029/2003WR002166
NWC (2008) National water commission groundwater position statement. http://www.nwc.gov.au/__data/assets/pdf_file/0009/9729/Groundwater-position_statement.pdf. Accessed 26 Apr 2013
NWC (2010) The impact of water trading in the southern Murray Darling basin: an economic, social and environmental assessment. NWC, Canberra
NWC (2011) Strengthening Australia's water markets. NWC, Canberra
NWC (2012) Groundwater essentials. NWC, Canberra
NWC (2013) Australian water markets: trends and drivers 2007–08 to 2011–12. NWC, Canberra
Palazzo A, Brozović N (2014) The role of groundwater trading in spatial water management. Agric Water Manage. http://dx.doi.org/10.1016/j.agwat.2014.03.004
Richardson S, Evans R, Harrington G (2011) Connecting science and engagement: setting groundwater extraction limits using a stakeholder led decision-making process. In: Grafton Q, Connell D (eds) Basin futures: water reform in the Murray-Darling basin. Australia National University Press, Canberra
RRB (Republican River Basin) (2013) Sustainability steps – previous and planned actions in the republican basin to preserve water. Available at: http://www.urnrd.org/. Accessed 10 May 2014
Shah T (1993) Groundwater markets and irrigation development. Political economy and practical policy. Oxford University Press, Bombay
Shah T (2009) Taming the anarchy: groundwater governance in South Asia. Resources for the Future, Washington, DC

Sitarz D (1993) AGENDA 21: the earth summit strategy to save our planet. Earth Press, Boulder
Skurray J, Pannell D (2010) Potential approaches to the management of third-party impacts from groundwater transfers. Hydrogeol J 20:879–891
Skurray J, Pandit R, Pannell D (2013) Institutional impediments to groundwater trading: the case of the Gnangara groundwater system of Western Australia. J Environ Plan Manag 56:1046–1072
van der Gun J (2012) Groundwater and global change: trends, opportunities and challenges. UNESCO, Paris
Wang J, Huang J, Blanke A et al (2007) The development, challenges and management of groundwater in rural China. In: Giordano M, Giordano M, Vilholth K (eds) The agricultural groundwater revolution: opportunities and threats to development. CABI, Wallingford/Cambridge, MA
Wentworth Group of Concerned Scientists (2012) Statement on the 2011 Draft Murray-Darling Basin Plan. http://wentworthgroup.org/wp-content/uploads/2013/10/Statement-on-the-2011-Draft-Basin-Plan.pdf. Accessed 10 May 2014
Wheeler S, Loch A, Zuo A, Bjornlund H (2014) Reviewing the adoption and impact of water markets in the Murray-Darling Basin, Australia. J Hydrol 518:28–41
Young M (2014) Designing water entitlement regimes for an ever-changing and ever-varying future. Agric Water Manag. http://dx.doi.org/10.1016/j.agwat.2013.12.002
Zekri S, Al-Marshudi A (2008) A millenarian water rights system and water markets in Oman. Water Int 33:350–360
Zhang L, Wang J, Huang J et al (2008) Development of groundwater markets in China: a glimpse into progress to date. World Dev 36:706–726

21 Integrated Assessment of Economic Benefits of Groundwater Improvement with Contingent Valuation

Cécile Hérivaux and Jean-Daniel Rinaudo

Abstract

This chapter investigates the potential and limits of the contingent valuation method for assessing the benefits of groundwater remediation or protection programs. The discussion is based on a review of the literature and on two original contingent valuation surveys conducted in France and in Belgium, in contexts where groundwater was expected to be particularly unfamiliar to respondents. Particular attention was paid to (i) people's perception and understanding of the resource under study, and (ii) type and quantity of information provided by the questionnaire. In both cases, we show that the population is concerned about groundwater remediation or protection, especially to guarantee the wellbeing of future generations. Overall, we highlight that assessing willingness to pay through contingent valuation surveys is helpful for conducting an integrated valuation of groundwater protection benefits. However, we also point out two main limits which might restrict the relevance of the results obtained: (1) the respondents' limited prior knowledge of groundwater and the risk that information provided by the questionnaire biases the elicitation process; and (2) two types of embedding effect, with the difficulty for respondents in considering the geographic extension of an aquifer and disentangling benefits derived from groundwater quality improvement from other environmental benefits.

C. Hérivaux (✉)
BRGM, New resources and economics Unit, 1039 rue de Pinville, 34000 Montpellier, France
e-mail: c.herivaux@brgm.fr

J.-D. Rinaudo
Water Department, BRGM, French Geological Survey, Montpellier, France
e-mail: jd.rinaudo@brgm.fr

A.J. Jakeman et al. (eds.), *Integrated Groundwater Management*,
DOI 10.1007/978-3-319-23576-9_21

21.1 Introduction

Since the industrial revolution, the development of industrial and other economic activities has generated significant pressures on groundwater resources, in developed and in developing countries. Many aquifers were contaminated by point and non-point source pollution or were over-abstracted, sometimes leading to irreversible damages, such as sea water intrusion or land subsidence (see Chap. 2). Groundwater deterioration went relatively unnoticed for decades, due to the invisible nature of the resource, lack of knowledge, inexistent monitoring networks and insufficient institutional frameworks (Chap. 1). Yet, over time, a growing number of users were affected by this "silent" groundwater deterioration. The cost to society became tangible as municipalities, households, industries or farmers were forced to shut down contaminated wells. This progressively triggered response from public authorities including the elaboration of more comprehensive legal frameworks for groundwater protection (see Chaps. 6 and 22) and the implementation of groundwater protection and reclamation programs.

Due to difficulties in identifying the actors who caused groundwater deterioration (e.g. diffuse pollution), or because they no longer exist (e.g. abandoned industrial sites), costs of groundwater remediation projects often have to be borne by public agencies. Because of limited available financial resources, economic considerations have increasingly played a key role in setting priorities between competing groundwater protection programmes or remediation projects. Cost-benefit analysis (CBA) has been used to identify groundwater basins where groundwater decontamination or protection is likely to generate the highest return on investments for society. This rationale for instance underlies the Superfund programme in the USA (Kiel and Zabel 2001). Alternatively, CBA is also used to identify sites where no action should be undertaken because remediation costs are outweighed largely by the expected benefits. This approach is implemented in Europe where CBA can be used to waive the general requirement to restore good chemical and quantitative status imposed by the Water Framework Directive (Brouwer 2008; Quevauviller 2008; Rinaudo and Aulong 2014).

This paper focuses on two main "integration" challenges faced by economists trying to assess in monetary terms the benefits of groundwater remediation or protection. The first one lies in integrating in their analysis the full range of positive impacts of such programs. Restoring groundwater quality or quantity is likely to improve the economic situation of many economic actors who directly use groundwater, including drinking water utilities, households depending on private wells, farmers irrigating their crops, industries using groundwater in their process (*direct use values*). It will also generate indirect benefits, often related to recreational activities (e.g. swimming, angling, canoeing) for users of groundwater dependent ecosystems (e.g., rivers, wetlands, gravel pit lakes) where ecological status is improved together with groundwater (*indirect use values*). Last but not least, groundwater remediation may also generate benefits not related to a particular use of the resource: these benefits refer to *non-use values* such as those associated with the possibility for others to use a groundwater in good status (*altruistic value*), or to the protection of the groundwater resources for itself (*existence value*). Economic valuation aims at integrating all these positive impacts into one single monetary estimate.

The second challenge lies in integrating in monetary valuation *the long term dimension* of groundwater protection benefits and in particular the value of groundwater for future generations. Indeed, restoring groundwater quality not only provides a flow of benefits for present generations. It also represents an increase of natural capital which might become a source of wealth in the future. Economists usually distinguish the *option value* associated with potential future use for present generations from *bequest value* associated with the preservation of an environmental good (natural heritage) for future generations.

This paper investigates the potential and limits of a specific economic valuation methodology – the contingent valuation method – which has often been recommended for conducting an *integrated economic assessment* of groundwater restoration benefits. The main objectives of the chapter are: (1) to present to non-economists how the contingent valuation method can be used for conducting an integrated economic assessment of groundwater protection and restoration benefits; and (2) to discuss the advantages and caveats of this method. The discussion is based on a review of the literature and on two original case studies to feed the debate.

The chapter is organised as follows. In the next section, we describe the different methods that can be used to assess the economic benefits of groundwater protection and remediation, with a specific focus on the contingent valuation method which is increasingly used in environmental economics. The paper then presents two original groundwater valuation studies conducted in Belgium and France, based on the contingent valuation method and using a similar protocol. Materials and methods are presented in Sect. 21.3 and results obtained in Sect. 21.4. We then discuss in Sect. 21.5 the limitations of the method in the context of groundwater valuation studies before concluding the chapter.

21.2 Valuing the Benefits of Groundwater Protection with Contingent Valuation: A Review

21.2.1 Methodological Approaches for Valuing Groundwater Protection Benefits

A popular approach among practitioners to assess the benefits of groundwater protection is the *avoidance-cost method* (e.g., see Abdalla 1994; Rinaudo et al. 2005). It consists of assessing the cost of actions undertaken by economic agents to cope with groundwater degradation, and pollution in particular. Typical avoidance costs are those related to the closure and displacement of contaminated drinking water wells (public or private), the installation of sophisticated water treatment units (municipal or domestic) or the purchase of bottled water when groundwater can no longer be used as a safe source of drinking water. One of the main advantages of this method is that it measures tangible costs that correspond to real expenditures made by concerned economic agents (investment, operation and maintenance costs). Results obtained are thus easy to grasp by policy makers and stakeholders. Its main weakness is that it only focuses on *direct use benefits*. It does not consider less tangible benefits related to: the possible uses of groundwater in the future (*option value*); the positive impact on groundwater dependent ecosystems (*indirect use benefits*); the transmission of a well-protected natural heritage to future generations (*bequest value*); the opportunity for other individuals to use groundwater in good status (*altruistic value*); and the protection of the groundwater resource for its own integrity (*existence value*). Benefits assessed with avoidance cost methods are thus generally considered as lower bound estimates.

An alternative method, widely used for practical applications in the United States, is the *contingent valuation method (CVM)*. Unlike the avoidance-costs technique, this method is not based on the observation of actual behaviours of economic agents to cope with existing groundwater deterioration. Instead, it relies on the implementation of surveys to elicit people's willingness to pay (WTP) for hypothetical environmental improvement scenarios. The assumption is that individual-stated WTP reflects the intensity of the benefits each respondent derives from the scenario. After the survey is completed, stated WTP can be aggregated over the sample, and then extrapolated to the entire population concerned by the groundwater remediation scenario, in order to produce an estimate of the total economic benefits of the restoration scenario. The information provided to respondents should describe the full range of benefits they will derive from the groundwater protection/restoration scenario, including direct and indirect use, for present and future generations. In theory, the main advantage of this method is its ability to integrate all the benefits – direct and indirect, present and future – in a single monetary indicator. Let us now look at how the method has been used in practice.

21.2.2 The Integrative Capacity of Contingent Valuation Method

The CVM was first, and predominantly, applied to assess groundwater restoration and protection benefits in the USA (see Table 21.1). The use of the method was recommended by the US Water Resources Council in 1983. Its use was fostered by the increasing number of groundwater contamination cases, affecting a very large number of households relying on private wells for drinking water supply. The first study was conducted by Edwards (1988) in a small Massachusetts community where water supply was fully dependent on groundwater. A survey was conducted to elicit the population's WTP for reducing the probability of water supply contamination. This seminal research was followed by a number of similar studies conducted in the 1990s. Overall, this first wave of groundwater contingent valuation studies primarily aimed at assessing people's WTP for an improvement in the quality of their domestic water supply (see for example Shultz and Lindsay 1990;

Table 21.1 CVM studies applied to groundwater valuation over the 1986–2013 period

Reference	Year[a]	Country	Location	Objective/issue	Average WTP (current currency value)[b]	Average WTP (PPP €2013)[c]
Edwards (1988)	1986	United States	Cape God, Community of Falmouth, Massachusetts	Benefits of reducing the probability of groundwater contamination	286–1130 $_{1986}$/hh/year	523–2065 €/hh/year
Wright (1988)	1987[a]	United States	Peninsula Township groundwater resources, Michigan	Benefits of protecting groundwater (nitrates)	296–696 $_{1987}$/hh/year	523–1230 €/hh/year
Shultz and Lindsay (1990)	1988	United States	Dover Community, New Hampshire	Benefits of reducing the probability of groundwater contamination, individual community	129 $_{1988}$/hh/year	220 €/hh/year
Sun et al. (1992)	1989	United States	Dougherty County, Georgia	Benefits to citizens of protecting groundwater supplies from agricultural chemical contamination	641 $_{1989}$/hh/year	1050 €/hh/year
Powell et al. (1994)	1989	United States	15 communities in Massachusetts, New York and Pennsylvania	Benefits of groundwater quality protection (agricultural chemicals, landfills, accidental spills and toxic chemicals)	62 $_{1989}$/hh/year	102 €/hh/year
Caudill (1992)	1990	United States	Michigan state	Benefits of protecting groundwater (nitrate and pesticides contamination)	34–69 $_{1990}$/hh/year	53–108 €/hh/year
Wattage (1993)	1991	United States	Bear Creek Watershed, Story and Hamilton counties, Iowa	Benefits of groundwater quality improvement (nitrates, pesticides)	90 $_{1991}$/hh/year	135 €/hh/year
Lazo et al. (1992)	1991[a]	United States	Denver, Colorado	Non-use benefits expected from groundwater quality improvement (domestic waste)	34–42 $_{1991}$/hh/year (2,81–3,54 $_{1991}$/household/month)	51–64 €/hh/year

(continued)

Table 21.1 (continued)

Reference	Year[a]	Country	Location	Objective/issue	Average WTP (current currency value)[b]	Average WTP (PPP €2013)[c]
McClelland et al. (1992)	1991	United States	National assessment	National benefits of cleaning groundwater contaminated by landfills, contaminates not specified	168 $_{1991}$/hh/year (14 $_{1991}$/household/month)	253 €/hh/year
Jordan and Elnagheeb (1993)	1991	United States	Entire state of Georgia, US	Benefits of improving drinking water quality	121–149 $_{1991}$/hh/year	182–224 €/hh/year
Poe and Bishop (1993)	1991–1992	United States	Portage County, Wisconsin	Benefits of protecting groundwater such that nitrate contamination levels would be below USEPA health advisory standards for the entire state of Georgia	225–685 $_{1991}$/hh/year	339–1031 €/hh/year
Stenger and Willinger (1998)	1993	France	10 communities located on the Alsatian aquifer	Benefits of preserving groundwater quality (various types of contaminants) – water users	617 FF$_{1993}$/hh/year	129 €/hh/year
Bergstrom and Dorfman (1994)	1993[a]	United States	Groundwater resource Dougherty County	Benefits of preserving groundwater quality (for domestic water supply)	320–2360 $_{1993}$/hh/year	455–3353 €/hh/year
de Zoysa (1995)	1994	United States	Maumee and Erie Lake Basin, Ohio	Benefits of groundwater quality improvement	53 $_{1994}$/hh/year	73 €/hh/year
Rozan et al. (1997)	1995	France	Two communities close to the Alsatian aquifer	Benefits of preserving groundwater quality (various types of contaminants) – non users	340 FF$_{1995}$/hh/year	69 €/hh/year
Lichtenberg and Zimmerman (1999)	1995	United States	Maryland, New York and Pennsylvania states, Mid-Atlantic region	Farmers' WTP for groundwater protection (pesticide leaching prevention)	1112–7078 $_{1995}$/farmer/year (17–35 $_{1995}$/acre/year)	1495–9517 €/agriculteur/an

Martin and Marceau (2001)	1997	Canada	Five districts North of Montréal	Benefits of groundwater status improvement (quality, quantity)	48 $\$CAN_{1997}$/hh/year	49 €/hh/year
Belloumi and Matoussi (2002)	1997	Tunisia	Oued Kheirate groundwater	Benefits of preserving groundwater quality (saline intrusion)	20 $dinars_{2002}$/hh/year	41 €/hh/year
Grappey (1999)	1997–1998	France	Bièvre-Liers plain aquifer, Isère	Benefits of preserving groundwater quality (nitrates)	251–402 FF_{1997}/hh/year	49–79 €/hh/year
White et al. (2001)	1999	New Zealand	Waimea plain (seven aquifers)	Benefits of improving the quantitative status of groundwater	183 $\$_{1999}$/hh/year	152 €/hh/year
Wei et al. (2007)	2004	China	Fengqiu County, Henan Province, North China Plain	Benefits of protection and restoration of groundwater (overexploitation)	1.26 $Yuan_{2004}$/hh/year	0.39 €/hh/year
Hasler et al. (2005)	2004	Denmark	National assessment	National benefits associated with increased protection of the groundwater resource (nitrates, pesticides)	711 DKK_{2004}/hh/year	87 €/hh/year
Rinaudo and Aulong (2014)	2006	France	Upper Rhine valley quaternary aquifer, France	Benefits of protecting and improving groundwater quality (chlorinated solvents)	42–76 $€_{2006}$/hh/year	47–85 €/hh/year
Brouwer et al. (2006)	2006	The Netherlands	Scheldt basin	Benefits of protecting and improving groundwater quality	31–72 $€_{2006}$/hh/year	36–84 €/hh/year
Miraldo Ordens et al. (2006)	2006	Portugal	Aveiro Quaternary aquifer	Benefits of protecting groundwater quality	38 $€_{2006}$/hh/year	54 €/hh/year
Pakalniete et al. (2006)	2006	Latvia	Shallow part of the groundwater body under Riga	Benefits of groundwater quality improvement	25 $€_{2006}$/hh/year	71 €/hh/year

(continued)

Table 21.1 (continued)

Reference	Year[a]	Country	Location	Objective/issue	Average WTP (current currency value)[b]	Average WTP (PPP €2013)[c]
Strosser and Bouscasse (2006)	2006	Slovenia	Krska kotlina aquifer	Benefits of protecting groundwater quality	1346–2493 SIT_{2006}/hh/year	120–222 €/hh/year
Chegrani (2009)	2006	France	Artois chalk and Lys valley aquifer	Benefits of improving groundwater quality (nitrates and pesticides)	24 $€_{2006}$/hh/year	27 €/hh/year
El Chami et al. (2008)	2007[d]	Lebanon	Byblos district	Benefits of the improvement of groundwater quality for irrigation (seawater intrusion)	102–167 $\$_{2007}$/irrigating farmer/year	104–170 €/hh/year
Rinaudo (2008)	2008	France	Lower Triassic Sandstone aquifer	Benefits of stopping the over exploitation of the aquifer	40$€_{2008}$/hh/year	43 €/hh/year
Tentes and Damigos (2012)	2009	Greece	Four towns located on the Asopos river basin aquifer	Industrial pollution, especially by Cr(VI) Benefits for restoring groundwater quality	180–239 $€_{2009}$/hh/year (15–20 $€_{2009}$/household/month)	227–301 €/hh/year
Hérivaux (2011)	2010	Belgium	Meuse alluvial aquifer near Liège	Benefits of restoring groundwater quality	40 $€_{2010}$/hh/year	42 €/hh/year
Martinez-Paz and Perni (2011)	2010	Spain	Gavilan aquifer, Segura basin	Benefits of improving water quality and quantity of the associated wetland	24 $€_{2010}$/hh/year	29 €/hh/year

[a]Year of the economic valuation
[b]hh: household
[c]Primary data are expressed in euro 2013, by using (i) the Purchasing Power Parity Index produced by the World Bank and OECD, et (ii) the Consumer Price Index produced by INSEE (French National Institute for Statistics and Economic Research)
[d]means that the year is not explicitly mentioned in the study

Sun et al. 1992; Powell et al. 1994; Caudill 1992; Jordan and Elnagheeb 1993; Poe and Bishop 1993; Lichtenberg and Zimmerman 1999). Estimated WTP were thus not reflecting the total value of groundwater improvement. Several studies have also shown that an important part of the elicited WTP may be related to the improvement of the groundwater resource itself or to the ecological services it provides through sustaining dependent ecosystems (see for example Lazo et al. 1992; McClelland et al. 1992).

In Europe, the use of the CVM to assess the economic value of groundwater protection has been more integrative. Studies were generally designed to capture a wider range of benefits and they were not solely focusing on the benefits associated with domestic water supply. In the first study, Stenger and Willinger (1998), followed by Rozan et al. (1997), designed a survey to assess the "patrimonial value" of the upper Rhine valley aquifer (Eastern France), explicitly considering the multi-generational dimension of groundwater. Their study was designed to elicit WTP of groundwater users and non-users. This integrative approach was further extended in the 2000s, following the publication of the Water Framework Directive, with a series of studies explicitly considering a wide range of potential benefits in Denmark (Hasler et al. 2005), France (Chegrani 2009; Rinaudo and Aulong 2014), the Netherlands (Brouwer et al. 2006), Portugal (Miraldo Ordens et al. 2006), Latvia (Pakalniete et al. 2006); Slovenia (Strosser and Bouscasse 2006), Greece (Tentes and Damigos 2012) and Spain (Martinez-Paz and Perni 2011). Similar studies have also been conducted in New Zealand (White et al. 2001), in China (Wei et al. 2007) and in Lebanon (El Chami et al. 2008).

One of the main findings of groundwater contingent valuation studies was to show that an important part of the elicited WTP may be associated with indirect use values or non-use values. In 1985, the USEPA reported that "*numerous cases have occurred where communities and public officials argue heatedly for complete clean-up of contaminated aquifers which are not even presently being taped*" Poe et al. (2000) shows in a meta-analysis that studies focusing only on use values had significantly lower WTP than studies that elicited total WTP for groundwater protection programs. Several studies have also shown that bequest values were quoted among the main reasons to contribute to a program of groundwater protection and may also statistically influence the willingness to contribute (e.g., Rinaudo and Aulong 2014).

21.2.3 The Limits of CV for Groundwater Economic Valuation

One of the main concerns with applying CVM to groundwater is that respondents may have a very limited knowledge of the environmental asset they are asked to value. In theory, CVM should only be used when respondents have what Lazo et al. (1992) call "perfect information," defined as: (i) a clear perception of the environmental asset they are asked to value; (ii) existing substitute commodities if any; and (iii) a good understanding of how changes in the level of provision of the commodity will affect them (e.g. the individual benefits of the scenario).

Evidence from various surveys shows that this is rarely the case. People generally have a very limited knowledge of groundwater resources and related management issues, even when they have a direct link to the resource through private wells. This is illustrated by the results of a survey conducted in 1995 in Massachusetts (Stevens et al. 1997) where 47 % of the respondents declared they knew little or nothing about groundwater, although half of the respondents had private wells and the second half was supplied by a municipal utility using groundwater. This knowledge problem is even worse in contexts where the population is supplied by public water networks and where "*the only link that exists between groundwater quality and households is the price they pay for the drinking water supply*" (Rinaudo and Aulong 2014). This is illustrated by the results of a series of European surveys: in the Netherlands, Brouwer et al. (2006) found that 40 % of the respondents were not familiar at all with groundwater; in Latvia, 46 % of the respondents connected to the domestic water supply network did not know the origin of their water and that 48 % of the respondents were not informed about the groundwater contamination problem (Pakalniete et al. 2006); in Eastern France, 82 % of respondents declared not being well-informed of groundwater management problems (Rinaudo and Aulong 2014).

In such situations, CVM specialists acknowledge that the method can still be used (Arrow et al. 1993). The burden of informing respondents about all the aspects of the environmental asset being evaluated then falls with the survey instrument. To avoid information bias, special attention should be paid to design the survey protocol and questionnaire, especially to select the nature, format and quantity of information provided to respondents. The researcher should ensure that this information is correctly understood by respondents by implementing a careful pretesting of the contingent valuation questionnaire. Complementary techniques can also be implemented. McClelland et al. (1992) for instance used a process of cognitive survey design, based on the pretesting of a 30–40 page perfect information questionnaire with randomly chosen people who were asked to speak continuously into a tape recorder as they completed the survey, in order to identify potential information problems. Mitchell and Carson (1989) conducted several focus groups to explore in-depth people's groundwater knowledge, concerns and preferences for groundwater protection. If sufficient information is provided "*in a way that is plausible, understandable and meaningful to respondents*" (Carson et al. 2001), some authors do not consider unfamiliarity as a problem for conducting a CV survey.

21.3 Empirical Case Studies: Objectives and Methodology

21.3.1 Context and Motivation for Conducting Two Additional Case Studies

The empirical research presented in this section was triggered by practical problems arising from the implementation of the European Water Framework Directive. In several European river basin districts, a number of groundwater bodies were so severely affected by human activities (overdraft or pollution) that stakeholders would not support the implementation of costly clean-up or replenishment programs. Clean-up or remediation costs were considered excessive as compared to financial capacities of actors and/or to the benefits that could be derived by potential groundwater improvement. However, justifying that benefits were much lower than remediation costs had to be supported by some evidence, which economists were asked to provide. The use of the contingent valuation method was advocated and several studies implemented in the framework of European and national research programs (see for example the Bridge-WFD program and the FRAC-WECO Belgian research project). The two case studies presented here were initiated in this context, with the intention of answering the following questions:

- Is contingent valuation an appropriate method for monetary valuation of benefits associated with groundwater protection and restoration, in locations where (1) people do not directly use groundwater through wells, and (2) where they have a very limited knowledge of groundwater resources?
- If appropriate, what type of information should be provided to respondents to make sure that they properly understand the multidimensional nature of the benefits associated with groundwater protection and restoration?
- Finally, what are people's stated preferences for the different components of groundwater protection and restoration benefits? Do they integrate use and non-use benefits, short and long term benefits?

21.3.2 Case Studies

The two selected case studies are complementary in terms of type of territory, type of resource and use, and management problem (see Table 21.2). The Meuse alluvial aquifer (MAA) case study (under the city of Liège, Belgium, 360,000 inhabitants) focuses on a large urban section of an alluvial aquifer which is no longer used due to historical industrial pollution. If implemented, a clean-up program (decontamination of brownfields) would not only restore groundwater quality but also contribute to improving the ecological status of the Meuse River (indirect use benefit). It would also generate a moral satisfaction in transmitting to future generations a

Table 21.2 Main characteristics of the two aquifers selected as case studies

Characteristics	Meuse alluvial aquifer (MAA) Liège region, Belgium	Lower Triassic Sandstone (LTS) Lorraine region, France
Aquifer type and scale	Shallow alluvial aquifer (15 m depth) Local resource	Deep confined aquifer (0–800 m depth) Regional resource
Type of territory	Densely populated urban area	Rural area
Management problem	Industrial pollution (brownfield)	Overexploitation
Groundwater use	Industrial Drinking water wells abandoned due to pollution Very few private wells	Main resource for municipal supply, food and beverage industry, industrial water bottling and cattle farms
Expected benefits	Ecological improvement of dependent ecosystems (indirect benefit) Improvement of natural heritage (bequest value) and potential future use (option value)	Continued long term access to groundwater implying continuation of cheap municipal supply in the future; and reduced risk in case of drought or contamination of superficial water resources

better environment cleared from historical pollution, and potentially offering an alternative to currently used superficial water supplies.

The Lower Triassic Sandstone (LTS) case study (Lorraine region, in Eastern France) deals with a large confined aquifer that is increasingly depleted (−68 m between 1968 and 2000). This aquifer has a strategic role at the regional level, since over 100,000 inhabitants depend on it for their water supply. A programme of measures aiming at restoring a balance between recharge and abstraction is currently being considered. In the absence of remediation action, a number of wells will run dry in the medium term (15–50 years) and local communities will have to switch to surface water supply, entailing higher investment and operation cost and a greater exposure to drought and surface water contamination risk. Note that the restoration program would not have any indirect ecological impact since this confined aquifer does not interact with surface ecosystems.

21.3.3 Overview of the Common Methodology Deployed in the Case Studies

The methodology deployed in the two case studies comprises the four following steps (Hérivaux 2011; Rinaudo 2008): (1) preliminary social survey; (2) questionnaire design and test; (3) survey implementation; and (4) data analysis.

Step 1 consists of a series of qualitative interviews to analyse people's perception and understanding of the groundwater resource under study. In the LTS, a total of 72 semi-structured face-to-face interviews were conducted to capture the lay vision of the reservoir, its characteristics and geographic extension; and to assess the level of understanding of the water cycle underground, with specific attention being paid to the understanding of exchanges between ground and surface water. Respondents were also asked to identify the services provided by groundwater to society. In the MAA case study, the same issues were addressed through informal discussion during the pre-test of the questionnaire and several open-ended questions administered at the beginning of each interview.

The results of this first step were used to construct a structured questionnaire, which was then carefully tested with about 50 respondents in each case study (step 2). Although differing in their contents, to be adapted to each case study, the contingent valuation questionnaires were similarly structured into four main sections. Section 21.1 consists of the presentation of the aquifer under study and it is followed by a series of questions aiming at assessing respondent's prior knowledge of this resource. Section 21.2 summarizes the groundwater management problem today and in the future if no action is undertaken. Impacts of groundwater overexploitation/ pollution on the current uses of the resources are also presented. Respondents are asked about their prior knowledge of this situation. Section 21.3 presents the groundwater improvement scenario. Proposed measures and expected impacts on groundwater quality and groundwater uses are listed. Respondents are asked if they would be willing to contribute financially (each year for 10 years) for such a scenario using the water bill as a payment vehicle. Those who agree are asked to specify an amount in euros per year on a payment card (for the household). Respondents are then asked to explain their motivations for accepting or refusing to contribute. Section 21.4 deals with socio-economic characteristics of the respondents (gender, age, employment, education, size of the household, income, perception of environmental problems, etc.).

The quantitative survey was then completed, with respectively 530 and 650 respondents in the MAA and LTS case studies (step 3). Face-to-face interviews were used in the MAA case study and a mail survey in the French LTS case study. Both methods have their advantages and their limits. For the MAA case study, the in-person survey seemed to be the most appropriate to collect answers to open-ended questions on groundwater and to minimize the non-response rate which was expected to be particularly high in this "non-use context". The mail survey method was chosen for the LTS case study to ensure that respondents would have sufficient time to get to know an unfamiliar subject and think about their preferences. The return rate was about 11 %.

Data obtained were then statistically analysed to check the consistency of responses and to identify factors determining stated WTP for groundwater protection (step 4). Different econometric models were estimated. Further detail on this part of the work is provided in the Appendix.

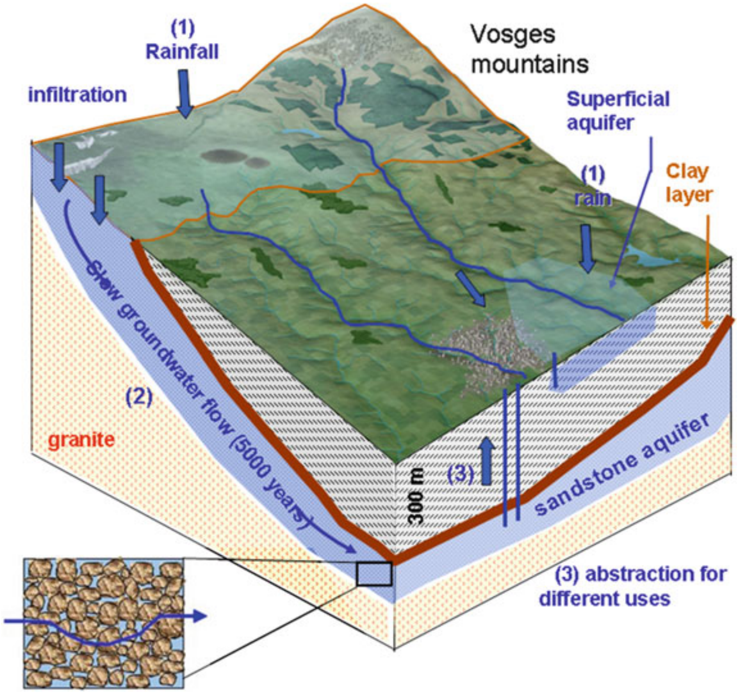

Fig. 21.1 Simplified representation of the Lower Triassic Sandstone aquifer (diagram used in the CV survey) (*Source*: Rinaudo 2008)

21.3.4 Sending Clear Messages About the Benefits of Groundwater Protection

When designing our CV survey, the main difficulty we had to address was to send clear messages about the benefits associated with the groundwater protection plan presented in the questionnaire. Given the complexity of the issue, we adopted a stepwise approach consisting of: progressive delivery of information on the groundwater resource itself and its current problems (Sect. 21.1); expected future evolution with a no-action scenario and possible consequences over time (Sect. 21.2); and a groundwater protection/restoration scenario, accompanied with a description of the potential benefits (Sect. 21.3).

In Sect. 21.1, we developed several simplified schemes depicting the geometry of the aquifer and the circulation of water and/or pollution loads within the reservoir (Fig. 21.1). The understanding of these visual supports as well as of the vocabulary used was checked during the pre-test phase. Maps were also used to delineate the spatial extent of the management problem so that each respondent could see if they

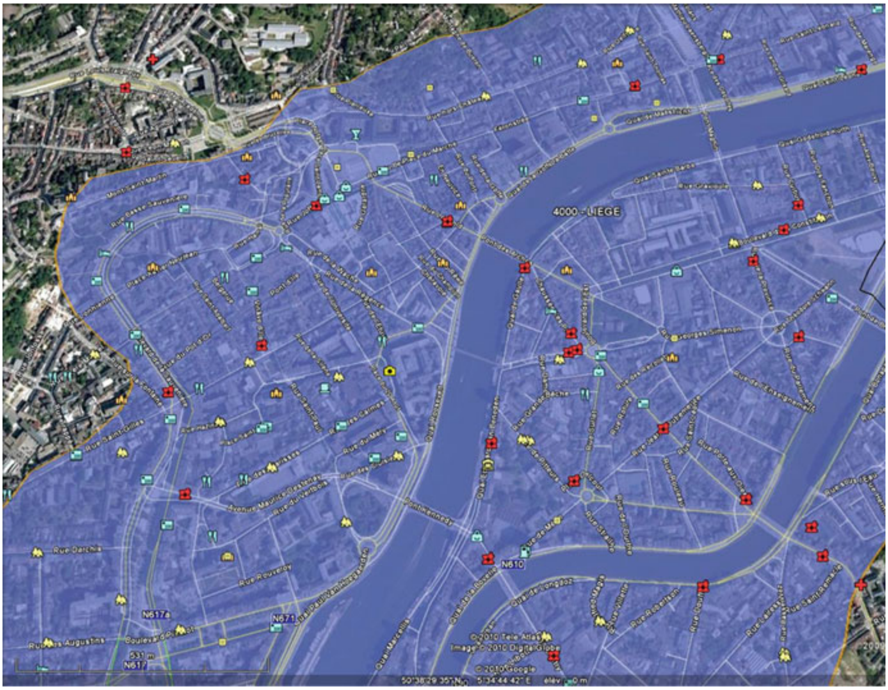

Fig. 21.2 Example of map combining aerial photographs and aquifer boundaries used during the survey (*Source*: Hérivaux 2011)

live above the aquifer or not, close or far from it. For the MAA case study, a series of maps combining Google Earth views and the aquifer boundaries were used during the survey to know if the respondent lives above the MAA (Fig. 21.2). Specific supports (maps or tables) were also used to show the origin of tap water for each municipality of the sample so that respondents could know if their water supply relies on the groundwater under study (Fig. 21.3).

When designing the questionnaire, specific efforts were made to describe the temporal dimension of groundwater deterioration (under the no-action scenario) or improvement (under the restoration scenario). In the LTS case study for instance, respondents were presented a map showing the date at which they would be impacted by groundwater depletion with the no action scenario (see Fig. 21.4). This map was elaborated based on the results of groundwater model simulations (Vaute et al. 2007). It was intended to help respondents in understanding if they would be personally concerned by groundwater protection benefits or if benefits would accrue to future generations.

Département de la Meurthe et Moselle (54)			
Barbonville	■	Remenoville	■
Charmois	■	Remereville	●
Diarville	●	Saint-Nicolas-de-Port	▲
Dombasle-sur-Meurthe	▲	Seichamps	●
Einvaux	■	Tantonville	●
Haussonville	■	Varangeville	▲
Herimenil	▲	Villacourt	■
Laloeuf	●	Virecourt	●
Lamath	■	Xirocourt	●
Lunéville	■		

Département des Vosges (88)					
Auzinvilliers	▲	Dompaire	●	Monthureux-le-sec	■
Bulgneville	▲	Evaux et Menil	▲	Nomexy	●
Charmes	●	Floremont	▲	Oelleville	■
Châtel-sur-Moselle	●	Gircourt les Vieville	▲	Poussay	▲
Chatenois	■	Gironcourt sur Vraine	■	Rainville	■
Contrexeville	▲	Hagecourt	▲	Remoncourt	■
Crainvilliers	▲	Houecourt	●	Rouvres en Xaintois	▲
Dombrot sur Vair	▲	Mandres sur Vair	▲	Suriauville	▲
Domjulien	▲	Mattaincourt	▲	Ubexy	▲
		Mirecourt	▲	Vittel	▲

The water you receive at your tap is pumped:

▲ In the lower triassic sandstone aquifer only

■ in the LTS aquifer for one part, and in rivers and other aquifers for another part

● only from rivers and other resources, and not from the LTS aquifer

Fig. 21.3 Table showing where tap water comes from in the municipalities selected for case study (used in the questionnaire) (*Source*: Rinaudo 2008)

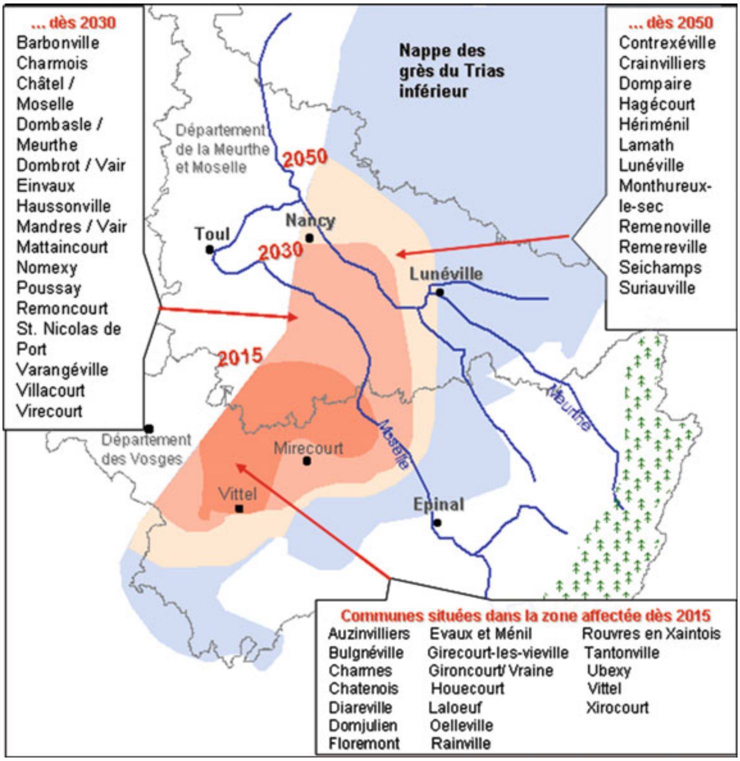

Fig. 21.4 Map depicting the area likely to be affected by the decline of water tables at three different dates. A list of municipalities included in each coloured pocket is provided so that respondents can locate themselves on the map (*Source*: Rinaudo 2008)

21.4 Empirical Results

21.4.1 The Impact of Prior Knowledge and Information Supply on WTP

In line with past research conducted in similar European contexts, these two case studies confirm that respondents are quite unfamiliar with groundwater. Many of them discovered the existence of the resource and its management problems as they completed the questionnaire (LTS) or answered the interviewer (MAA). In both case studies, there is a large percentage of the population that does not even know of the existence of the groundwater body presented in the survey - 80 % in the MAA case study and 46 % in the LTS. Few respondents were also aware of the pollution or overexploitation problems threatening local groundwater (76 % and 54 % of the respondents for the MAA and LTS case studies). And less than half of them knew if their water supply was dependent or not on groundwater (see Fig. 21.5).

One of the reasons for this limited knowledge is obviously that most respondents have no direct use of groundwater. Their lack of interest for groundwater is further accentuated by the limited coverage of this issue by the media and local political

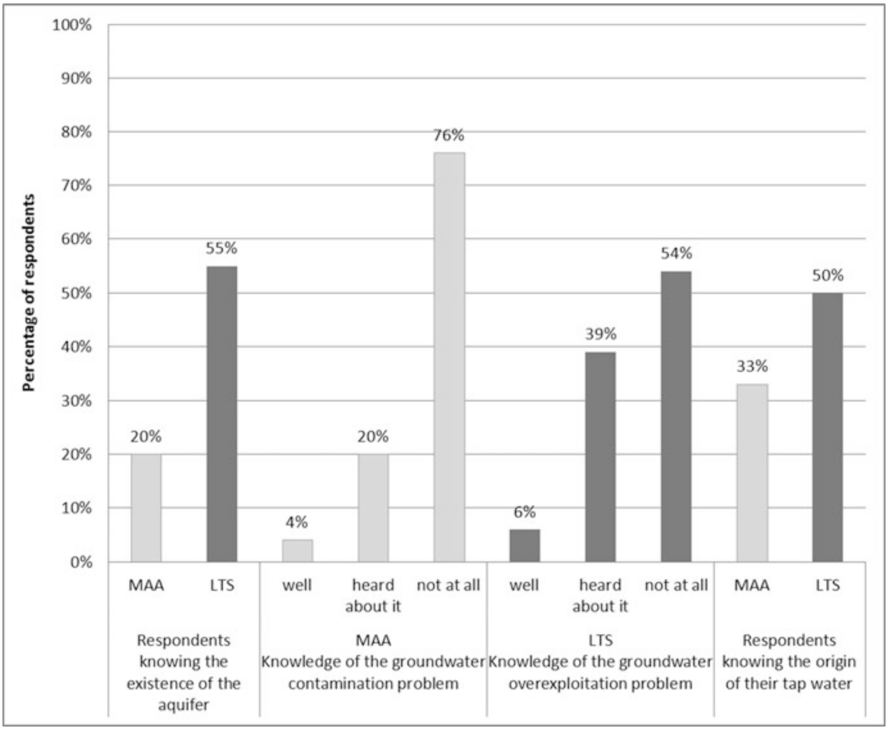

Fig. 21.5 Respondents' prior knowledge level (*MAA* Meuse alluvial aquifer, *LTS* Lower Triassic Sandstone aquifer)

debate. The second reason, identified through semi-structured interviews conducted in the LTS case study relates to the public's mental representation of groundwater. Although lay people have a general understanding of what groundwater is, they do not spontaneously grasp the concept of an aquifer, defined as a three-dimensional geological reservoir and the water it contains. Laymen can hardly locate water resources on a map and find it very difficult to explain how and why water moves underground, eventually reaching the surface through springs or river banks. Groundwater is generally perceived as a ubiquitous resource, not as a well spatially-defined object.

Despite limited prior knowledge, the two case studies show that it is possible to supply adequate information during a survey, either through face-to-face interviews (MAA case study) or postal surveys (LTS). Maps and diagrams presented to respondents present no major understanding challenges because "*they echo what they learnt on the water cycle at secondary school*" (quote from several respondents). The information provided was considered by respondents as sufficient to inform their decision to contribute financially to groundwater restoration (e.g., 84 % in the MAA).

However, one can wonder how the information supplied influences stated WTP. While the questionnaires provide the same information to the respondents through a detailed description of the aquifer, its uses, its management problem and the benefits expected from a good status, the appropriation of this complex information can be different between those who discovered the aquifer under study during the survey (situation of preferences construction) and those who had a prior knowledge of the aquifer and its management problem (situation of established preferences). This was actually tested in the two case studies by comparing the average WTP of respondents with and without prior knowledge of the problem. No statistically significant impact was found in the MAA. By contrast, respondents' prior level of information had a significant negative impact on WTP in the LTS case study (see the statistical results in the Appendix). Variable "info" in the OLS model has a negative sign. It is significant at the 5 % level. This suggests that the information provided in the questionnaire may have a WTP enhancing effect. Similar findings were reported by Venkatachalam (2004) who found that additional information, provided about drinking water quality to respondents who possessed different levels of information about the water quality, can significantly influence the WTP values.

21.4.2 Motivations Underlying WTP

In the two case studies, about two third of the respondents accepted paying, revealing a real concern for groundwater protection. The average stated WTP was approximately 40 €/ household/year over 10 years in each of the two case studies. This value lies at the lower bound of the range of WTP reported in the literature. Multivariate regression analyses were performed using several econometric models

Table 21.3 Willingness to pay and underlying motivations in the two case studies (motivation statements were listed in the questionnaire and selected by respondents)

	Meuse Alluvial Aquifer		Lower Triassic Sandstone aquifer	
	Willingness to pay % accepting to pay Average WTP/year/household	66 % 40 €	**Willingness to pay** % accepting to pay Average WTP/year/household	67 % 39 €
	Main motivation for paying		**Main motivation for paying**	
Bequest value	To pass on to future generation groundwater of better quality	49 %	Groundwater is what my grandchildren will drink in 40 years	52 %
Indirect use value	To improve the quality of dependent ecosystems (fauna, flora) in the Meuse valley	22 %		
Option value	To make possible future use of the aquifer for the city of Liège if needed	22 %	I prefer to pay now for groundwater protection than later to bring water from far away	19 %
Direct use value	To keep the possibility of using groundwater through a private well	3 %	I accept to pay because I use this aquifer/my drinking water supply depends on it Depleting this aquifer would represent a handicap for the local economy	20 % 9 %

to check the consistency of answers. Some three models were estimated: a logistic regression model to explain the yes/no response to the WTP question; an ordinary least square regression model to explain the positive WTP amounts; and a Tobit regression model to explain positive or true zeros WTP amounts. Results of various multivariate regression models are presented in the Appendix. The analysis was useful in understanding how various motivations for paying influence the stated amount.

The main motivations underlying the decision to pay are given in Table 21.3. These motivations are helpful in identifying to which component of the total economic value different individuals are sensitive. Looking at the main motivation quoted, we can distinguish four groups of respondents:

- In the first group, the concern for future generations is the main motivation for paying (respectively 49 % and 52 % of the MAA and LTS samples). Groundwater is clearly perceived as a natural heritage which should be preserved to guarantee future generations wellbeing, either as a clean, cheap and protected drinking water source or as a support of the local economy. For these respondents, higher WTP may reflect a feeling of moral responsibility for contributing to the protection of groundwater for future generations. WTP reflects altruism more than economic self-interest. In the LTS, the econometric analysis shows that respondents ranking by future generation as a first motivation have an 11 % higher WTP (variable "futgen" significant at the 1 % level, see Appendix).

- The second group comprises respondents whose main motivation is protecting (LTS) or restoring (MAA) the groundwater resource which they could personally be using in the future. WTP stated by these respondents thus reflects the *option value* of groundwater, defined as the benefits that could be derived from potential future use. Their WTP is not statistically different from the average.
- The third group is mainly motivated by the protection of a resource which they already use, either directly through a private well, or indirectly when their municipal water supply depends on groundwater. They represent approximately 20 % of respondents in the LTS, but only 3 % in the MAA where the aquifer is not usable in its current status. In LTS, these respondents have a statistically lower WTP than the sample average.
- The fourth groups say their main motivation is to contribute to the environmental improvement of dependent ecosystems. They represent 22 % of the MAA sample. This motivation is not expressed in the LTS due to the confined nature of the aquifer, and the absence of an impact on surface dependent ecosystems.

Overall, these results highlight that stated WTP is an indicator that actually captures the different dimensions of groundwater protection benefits: direct use benefits; indirect use benefits (dependent ecosystems); option value (opportunity to use in the future); and bequest value (value for future generations).

21.4.3 Mental Models and Embedding Effects

An abundant literature describes the potential bias associated with the use of contingent valuation for valuing environmental goods (Venkatachalam 2004). Our case studies suggest that there are additional problems related to the specific characteristics of groundwater and to what environmental economists call an *embedding effect* or a *part-whole effect*. This embedding effect seems to be closely related to the "mental model" of joint products highlighted by Schulze et al. (1998): respondents may have different mental models, often strongly held, which will replace whatever mental model the researcher intended to impose on the respondent. Some respondents will accept the implicit mental model used by the researcher in designing the survey while others will not. Increased information does not address the possibility that individuals may have different mental models. Our results highlight two kinds of potential embedding effects:

- Due to insufficient knowledge, some respondents perceive groundwater as a ubiquitous and uniformly distributed resource, rather than a collection of well-defined and spatially delineated reservoirs. These respondents are thus not able to make a clear distinction between protecting groundwater in a broad sense on the one hand, and protecting a specific aquifer on the other hand. This remains true even if maps and schemes are provided in the survey. The existence of such an embedding effect is supported by much evidence in our two case studies: in the MAA, we asked respondents who accepted to contribute if they would be willing to contribute for any other groundwater body. The answer was positive for 71 %, with 41 % declaring the same WTP. In the LTS, 44 % of the respondents declared they would consent to pay a similar amount for the protection of any other aquifer in France. Such results cast doubts on the meaning of elicited WTP values, which could be considered as the WTP to protect groundwater resources in general (and not specifically the groundwater body under study).

- The second embedding effect is more specifically linked to situations where groundwater protection or restoration programs generate a wide range of environmental benefits. This effect is observed mainly in the MAA case study where some respondents faced difficulties in clearly disentangling those benefits derived from groundwater quality improvement from those of other environmental benefits. Especially in the context of orphan brownfields management, it is clear that actions aiming at improving groundwater quality will also bring other types of benefits to the population (positive landscape amenities, improvement of soil quality, etc.). Even if a survey clearly focuses on groundwater resources we cannot be sure that all respondents accept the implicit mental model used by the researcher in designing the survey. Results provide evidence of this risk: respondents who declare being concerned by a high number of environmental problems have a higher probability of accepting to pay, and a greater WTP. This reflects a difficulty for respondents to disconnect groundwater resources from other environmental compartments (air, soil, surface water, etc.). The survey may have influenced them in that direction by explaining the link between contaminated soil and groundwater quality on the one hand, and groundwater quality and surface ecosystems on the other hand. Such a result raises doubts as to the meaning of the WTP value, which could be considered as their WTP to improve the environment quality in general in their community (and not specifically the groundwater resource).

21.5 Discussion, Conclusions and Recommendations

In a context of mounting financial constraints, policy makers and the managers of river basins increasingly tend to use economic appraisal techniques to screen and compare competing groundwater protection and remediation projects. This generally involves assessing and comparing the costs and benefits associated with such projects. One of the main difficulties reported by economists is conducting an integrated assessment of the wide range of benefits generated by groundwater protection. Indeed groundwater protection or remediation not only improves the welfare of economic agents exploiting this resource (households, municipalities, industries, farmers), it also contributes to improving ecological services produced by groundwater dependent ecosystems (e.g. rivers and wetlands). Moreover, there are clear long term benefits associated with the protection of groundwater resources for future generations, considering their buffering role in situations of drought or extreme pollution events for instance.

One of the methods recommended and widely used to assess all these benefits is contingent valuation. The method comprises eliciting people's WTP for improving groundwater and the associated benefits. One of the strengths of this method is providing a single monetary estimate that theoretically includes direct and indirect use values as well as option and bequest values. A number of applicative studies, reviewed in this chapter, illustrate the integrative potential of the method. They also highlight some of its limitations and caveats. In particular, doubts exist about the validity of the method when applied to situations where respondents have a very limited knowledge of groundwater; and where direct uses being limited, most of the benefits are linked to indirect impacts on dependent ecosystems.

Two original case studies representative of this situation are presented in the chapter. They show how the method can be used in contexts where respondents are not familiar with groundwater. Overall, selected results highlight that WTP is an indicator that captures the whole range of groundwater protection benefits. Assessing WTP through contingent valuation surveys therefore is helpful for conducting an integrated valuation of groundwater protection benefits. Based on the results from the surveys, the message to water planners and policy makers is that people do care for groundwater protection and remediation, especially to guarantee the wellbeing of future generations.

However, the studies also point out some limits that might restrict the relevance of the results obtained. The first limit is related to the respondents' limited prior knowledge of groundwater. Our case studies suggest that it is possible to convey sufficient information to support respondents' contribution decision. However, there is a clear risk that this information biases the elicitation process, either enhancing or reducing WTP. This statement also raises doubts as to the representativeness of the sample of CVM respondents, as the survey sample on average is more informed about groundwater than the public in general. The second limit is related to two types of the so-called embedding effect: (1) because lay people often perceived groundwater as a uniformly distributed resource, some of them may be unable to assess the benefits associated with the protection of a distinct aquifer, considering its geographic location and extension and its specific hydrogeological properties; and (2) in situations where the groundwater management actions are expected to bring a wide range of environmental benefits (e.g. on water quality but also on landscape amenities and soil quality), respondents may face difficulties to clearly disentangle benefits derived from groundwater quality improvement from other environmental benefits.

This leads us to formulate two main recommendations. The first one is that a 30-min or so face-to-face interview or an eight-page questionnaire, say, may not be sufficient for people to correctly understand the characteristics of the aquifer under study and the benefits ensuing from its protection. More time should be dedicated to this preliminary step to ensure that respondents adopt the "mental model" used by the survey designers. Techniques such as focus groups could be used to achieve this objective. The second recommendation is to favor assessing the benefits of groundwater protection programs for the full range of expected environmental improvements at the local scale (rather than only for the groundwater quality improvement), either by the use of the CVM or by the use of other types of revealed preferences methods such as choice experiments which could be more appropriate.

Acknowledgements The authors wish to thank the Belgian Federal Science Policy Programme BELSPO for the financial support provided for the FRAC-WECO research project, and the European Commission for the financial support provided for the BRIDGE-WFD research project. The chapter has been prepared with the financial support of BRGM research program 30 (Environmental and Risk economics).

Appendix

Detailed Description of Survey Results

Tables 21.4 and 21.5 provide the results of the estimated econometric models. The logistic model aims at identifying variables determining the probability that a given respondent accepts contribution. The dependent variable is 1 if the respondent is willing to pay, 0 otherwise.

The Ordinary Least Square (OLS) regression model aims to identify the variables that determine the amount respondents are willing to pay. The OLS model only uses strictly positive WTP, zeros being excluded. The Tobit model is a variant of this model, which accounts for zeros.

Table 21.4 Results of the econometric models (Meuse alluvial aquifer case study)

			Logistic regression		OLS regression		Tobit regression	
Type	Variables	Description	Coef.	z	Coef.	t	Coef.	t
	Intercept		−4.308***	−5.67	2.418***	8.17	−1.382**	−2.06
Geographic location	hnappe	The respondent lives above the RWM073 groundwater body (0/1)	0.655***	2.88				
	distance	Distance from the centroid of the commune to the Meuse (km)			−0.106**	−2.26	−0.129*	−1.74
Groundwater use	aepnappe	The respondent is supplied at least partly from the Meuse alluvial aquifer (0/1)	0.829**	2.45				
	eaupuits	The respondent uses water abstracted from a well (0/1)	−0.966*	−1.72			−1.334***	−3.14
Perception	nbrisque5	The groundwater quality constitutes a risk for five types of uses (0/1)	2.010**	2.02				
	rpot	The groundwater quality may constitute a risk if the water is used for gardening (0/1)			0.227*	1.90		
Likelihood/ realism	realiste	Level of realism attached to the improvement scenario (from 0: not realistic at all to 3: quite realistic)	0.414***	3.59				
	realiste1	The respondent finds the improvement scenario rather realistic (0/1)					−0.298*	−1.72
Importance	import	Level of importance attached to the improvement of the groundwater quality (from 0: not important at all to 3: quite important)	1.158***	4.74			1.007***	4.72
Benefits	nbbenef5	Five motivations for contributing are quoted (0/1)			0.763**	2.04		
	bpusage	The main motivation for contributing is related to the direct use of the aquifer today or in the future (0/1). Other possible			−0.304***	−2.63		

		motivations are: the possibility to transmit a groundwater body of better quality to the future generations and improvement of the quality of water feeding the Meuse, improvement of flora and fauna living conditions						
	bnappebis	The respondent would also contribute for another aquifer, with a lower WTP (0/1)			0.388***	3.54		
Environmental problems	nbprobleme	Number of environmental problems encountered by the respondent (from 0 to 6), among noise, water, atmospheric, soil pollution, loss of biodiversity, waste problems, other environmental problems	0.132**	2.30				
	nbproblemebis	The respondent is affected by at least five environmental problems (0/1)			0.334***	2.61		
	epolsol	The respondent is affected by soil pollution (0/1)					0.458**	2.43
Socio-economic characteristics	sexe	Gender (0 for man/1 for woman)	−0.481**	−2.23	−0.237**	−2.32	−0.457***	−2.85
	enfant1	1 child < 18 years lives in the household (0/1)	−0.611**	−2.16	0.290*	1.95		
	educ	Level of education (from 1 to 6)			0.099**	2.24	0.285***	4.26
	etud	The respondent is a student (0/1)	1.745***	4.24				
	rev	Average monthly household income (k€)	0.351***	3.50			0.290***	4.54
	sqrt_rev	Square of average monthly household income			0.008**	2.20		
Questionnaire	qdiff3	The respondent estimates the WTP question as very difficult			−0.360*	−1.74		

(continued)

Table 21.4 (continued)

			Logistic regression		OLS regression		Tobit regression	
Type	Variables	Description	Coef.	z	Coef.	t	Coef.	t
			N = 520 LR chi2(11) = 101 Prob > chi2 = 0.0000 Pseudo R2 = 0.1537		N = 319 F(12,306) = 6.21 Prob > F = 0.0000 R2 = 0.1958 Pseudo R2 = 0.1643		N = 397 LR chi2(8) = 92 Prob > chi2 = 0.0000 Pseudo R2 = 0.0619	

Note: *Coef.*: coefficient
*10 % significance level, **5 % significance level and ***1 % significance level

Table 21.5 Results of the econometric models (Lower Triassic Sandstone confined aquifer case study)

			OLS regression		Tobit regression	
Type	Variables	Description	Coef.	t	Coef.	t
	Intercept		2.556***	13.88	0.986***	5.06
Information/ knowledge	info	The respondent considers himself as well informed about the groundwater overexploitation problem and the origin of his tap water (0/1)	−0.238**	−2.00		
Likelihood/realism	cred_ref	The respondent finds the reference scenario not credible (0/1)	−0.832**	−2.56	−0.974**	−2.46
Benefits	before2015	The respondent lives in a municipality where the benefits will take place in the very short term (before 2015) (0/1)	0.248**	2.14		
	benef_15Y	The respondent can expect to benefit from groundwater improvement for more than 15 years in the locality where he/she lives			0.227*	1.74
	futgen	The following sentence is quoted as a motivation for paying : "This groundwater is what my children and grandchildren will drink in 40 years' time" (0/1)	0.584***	4.70	1.440***	10.56
	warm_glow	The respondent agrees with the following statement: "I am willing to pay for this aquifer as I would be willing to pay for any other aquifer in France" (0/1)	0.759***	3.43	1.485***	5.66
Water bill and savings	wat_price	The respondent perceives water as expensive (0/1)	−0.446***	−3.95	−0.66***	−5.18
	wat_sav_fin	The respondent makes significant efforts to reduce his water consumption and declares doing so for financial reasons (0/1)	−0.290**	−2.40		
	wat_sav_env	The respondent make significant efforts to reduce his water consumption and declares doing so for environmental concerns.			0.385**	2.24

(continued)

Table 21.5 (continued)

			OLS regression		Tobit regression	
Type	Variables	Description	Coef.	t	Coef.	t
Other	Leisure	The respondent practices often or very often at least one activity related to water, including fishing, canoeing, swimming or walking among rivers and lakes (0/1)	−0.261**	−2.26		
Socio-economic characteristics	Income	Yearly net income of the household	0.000***	6.97	0.000***	4.80
	Education	Education level			0.153***	3.35
			N = 354 R2 = 0.2976 Pseudo R2 = 0.2792		N = 347 LR chi2(9) = 215 Prob > chi2 = 0.0000 Pseudo R2 = 0.1490	

Note: *Coef*. coefficient
*10 % significance level, **5 % significance level and ***1 % significance level

References

Abdalla CW (1994) Groundwater values from avoidance cost studies: implications for policy and future research. Am J Agric Econ 76:1062–1067. doi:10.2307/1243392

Arrow K, Solow R, Portney PR, Leamer EE, Radner R, Schuman H (1993) Report of the NOAA panel on contingent valuation. Fed Regist 58(10):4601–4614

Belloumi M, Matoussi MS (2002) Evaluation de la valeur de préservation de la qualité de la nappe d'Oued Kheirate. New Medit 1(4):39–45

Bergstrom JC, Dorfman JH (1994) Commodity information and willingness to pay for groundwater quality protection. Rev Agric Econ 16:413–425

Brouwer R (2008) The potential role of stated preference methods in the Water Framework Directive to assess disproportionate costs. J Environ Plan Manag 51:597–614

Brouwer R, Hess S, Bevaart M, Meinardi K, (2006) The socio-economic costs and benefits of environmental groundwater threshold values in the Scheldt basin in the Netherlands, November 2006. Deliverable D26 of the BRIDGE EU funded research project, Amsterdam, the Netherlands

Carson RT, Flores NE, Meade NF (2001) Contingent valuation: controversies and evidence. Environ Resour Econ 19:173–210. doi:10.1023/A:1011128332243

Caudill JD (1992) The valuation of groundwater pollution: the differential impacts of prevention and remediation. PhD thesis, Department of Agricultural Economics, Michigan State University, East Lansing, the United States

Chegrani P (2009) Restaurer les eaux souterraines: quels coûts ? quels avantages ? Cas de la nappe de la craie de l'Artois et de la vallée de la Lys. Etudes et documents CGDD n°2, Mars 2009

de Zoysa ADN (1995) A benefit evaluation of programs to enhance groundwater quality, surface water quality and wetland habitat in Northwest Ohio. Dissertation, The Ohio State University, Columbus, the United States

Edwards SF (1988) Option prices for groundwater protection. J Environ Econ Manag 15:475–487

El Chami D, El Moujabber M, Scardigno A (2008) The Contingent Valuation Method for the economic assessment of Groundwater: a Lebanese case study. New Medit 7:19–24

Grappey C (1999) Fiabilité des résultats de la méthode d'évaluation contingente et modes d'interrogation, Une application à la ressource en eau souterraine. Economie Rurale 254:45–53

Hasler B, Lundhede T, Martinsen L, Neye S, Schou JS (2005) Valuation of groundwater protection versus water treatment in Denmark by Choice Experiments and Contingent Valuation. NERI technical report n°543

Hérivaux C (2011) Economic analysis applied to groundwater degradation due to contaminated sites, Public perception and willingness to pay for the RWM073 groundwater quality improvement. Deliverable 5.5 of the FRAC-WECO project. BRGM-RP-59800-FR

Jordan JL, Elnagheeb AH (1993) Willingness to pay for improvements in drinking water quality. Water Resour Res 29:237–245

Kiel K, Zabel J (2001) Estimating the economic benefits of cleaning up superfund sites : the case of Woburn, Massachussetts. J Real Estate Financ Econ 22:163–184

Lazo JK, Schulze WD, McClelland GH, Doyle JK (1992) Can contingent valuation measure nonuse values? Am J Agric Econ 74:1126–1132

Lichtenberg E, Zimmerman R (1999) Farmers' willingness to pay for groundwater protection. Water Resour Res 35:833–841. doi:10.1029/1998WR900066

Martin M, Marceau R (2001) The economic value of groundwater. Working document, Access to the results via the EVRI database

Martinez-Paz JM, Perni A (2011) Environmental cost of groundwater: a contingent Valuation Approach. Int J Environ Res 5:603–612

McClelland GH, Schulze WD, Lazo JK, Waldman DM, Doyle JK, Elliot SR, Irwin JR (1992) Methods for measuring non-use values: a contingent valuation study of ground water cleanup. Final report, Office of Policy, Planning and Evaluation, U.S. Environmental Protection Agency, Cooperative Agreement #CR-815183, 1992

Miraldo Ordens C, Bertin S, Brouwer R, Condesso Melo T (2006) Assessing the costs and benefits of groundwater quality improvements in the Aveiro Quaternary Aquifer in Portugal, December 2006. Deliverable D28 of the BRIDGE EU funded research project

Mitchell RC, Carson RT (1989) Existence values for groundwater protection. Draft final report to US Environmental Protection Agency. Resources for the Future, Washington, DC

Pakalniete K, Bouscasse H, Strosser P (2006) Assessing socio-economic impacts of different groundwater protection regimes, Latvian case study report, November 2006. Deliverable D29 of the BRIDGE EU funded research project

Poe GL, Bishop RC (1993) Information, risk perceptions and contingent values for groundwater protection. In: Bergstrom JC (comp.) Western Regional Research Publication, W-133. Benefits & costs transfer in natural resource planning. Sixth interim report. University of Georgia, Athens. http://fes.forestry.oregonstate.edu/sites/fes.forestry.oregonstate.edu/files/PDFs/W133%206th%20Interim%20Report%201993.pdf

Poe GL, Boyle KJ, Bergstrom JC (2000) A meta analysis of contingent values for groundwater quality in the United States. http://econpapers.repec.org/paper/agsaaea00/21871.htm

Powell JR, Allee DJ, McClintock C (1994) Groundwater protection benefits and local community planning: impact of contingent valuation information. Am J Agric Econ 76:1068–1075. doi:10.2307/1243393

Quevauviller P (2008) From the 1996 groundwater action programme to the 2006 groundwater directive – what have we done, what have we learnt, what is the way ahead? J Environ Monit 10:408–421

Rinaudo J (2008) Assessing the benefits of groundwater protection. A case study in the Rhine district, France. Deliverable of the EU funded AQUAMONEY project

Rinaudo J-D, Aulong S (2014) Defining groundwater remediation objectives with cost-benefit analysis: does it work? Water Resour Manag 28:261–278

Rinaudo J-D, Arnal C, Blanchin R, Elsass P, Mailhac A, Loubier S (2005) Assessing the cost of groundwater pollution: the case of diffuse agricultural pollution in the Upper Rhine valley aquifer. Water Sci Technol 52(9):153–162

Rozan A, Stenger A, Willinger M (1997) Valeur de preservation de la qualite de l'eau souterraine: une comparaison entre usagers et non-usagers. Cahiers d'economie et sociologie rurales, INIST-CNRS, France, pp 61–92

Schulze WD, McClelland GH, Lazo JK, Rowe RD (1998) Embedding and calibration in measuring non-use values. Resour Energy Econ 20:163–178. doi:10.1016/S0928-7655(97)00034-1

Shultz SD, Lindsay BE (1990) The willingness to pay for groundwater protection. Water Resour Res 26:1869–1875. doi:10.1029/WR026i009p01869

Stenger A, Willinger M (1998) Preservation value for groundwater quality in a large aquifer: a contingent-valuation study of the Alsatian aquifer. J Environ Manage 53:177–193. doi:10.1006/jema.1998.0197

Stevens TH, Barrett C, Willis CE (1997) Conjoint analysis of groundwater protection programs. Agric Resour Econ Rev 26:229–235

Strosser P, Bouscasse H (2006) Assessing socio-economic impacts of different groundwater protection regimes, Slovenian case study report, November 2006. Deliverable D42 of the BRIDGE EU funded research project

Sun H, Bergstrom JC, Dorfman JH (1992) Estimating the benefits of groundwater contamination control. South J Agric Econ 24:63–71

Tentes G, Damigos D (2012) The lost value of groundwater: the case of Asopos River Basin in Central Greece. Water Resour Manag 26:147–164. doi:10.1007/s11269-011-9910-2

Vaute L, Nguyen-The D, Gigleux S (2007) Eaux souterraines du département des Vosges: caractérisation des principales ressources exploitables et révision du modèle de gestion de la nappe des grès du Trias inférieur. Report BRGM RP 55653-FR

Venkatachalam L (2004) The contingent valuation method: a review. Environ Impact Assess Rev 24:89–124. doi:10.1016/S0195-9255(03)00138-0

Wattage PM (1993) Measuring the benefits of water resource protection from agricultural contamination: results from a contingent valuation study. Dissertation, Iowa State University, Ames, The United States

Wei Y, Davidson B, Chen D, White R, Li B, Zhang J (2007) Can contingent valuation be used to measure the in situ value of groundwater on the North China Plain? Water Resour Manag 21:1735–1749. doi:10.1007/s11269-006-9123-2

White PA, Sharp BM, Kerr GN (2001) Economic valuation of the Waimea Plains groundwater system. J Hydrol (New Zealand) 40:59–76

Wright C (1988) An economic assessment of groundwater pollution. Master thesis, Central Michigan University, Mount Pleasant, the United States

Controlling Groundwater Exploitation Through Economic Instruments: Current Practices, Challenges and Innovative Approaches

22

Marielle Montginoul, Jean-Daniel Rinaudo, Nicholas Brozović, and Guillermo Donoso

Abstract

Groundwater can be considered as a common-pool resource, is often overexploited and, as a result, there are growing management pressures. This chapter starts with a broad presentation of the range of economic instruments that can be used for groundwater management, considering current practices and innovative approaches inspired from the literature on Common Pool Resources management. It then goes on with a detailed presentation of groundwater allocation policies implemented in France, the High Plains aquifer in the USA, and Chile. The chapter concludes with a discussion of social and political difficulties associated with implementing economic instruments for groundwater management.

22.1 Introduction

As detailed in Chap. 2 and elsewhere in this book, groundwater abstraction has increased considerably over the last few decades for both agricultural and urban uses. In many parts of the world, government agencies have not paid sufficient

M. Montginoul (✉)
Irstea – UMR G-Eau, Montpellier, France
e-mail: marielle.montginoul@irstea.fr

J.-D. Rinaudo (✉)
Water Department, BRGM, French Geological Survey, Montpellier, France
e-mail: Jd.rinaudo@brgm.fr

N. Brozović
Robert B. Daugherty Water for Food Institute, University of Nebraska, Lincoln, NE, USA

G. Donoso
Department of Agricultural Economics, Pontificia Universidad Católica de Chile, Santiago, Chile

A.J. Jakeman et al. (eds.), *Integrated Groundwater Management*,
DOI 10.1007/978-3-319-23576-9_22

attention to this ‘silent revolution’. Groundwater development has thus taken place in an institutional setting that placed no or few limits on groundwater use. Tens of thousands of wells and boreholes were constructed by small private agricultural or urban economic actors, leading to overdraft and associated environmental impacts (e.g. sea water intrusion, declining water tables, impacts on dependent ecosystems). In countries where groundwater has long been considered as an open access good, the establishment of new rules for governing access to groundwater and its use is increasingly perceived as necessary. This calls for the design of innovative institutional frameworks, involving the redistribution of responsibilities between the State and user communities, and an increased use of economic instruments providing incentives and theoretically leading to higher water use efficiency.

In practice, the shift from an open access to a regulated use regime has been implemented with three distinct policy approaches, depending on the local or national economic, legal and social context. The first approach (command and control) consists of establishing or reinforcing direct administrative regulation, with systematic registration of abstraction points, the issuance of pumping permits, and the award and enforcement of individual volumetric quotas. This approach is illustrated by the case of France, described in detail in Sect. 22.3 of this chapter. The second approach is founded on private appropriation of the resource, and involves the allocation of water use rights (the nature of which can differ significantly from one country to another) which can be traded amongst users, under supervision of a State agency. Such groundwater markets exist in several countries including the USA, Chile (see Sects. 22.4 and 22.5 of this chapter), Australia (Skurray et al. 2012), China (Zhang et al. 2008) and Spain (Garrido et al. 2012), among others. The third approach is founded on the decentralization of water allocation policies and the devolution of a number of State responsibilities to Water Users Communities or Associations. This model has been implemented with varying level of success in Spain or Mexico (Mukherji and Shah 2005), and underlies the recent evolution of groundwater policy in France.

In each of these three policy approaches, water managers are dealing with similar issues, including: the definition of the nature of water use rights; the control of free riding behaviors and the access to information on abstraction points and actual water withdrawals. In the following sections, we illustrate how these issues have been addressed in three different contexts in France, the USA and Chile. We also describe existing economic instruments and innovative ones that could be implemented to control access to and the use of groundwater.

The chapter is organized as follows. It starts with a broad presentation of the range of economic instruments that can be used for groundwater management, considering current practices and innovative approaches inspired from the literature on Common Pool Resources management (Sect. 22.2). The chapter then goes on with a detailed presentation of groundwater allocation policies implemented in France (Sect. 22.3), the High Plains Aquifer in the USA (Sect. 22.4), and Chile (Sect. 22.5). The chapter ends with a discussion of social and political difficulties associated with implementing economic instruments for groundwater management.

22.2 Economic Instruments for Groundwater Management: Approaches and Challenges

Since the 1980s, there has been a growing recognition that economic instruments should be used to regulate the access to and the use of water resources. However, a review of existing practices shows that situations resembling Hardin's tragedy of the commons still prevail in most places around the world (see Chap. 23). This situation reflects the significant difficulties encountered by policy makers and managers to deploy economic instruments, in particular due to the lack of information on water users, abstraction points and water withdrawals, as well as the difficulties in enforcing allocation rules and instruments. This first part of the chapter proposes to look at existing and innovative tools that are, or could be, deployed to ensure sustainable management of overexploited aquifers.

22.2.1 The Information Problem

One of the main challenges faced by water managers attempting to control groundwater use is the lack of information regarding the hydrology of the aquifer and the abstractions. More specifically, well developed and calibrated models are not usually available, which does not facilitate estimation of the stock and recharge levels. In Chile, for example, there is little to no knowledge of the aquifers south of Central Chile. Moreover, the number of abstraction points, their location, the average volume pumped and the period at which the pumping takes place are often unknown. Indeed, the control of groundwater – a three-dimensional system – is more complex than for surface systems (one-dimension). The existence of undeclared or illegal wells remains an issue even in developed countries, both in the urban and agricultural sectors. When abstraction points are known, meters are not always installed or they can be temporarily removed or tampered with. This is illustrated with several agricultural and urban case studies selected in southern Europe such as in Spain or in France (de Stefano and Lopez-Gunn 2012; Montginoul and Rinaudo 2011), and elsewhere in the world.

In such contexts, groundwater abstraction control policies have focused on circumventing the monitoring problem by using readily observable information that can be used as a proxy for groundwater abstraction. Four different levels of information can be targeted depending on the effort made.

– On the first level, the agency decides to rely on aggregate information which provides a proxy for the overall groundwater abstraction – for instance the measurement of groundwater table levels. A decline of water table (adjusted considering climatic conditions) indicates an increase of water abstraction and can trigger temporary bans on irrigation, for instance. Sophisticated groundwater models can also be used to assess total abstraction with better accuracy.

– The second level consists of identifying and locating all abstraction points and users. This can be done in a deterministic way (through field surveys for instance) or based on self-declaration.
– This information can be improved (third level) by collecting technical information on the characteristics of the wells (pump capacity), on irrigated areas and type of crops grown by farmers and on the type of irrigation system used (drip or furrow irrigation). Rough estimates of individual abstraction can then be derived from this information.
– The fourth level of information is when water use is fully metered, the agency knowing who uses how much water in which place at different periods of the year.

22.2.1.1 Current Policies

Policies currently implemented by groundwater management agencies to reveal groundwater use information mostly rely on command and control mechanisms. The most frequently used approach relies on random control and penalties. Two main constraints usually limit the efficiency of this type of system: first, the agency often lacks the required human resources to inspect a significant proportion of users; second, fines imposed are kept low for political reasons. Overall, the risk of running an illegal well or under-declaring water abstraction is perceived as very limited by users who are facing little incentives to comply with the regulatory framework (cost of non-compliance is lower than cost of compliance). The efficiency of the inspection and sanction system can however be improved in several ways. The first one consists of increasing inspection probability or the fine for users who were caught in fraud. The second one could consist of providing incentives for all users getting involved in the monitoring of groundwater abstraction, in order to increase the probability of control. The cost of decentralized monitoring is expected to be lower, since agents possess information on the actions of other agents (areas and crops irrigated, irrigation practices and frequencies, etc.). The incentive to participate in a decentralized monitoring system can be provided by redistributing a share of the fine to the person who discovers the violator. This system has been used for centuries for regulating access to common pastures and forests in the Italian Alps (Casari and Plott 2003). It may however be strongly assimilated to denouncement and thus rejected in many cultural contexts.

The second policy approach, mainly used in the agricultural sector, consists of assessing individual water abstractions through indirect information, such as the observation of cropping patterns with satellite images (Castaño et al. 2010) or electricity bills (when wells are electric-powered). An illustration can be found in Mancha Oriental (Spain), where a groundwater user association (Junta Central de Regantes de la Mancha Oriental) uses satellite images to assess monthly groundwater use for each individual farmer. If the estimated water abstraction exceeds the quota allocated to the farmer (4000 m^3/ha), a field inspection is carried out and a fine is charged to the farmer in the case of non-compliance (Martin de Santa Olalla et al. 1999, 2003).

Desprats et al. (2011) suggested that a similar approach could be used to identify unlicensed urban groundwater users. This would apply to low density urban areas where households use private wells for watering lawns and gardens and filling swimming pools. Their method consists of using high resolution aerial photographs to assess irrigated lawn areas and swimming pools and to compute the corresponding outdoor water use for each single family house. They then compare estimated outdoor water requirements with metered water bills to identify households using private wells. The method is applied to a southern France case study to detect undeclared domestic boreholes.

Another way to incentivise users to reveal more accurate information is the charging of a high flat rate when users refuse to declare information on abstraction. This is actually used by the Rhône Water Agency in France, which charges high irrigation water fees on a per hectare basis (crop differentiated) to farmers who refuse to meter water abstraction. However, in spite of the economic incentives, some farmers prefer paying high charges for preserving the information asymmetry, fearing that water fees may rise in the future once meters have been installed everywhere. This echoes the "ratchet principle" enunciated by Weitzman (1980): economic agents may refuse higher rewards for better current performance by fear of future assignment of more ambitious targets.

A fourth policy approach comprises linking groundwater management with other economic policies. In Europe for instance, the grant of subsidies under Common Agricultural Policies is conditioned by full compliance with environmental regulations (eco-conditionality). This compels farmers to declare their wells to the relevant authorities and to demonstrate that appropriate metering devices are installed. Similar constraints are imposed on farmers by supermarkets through the use of certification standards (e.g. Global Gap) which aim at providing consumers the security that the products they purchase have been produced in conformity with existing environmental regulations.

22.2.1.2 Alternative Policy Options Based on Incentives

Several other proposed instruments have been suggested in the Common Pool Resources literature to force users to reveal information on harvesting level. Although none of them have been applied to groundwater management, they can theoretically be considered as possible options worth being assessed in terms of efficiency, equity and acceptability.

One of these theoretical options involves combining an upfront payment with compliance rebate. The mechanism is inspired from the "guilty until proven innocent" principle enunciated by Swierzbinski (1994) in his work on pollution control. Applied to groundwater abstraction, it could work as follows. Every user is requested to declare what his groundwater abstraction is (self-reporting principle) and he pays an initial fee or tax that depends on what he reports. The agency in charge then conducts random inspections and quantifies actual water abstraction, based on costly audit. In the case of proven non-compliance, the user is punished with a dissuasive fine; if findings of the audit are consistent with the initial declaration, the user is rewarded with a rebate. Auditing probability is inversely correlated to the declared intensity of groundwater use (in m^3 per hectare for instance). The relative values of the fine and of the rebate determine on which of the two mechanisms (sanction or reward) the incentive structure depends.

A variant of this instrument can be proposed if we assume that the audit cost can be lowered through active cooperation of the user (e.g. weekly on-line recording of water uses). In that case, voluntary agreements could be signed between users willing to be audited and the regulator. The main advantage of this system is that it shifts the burden of proof from the regulator to the user. This mechanism is similar to deposit-refund systems which have been advocated to control other environmental problems.

22.2.2 Instruments for Groundwater Abstraction Control

Based on Salzman's classification, five instruments can be used to control groundwater abstraction (Salzman 2005): (1) command and control; (2) penalty (including tax); (3) payment (including subsidies); (4) appropriation (tradable property rights); and (5) persuasion. Some of them are incentive-based instruments (2-3-4), others aim to manage groundwater abstraction through an administrative or concerted share of available water, or through influencing withdrawers taking into account psychological and social aspects. Although this chapter is primarily dedicated to economic instruments, these five instruments are presented here because they can be combined to increase the efficiency of incentive-based instruments or are in competition.

22.2.2.1 Command and Control

The command and control approach relies on the definition of restrictions of use that can take different forms depending of the level of available information. When abstraction points are known and water uses fully metered, a system of individual abstraction quotas can be implemented. Quotas can be adjusted every year to account for variability of groundwater recharge. Enforcement requires a system of control (meter reading) which can be costly. This allocation procedure is a source of economic inefficiency, quotas being frequently allocated based on historical records. More simple restriction approaches are used when information is lacking, such as a temporary ban on irrigation when groundwater levels fall below certain pre-specified threshold level. An intermediate approach lies in restricting the pumping capacity of users while granting pumping licenses. Water abstraction can also be controlled through rationing energy used for pumping, a current practice in several Indian States (Shah 2008). An alternative is non-tradable water rights (water use rights) that specify maximum allowable extraction water flows for each abstraction point. The advantage of this command and control instrument is that it allows the taking into account of geographical differences in water abstraction levels for the same aquifer. As with the quota system, non-tradable water rights require a costly system of control. Chile's 1951 Water Code (Ley 9909, 1951) employed this instrument.

22.2.2.2 Abstraction Tax Systems

The tax approach assumes that consumption (households) or production decisions (farmers) can be influenced by the cost of water supply. The type of tax system that can be implemented again depends on the level of information available to the regulator.

If water abstraction is metered, an individual (Pigouvian) tax system can be used. The tax can also be levied on inputs used for pumping such as electricity. In both cases, the choice of an efficient tax level is not trivial, in particular where demand and available resource significantly fluctuate over time. If the tax level is set to ensure that no over-exploitation takes place in a normal climatic year, it will not allow meeting this objective in drought years, when farmer's willingness to pay for water is extremely high. If on the contrary, the tax level is set taking drought years into consideration, it will represent an unacceptable economic burden for farms during normal years. The choice of an efficient tax level is further complicated by conjunctive use of surface and groundwater, farmers' decisions to use one or the other resource being influenced by the relative level of taxes charged for the two different resources (Lenouvel and Montginoul 2010).

If abstraction points are unknown or if water use is unmetered, the regulator can charge all actors using groundwater with an ambient tax with level proportional to the aggregate over-exploitation level (Segerson 1988). The regulator can assess the aggregate abstraction level based on simple observation of groundwater level decline, or use more sophisticated groundwater models that account for climatic and other natural recharge conditions. Each user is then charged with the same tax level, irrespective of his or her actual groundwater use. To cope with the risk of excessive fines, Segerson also proposed to supplement ambient taxes with a lump sum subsidy which ensures that the correct group of users remain in production.

22.2.2.3 Payment

The payment approach assumes that water demand can be curved downwards by subsidies which reduce the profitability of activities using a lot of water. The instrument can be implemented even in the absence of accurate information on water use, since the payment is based on observable characteristics (crop choice or irrigation equipments) that are assumed to be strongly linked with groundwater use. This approach has been implemented in Europe where farmers agreeing to stop irrigation are granted significant subsidies during a 5-year period in order to reorganize their farm for rainfed crops. The payment can be offered on an individual basis or made dependent on collective change, for instance in terms of irrigation practices by all farmers in a specific groundwater recharge area. The payment is generally part of a contract signed between the regulator and one or several groundwater users (Salzman 2005). The main difficulty of such an instrument lies in its sustainability: funds must be provided and once subsidies are stopped, farmers may once again increase their water consumption to maintain their income.

22.2.2.4 Tradable Abstraction Water Rights

Appropriation is a fourth approach. It assumes that the distribution of individual or collective property rights may support the development of rules and associated micro-institutions (Ménard 2003) to enforce those rights by local communities (in particular in the case of collective appropriation); the main assumption is that this local regulation will facilitate coordination between actors and reduce transaction costs. Appropriation through tradable water rights enables the development of water markets through which water can be reallocated among users, theoretically leading to improved water use efficiency. This policy approach is illustrated with the US High Plains case study below.

22.2.2.5 Persuasion

Persuasion is the fifth approach. It assumes that water use can be significantly reduced by providing users with information on the consequences of over-exploitation (in particular when irreversibility occurs with implication for future generations) and by increasing transparency on who uses what. This is supported by recent developments in psychological research dealing with common dilemmas, which highlight "that people are not just motivated by narrow (economic) self-interest but that they also consider the broad implications of their decisions for others and for the natural environment" (Van Vugt 2009).

22.3 From Command and Control to Self-Regulation: The Case of France

The case of France is illustrative of a transition from command and control to a decentralized groundwater management policy, where economic incentives play a very limited role and appropriation is still resisted by policy makers and the society in general.

22.3.1 Legal and Institutional Framework

In France, as in many other EU countries, groundwater development has occurred in an institutional setting that imposed few if any limits on groundwater use. Until the 1992 water law, existing regulation mainly focused on surface waters and on objectives related to minimum in-stream flow and aquatic ecosystems protection. Few constraints were imposed on groundwater development until the 1990s. Wells were not always notified and authorized discharges were not complied with. A rapid development of agricultural groundwater use ensued. Since 2000, half of the total agricultural irrigated area in France depends on groundwater (Garin et al. 2013). In several parts of France, this has resulted in declining water tables, with significant impacts on dependent rivers and ecosystems.

The situation started to evolve with the 1992 water law which strengthened the well licensing system and imposed the use of meters. The law also established the concept of “water scarcity zones”[1] where local regulators could ban the construction of new wells and restrict pumping through allocating individual abstraction ceilings (in volume per year). This new regulatory framework was implemented in several groundwater basins (Fig. 22.1), the most well-known being the Beauce aquifer in central France.

Public water utilities were given priority over other uses in water allocation. Concerning agriculture, the allocation of individual volumes was made by governmental agencies, based on environmental impact considerations, after consultation with the Chamber of Agriculture. The State kept the sole responsibility for enforcing water allocation, although it lacked the human and financial resources to conduct the required controls. Conflict resolution relied fully on judicial procedures, but court cases were often abandoned and penalties charged to offenders were not dissuasive. Overall, this “command and control” institutional set-up established by the 1992 law did not succeed in averting over-exploitation. The frequency of water crises increased and temporary restrictions and even total irrigation bans were promulgated every year in many groundwater basins.

The regulatory framework was again reformed in 2006 with the promulgation of a new Law on Water and Aquatic Ecosystems. In aquifers considered at risk of over-exploitation, hydrogeological studies need to be conducted to assess the total maximum volume that can be abstracted (capping procedure). This volume (which can be much lower than current aggregate use) must then be shared among users. Urban water supply is still given priority. Concerning agricultural use, Groundwater User Associations[2] (GWUAs) must be established locally to share the available amount of water among farmers (Fig. 22.1). GWUAs also have the option to raise water fees, and to implement new instruments to enforce allocation. This opens an interesting space for testing innovative instruments, inspired from theoretical research and from on-going experiences in other countries.

This brief historical description shows two main transformations underlying groundwater policy reform. First, the focus is shifted from command and control to a decentralized management approach. The State is progressively transferring responsibilities to farmers, through the establishment of micro-institutions which are “inserted between global rules that circumscribe the environmental context on the one hand, and agents, organizations and contractual agreements they are tied with on the other hand” (Ménard 2003). Such intermediary institutions adapt general institutional rules to effective local organizations and allow transaction costs to be reduced. As for groundwater, it is assumed that a locally-designed institution will be more efficient than the government at enforcing a groundwater quota system. The second transformation relates to allocation procedures. The

[1] «Zones de Répartitions des Eaux» in French.

[2] Organisme Unique de Gestion Collective (OUGC) in French.

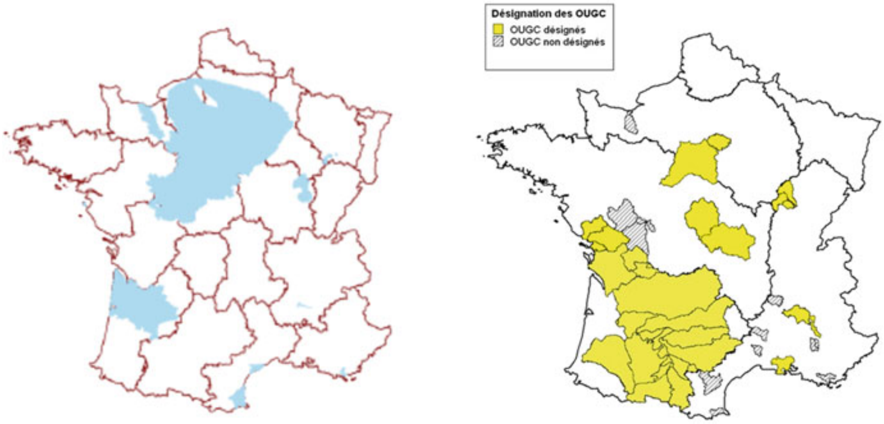

Fig. 22.1 Groundwater scarcity areas (*left*) and areas where Water Users associations have been established (surface and groundwater)

establishment of individual quotas can be considered as a first move towards an appropriation approach. In theory, quotas are very far from being property rights, since they can be reduced or even suppressed without any compensation. In practice, administrative pumping authorizations remain attached to the land in the case of land transactions, which implies that the land price reflects the value of the rent attached to the water quota. Appropriation is well underway, although this is not recognized officially.

22.3.2 Economic Instruments in Place

As shown in the previous section, groundwater allocation is mainly driven by command and control instruments, including temporary restrictions and individual quotas in "water scarcity zones". And since the 1964 Water Law an abstraction tax is also charged by Water Agencies. The main objective of this tax is not to signal scarcity, but to raise revenues that can be used to subsidize water related projects. The tax level is regulated by the National Parliament which sets a maximum level for different uses (see Table 22.1). Tax levels are far too low to provide any real incentive to reduce groundwater extraction. For instance, the average rate charged for irrigation (traditional gravity systems excluded) is only 3.6 € per thousand cubic meters. Although it is doubled in "water scarcity zones", it does not signal water scarcity. Moreover, the abstraction fee is not recovered from small water users (less than 10,000 m^3 per year). Small economic enterprises and domestic users who directly pump groundwater are therefore exempted from the tax.

Table 22.1 Maximum tax level (€/m^3) on water resource extraction (applied from January 2013)

Uses	Normal rate (€/m^3)	Water scarcity zone (€/m^3)
Irrigation (except by gravitary)	0.036	0.072
Gravitary irrigation	0.005	0.01
Potable use	0.072	0.144
Industrial cooling (with more than 99 % of water restitution)	0.005	0.01
Canal alimentation	0.0003	0.003
Other economic uses	0.054	0.108

Source: Code de l'Environnement, articles L213-14-1 et L213-10-9

22.3.3 Issues and Problems

The main problems and policy issues in current groundwater policies are now covered in this subsection. The first problem relates to law enforcement. Since 1997 all wells and borewells should be declared and equipped with meters. There are however still a number of places where this does not happen. Field investigations conducted by the authors in the Roussillon plain, Southern France, showed that only 1 % of domestic boreholes and 40–63 % of agricultural boreholes have been declared (Montginoul and Rinaudo 2009; Desprats et al. 2011). In that case study area, the Chamber of Agriculture collects the information on wells from farmers but they withhold it fearing that it can be used against them in the future. And when wells are declared, farmers prefer continuing to pay the flat rate abstraction fee to the Water Agency rather than declaring the volumes they actually used, even though this would clearly be favorable to them. The situation persists because sanctions are not dissuasive, the probability of control is too low, offenders are not systematically prosecuted (many cases are abandoned in overburdened courts), and due to a general lack of political will.

The second problem relates to water allocation efficiency. Water quotas have generally been granted based on records of historical use. In certain areas, like in the *Tarn et Garonne* county, the "*use it or lose* it" rule that should theoretically prevail in France, where water is considered as a public trust, is not applied. This results in situations where farmers may keep control over water quotas which they do not use, at the expense of other farmers who are queuing-up to obtain a quota from the government agency in charge. The corollary is a progressive feeling of private appropriation of water by farmers (and other users) who have been benefiting from a quota for years. The value of land reflects the existence and the magnitude of the attached water quotas, meaning that the water rent is appropriated by the land owner. This trend reflects current administrative practices which are in contradiction with the foundations of the 1992 and the 2006 water laws, both stating that water is a Nation's common heritage.

The third problem is that of perceived (un)fairness of water allocation. Many of the farmers in various French basins contest current water allocation which they find unfair and not equitable. They particularly contest the priority given to urban areas first before environment and agriculture. Another issue of controversy is around the rules for sharing water among farmers. The grandfathering principle, advocated by those benefiting from a quota based on historical use, is contested by other users who would like to enter the groundwater economy. This is nicely shown by a survey on water allocation rules conducted in five French regions, where the diversity of positions defended by farmers on this issue can only be understood by analyzing self-interest economic motivations jointly with ethical beliefs and values (Chap. 11).

Last but not least, groundwater policy reform is somehow blocked by lobbying efforts made by agricultural stakeholders who try to obtain public subsidies to construct small reservoirs as a substitute for groundwater use.

22.3.4 Options for Future Policy

In France, policy makers are at a crossroads where three different approaches can be chosen to develop national groundwater regulation.

- **Pursuing decentralization**

  The first policy approach consists of pursuing decentralization. It requires strengthening the legal status and the internal capacity of newly established GWUAs to setup and implement their own groundwater regulation. GWUAs would become more involved in conflict resolution, for instance through establishing a "groundwater tribunal" composed of elected farmers and government representatives and who would arbitrate conflicts and charge penalties on offending farmers. GWUAs would also need to design their own rules for allocating water among their members and facilitating (monetary or non-monetary) exchanges between their members, in search of flexibility and efficiency. Contract-based instruments may play a significant role in decentralized management. For instance, Figureau et al. (2015) have proposed a "pooling agreement" through which farmers would agree to mutualize their quotas, in search of greater flexibility. The contract is favorable to the agents as a team relative to the standard penalty system provided that the team does not exceed the targeted abstraction level, but unfavorable to the team if the target is exceeded. Participating in a group remains a voluntary decision and not all farmers are expected to engage in these types of agreements.

  As shown by the abundant literature on common pool resources, the main advantage of decentralized groundwater management is that rules are likely to be adapted to the local context. In France, this would respond to a real demand from farmers, as shown by the above-mentioned recent farm survey (Chap. 11) in five very different French counties. It highlights that farmers have highly diverging views concerning which criteria should be used to share water and how frequently allocation should be revised. For instance, while fruit farmers in the west (Tarn et Garonne) are asking for 15–20 years of water use concessions, cereal and vegetable growers in the north (Aisne county) would like allocation to be revised every year.

- **Strengthening administrative regulation**

  The second approach involves strengthening direct administrative regulation, with systematic registration of abstraction points, the issuance of pumping permits, and the awarding and enforcement of individual volumetric quotas. Water quotas are granted for a duration compatible with irrigation investments (e.g. 15 years) and have the status of concessions as practised under the Spanish law. Beneficiaries of concessions must report detailed information to government agencies on where they use water and for which crop, using an internet-based geographic information system similar to what is currently required by the Common Agriculture Policy subsidies. Automated reading meters such as those used in the drinking water sector help solve the information problem. The enforcement problem is dealt with by the use of sophisticated remote-sensing technology coupled to field inspections. A fine, proportional to the excess water used, is applied in case of non-compliance. One of the drawbacks of this policy approach is the lack of flexibility: newcomers (young farmers) are unable to obtain a concession until another farmer relinquishes a license – possibly providing incentives for farmers to drill illegal wells or to engage in informal water trading. Water use efficiency is obviously another issue. And enforcement is likely to be problematic in a context where scarce financial resources are allocated to government agencies in charge of water and environmental policies.
- **Using incentive-based economic instruments**

  The third model gives more importance to incentive-based economic instruments, which can be implemented by the State or within GWUAs. Several tools have been proposed and tested experimentally by French economists.
  - The establishment of markets where water quotas could be traded has been advocated since the early 2000s (Strosser and Montginoul 2001) and more recently evaluated through consultation with farmers in different regions (Rinaudo et al. 2012, 2014). Creating markets would not require many institutional changes if water abstraction is properly capped (as suggested in the second approach) and they could even operate without privatizing water, based on a concession system as currently is happening in Spain.
  - Lenouvel et al. (2011) tested an instrument combining an ambient tax with a contract. The ambient tax is indexed according to groundwater level, and it is charged to all farmers of the area. Farmers are offered the option to sign a contract with the GW basin agency in which they commit to provide true information to the agency concerning the location of their wells, irrigated fields, and volume pumped, and to facilitate the control of this information. These farmers are exempt from the ambient tax. The information they provide is verified using remote sensing and field inspections.
  - Figureau et al. (2015) have proposed combining payments and fines. Farmers exceeding their quota pay an increasing block fine for the extra volume pumped. The sum of the fines collected is then shared between those farmers who use less than their entitlement, the received amount being proportional to the water saving effort made. This instrument, which is expected to meet water and budget balance simultaneously, is currently being tested through experiments with farmers.

22.3.5 Social Expectations

Considering a 20-year time horizon, the three paths represent alternative feasible options, provided significant evolution of the legal framework occurs. However, future evolution may be strongly determined by social expectations. A series of workshops conducted with 80 farmers and 44 institutional stakeholders suggest that there is a strong social preference for decentralized solutions and cooperative arrangements, while economic instruments like taxes and market are strongly rejected mainly based on ethical considerations (Figureau et al. 2015; Rinaudo et al. 2014). Similar conclusions were reached by Montginoul and Rinaudo (2009) from a survey conducted in southern France by Rinaudo et al. (2014). Overall, water remains perceived as a free access good and implementing economic instruments is considered to be a drastic shift in paradigm. Transition towards a mature water economy will necessarily take place as climate changes and demand increases, but this will take time.

22.4 From Command and Control to Markets: Examples from the High Plains Aquifer, USA

22.4.1 Background on Groundwater Management in the United States

In the United States, the connections between groundwater pumping, local economies, and freshwater ecosystems that are fed by groundwater have been the subject of extended study and litigation over the last decade (e.g. Hathaway 2011; Van Kirk and Naman 2008; Scanlon et al. 2012; Gleeson and Cardiff 2013; Steward et al. 2013). Importantly, there is no national water policy related to groundwater use in the United States (see also Chaps. 6, 7, and 8). Instead, groundwater regulations are often set and implemented locally and not at a state or federal level. Changes in regulations are primarily driven by legal impositions on local groundwater management districts, or by a desire to preserve a rural way of life for future generations.

Common concerns about the sustainability of groundwater use may be divided into three broad categories: concerns over aquifer depletion (Konikow 2013; Laukaitis 2013; Steward et al. 2013; Terrell et al. 2002; Wines 2013), concerns over damages to transboundary surface water resources resulting from surface water-groundwater interaction (Kuwayama and Brozović 2013; McCarl et al. 1999), and concerns over damages to groundwater-dependent ecosystems and endangered species from surface water-groundwater interaction (Van Kirk and Naman 2008).

As a result, there is a very fine-scale heterogeneity of regulations related to groundwater use. Whereas large portions of the United States do not have any meaningfully binding restrictions on groundwater use, there is also a growing number of areas where quantification, monitoring, and enforcement of pumping rights have been implemented. Moreover, there are also examples where markets in groundwater pumping rights are emerging. Finally, in at least one case, voluntary changes in water rights that allow binding reductions in agricultural groundwater pumping have occurred (Kuwayama and Brozović 2013; NE DNR and MRNRD 2010; NE DNR and TBNRD 2012; NE DNR and URNRD 2010; Thompson et al. 2009). In the remainder of the section, we will focus on describing some of these recent, innovative approaches to groundwater management.

22.4.2 Introduction to the High Plains Aquifer Region

The High Plains aquifer system is one of the largest groundwater aquifers in the world (McGuire et al. 2012; Fig. 22.2). It supports endangered species, ecosystems, and rural economies in an area covering multiple states (Gutentag et al. 1984; Rosenberg et al. 1999; Dennehy et al. 2002) and a variety of hydrologic and climatic settings. As a result, both the management concerns and institutional responses to these concerns vary enormously across the region.

Each state above the High Plains aquifer has its own groundwater administration areas. These areas are called Natural Resources Districts (NRDs) in Nebraska, Groundwater Management Districts (GMDs) in Kansas, and Groundwater Conservation Districts (GCDs) in Texas. All three categories of groundwater-related conflict discussed in the previous section are observed in the High Plains (Fig. 22.2). First, the major concern over groundwater may be related to declining well yields as pumping reduces saturated thicknesses (e.g. Northwest Kansas GMD#4, North Plains GCD). Second, stream depletion related to groundwater pumping may lead to conflict between groundwater users and downstream surface water users (e.g. the Upper and Middle Republican NRDs, Big Bend GMD#5). Finally, stream depletion may negatively impact endangered species and instream habitat (e.g. the Twin and Central Platte NRDs).

Effective groundwater management requires monitoring and enforcement of groundwater use. In the High Plains region, a large portion of the states of Kansas and Nebraska requires that all irrigation wells are metered and pumping reported annually. Meters are less common in Texas, but some groundwater management districts such as the North Plains Groundwater Conservation District are now phasing-in meter installation.

As noted above, monitoring of groundwater use is only meaningful to resource management to the extent that there is enforcement when violations occur. Where reporting of metering data is voluntary and without sanction, there is little incentive to provide timely or accurate readings. Conversely, in some groundwater management districts, paid district employees do the meter reading, with fines for broken meters and severe penalties for violators. For example, in 2010, the Upper Republican Natural Resources District in Nebraska revoked groundwater pumping rights, estimated to be worth in excess of $3 million, for several groundwater users who

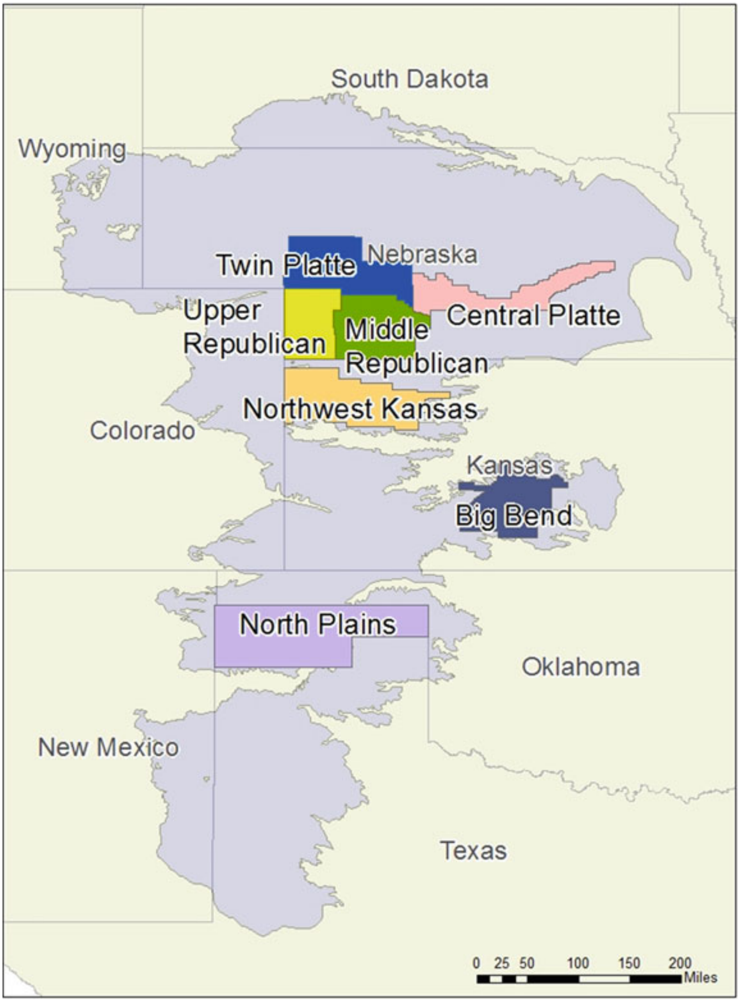

Fig. 22.2 High Plains Aquifer region, with key administrative areas in Kansas, Nebraska, and Texas

had attempted to increase their water use illegally through bypassing their well flow meters.

Note that even without metering of groundwater use, it is possible to estimate groundwater use, and depending on the situation, imperfect monitoring may be sufficient for management. For example, some natural resources districts in Nebraska quantify and enforce the right to irrigate a certain area of land, but do not meter water use (e.g. the Twin Platte and Central Platte NRDs). If crop water demands on a per-area basis are similar, then the estimation error from not metering may be small. Thus, depending on the goals of groundwater management, it may be preferable to avoid the potential difficulties associated with metering. However, there is still a need to enforce limits on the irrigated areas for such systems to succeed.

22.4.3 Transferable Schemes for Groundwater Pumping Rights

Policies that seek to reallocate groundwater pumping rights must deal with a number of issues. While some of these are well-known from markets for surface water rights (Chong and Sunding 2006; Saliba 1987; Young 1986), others are specific to groundwater pumping. Groundwater pumping leads to several kinds of spatial and intertemporal externalities (Brozović et al. 2010; Kuwayama and Brozović 2013). Indeed, groundwater management schemes that reallocate water between alternate pumping locations are often explicitly designed to change the distribution and magnitude of pumping externalities. Reallocation may be designed to minimize unwanted impacts on third parties or to encourage trades that reduce the magnitude of externalities (Palazzo and Brozović 2014; Brozović and Young 2014).

Externalities arising from groundwater pumping depend on local hydrologic properties and are spatial and intertemporal (Brozović et al. 2010). In principle groundwater pumping produces well interference and induces drawdown in adjacent wells. However, to date interference between adjacent wells with different ownership has not obviously restricted groundwater trading in the High Plains region. One possible explanation is that existing well spacing regulations are enough to prevent significant well interference between adjacent wells. Because trading of the right to pump groundwater changes the location of pumping but does not involve the physical transfer of water above ground, in general no water conveyance system is needed. Note that this is different to most surface water markets, where the need for water conveyance may be a major limitation to trading. Moreover, in groundwater management areas where there are already binding restrictions on groundwater use, water users that are looking to purchase additional pumping rights often have excess pumping capacity and may be able to use any permits they purchase without needing any further capital investment.

Existing groundwater permit trading schemes typically use applied water, rather than consumptive water use, as the unit of trade. Again this is in contrast to surface water markets, where it is common for only consumptive water use to be tradable. The main reason for the difference is likely pragmatic. Well metering quantifies applied water rather than consumptive use and represents a unit of transfer that is politically acceptable to water user groups. Moreover, in many cases both buyers and sellers of groundwater use rights have the same irrigation technology (typically centre pivot systems in the High Plains region of the United States). Consequently, differences in consumptive use between buyers and sellers may be negligible. Conversely, in surface water markets where water is moved outside of basins, or between agricultural and urban water users, the need to quantify consumptive use is much greater.

22.4.4 Innovations in Groundwater Management: Nebraska

Management of groundwater in Nebraska is undertaken by Natural Resources Districts (NRDs). The NRDs are operated as local government agencies but may be thought of as large groundwater user associations. The NRDs have a relatively large amount of autonomy, and determine their rules and regulations in consultation at the state level through the Nebraska Department of Natural Resources. As a result, a wide variety of groundwater management institutions have evolved at an NRD level, reflecting local concerns about water use (Fig. 22.2). For example, (NE DNR and MRNRD 2010; NE DNR and TBNRD 2012; NE DNR and URNRD 2010) in the Platte River Basin in Nebraska, groundwater regulation is driven by stream depletion impacting endangered species habit for fish and migratory birds (Fig. 22.2). There is currently no metering of wells in the NRDs within the Platte River Basin. The Twin Platte, Central Platte, and Tri-Basin (Platte River portion) NRDs currently allow transfers of groundwater pumping rights. Each of these NRDs uses certification of irrigated acres to place an upper bound on the land area that can be irrigated. Then, transfers of certified irrigated acreage are allowed. Stream depletion is calculated over a 50-year horizon and, depending on the NRD, transfers may be adjusted if acreage is transferred to a location with higher stream depletion than the original location. There are also additional spatial limits on trading, such as constraints that trades cannot move water upstream (Twin Platte and Central Platte NRDs) or outside of specified zones (Tri-Basin NRD). Note that the use of certified irrigated acres as the unit of transfer corresponds to an imperfect monitoring of groundwater pumping. However, when the primary concern is stream depletion, encouraging trading to move water further from the river is desirable and, over short to medium management timescales, the benefits of this spatial reallocation may outweigh modest increases in total pumping.

Conversely, groundwater regulation in the Republican River Basin of Nebraska has been driven by interstate litigation between Kansas, Nebraska, and Colorado over the allocations of surface water to each state from the Republican River (McKusick 2002; Figure 2). As a result of a long litigation between the states, all wells in the Nebraska portion of the Republican River Basin are metered, with mandatory annual reporting and moratoria on new wells. The Upper Republican NRD completed metering in 1982, and the remaining NRDs completed metering in 2005. There are pumping quotas in place with complex and changing intertemporal carry forward provisions that allow banking of unused rights for future use. Current updates of the integrated management plans for three of the NRDs in the Republican River Basin, the Upper (UR) and Middle (MR) Republican and Tri-Basin (TB) (Republican River portion) NRDs, allow for some trading of groundwater pumping rights.

The Republican River Basin NRDs that allow trading each have slightly different rules that constrain trading. For example, in the Upper Republican NRD, trades must stay within an area equal in size to a township (36 mile^2 or around 90 km^2). In the Middle Republican NRD, trading is limited to groundwater users within certain distances from streams. In years in which the Middle Republican NRD is concerned about meeting its stream depletion targets under the Republican River Compact, trading may be suspended at the discretion of the NRD. In each of the NRDs, there is an adjustment for differences in stream depletion if pumping rights are transferred to a location where stream depletion is greater than the original pumping location. However, if pumping rights are transferred to a location with lower stream depletion than the original location, no adjustment to the rights takes place.

22.4.5 Innovations in Groundwater Management: Kansas

Kansas is unusual in having appropriative, rather than correlative, rights for groundwater. This complicates any policy that seeks to reallocate groundwater pumping between users as any transfer must not demonstrably impact any senior rights holders. Thus, it is possible that concerns over well interference might restrict the potential applicability of groundwater trading schemes. Despite this, groundwater trading has been established in two areas of the state. First in the Big Bend Groundwater Management District (GMD) No. 5, the Wet Walnut Creek Intensive Groundwater Use Control Area is metered with pumping allocations, and transfers are allowed, though they have not yet occurred. GMD No. 5 also operates a groundwater bank through which transfers may occur, subject to large conservation offsets and regulatory complexity. One trade has occurred in the bank.

Second, in the Northwest Kansas Groundwater Management District No. 4, a portion of the district (the Sheridan-6 area) was designated a Local Enhanced Management Area (LEMA) in early 2013. This is the first such area in the state. The LEMA is self-regulating, and has chosen to equalize the seniority of its water rights and reduce the total water allocation by 20 % relative to historic use. Trading is allowed and will be on a volumetric basis without adjustment, as the primary concern is aquifer depletion and not stream depletion.

22.4.6 Innovations in Groundwater Management: Texas

Although metering is slowly being introduced to groundwater conservation districts in Texas, conveyance is an impediment to trading in Texas. Under current groundwater law, trading is allowed but the buyer is expected to pump the water at the location of purchase, on the seller's land. Portions of land overlying the Edwards Aquifer (not a part of the High Plains Aquifer) are an exception to this rule, where trading is allowed to change the location of pumping as it is assumed that the area encompassing all potential transfers is small enough that impacts on third parties will not be altered significantly by transfers. The Edwards Aquifer Authority in Texas has implemented well permitting and metering programs and allows transfers of the right to pump up to 1 acre-foot/acre of certified irrigated land (EAA 2012). Both permanent transfer and lease markets exist.

22.5 From Command and Control to Markets: Examples from Chile

The case of Chile is illustrative of a transition from command and control to market based groundwater management policy, where economic incentives play a significant role in allocation of water use rights.

22.5.1 Legal and Institutional Framework (an Historical Perspective and Recent Evolution)

The first Chilean text to regulate the use of water is an 1819 Executive Decree which defined the dimensions of an irrigation water use right and responsibility for water intakes. The 1855 Civil Code was the first legal instrument to define that “the rivers and all waters running within natural channels are national goods of public use.” In addition, it establishes that access to water is obtained by means of water-use rights (WUR) “granted by the competent authority.” The concept of WUR was further developed in the 1930 Water Code proposal and 1951 Water Code. The latter code defines WUR as follows: “A water use right is an actual right that falls on publicly owned waters which consists in the use, possession and disposal of such waters fulfilling the requirements and in accordance with the rules prescribed herein” (Hearne and Donoso 2005). The 1967 Water Code, implemented in a more centralized political context, reinforces the concept of water as being within the public domain and changed the legal nature of WUR, stressing that these were administrative rights where the State grants the use of the waters, subject to public regulation. These WUR could expire, and the process of water reallocation was to be based on regional water-use plans executed by means of studies that determined the rate of rational and beneficial use (Hearne and Donoso 2005).

The Water Code of 1981 (WC 1981) maintained water as “national goods of public use,” but granted permanent, transferable WUR to individuals so as to reach an efficient allocation of the resource through market transactions of WUR. The holder of the WUR is the owner of the right in perpetuity, ownership that is protected constitutionally. However, it is important to note that granted WUR do not constitute a transfer of ownership of the water. The WC 1981 allowed for freedom in the use of water to which an agent has WUR; thus, WUR are not sector specific and can be transferred between sectors as well as within economic sectors. Similarly, the WC 1981 abolishes the water use preferential lists, present in the Water Codes of 1951 and 1967. Additionally, WUR do not expire and do not consider a “use it or lose it” clause.

The WC 1981 specifies consumptive and non-consumptive WUR for both surface and groundwater. Non-consumptive use rights allow the owner to divert water with the obligation to return the same water unaltered to its original source. Consumptive use rights do not require that the water be returned once it has been used. Consumptive and non-consumptive WUR are, by law, specified as a volume per unit of time. In addition, consumptive and non-consumptive rights can be exercised in a permanent or contingent manner and in a continuous, discontinuous or alternating mode. Permanent use rights are rights specified as a volume per unit of time, unless there is water scarcity in which these WUR are recognized as shares of water flows. Contingent rights are specified as a volume per unit of time and only authorize the user to extract water once permanent rights have extracted their rights. Continuous rights are those use rights that allow users to extract water continually over time. On the other hand, discontinuous rights are those that only permit water to be extracted at given periods. Finally, alternating rights are those in which water extraction is distributed among two or more persons.

Groundwater in Chile is regulated in Book I, Title VI of the WC 1981 in Articles 58–68. In addition, groundwater is administratively regulated by Resolution No. 425 of the *Dirección General de Aguas* (DGA – General Water Directory) approved in 2008. Article 58 establishes that any person can explore in order to find groundwater on their property. Exploration on public property requires an authorization by the DGA; should two or more petitions for exploration be presented for the same geographic area, the DGA will define who receives the exploration right based on an auction. If groundwater is found, the user can petition the DGA for a new groundwater use right. The groundwater use right petition must meet the following requirements:

(a) Identification of the aquifer from which the water is to be extracted;
(b) Definition of the quantity of water to be extracted, expressed in liters per second;
(c) Yield and depth of the extraction well;
(d) Specification of the water extraction points and the method of extraction; and
(e) Definition of whether the right is permanent or contingent, continuous, discontinuous or alternating.

The administrative procedure requires that this WUR petition be published in the *Diario Oficial*, in a daily Santiago newspaper, and in a regional newspaper, where applicable. Previous to the WC 1981 reform of 2005, the DGA could not refuse to grant new water rights without infringing a constitutional guarantee, provided there was technical evidence of the availability of water resources and that the new use would not harm existent rights holders.[3] At present, if the petition is found to be for speculative reasons the DGA can refuse to grant the solicited WUR. If there is competition for solicited water rights, they are to be allocated through an auction with an award to the highest bidder. This allocation rule between competing WUR petitioners allows water to be allocated to its highest use value.

The Law N°. 20,017 of 2005 amended the procedure to grant new WUR of the WC 1981 and introduced a non-use tariff (*patente de no-uso*). Due to the difficulties of monitoring the effective use of all WUR, the non-use tariff is applied to all

[3] But, the DGA can declare certain aquifers to be fully exploited and refuse to grant new groundwater use rights.

consumptive permanent groundwater WUR that do not count with water intake infrastructure, and to all non-consumptive WUR that do not have water intake and return infrastructure (Law N°. 20,017 of 2005, art. 129 bis 4-6).

Groundwater resources can be classified as: free, under restriction, and under prohibition. A groundwater resource classified as free implies that new WUR can be granted to petitioners. Groundwater declared under restriction[4] only allows provisional WUR to be granted; meanwhile, if it is under prohibition,[5] no new WUR can be granted.[6] In Chile, the possibility of limiting withdrawals has been contemplated since 1983 (Res DGA 207 of 1983). However, this resolution does not indicate how these restricted groundwater resources were to be managed. DGA Res 186, which establishes that groundwater user communities (GUC) will manage restricted groundwater resources, clarifies this in 1996; additionally, DGA Res 186 establishes that all restricted groundwater resources must have a GUC. At present Res 341 of 2005, Article 63 of the WC 1981, and Article 39 of Resolution 425 of the DGA establishes that GUC are responsible for the management of groundwater resources and of water extractions.

Approximately 70 % of Chilean territory presents no restrictions for groundwater exploitation. There are at least 50 aquifers with a declaration of restriction, all located from the Region of Arica and Parinacota to O'Higgins (Fig. 22.3). There are only two aquifers under prohibition: the first is the aquifer of San José de Azapa in the Region of Arica and Parinacota and the second is the aquifer of Copiapó in the Atacama Region. Even though there could be over 50 GUC, only two GUC exist at present in Chile; one manages groundwater in the restricted aquifer of Copiapó Province and the second one can be found in the Yali sector of the Melipilla Province of the Metropolitan Region.

22.5.2 Economic Mechanisms/Instruments in Place

The WC 1981 established that WUR are transferable in order to facilitate WUR markets as an allocation mechanism. Although private water use rights existed in Chile prior to 1981, the previous water codes restricted the creation and operation of efficient water markets. The framers of the 1981 Water Code sought to achieve the efficiencies of market reallocation of water, "the objective of the governmental

[4] The DGA can declare an aquifer under restriction if there is a risk of negative impacts of new WUR on existing WURs.

[5] The DGA can declare an aquifer under prohibition if there is clear evidence of a risk of resource depletion due to over-extraction.

[6] The DGA has the authority to provisionally grant groundwater use rights in those areas that have been declared under restriction. The effects of these provisional WUR on other groundwater use rights holders are studied. Should negative impacts be identified in these areas, these provisional WUR are anulled by the DGA; i.e. groundwater may no longer be extracted with these WUR. However, if no effects are identified after 5 years of water extraction, these provisional WUR can become definite WUR.

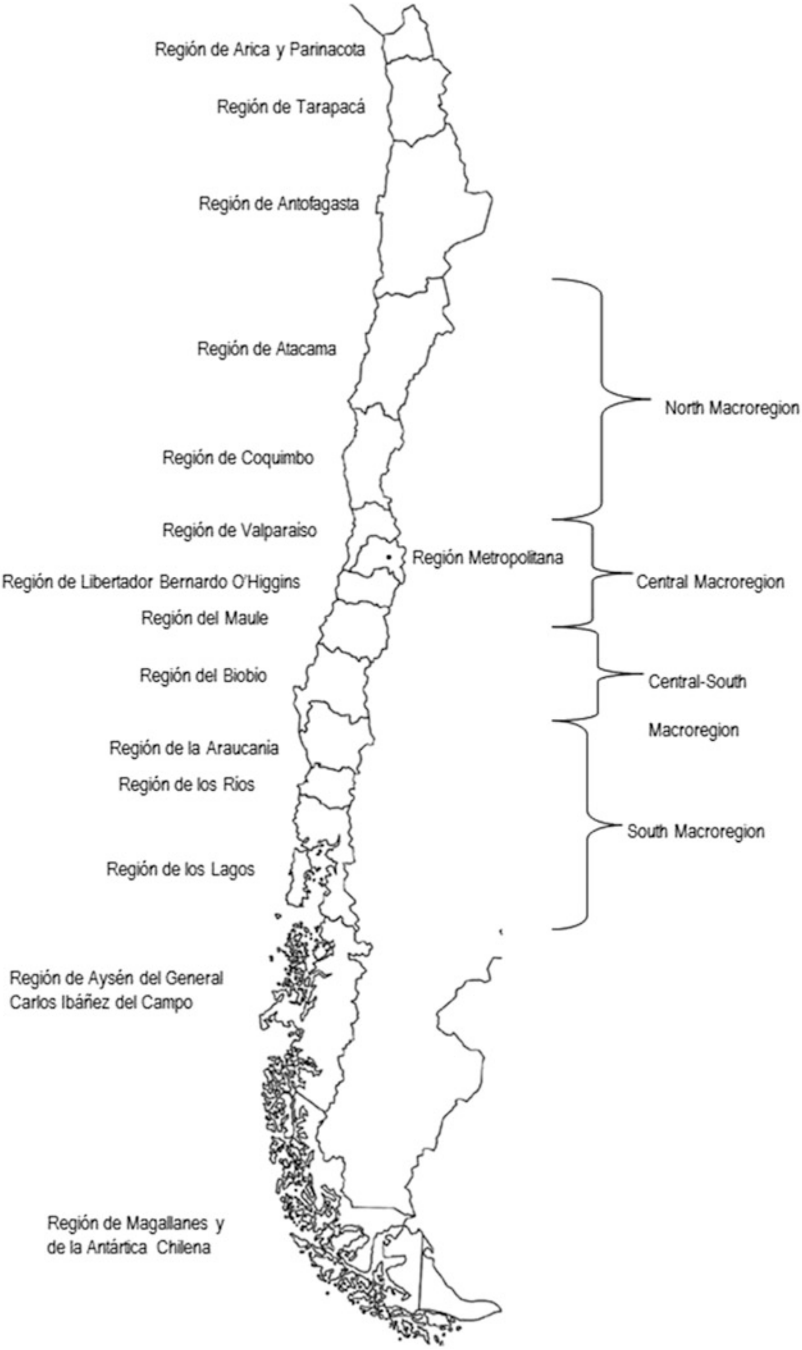

Fig. 22.3 Map of Chile showing different regions

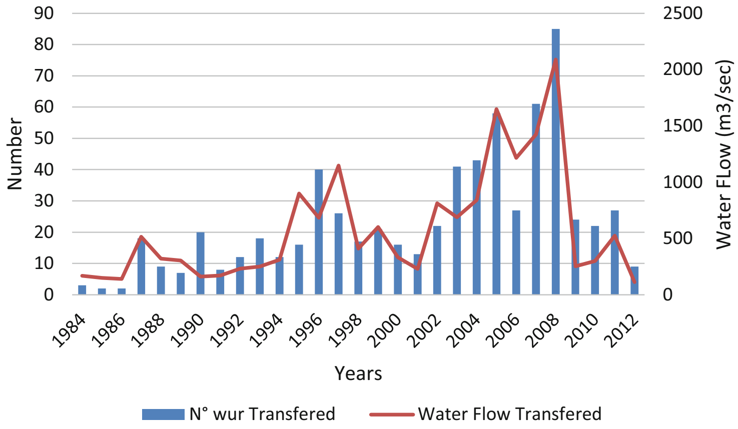

Fig. 22.4 Water flow and number of WUR traded in the Copiapó Aquifer (CNR 2012)

action in this field was to create solid WUR in order to facilitate the proper operation of the market as an allocation mechanism" (Buchi 1993, pp. 85–87). Thus the WC 1981 was designed to protect traditional and customary WUR and to foster economically beneficial reallocation through market transfers (Bauer 2004; Buchi 1993; Hearne and Donoso 2005).

Although market reallocation of water has not been common throughout most of Chile, the existence of water markets has been documented. As Donoso (2012) concludes, studies have shown active trading for WUR in the Copiapó aquifer where water is scarce with a high economic value, especially for the mining sector and the high valued agricultural export sector (CNR 2012). Inter-sectoral trading has transferred water to growing urban areas in the Elqui Valley (Hearne and Easter 1997) and the upper Mapocho watershed, where water companies and real estate developers are continuously buying water and account for 76 % of the rights traded during the 1993–1999 period (Donoso et al. 2002). Other studies have shown limited trading in the Bío Bío, Aconcagua, and Cachapoal Valleys (Bauer 1998; Hadjigeorgalis and Riquelme 2002).

A key conclusion of these studies is that water markets are driven by demand from relatively high-valued water uses, and facilitated by low transactions costs in those aquifers that the DGA has declared as restricted or protected and where there are GUCs present that assist in the transfer of water. For example as Fig. 22.4 shows, in the Copiapó basin, the volume of water and number of WUR traded began to increase as of 1994, when the DGA declared the aquifer under protection (CNR 2012). There was a second increase as of 2002 when the DGA maintained the prohibition for Sectors 1–4 and declared restrictions for Sectors 5 and 6. This resolution reinforced the signal to water users that new WUR were not available for the Copiapó aquifer and, thus new water demands must be satisfied through the market for WUR.

In the absence of these conditions, trading has been rare and water markets have not become institutionalized in most aquifers. It should be noted that during the

2000s, the market was more active than in the previous two decades, that is in the 1980s and 1990s (Donoso 2012).

22.5.3 Issues and Problems

The WC 1981 did not pay much attention to the sustainable management of groundwater because at that time groundwater extraction was marginal during the early 1980s. Recognizing the need to improve groundwater management regulation due to increased groundwater pumping, the 2005 amendment of the WC 1981 introduced procedures to reach a sustainable management of underground water resources. The main provisions are: (a) extraction restrictions when third parties are affected; (b) authorization for the DGA to impose the installation of extraction measurement equipment in order to monitor extractions effectively; (c) the establishment of areas subject to extraction prohibitions and restrictions; and (d) the need to consider the interaction between surface water and groundwater when analyzing petitions for new surface or groundwater WUR.

However, a World Bank study (2011) concluded that there exist various problems associated with groundwater management. A major concern is the general lack of information about groundwater and insufficient knowledge about its dynamics, in particular its interaction with surface waters. There are significant gaps in the registry of wells, extraction and quality measurements, recharge balances, and identification of pollution sources. In general, information systems are not linked to the measurement and monitoring of aquifers to estimate groundwater withdrawals. An effective information system is a prerequisite to be able to control and sustainably manage an aquifer.

The sustainability of northern aquifers is compromised due to the over-provision of WUR related to the practice of allocating WUR based on foreseeable use. The foreseeable use considers the probable effective water extraction of different sectors when analyzing whether there is sufficient water to grant new WUR. For example, an agricultural WUR does not extract water in winter months, whereas a mining WUR extracts water all year round. In this case, the authority would consider a lower pressure on water resources of an agricultural WUR with respect to the pressure of a mining WUR. This practice commits the mistake of not considering the transferable nature of WUR. Thus, when water scarcity increases and inter-sectoral WUR transactions increase, water resources will be overexploited and unsustainable. Additionally, the over-provision of WUR gave rise to increased water conflicts as WUR are transferred to users with a more intensive water use, such as from agriculture to mining in the northern basins.

An additional challenge for a sustainable groundwater management is the fact that at present ground and surface waters are managed independently despite their recognized interrelations even though the 2005 reform of the WC 1981 establishes that surface and groundwater must be jointly managed. This implies that at present there is no conjunctive management of surface and groundwater, which has proven to be an effective adaptation mechanism for climate change.

There are, in general, no GUCs that manage groundwater user rights; the only exception is in some sections of the over-exploited Copiapo aquifer. There should exist a GUC at least for all aquifers that have a restriction or prohibition declaration by the DGA. The fact that users have not yet organized themselves in GUCs to take over the management of groundwater reflects the lack of understanding of a large proportion of users of the long term effects that uncontrolled exploitation of aquifers may cause. In the absence of GUCs, the WC 1981 establishes that the DGA is responsible for controlling and monitoring groundwater withdrawals. Evidence has shown that the DGA does not have the necessary resources (human, technical, and financial) to monitor all groundwater extractions.

There is an incentive for the adoption of water saving technologies by farmers (Law No. 18,450). This program subsidizes small scale, private irrigation investments. It has supported much of the installation of drip irrigation systems in the dry north and spray systems in the humid south. However, there has been no assessment of the impacts of this incentive instrument on groundwater recharge and sustainability. Hence, it is essential to strengthen the coordination between sectoral policies and water management policies.

22.6 Conclusions

One of the lessons learnt from the three case studies is that policies implemented in practice often combine instruments which text books often present as competing options. In Chile, France and the High Plain case studies, policy makers and local managers are actually trying to combine (i) instruments which provide economic incentives and allow for reallocating water with (ii) the development of water user associations and, to some extent, (iii) the formalization of water (use) rights. There is nothing in reality that looks like a pure “market” approach.

Another key lesson is that monitoring and control remains an issue in the three very different contexts, even where full property rights have been established for decades. It is also interesting to note that solutions implemented to solve information problems are somewhat the same in the different countries – all assume that perfect information on water abstraction (e.g. metering) is not a prerequisite and that management can work with less precise information such as a measurement of irrigated area for instance.

A third lesson is that economic instruments enter the management tool box only when water scarcity becomes a real problem or, to use Randall’s terminology, when the water economy matures. The High Plain case study shows that different “maturity” levels may co-exist in the same State. Put differently, this implies that the choice of economic instruments that can be used in each specific situation is far from being fully determined by the national legal, institutional, societal and economic framework. Therefore there is probably plenty of room for manoeuvre for local stakeholders to explore the potential for innovative approaches.

Table 22.2 synthesizes the main characteristics of groundwater management in the three case studies. It highlights that incentive-based instruments are framed

Table 22.2 Comparison of groundwater management in the three case studies

	Chile	France	USA – high plains aquifer
Level of aquifer regulation	A national policy locally translated	A national policy locally translated	No federal policy regulation. May be some state oversight. Groundwater regulation at local level, which can differ from one State to another
Groundwater areas	Free (70 % of aquifers), under restriction (~50 aquifers), under prohibition (2 aquifers)	89 % of aquifers reputed in good status (Vial et al. 2010)	Most aquifers with no restrictions, but a growing number of active management areas Three types of problems: aquifer depletion, damages to transboundary surface water resources or to ecosystems
Water rights	Ancient (1855) water-use rights –WUR- based on maximal consumptive levels. Constitutionally protected. No "use it or lose it" clause	No water right. Only yearly and revocable water abstraction authorizations. Presently, definition of an upper limit to water abstraction per groundwater basin to be shared between users	Generally no or very few limits on groundwater use. In some regions, water rights defined with or without water meters. Kansas: appropriative rights; other States: generally correlative rights
Groundwater withdrawals' management	Water markets authorized since 1981. Active only in scarcity areas, when there exist high-valued water uses and low transactions costs	A fee paid to Water Agency. Creation of water users' associations charged to share global water quota. No water market	A variety of mechanisms including no restrictions, well moratoria, limits on irrigated acreage, limits on pumping, water markets
Water users' associations	Compulsory in scarcity areas since 1983	Compulsory in scarcity areas since 2014	Yes, in some areas
Problems	No conjunctive ground and surface water management and more generally no coordination between sectoral policies Lack of information on groundwater dynamics Few WUA (2) and lack of monitoring in other cases Water markets lead an unsustainable increase of water consumption	Levels of water fees not incentive Law enforcement Water allocation efficiency A perceived unfair allocation	Generally there are few restrictions on groundwater use Generally, no conjunctive ground and surface water management Extended litigation is often a prerequisite for management changes

taking into account local contexts, in particular historical, institutional and cultural aspects. Where groundwater was traditionally considered as an open access resource, introducing regulations represents a shift in paradigm and is likely to raise significant opposition. Moreover, the level of involvement of users in the definition of groundwater sharing rules is key to understanding the type of instrument chosen and its efficiency. All these aspects explain the current institutions for groundwater management that have developed in the three case studies: the external imposition of water markets in Chile which do not function as expected, a management mostly based on quantitative sharing in France (with few economic instruments), and nascent market instruments in the High Plains Aquifer of the United States.

To conclude, economic instruments are used to encourage groundwater users to adopt water saving behaviours and then to not overexploit groundwater resources while maximising water efficiency. However, using economic instruments for groundwater management is challenging due to the nature of the resource: it is often complicated to define satisfactorily the level of abstraction that allows a sustainable exploitation; it is also difficult to detect groundwater usage, especially where surface water can also be used. Together, this explains why economic instruments sometimes do not function as anticipated because of incomplete information.

Apart from such difficulties, the three case studies point out two main challenges to be able to control groundwater over-exploitation through economic instruments. First of all is the acceptability challenge. For instance, in France, water markets are nowadays not acceptable mainly for ethical reasons; water taxes can also be rejected, a taxable user finding unfair such an instrument which is seen to unduly increase State receipts. Similarly, over most of the United States, restrictions on groundwater use are currently not acceptable to key user groups. The second challenge is enforcement. An example is given by the Chile case where an enforceable property rights' system combined with an appropriate information level of groundwater availability and demand is still lacking; in France, sanctions applicable in respect of non-registered withdrawals are sometimes not applied. Threats cannot be credible, and then an instrument based on them will not function at all.

References

Bauer C (1998) Against the current: privatization, water markets, and the state in Chile. Kluwer, Boston

Bauer C (2004) Siren song: Chilean water law as a model for international reform. Resources for the Future Press, Washington, DC

Brozović N, Young R (2014) Design and implementation of markets for groundwater pumping rights. In: Easter K, Huang Q (eds) Water markets for the 21st century: what have we learned? Springer, Netherlands

Brozović N, Sunding DL, Zilberman D (2010) On the spatial nature of the groundwater pumping externality. Resour Energy Econ 32(2):154–164

Buchi H (1993) La transformación económica de Chile. Del Estatismo a la libertad económica. Norma, Bogota

Casari M, Plott CR (2003) Decentralized management of common property resources: experiments with a centuries-old institution. J Econ Behav Organ 51(2):217–247. doi:10.1016/S0167-2681(02)00098-7

Castaño S, Sanz D, Gómez-Alday J (2010) Methodology for quantifying groundwater abstractions for agriculture via remote sensing and GIS. Water Resour Manag 24(4):795–814. doi:10.1007/s11269-009-9473-7

Chong H, Sunding D (2006) Water markets and trading. Annu Rev Environ Resour 31(2):239–264

CNR (2012) Capacitación y Apoyo a Comunidades de Aguas Subterráneas, en el Valle de Copiapó. Report Comisión Nacional de Riego (CNR), Ministerio de Agricultura, Chile

de Stefano L, Lopez-Gunn E (2012) Unauthorized groundwater use: institutional, social and ethical considerations. Water Policy 14(S1):147–160

Dennehy KF, Litke DW, McMahon PB (2002) The High Plains Aquifer, USA: groundwater development and sustainability. Geol Soc Lond Spec Publ 193(1):99–119

Desprats J-F, Rinaudo J-D, Montginoul M (2011) Analyse de la relation entre le type d'urbanisation et la consommation en eau des ménages – Le cas de l'agglomération de Perpignan. BRGM, Orléans

Donoso G (2012) The evolution of water markets in Chile. In: Maetsu J (ed) Water trading and global water scarcity: international perspectives. RFF Press, Washington, DC, pp 111–129

Donoso G, Montero JP, Vicuña S (2002) Análisis de los Mercados de Derechos de Aprovechamiento de Agua en las Cuencas del Maipú y el Sistema Paloma en Chile: Efectos de la Variabilidad de la Oferta Hídrica y de los Costos de Transacción. In: Embid A (ed) El Derecho de Aguas en Ibero América y España: Cambio y Modernización en el Inicio del Tercer Milenio. Civitas, Madrid, pp 109–151

EAA (2012) Edwards aquifer authority rules. http://www.edwardsaquifer.org/files/download/2b4674cbea20e5b

Figureau A-G, Montginoul M, Rinaudo J-D (2015) Policy instruments for decentralized management of agricultural groundwater abstraction: a participatory evaluation. Ecological Economics 119:147–157, http://dx.doi.org/10.1016/j.ecolecon.2015.08.011

Garin P, Loubier S, Campardon M (2013) Irrigation individuelle – irrigation collective: état des lieux et contraintes. Revue SET 11:86–89

Garrido A, Rey D, Calatrava J (2012) Water trading in Spain. In: De Stefano L, Llamas MR (eds) Water, agriculture and the environment in Spain: can we square the circle? CRC Press, Botín Foundation, London, pp 205–216

Gleeson T, Cardiff M (2013) The return of groundwater quantity: a mega-scale and interdisciplinary "future of hydrogeology"? Hydrogeol J 21(1169–1171). doi:10.1007/s10040-013-0998-8

Gutentag ED, Heimes FJ, Krothe NC, Luckey RR, Weeks JB (1984) Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. US Department of the Interior, Geological Survey, Washington, DC

Hadjigeorgalis E, Riquelme C (2002) Análisis de los Precios de los Derechos de Aprovechamiento de Aguas en el Río Cachapoal. Ciencia e Investigación Agraria 29(2):91–99

Hathaway D (2011) Transboundary groundwater policy: developing approaches in the Western and Southwestern United States. J Am Water Resour Assoc 47(1):103–113

Hearne R, Donoso G (2005) Water institutional reforms in Chile. Water Policy 7(1):53–69

Hearne R, Easter KW (1997) The economic and financial gains from water markets in Chile. Agric Econ 15:187–199

Konikow LF (2013) Groundwater depletion in the United States (1900–2008). US Department of the Interior, US Geological Survey, Reston, Virginia

Kuwayama Y, Brozović N (2013) The regulation of a spatially heterogeneous externality: tradable groundwater permits to protect streams. J Environ Econ Manag. doi:10.1016/j.jeem.2013.02.004

Laukaitis AJ (2013) Drought's toll on groundwater is steepest on record. Lincoln J Star. http://journalstar.com/news/local/drought-s-toll-on-groundwater-is-steepest-on-record/article_8c3d377d-7dd1-5d11-bdce-7498476a032f.html. Accessed 9 May

Lenouvel V, Montginoul M (2010) Groundwater Management Instruments in a Conjunctive Use System: assessing the Impact on Farmers' Income Using a Mixed Integer Linear Programming (MILP). Ger J Agric Econ 59(3):158–172

Lenouvel V, Montginoul M, Thoyer S (2011) From a blind truncheon to a one-eyed stick: testing in the lab an optional target-based mechanism adapted to groundwater withdrawals. Paper presented at the 18th annual conference of European Association of Environmental and Resource Economists, Rome, 29 June–2 July 2011

Martin de Santa Olalla F, Brasa Ramos A, Fabeiro Cortés C, Fernández González D, López Córcoles H (1999) Improvement of irrigation management towards the sustainable use of groundwater in Castilla-La Mancha, Spain. Agric Water Manag 40(2–3):195–205. doi:10.1016/s0378-3774(98)00121-8

Martín de Santa Olalla F, Calera A, Domínguez A (2003) Monitoring irrigation water use by combining Irrigation Advisory Service, and remotely sensed data with a geographic information system. Agric Water Manag 61(2):111–124. doi:10.1016/s0378-3774(02)00169-5

McCarl B, Dillon C, Keplinger K, Williams R (1999) Limiting pumping from the Edwards Aquifer: an economic investigation of proposals, water markets, and spring flow guarantees. Water Resour Res 35(4):1257–1268

McGuire B, Lund K, Densmoe B (2012) Saturated thickness and water in storage in the High Plains Aquifer, 2009, and water- level changes and changes in water in storage in the High Plains Aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009. U.S. Geological Survey Scientific Investigations Report 2012–5177, 28 p

McKusick V (2002) State of Kansas v. State of Nebraska and State of Colorado: joint motion of the states for entry of proposed consent judgement and approval and adoption of final settlement stipulation. Supreme Court of the United States, Washington DC

Ménard C (2003) L'approche néo-institutionnelle: des concepts, une méthode, des résultats. Cahiers d'Economie Politique 44:103–118

Montginoul M, Rinaudo J-D (2009) Quels instruments pour gérer les prélèvements individuels en eau souterraine? Le cas du Roussillon. Economie Rurale 310:40–56

Montginoul M, Rinaudo J-D (2011) Controlling households' drilling fever in France: an economic modeling approach. Ecol Econ 71:140–150

Mukherji A, Shah T (2005) Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeol J 13(1):328–345. doi:10.1007/s10040-005-0434-9

NE DNR, MRNRD (2010) Integrated management plan. Nebraska Department of Natural Resources and Middle Republican Natural Resource District, Nebraska

NE DNR, URNRD (2010) Integrated management plan. Nebraska Department of Natural Resources and Upper Republican Natural Resource District, Nebraska

NE DNR, URNRD (2012) Integrated management plan. Nebraska Department of Natural Resources and Tri-Basin Natural Resources District, Nebraska

Palazzo A, Brozović N (2014) The role of groundwater trading in spatial water management. Agric Water Manag 145:50–60. doi:10.1016/j.agwat.2014.03.004

Rinaudo J-D, Montginoul M, Varanda M, Bento S (2012) Envisioning innovative groundwater regulation policies through scenario workshops in France and Portugal. Irrig Drain 61 (1):65–74

Rinaudo J-D, Montginoul M, Hérivaux C, Figureau A-G (2014) Quels instruments pour une gestion collective des prélèvements agricoles individuels en eau souterraine ? Mise en débat de scénarios avec des acteurs du territoire dans 5 départements français. BRGM/RP-63259-FR, Montpellier, February, p 93

Rosenberg NJ, Epstein DJ, Wang D, Vail L, Srinivasan R, Arnold JG (1999) Possible impacts of global warming on the hydrology of the Ogallala aquifer region. Clim Change 42(4):677–692

Saliba BC (1987) Do water markets "work"? Market transfers and trade-offs in the Southwestern States. Water Resour Res 23(7):1113–1122

Salzman J (2005) Creating markets for ecosystem services: notes from the field. N Y Univ Law Rev 80(6):870–961

Scanlon BR, Faunth CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB (2012) Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proc Natl Acad Sci. doi:10.1073/pnas.1200311109

Segerson K (1988) Uncertainty and incentives for nonpoint pollution control. J Environ Econ Manag 15(1):87–98

Shah T (2008) Taming the Anarchy: Groundwater Governance in South Asia. Resources for the Future Press (RFF Press), Washington, p 310

Skurray JH, Roberts EJ, Pannell DJ (2012) Hydrological challenges to groundwater trading: lessons from south-west Western Australia. J Hydrol 412–413(0):256–268. doi:10.1016/j.jhydrol.2011.05.034

Steward DR, Bruss PJ, Yang X, Staggenborg SA, Welch SM, Apley MD (2013) Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. Proc Natl Acad Sci 110(37):E3477–E3486

Strosser P, Montginoul M (2001) Vers des marchés de l'eau en France ? Quelques éléments de réflexion. Annales des Mines, Responsabilité et Environnement 23:13–31

Swierzbinski JE (1994) Guilty until proven innocent-regulation with costly and limited enforcement. J Environ Econ Manag 27(2):127–146

Terrell B, Johnson P, Segarra E (2002) Ogallala aquifer depletion: economic impact on the Texas high plains. Water Policy 4(1):33–46

Thompson CL, Supalla RJ, Martin DL, McMullen BP (2009) Evidence supporting cap and trade as a groundwater policy option for reducing irrigation consumptive use. J Am Water Resour Assoc 45:1508–1518

Van Kirk RW, Naman SW (2008) Relative effects of climate and water use on base-flow trends in the lower Klamath basin. J Am Water Resour Assoc 44(4):1035–1052

Van Vugt M (2009) Averting the tragedy of the commons: using social psychological science to protect the environment. Curr Dir Psychol Sci 18(3):169–173

Vial I, Lalement R, Deronzier G (2010) De l'état des eaux en 2009 aux objectifs 2015. Office national de l'eau et des milieux aquatiques (Onema) Paris

Weitzman ML (1980) The "ratchet principle" and performance incentives. Bell J Econ 11 (1):302–308

Wines M (2013) Wells dry, fertile plains turn to dust. New York Times 19 May

World Bank (2011) Chile: Diagnóstico de la gestión de los recursos hídricos. The World Bank, Washington, DC

Young RA (1986) Why are there so few transactions among water users? Am J Agric Econ 68:1144–1151

Zhang L, Wang J, Huang J, Rozelle S (2008) Development of groundwater markets in China: a glimpse into progress to date. World Dev 36(4):706–726. doi:10.1016/j.worlddev.2007.04.012

Liberation or Anarchy? The Janus Nature of Groundwater Use on North Africa's New Irrigation Frontiers

23

Marcel Kuper, Nicolas Faysse, Ali Hammani, Tarik Hartani, Serge Marlet, Meriem Farah Hamamouche, and Fatah Ameur

Abstract

Two contrasting views prevail on groundwater use in situations of predominantly state-led irrigation development. The first considers 'groundwater as liberation', i.e., how, by capturing the irrigation initiative, farmers liberated themselves from 'state' water, enabling more intensive and productive agriculture. The second view – 'groundwater as anarchy' – considers groundwater as a

M. Kuper (✉)
Cirad, Umr G-Eau, Montpellier, France

IAV Hassan II, Rabat, Morocco
e-mail: Marcel.kuper@cirad.fr

N. Faysse
Cirad, Umr G-Eau, Montpellier, France

National Agronomy School (ENA), Meknes, Morocco

A. Hammani
IAV Hassan II, Rabat, Morocco

T. Hartani
ENSA, El Harrach, Algeria

S. Marlet
Cirad, Umr G-Eau, Montpellier, France

National Research Institute in Rural Engineering, Water Management and Forestry (INRGREF), Tunis, Tunisia

M.F. Hamamouche • F. Ameur
Cirad, Umr G-Eau, Montpellier, France

IAV Hassan II, Rabat, Morocco

ENSA, El Harrach, Algeria

A.J. Jakeman et al. (eds.), *Integrated Groundwater Management*,
DOI 10.1007/978-3-319-23576-9_23

declining resource, overexploited by millions of individualistic farmers in the absence of effective groundwater governance with mounting inequalities in groundwater use. We analyse the Janus nature of groundwater in the expanding groundwater economy in Morocco, Algeria and Tunisia. Groundwater has redesigned irrigation frontiers, and caters to over 60 % of the total irrigated area, supplying more than 500,000 farms with irrigation water. However, more than half of the aquifers are overexploited, and typically only 40–50 % of farmers in a given area access groundwater. We conclude that groundwater use in North Africa cannot be qualified as anarchy, but rather as a negotiated disorder where the interests of farmers, the private sector, and the state, are continuously realigned. Groundwater 'liberated' farmers only partially from 'state' water, as the state has remained present in groundwater economies. Moreover, groundwater concerned a minority of farmers, who are often keen to get state support when facing resource depletion or harsh agricultural markets. Breaking the current conundrum will require creating space for change, by making visible the current and future effects of groundwater dynamics to local actors, and supporting the building of coalitions of actors towards a sustainable agricultural use of groundwater.

23.1 Introduction: Private Groundwater Use in a Context of State-Led Irrigation Development

The development of irrigation in North Africa in the twentieth century was long associated with state-implemented large-scale surface irrigation schemes. This masked the less visible but continuously increasing exploration and development of groundwater resources (Swearingen 1987; Côte 2002; Mamou and Kassah 2002). The increase in the use of groundwater probably remained more or less unseen – from the State's point of view – because groundwater was used by private settlers or communities, "*without order or specific plan*" (Chevalier 1950). The rapid and massive development of groundwater use, especially since the 1980s, has changed this viewpoint. Today, groundwater is delivered through hundreds of thousands of mostly private (tube-) wells to more than 500,000 farm holdings in Algeria, Morocco and Tunisia, irrigating more than 1.75 million ha, and opening up new irrigation frontiers every day.

Two contrasting views prevail in the literature on the emergence of a *groundwater economy*, especially in countries with predominantly State-led irrigation development (Shah 2009). The first considers 'groundwater as liberation', i.e., how, by recapturing the irrigation initiative, farmers 'liberated' themselves from *State water*, and consequently from increasingly inadequate irrigation services, compulsory cropping patterns, and more generally from the "*implacable order of an extraordinary authority that is at the origin of the distribution of life*" (Pascon 1978). According to this view, private groundwater use enabled more intensive and productive agriculture. Siebert et al. (2010) estimated that 113 out of 300 million ha in the world are currently irrigated with groundwater. Groundwater-based systems generate annual revenues of $210–230 billion (Lopez-Gunn and Llamas 2008; Shah 2009), and are economically three to ten times more efficient than surface water systems (Llamas and Martinez-Santos 2005). Groundwater also provides social status, as farmers who are part of the groundwater economy qualify themselves as 'modern' (Quarouch et al. 2014). Finally, groundwater has a pro-poor aura as it has enabled the survival of many small-scale farms with insufficient access to surface irrigation (Penov 2004; Kuper et al. 2012).

The second view – 'groundwater as anarchy' – considers groundwater as a declining resource, overexploited by millions of individualistic farmers in the absence of effective groundwater governance (Shah 2009). More than 10 % of the world's food production depends on aquifers that are overexploited and threatened (Postel 1999). In addition, inequalities in groundwater access, often building on the individual's position in society, were shown to contribute to marginalization of certain categories of farmers and to favour social differentiation (Prakash 2005; Amichi et al. 2012). According to this view, the growing *anarchy* in the exploitation of groundwater for irrigation is due to 'inherent' features of the groundwater economy, i.e. the rapid development of mostly 'illicit' tube-wells at the initiative of private farmers, the diffuse and relatively cheap access to groundwater through individual pumps, limited scientific knowledge and data, and the political weight of groundwater users (Allan 2007; Moench 2007; Shah 2009). Such features make conventional management responses to groundwater overexploitation, including administrative regulation, economic instruments, water markets, community management, generally at best a theoretical exercise far from reality in the field (Moench 2007). In India for example, such "*policy measures... have all been discussed ad nauseum... as the groundwater situation is turning from bad to worse*" (Shah et al. 2003).

Both views acknowledge the weaknesses of the state in controlling the dynamics of groundwater economies; the first one praises this situation, while the second one laments it. They describe the state as the main *absentee* of these new dynamics. But is this really the case in Algeria, Morocco and Tunisia, where the state had such a prominent role in earlier surface irrigation development? In this chapter, we want to explore the dynamics of groundwater economies: their growth and the new irrigation frontiers they set, what takes place at farm level, and the imminent risks at farm and aquifer level. This will help us reconsider whether the state is as absent as it seems at first sight, and whether it should remain so. To do so, we acknowledge the Janus nature of groundwater, as both an "*enabler of important rural socio-economic transition*", but which is exploited by "*short-term water-using practices*" and presided over by *passive* political economies (Allan 2007). We provide a brief history of the emergence and size of the groundwater economy at national level, and we analyse the pathways of some contrasting local groundwater economies in order to engage the debate on current groundwater use practices, the actors involved (and those who are excluded).

23.2 The Emergence of the Groundwater Economy

23.2.1 Groundwater Use Was Long Masked by Large-Scale Irrigation Development (1920–1980)

Algeria, Morocco and Tunisia have a long-standing tradition of using groundwater for irrigated agriculture. Communities created and managed irrigation systems, including groundwater-based systems such as the *foggara* or *khettara* systems, which are "*subterranean aqueducts engineered to collect groundwater and channel it to surface canals*" (Lightfoot 1996), but also through artesian wells and springs. In the twentieth century, surface and groundwater resources were progressively placed in the public domain, thereby limiting traditional water rights in time and in space, and liberating water resources for "State water" (Pascon 1978; Riaux 2013). This allowed the different States, first under French (in)direct rule, then after Independences, to develop State-managed large-scale irrigation. Not a single drop was to go to the sea (Swearingen 1987), and 980,000 ha of large-scale irrigation schemes were developed in Algeria, Morocco and Tunisia from 1920 to 1980, providing access to irrigation water to hundreds of thousands of farmers (Benmoufok 2004; El Gueddari 2004; Al Atiri 2007).

These large-scale State-led projects masked the more discreet exploration and development of groundwater resources mainly by French settlers, who installed tube-wells from the late nineteenth century and beginning of the twentieth century onwards, often encouraged by the States themselves (Swearingen 1987; Côte 2002; Mamou and Kassah 2002). In Algeria, for instance, there were about 12,000 tube-wells operational by 1960 (MRE 2009). The attention of the State was only episodically drawn to groundwater resources for two main reasons. First, the exploitation of groundwater resources was increasingly considered a profitable economic activity.[1] Hydro-geologists undertook several studies to determine the potential yield of aquifers, and the economic interest of exploiting them for irrigation. These studies were followed by public programmes to drill tube-wells of considerable depth (100–200 m), for example during the 'artesian campaigns' in the oases in southern Algeria from 1856 to 1878 (Jus 1878), or the Moroccan programme in the 1920s to encourage private settlers (Célérier and Charton 1925). Second, by 1950 the first problems of overexploitation of aquifers appeared, especially in the coastal areas, where export-oriented horticulture had led to intensive groundwater use. This led to a drop in groundwater tables and even to problems of marine salt intrusion (Monition and de Lesguise 1954). Similarly, there were concerns about the loss of artesianism of sources, for example in oases in southern Tunisia (Mamou and Kassah 2002). In the early twentieth century, the

[1] From a more political perspective, Swearingen (1987) described how providing access to groundwater was thought to help pacify rebellious areas. In 1929, "wells of security" were installed to "fix to the soil" nomadic tribes in the Tadla area (Morocco): "As one newspaper editor paraphrased a Lyauté maxim: A well is worth a battalion".

States reacted by incorporating groundwater resources in the public domain, by establishing procedures for the authorization and payment of water fees, and by conducting scientific studies to find solutions to the problems that were beginning to appear.

23.2.2 Development of an Informal 'Groundwater Economy' (1980 to Date)

From the early 1980s onwards, large-scale exploitation of groundwater for agriculture began in Algeria, Morocco, and Tunisia (Mamou and Kassah 2002; Hammani et al. 2009). The State initially encouraged groundwater exploitation to compensate for severe droughts by drilling deep state-owned tube-wells. Stimulated by expanding agricultural markets, on their own initiative, farmers rapidly took over and hundreds of thousands of private (tube-) wells were created (Mamou and Kassah 2002). Farmers increasingly preferred tube-wells to wells. The rapid expansion of tube-wells was due to declining water tables, but also to relatively cheap technologies both for installing them, which was generally handled by informal service providers capable of drilling deep tube-wells in only a few days, and for running them. The supply of energy for the tube-wells was often indirectly subsidized (butane gas in Morocco, electricity in Algeria and Tunisia), and the cost of equipping the tube-well (pump, engine) went down. Rural development programmes enabled the electrification of many tube-wells.

The flexible use of groundwater allowed the intensification and diversification of existing farming systems, and strengthened farmers' economic conditions. At the same time, farmers also became exposed to new risks, related for instance to fluctuating market prices for agricultural products. Intensive groundwater use in Algeria, Morocco and Tunisia enabled the development of a 'vibrant wealth-creating agriculture', to which Shah (2009) – in the South-Asian context- referred to as the 'groundwater economy'. This represents a social-ecological system (see also Chap. 3), where socio-economic and biophysical dynamics are interdependent. The system combines two extremely complex systems: (1) the aquifer system, where 'virgin' recharge and discharge mechanisms and groundwater abstraction through tube-wells are intimately intertwined; and (2) a "*people's irrigation economy' in which the initiative, investment, and management have come primarily from farmers*" (Shah 2009). Farmers stimulated the development of a huge grey support sector through their ever-increasing demand for services, including the installation of tube-wells, the supply of inputs (seeds, fertilizers, herbicides and pesticides) and farm equipment (including irrigation equipment), counselling, and the sales of agricultural products (Poncet et al. 2010). This support sector in turn accompanied and even stimulated the expansion of groundwater-based agriculture.

The groundwater economy in Algeria, Morocco and Tunisia involves different territories. First, access to groundwater converted pastoral land, land dedicated to rain-fed agriculture, and even waste land into land used for irrigated agriculture, thereby creating new irrigation frontiers. Referred to as 'private irrigation', this is the context in which the most rapid and extensive growth of the groundwater economy occurred. From the mid-1990s onwards, the increasing use of groundwater was often accompanied by pressurized piped irrigation (particularly drip irrigation) in a mutually reinforcing process. Access to groundwater enabled farmers to increase their irrigated area without connecting to existing surface irrigation systems, and pressurized irrigation could be practiced in areas where surface irrigation could not (sandy soils, unsuitable relief).

Second, paradoxically, groundwater use also involved large-scale surface irrigation systems, which were affected by water scarcity. For instance, in the 100,000 ha Tadla irrigation scheme in Morocco, the number of (tube-) wells rose from a few hundred in the early 1980s to about 8,300 in 2008 (Hammani et al. 2009). This marked the transition from irrigation overwhelmingly based on *flow* irrigation to irrigation also, and increasingly, relying on *pump* irrigation (Shah 2009). This transition can be explained by the increasing demand for water for intensive agriculture in these schemes, as the droughts in the 1980s had affected the surface water supply, but also by the fact that the groundwater economy “liberated” farmers from State-led agriculture, in which even cropping patterns were imposed (Kuper et al. 2009). Nevertheless, farmers generally continued to use both water resources, as surface water was usually cheaper, and farmers were also keen to maintain a relationship with the State (ibid.).

Third, a number of community-managed irrigation schemes continued to rely on groundwater resources. This was the case of the *khettara/foggara* systems in the Atlas and Saharan areas, and of the irrigation systems in the piedmont, which relied on springs. A considerable number of public tube-well irrigation schemes also continued to function in Algeria and Tunisia. These were generally deep tube-wells, installed on State initiative, with collective access to groundwater for farmers’ associations. However, community-managed irrigation schemes are increasingly faced with individual initiatives of farmers or private investors installing tube-wells, either inside these systems, or (more often) in the vicinity of these systems. For instance, in southern Tunisia, Mekki et al. (2013) reported that both the irrigated area and the total water abstraction increased fivefold from 1970 to 2008. The appearance of pump irrigated ‘modern’ agriculture often jeopardized ‘traditional’ flow irrigated systems, sometimes leading to their destruction (Popp 1986).

23.3 Magnitude of the Groundwater Economy Today

23.3.1 Observing a Furtive Groundwater Economy

Official statistics on groundwater-based systems, and more particularly those pertaining to individual pump irrigation, are generally difficult to obtain. The data are fragmented and diffuse, mirroring the image of the furtive groundwater economy itself. The information is in the hands of different administrations, who commission private consultants to conduct surveys whose results are not always made public. The FAO Aquastat database, for instance, which we accessed on July 15th 2013, provided figures for groundwater-irrigated areas that date back to 2000 (Morocco, Tunisia), and 2001 (Algeria)! A scholar who wishes to understand the magnitude of the groundwater economy faces a number of problems, which we discuss further below: (1) the groundwater economy is often considered to be a private business by its protagonists, and the legitimacy of the State to even collect data is frequently challenged; (2) the diffuse, and often informal nature of the rapidly developing groundwater economy makes it an extremely complex system to observe; and (3) aquifer dynamics are complex, even more so when they are intertwined with human practices.

23.3.1.1 A Furtive Economy

The groundwater economy is mainly a private irrigation economy developed during a period when the dominant paradigm called for the State, already in the process of disengaging, to get out of the way of private initiative. Not only did the State install fewer public pumping schemes, but even controlling the development of individual wells and tube-wells was often impossible. "Illegal" private (tube-) wells, which are often not included in official statistics, account for the vast majority of pumping devices. Many actors of the groundwater economy are "invisible", since they crop and irrigate the land under informal contracts as lessees or tenants, while equally informal intermediaries provide inputs, credit, and sell their agricultural products (Daoudi and Wampfler 2010). In the Mitidja plain (Algeria), for instance, Imache et al. (2010) estimated that 23 % of the volume of irrigation was used to irrigate horticultural crops grown by lessees whose presence is not officially acknowledged, through informal water transactions. Even when farmers declare their tube-well, they tend to make their declaration conform to current legislation, and not to field realities. This may lead to tube-wells installed inside wells, so they can be declared as wells. This also often leads to farmers under-declaring the depth of their tube-well. For example, a farmer we met in Kairouan (Tunisia) in 2012 had a 120-m deep tube-well, which he had declared as being 50 m deep. Fifty metres is the limit for water-lifting devices to qualify as 'surface wells', which were tolerated by the administration. As we met him after the Tunisian "revolution" in 2011, he was proud to show us his tube-well, which in his view almost qualified as an act of resistance against the previous regime: "*in the past, I had to cover it with plastic, but now I am free to show you my tube-well*". This is a good example of law breaking (i.e. ignoring the official ban on drilling beyond a depth 50 m), but is also symptomatic of the continuous negotiation between the State and irrigators, which certainly influenced the expansion of groundwater use.

23.3.1.2 Surveys Are Out of Date the Day They Are Published

The 'atomistic' informal nature of the groundwater economy, which relies on individual and diffuse access to groundwater, along with its extremely rapid development makes it difficult to monitor (Shah et al. 2003; Moench 2007). In addition, in Algeria, Morocco and Tunisia, mixing resources is common; for example, in large-scale surface irrigation schemes most farmers also have access to groundwater through private pumps, or in Saharan oases, making it difficult to distinguish between areas irrigated with surface water or groundwater. Occasionally, extensive regional or national surveys have been undertaken to count the number of (tube-) wells and determine the areas irrigated by groundwater. A survey on 'private' irrigation financed by the World Bank was conducted in Morocco in 2002, while in Algeria a survey was conducted in 2009 (Bouchedja 2012), and in Tunisia in 2010. These surveys are often incomplete, and are out of date the day they are published. At any time, farmers may close wells which run dry, deepen them, or convert wells into tube-wells, while ever increasing numbers of farmers join the groundwater economy each day by installing new tube-wells. Others obtain access to groundwater through informal water transactions, which are difficult to account for without close observation. Then again, even when the number of wells and tube-wells is known, this does not provide information on groundwater use. Field observations in the Tadla (Morocco) revealed considerable differences in the use of similar tube-wells (depth, discharge, source of energy) between neighbouring small and medium-scale farmers (Kuper et al. 2003). The annual utilization rate varied from 600 to 1,870 h, and the annual volumes pumped from 32,000 to 101,000 m^3, depending on the crops grown, irrigation practices, the area served, and the number of farmers who relied on the tube-well. The inherent complexity of groundwater use means it is often estimated for regional water balances rather than established in the field.

23.3.1.3 Overexploitation, an Established Fact?

Aquifer dynamics are extremely complex and the values of different hydrological parameters vary considerably under different scenarios of change, including climate change, and human practices such as pumping. This makes modelling groundwater and predicting the behaviour of a particular groundwater system a difficult exercise (Rojas et al. 2010). Whether groundwater comes from renewable or non-renewable sources, and to what extent specific aquifers are overexploited is the subject of lively debate (Konikow and Kendy 2005). While major uncertainties remain on the hydrological impact of recent rapid changes, including groundwater pumping, hydro-geologists agree that the "*present development of agriculture is... unsustainable*" (Leduc et al. 2007). River basin agencies routinely present graphs of declining groundwater tables. Perhaps more surprisingly, most groundwater users are also aware of the coming groundwater crisis (Bekkar et al. 2009), and some even anticipate their *exit* from groundwater-related agriculture. Groundwater resource overdraft is no longer an issue only pointed out by hydro-geologists (e.g. Llamas 1998), but has become common discourse. But up to now, this apparent consensus has not led to using existing information for better management of groundwater use in the region (Hammani et al. 2009). This pleads for more attention to be paid to the *use* of information, as much as to the production of information, and hence to obtaining more insights into the users' point of view of groundwater exploitation (Mitchell et al. 2012).

23.3.2 Official Figures: Redrawing the Irrigation Map in North Africa

Despite the difficulties of obtaining data on the groundwater economy in Algeria, Morocco and Tunisia, and the doubt surrounding the accuracy and utility of such data, we synthesized – to the best of our knowledge – some figures based on the different national statistics (Table 23.1). This exercise is fraught with danger, and

Table 23.1 Official figures concerning the groundwater economy in Algeria, Morocco and Tunisia

	Algeria	Morocco	Tunisia
Total irrigated area (ha)	1,006,198[a]	1,458,160[b]	404,375[c, d]
Area irrigated by groundwater pumps (in ha and as % of total area)	883,004[a, e] 88 %	615,881[b, f] 42 %	258,547[c, g] 64 %
Total annual renewable groundwater resources (km^3)	7.1[h, i]	4.1[j]	2.2[k]
Annual groundwater withdrawal for irrigation (km^3)	8.1[l, m]	3.5[j]	2.0[k]
Annual groundwater withdrawal for drinking water (km^3)	1.6[a]	0.4[j]	0.4[c]
Number of overexploited aquifers/total number of aquifers	North: 23/38[l] South: all[l]	57/99[j]	71/273[n, o]
Number of (tube-)wells for irrigation	144,050 wells[a] 62,967 tube-wells[a]	100,000[b]	137,709 wells[k, p] 6,167 tube-wells[c]

[a]MRE (2011)
[b]MAPM (2012)
[c]DGGREE (2006)
[d]The total irrigated area of 'intensive' irrigated agriculture in 2013 was 416,000 ha (DGGREE). The area irrigated by groundwater is certainly underestimated, as farms in public surface irrigation schemes (138,248 ha in 2006) may use groundwater
[e]This includes the area irrigated by wells (316,198 ha) and tube-wells (486,806 ha) in small- and medium-scale irrigation schemes, and pump irrigation in large-scale irrigation schemes (~80,000 ha; Benblidia 2011)
[f]This includes "private irrigation" (435,881 ha), and pump irrigation in large- as well as small- and medium-scale irrigation schemes (~180,000 ha)
[g]This includes 180,283 ha of private irrigation and 78,264 ha of public tube-well schemes
[h]Bouchedja (2012)
[i]This includes 5 km^3/year of non-renewable or little renewable groundwater resources in the Sahara
[j]Ziyad (2007), ABH (2011)
[k]DGRE (2005, 2008)
[l]MRE (2009)
[m]Value estimated on the basis of cropped areas and theoretical crop water requirements
[n]TICET (2009)
[o]Tunisia identified a higher number of aquifers than the other countries as it privileged a local management perspective (Faysse et al. 2011)
[p]According to the Ministry of Agriculture, only 94,691 out of 137,709 wells were 'equipped' with a pump/engine (DGGREE 2006)

the figures should be interpreted with great caution. Despite these reservations, we feel this is a useful exercise, as it provides some idea of the comparative importance of the groundwater economy in the three countries. If considered in conjunction with more detailed local studies, these figures provide an interesting perspective of the rapidly evolving, informal, atomistic groundwater economy.

Three conclusions can be drawn from this table. Firstly, it shows the importance of the groundwater economy in these three countries. According to these data, the groundwater economy caters to more than 1.75 million ha of irrigated land (more than 60 % of the total irrigated area), farmed by probably more than 500,000 farm holdings (293,033 farm holdings in Algeria alone). The countries regularly publish information on the substantial added value of irrigated agriculture for which groundwater has become indispensable. In Morocco, the High Commission for Planning (2008) stated that in an average year, the irrigated sector, while only accounting for 13 % of the agricultural area, contributes about 45 % of agricultural added value, and 75 % of agricultural exports and accounts for 35 % of rural employment. The irrigated sector is responsible for all citrus and sugar production, and supplies 80 % of horticultural products, fodder and milk. Twenty per cent of meat and cereals come from irrigated areas. At the same time, the groundwater economy appears to benefit a minority of farmers. From the official agricultural census in the different countries, it can be deduced that only 20–30 % of all farmers have access to groundwater.

Secondly, the official data show that the current status of aquifers is not good. More than half the aquifers in Algeria and Morocco, and about one quarter of the aquifers in Tunisia are overexploited, and the potential of aquifers in Tunisia is severely limited by salinity. All three countries rely to a considerable extent on groundwater resources, especially Algeria (88 % of the total irrigated area, Table 23.1) and Tunisia (64 %). Morocco (42 %) benefits from more generous (renewable) surface water resources. This is probably why, as opposed to Algeria and Tunisia, Morocco never developed many public tube-well schemes. In Tunisia public tube-well schemes officially still account for 30 % of the pump-irrigated area. This figure is certainly overestimated, as farmers installed private tube-wells even inside public irrigation schemes. According to official statistics the groundwater economy in Algeria, Morocco and Tunisia is served by about 450,000 (tube-) wells for a total withdrawal for irrigation of 13.6 km^3; these values are probably the most questionable figures in the table due to the difficulty of keeping track of the (tube-) wells, and of monitoring the withdrawals. In all three countries, farmers are increasingly turning to tube-wells, whereas the total number of wells is not progressing, or is even declining. Farmers are accessing deeper (confined) aquifers, where the supply – in the short term – is better, but where the water resources are even less renewable. Finally, some of the most rapidly growing irrigated areas were based on the mining of non-renewable groundwater resources (Margat 2008).

Thirdly, when comparing these data with earlier official data, (available on the FAO database) it appears that the groundwater economy has expanded at a remarkable pace. Nowhere is this clearer than in Algeria, where the irrigated area increased from 228,000 ha in 1985 to slightly over a million ha in 2011. While the latter figure may be optimistic, there is no doubt about the galloping development of Algeria's groundwater economy. Algeria's irrigation map was redrawn after the exploitation of huge groundwater reserves in the south, ranking the country second only to Libya in terms of available groundwater resources in Africa (MacDonald et al. 2012).

23.3.3 Policy Measures

Irrigated agriculture has been consistently and "*disproportionately prominent in national water allocation policy discourse*" in the Middle East and North Africa's political economies (Allan 2007). Irrigated farming was not only a "*deeply entrenched social phenomenon*" (ibid.), but was also considered to be a political priority in building the independent Nation (Akesbi and Guerraoui 1991). Policies initially focused on building dams for surface irrigation but, from the 1970s on, groundwater resources were included in water master plans, as surface resources gradually became insufficient (Al Atiri 2007).

For many years, groundwater was mainly seen as a complementary resource that could be used for more intensive irrigated agriculture. Following the 1992 Dublin conference, international discourse on integrated water resources management gained importance in the Mediterranean area and coincided with increasing awareness of the limits of existing water resources (Margat and Vallée 1999). These debates inspired recent water laws and strategies in Algeria, Morocco and Tunisia, leading to institutional reforms (e.g. the creation of river basin agencies), and to a series of measures promoting the *rational* use of water (El Alaoui 2006; Al Atiri 2007; Benblidia 2011). Basically, the idea was to promote *water demand management* as opposed to a *supply-based approach*, as the latter had led to ever-increasing pressure on water resources (Margat and Vallée 1999). Agriculture was specifically targeted as a sector in which water was 'wasted.' Water demand management meant identifying possible ways of saving water, so water could be used more productively, while decreasing the existing pressure on water resources. However, the different economic, regulatory and participatory instruments proposed and debated never focused on water demand management alone, and the different states continued to explore ways to increase the water supply, for example through desalination (Benblidia 2011).

Faysse et al. (2012) conducted an inventory of the different policy instruments focused on groundwater, implemented and discussed in Algeria, Morocco and Tunisia on the basis of the expected impacts: (1) direct regulation of the water demand (authorization, control of extracted volumes); (2) incentives for water demand management (tariffs, subsidies for micro-irrigation); and (3) measures for increased water availability (desalination, groundwater recharge). In addition, a limited number of initiatives on participatory instruments were identified, including groundwater users associations in Tunisia, and aquifer contracts in Morocco (ibid.). There has been little public debate on the environmental, social, and economic sustainability of the groundwater economies in the region. The question is whether the future pathways of these groundwater economies only concern farmers who are currently overexploiting them? Or do they also concern farmers who currently have no access? When dealing with groundwater overexploitation today, it is probably more realistic to first involve farmers who pump large volumes. If the stakes related to equity, rural poverty or agricultural productivity were taken into account, the debate could extend to rural areas, or even to society at large.

After more than a decade of lively debate and policy initiatives promoting water demand management, paradoxically, irrigated agriculture appears to be no longer in the 'dock' for wasting water, even though in the meantime the pressure on groundwater resources has increased. This increased pressure may be partly due to recent ambitious agricultural policies (e.g. the 2008 Green Morocco Plan), which promote modern "*excessively intensive*" agricultural models with increased pressure on water resources (Akesbi 2014). In parallel, the agricultural sector started several subsidy programmes for water saving irrigation technologies, especially drip irrigation. The amount of water saved as a result of these programmes has rarely been evaluated (Benouniche et al. 2014), but the programmes were probably essential in providing agriculture with a more positive image of "*efficiency, productivity and modernity*" (Venot et al. 2014). Through the "*alignment of farmers' interests and those of the political class*" (Allan 2007), solutions are once again being sought in supply management approaches (desalination, inter-basin transfers) or in technological inventions, such as water saving irrigation technologies.

23.4 Illustrating the Rapid Massive Development of North Africa's Groundwater Economy

We use two contrasting case studies to illustrate the diversity of the different local groundwater economies encountered in North Africa, focusing on the three issues mentioned in the introduction, i.e. the apparent contradiction of groundwater as an "*enabler of an important rural socio-economic transition*", used with "*short-term water-using practices*" and presided over by *passive* political economies (Allan 2007). The first case study concerns the Biskra district in the Algerian Sahara (less than 150 mm of rain annually), where the rapid irrigation development relies almost exclusively on non- or little renewable groundwater resources (Fig. 23.1). The second case study was conducted in the rich agricultural Saiss plain in northwestern Morocco (with 400–600 mm rainfall regime), where farmers turned to irrigated agriculture by exploiting a rich but overexploited aquifer system (Fig. 23.2).

23.4.1 Biskra: Why Deal with the Problems Now?

Groundwater experts put North African countries such as Algeria and Libya on the map as the most water-rich countries of the continent thanks to enormous, but not very actively recharged, sedimentary Saharan aquifers (MacDonald et al. 2012).

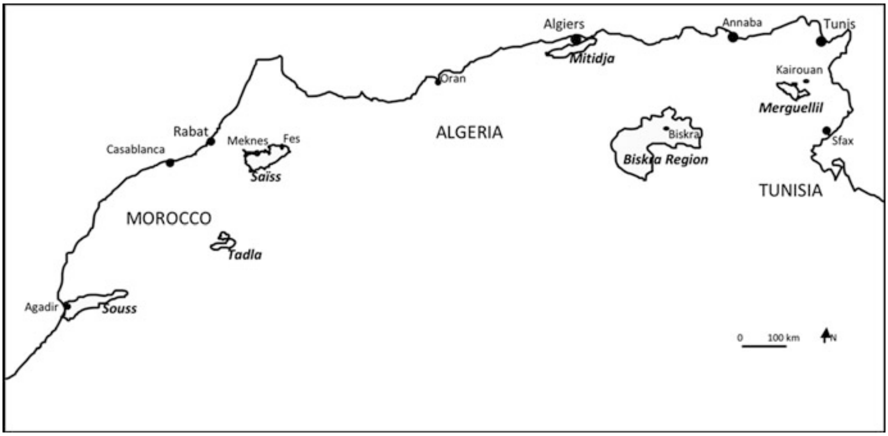

Fig. 23.1 Location of the case studies in North Africa

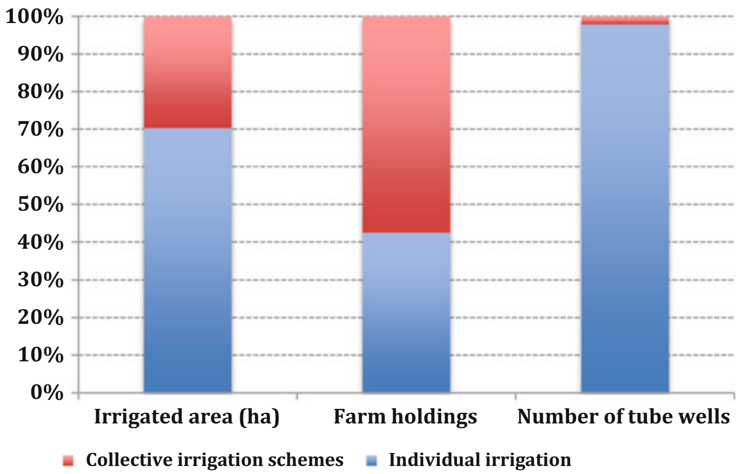

Fig. 23.2 Private and collective irrigation in the Biskra district (Source: MRE 2009)

These countries did not stand out in FAO irrigation statistics in the past due to limited development of State-led irrigation, but rapid private irrigation expansion linked to groundwater is changing the outlook and scale of the irrigated sector. In Algeria, groundwater is shifting the balance between traditional irrigated areas in the North, and rapidly developing irrigated agriculture in the Sahara.

Oases had been declining since the sixteenth century with the demise of Trans-Saharan trade when an astonishing agricultural revival started in the early twentieth century linked first to the exploration of new artesian tube-wells, and more recently to pump irrigation. Groundwater allowed the rapid expansion of palm groves in the Algerian Sahara, which increased from 5.5 million palm trees in 1959 to 12 million in 2000, and to 17 million in 2011 (Côte 2002; Benziouche et Cheriet 2012). The rapid agricultural development of the Biskra district made it one of the most important Saharan agricultural regions in Algeria. The irrigated area increased fivefold from 16,615 ha in 1969 to 83,350 ha in 2008 and 94 % of the irrigation water is currently supplied by groundwater through 4,293 wells and 9,075 tube-wells (MRE 2009).

While palm groves were traditionally irrigated through community-managed collective irrigation schemes around artesian wells, springs, or diverted river flow, more than 70 % of the total irrigated area is now qualified as private or individual irrigation areas (Fig. 23.2). The figure confirms the rapid expansion of private irrigation, which took place mostly outside the traditional oases. However, collective irrigation schemes continued to serve almost 60 % (19,305 farms) of the total number of irrigated farm holdings in the Biskra district. These collective schemes are served by powerful tube-wells (>100 l/s) or more rarely, by artesian wells, in some cases enhanced by surface water or springs. This explains the limited number of tube-wells in these schemes, according to official data (Fig. 23.2).

In the next two sections, we will show first how groundwater was integrated into the existing farmer-managed surface irrigation system of the oasis of Sidi Okba through a complex mix of private and collective (tube-) wells. The state played an important role in unlocking the access to groundwater. We will then present the new irrigation frontiers, outside of the oases, where groundwater is accessed through private tube-wells enabling commercial date production and greenhouse horticulture.

23.4.1.1 Traditional Oases: Integrating Groundwater in the Existing Farmer-Managed Irrigation System

Access to water resources in traditional oases is rather complex. We analysed changes in access to groundwater in the 970 ha Sidi Okba palm grove, situated in the Biskra district. This mythical palm grove, laid out around the 686 mosque commemorating the Arab conqueror Oqba Ibn Nafaa, was traditionally supplied by surface water (Oued El Abiod), but increasingly relies on groundwater (Fig. 23.3). Officially, the palm grove is irrigated by surface water (Foum El Gherza dam) and five functioning state-created tube-wells managed by a farmers' cooperative. However, there is also a large number of individual or community-owned collective tube-wells. In 2013, a total of 71 State and private tube-wells (collective or individual) were counted of which only 42 were functioning.

Access to groundwater started in the 1920s, when farmers dug hand-operated wells, which they mechanized from 1950 onwards (Fig. 23.3). These wells were progressively abandoned in the 1960s and 1970s. In 1979, access to the confined aquifer was initiated by the State to compensate for dwindling surface water resources following droughts. The State had two-tube-wells drilled to great depths (632 and 807 m, respectively), followed by six more later on. Farmers followed suit and drilled 63 collective and individual tube-wells.

The figure illustrates three main issues of Biskra's groundwater economy. Firstly, the different groundwater resources were successively unlocked over a

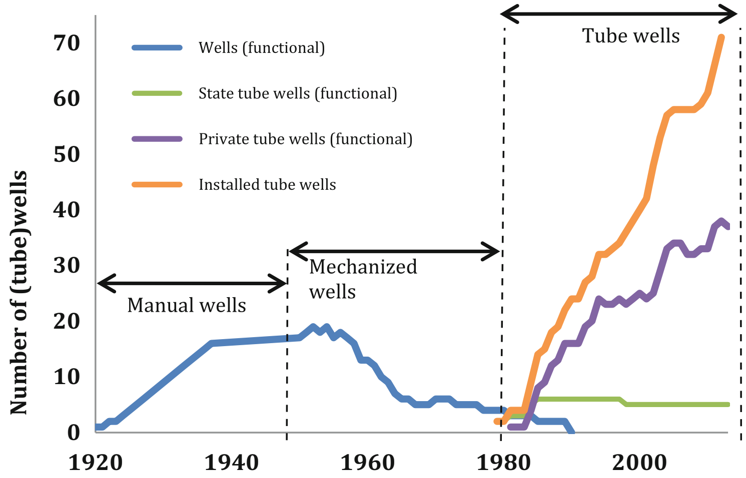

Fig. 23.3 Development of wells and tube-wells in the Sidi Okba palm grove (Biskra region)

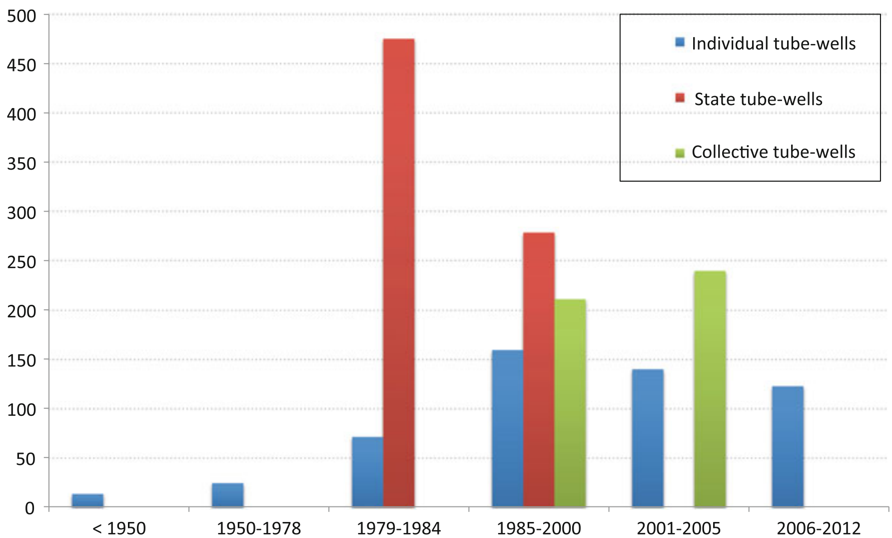

Fig. 23.4 Changes in the depth of (tube-)wells drilled in the Sidi Okba palm grove (Biskra region)

long period of time. Farmers look for water at increasing depth, and as a result, they may even change an aquifer's behavior (Fig. 23.4). While they initially exploited the phreatic aquifer using 10–30-m deep wells or relatively shallow tube-wells (50–70 m), they started drilling deep tube-wells in the early 1980s thereby accessing the first confined aquifer. The State-led drilling of deep tube-wells having a high discharge, and delivering relatively good quality water, prompted farmers to drill individual tube-wells to a depth of 100–150 m. Some even drilled to a depth of 200 m for individual tube-wells, and to 280 m for collective tube-wells. From 2002 onwards, the State managed to impose some norms on the depth of tube-wells, at least on those that were subsidized: individual tube-wells should not exceed 150 m, and collective tube-wells should not exceed 250 m. Groundwater also “liberated” farmers, and especially the former sharecroppers, to go beyond the frontiers of the traditional palm grove, and settle on new lands to establish new farming systems, including commercial dates and horticulture.

Secondly, the State as well as the irrigation community continued to play an important role in managing groundwater, and access did not become entirely private. In the Sidi Okba palm grove, 30 tube-wells (out of 71) were either installed or subsidized by the State, of which 12 were collective tube-wells. The existing farmer-managed irrigation cooperative was able to integrate progressively (part of the) groundwater resources in the collective management of the surface irrigation system. The cooperative continued to distribute surface water, but also included the state tube-wells in the water distribution programme. The irrigation community installed a further 10 collective tube-wells, which were shared by neighbours or relatives. The community even created three larger informal tube-well associations (using four collective tube-wells), where farmers were supplied with water according to the shares they had in the tube-well. This collective organization (20–60 members per association) is perhaps due to the fact that the irrigation community already managed a collective surface irrigation scheme at the time. Collective action is probably also linked to the high cost of accessing confined aquifers at substantial depth. However, in the past 10 years, only individual tube-wells were drilled in the palm grove, encouraged by individual State subsidies.

Thirdly, farmers faced many hazards in accessing groundwater. They progressively abandoned the 37 wells in the palm grove, due to the drop in groundwater levels, and the increasing salinity of the phreatic aquifer. Another problem was the limited know-how of private companies who improvised the installation of tube-wells in the 1980s and 1990s. Some tube-wells became obsolete after only functioning for a few years. Twenty-nine (out of 63) individual and collective tube-wells drilled between 1979 and 2000 stopped functioning (Fig. 23.3), mainly due to the poor quality of the equipment (tubing, pump). The State-installed tube-wells also often broke down because of age and the high cost of repairs. Three out of eight tube-wells in this category are no longer functional today.

23.4.1.2 Outside the Oases: Exploring New Irrigation Frontiers

Outside the traditional oases, palm groves no longer followed the classical three-stage oasis system, but were new mono-cropped plantations focused on the production of *deglet nour*, a readily marketable date for the domestic and export market. More surprisingly, groundwater also enabled new farming systems, in particular greenhouse horticulture (tomatoes, peppers, chillies, aubergines, (water) melons), which arrive early on the domestic markets thanks to favourable climatic conditions. Greenhouse horticulture started in the 1980s, and expanded rapidly (Khiari 2002). Recent figures from the Ministry of Agriculture mention almost

100,000 greenhouses (about 4,000 ha) in 2010. New palm groves and greenhouses spread rapidly in the Biskra district, following the availability of groundwater resources. The region ranks second in Algeria in agricultural production (around 1.24 billion € in 2012), only behind another Saharan region (El Oued). In 2012, Biskra accounted for 37 % of dates grown in Algeria, and for 25 % of tomatoes.

The question is what are the limits to the development of this Saharan groundwater economy? On the one hand, official data imply serious overexploitation of groundwater resources, and ever-increasing numbers of tube-wells. Groundwater use for irrigation in Biskra is estimated to be around 1.2 km^3 per year (MRE 2009), which is 467 % of the volume of the renewable groundwater resources that can be exploited (0.26 km^3/year). However, the different actors largely ignore this "safe yield" (Alley and Leake 2004), and continue to overexploit the different aquifers, including the Continental Intercalaire aquifer, which is non- or little renewable, but represents an enormous reserve (91,900 km^3; MacDonald et al. 2012). Farmers are confronted with decreasing groundwater tables, and frequently deepen their tube-wells.

On the other hand, the Saharan groundwater economy continues to grow rapidly, mainly through private investment and 'resource pooling' (Amichi et al. 2013). Farmers come from hundreds of kilometres away, attracted by the abundant land and water resources of the area, and bring know-how, energy and financial resources. These integrative farming systems continue to attract new financial, and human resources which, in turn, further extend the irrigation frontiers of Saharan agriculture. The State contributed to this development enabling access to land and water by providing agricultural subsidies, but also, and perhaps most importantly, by developing the basic infrastructure to ensure the logistics for intensive agriculture, and support the newcomers (wholesale markets, roads, health facilities and schools, electricity supply).

This illustrates not only Biskra's attraction for private investment in agriculture, but also how private investment is supported by ambitious public policies and investments aiming to "transform the Algerian Sahara into an agricultural *Eldorado*" (Otmane and Kouzmine 2013). In a survey of 150 farmers, 84 % declared they had made substantial investments since 2000 (plantations, pumping station, drip irrigation), and 52 % said they had obtained subsidies for these investments (MRE 2009). However, this mainly concerned established farmers. Most informal actors, particularly in the horticultural sector (tenants, lessees), may not even have been interviewed, as they are generally not registered as farmers. They manage without subsidies, because of buoyant agricultural markets and a strong national demand for fresh vegetables.

In sum, Biskra's thriving groundwater economy continues to develop at a breathtaking pace both inside and outside the traditional oases. The limiting factors which generally limit the development of agriculture (markets, capital, labour, land, water) will surely surface sometime, but in the meantime, business as usual – that is rapid expansion – is likely to continue.

23.4.2 Saiss: "He Has Committed the Crime Who Profits by It" (Seneca)

The Saiss plain is a well-known rich agricultural area in Morocco in the vicinity of Fes and Meknes, covering about 220,000 ha. In the past, the Saiss plain was known for rain-fed crops (cereals, vineyards, olive trees). Some small community-managed irrigation schemes, which depended on springs, made it possible to irrigate certain crops (tobacco, fodder, vegetables). The Saiss always attracted newcomers because of its rich productive resources, and its proximity to Fes and Meknes. During the first half of the twentieth century, French settlers occupied some of the best lands accounting for about one third of the total surface area. Some stayed until 1971. This land was then partly redistributed to landless farmers or labourers who formerly worked on colonial farms. Some lands were grouped in agrarian reform cooperatives under close State supervision, and some were converted into State farms. Both types of agrarian structures disappeared over the past 10 years following structural reforms and State disengagement from direct agricultural production.

Droughts in the early 1980s along with a liberalisation of the agricultural sector prompted a series of rapid transformations whereby the groundwater economy rapidly gained momentum. There was a tremendous increase in pump-irrigated area, but also a decrease in the area irrigated by small-scale surface irrigation schemes. A survey by the Ministry of Agriculture in 2012 showed a total irrigated area of 49,677 ha (out of 220,000 ha), of which 45,316 ha depended on pump irrigation. Today, irrigation caters principally for orchards (olives, plums, peaches, apples), and vineyards, horticulture (onions, potatoes), and fodder crops.

Saiss' rich aquifer system is composed of a phreatic aquifer and the Lias confined aquifer; its potential was explored early on, and some (tube-)wells were installed during the protectorate. According to the river basin agency, groundwater tables have decreased considerably (ABH 2011). Groundwater levels in the phreatic aquifer, generally between 10 and 40 m, decreased by about 10 m between the early 1980s and 2005, with a sharper decline after 2000 when water levels decreased by about 1 m per year. The decline in groundwater tables was even more marked in the confined aquifer. In the west (Meknes area), the decline was about 65 m between 1979 and 2004, i.e. 2.6 m per year. In the east, the decline was about 20–25 m over the same period.

Field observations conducted in an area of 4,153 ha in the Saiss near the town of El Hajeb illustrate the rapid transformations (Fig. 23.5). In 1989, the area was characterized by the contrast between an irrigated State farm (1,374 ha) and a large collective agrarian reform cooperative (1,888 ha), growing rain-fed cereals. In the cooperative, the land was not attributed to individual farmers, and the assignees basically had the status of labourers working under State supervision. There was no room for private initiative to grow other crops, or change to irrigated agriculture, whereas on a nearby smaller agrarian reform cooperative (340 ha), assignees had been attributed individual plots. They were supposed to work the land together with other assignees, but in practice managed to progressively install wells to irrigate

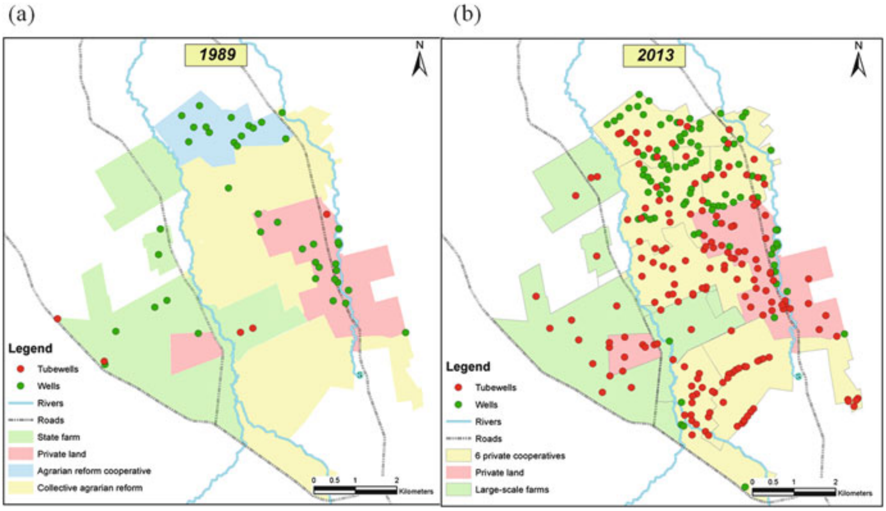

Fig. 23.5 Maps showing the proliferation of wells and tube-wells in the study area (4,153 ha) in the Saiss in 1989 (**a**) and 2013 (**b**)

part of their land in the context of State disengagement. Farmers on private land in the study area (551 ha) also installed wells. In 1989, the total number of pumping stations in the study area was 67, of which 62 were wells, i.e. a density of about 1 (tube-) well for every 62 ha.

In 2013, the situation had drastically changed due to liberalisation. The State farm had been split in two, and leased out to private investors, who continued pump irrigation for orchards and vineyards. In 1991, the collective agrarian reform cooperative was split into small cooperatives with individual plots attributed to the assignees. Assignees diversified cropping patterns, and progressively gained access to groundwater through wells. In 2005, a government decree set off a process of land privatization of the agrarian reform cooperatives; once they had paid off all their debts, assignees could obtain a private land title. During this process, a lively land market emerged, resulting in the massive arrival of newcomers to these often-rich lands. Assignees sold part of their land to pay their debts; some even sold all of their land. Large numbers of farmers (especially newcomers) joined the groundwater economy, but this time mainly through tube-wells which accessed both aquifers. The groundwater-based agricultural boom had considerable consequences for the groundwater availability. In 2013, half the wells (96 out of 193), mostly belonging to former assignees, were no longer functional, largely because they had run dry. But sometimes the farmers did not have the resources to make them function because they had ventured into more risky market crops, and ended up with debts. Other assignees managed to install tube-wells and ensure their access to groundwater. Newcomers generally invested in orchards, which required a tube-well usually with a drip irrigation kit. The total number of functional pumping stations amounted to 275, of which 178 were tube-wells. The density of (tube-) wells in this study area increased to 1 (tube-)well for every 15 ha.

The antagonism between newcomers and local farmers is nowhere more clearly expressed than in the former agrarian reform cooperatives, where different farming models exist side by side. While most of the former assignees practise diversified cropping (cereals, horticulture, fodder) and both irrigated and rain-fed agriculture, newcomers prefer mono-cropped irrigated trees. The assignees mostly rely on wells, and have increasing difficulty in running their well, while the newcomers largely invest in tube-wells. Most of the local farmers, who were previously assignees in the different agrarian reform cooperatives, therefore tend to blame the newcomers, who are referred to as "investors", "buyers", or simply as "foreigners" (to the area), for causing their wells to run dry.

In two former cooperatives in the study area (here referred to as Alif and Ba), we investigated this mounting feeling of inequity in access to groundwater. To our surprise, the vast majority of farmers did have access to groundwater (respectively 88 % and 75 %; Table 23.2), which, in other regions in North Africa, had been shown to be a *first order* inequity where this rate is usually much lower (Hammani et al. 2009). This high rate was probably for the following reasons: (1) the phreatic aquifer was rather shallow, particularly in the 1980s and 1990s; (2) farm holdings were relatively large compared to Moroccan standards, due to the recent distribution of land; (3) some assignees obtained access through tenancy arrangements, whereby the tenant or lessee obtained the land for a period of 5–6 years, and installed a (tube-)well, which reverted to the owner once the lease ended; and (4) the State subsidized the access to groundwater and the irrigated agriculture depending on groundwater.

A *second order* inequity concerned the pump equipment of farmers. The wells of most assignees were not adequately equipped (second-hand engine, vertical axial flow pumps), and could consequently only irrigate about 1–2 ha of land (mainly onions or potatoes). In addition, many of the wells of the assignees are running dry (about 50 % and 25 %, respectively in both cooperatives; Table 23.2). Newcomers, on the other hand, used well-equipped tube-wells, and could easily irrigate 5–8 ha

Table 23.2 Access to groundwater of farmers in agrarian reform cooperatives Alif and Ba (Saiss plain)

	Cooperative Alif	Cooperative Ba
Surface area	340 ha	392 ha
Number of farmers	33	51
Number of farmers having access to groundwater	29 (88 %)	38 (75 %)
Number of tube-wells	12	19
Number of wells	43	31
Functional	22	23
Non-functional	21	8
Irrigated area	33 %	41 %
Rainfed area	67 %	59 %

of orchards. The cost of a fully equipped tube-well was 15,000–25,000 €. The newcomers often had an off-farm income and usually obtained subsidies for investments. As a consequence, in the Alif cooperative, almost all farmers had access to groundwater but only one third of the land was irrigated. In the Ba cooperative, fewer farmers had access to groundwater but the percentage of irrigated land was slightly higher (41 %). The newcomers had more land (53 ha of arboriculture) than in the Alif cooperative (6 ha of arboriculture), which explains the difference in irrigated area.

Groundwater use is likely to increase in the near future, as tube-wells progressively replace wells. Tube-wells in the study area pump at least twice as much water (up to 40,000–65,000 m^3/year) as wells. The extra volumes of water available will likely extend the irrigated area, as almost two-thirds of the area is not yet irrigated. Moreover, newcomers have a mainly economic view of agriculture, with offensive strategies to maximize profits (Bekkar et al. 2009).

A *third order* inequity in the study area related to the economic situation of different social categories of farmers. Assignees had problems obtaining the other agricultural inputs required for irrigated agriculture, which limited their use of groundwater. This has an impact on the volume of water extracted by each category (Fig. 23.6).

Figure 23.6 shows that 3.6 % of the farmers (>20 ha) own more land (44 %) than 82.5 % of the farmers (<10 ha) who own only 40.3 % of the land. In the literature, this well-known skewed landownership is rarely interpreted in terms of the differential contribution of these farm holdings to the overexploitation of groundwater. Instead, this overexploitation is generally attributed to the agricultural sector as a

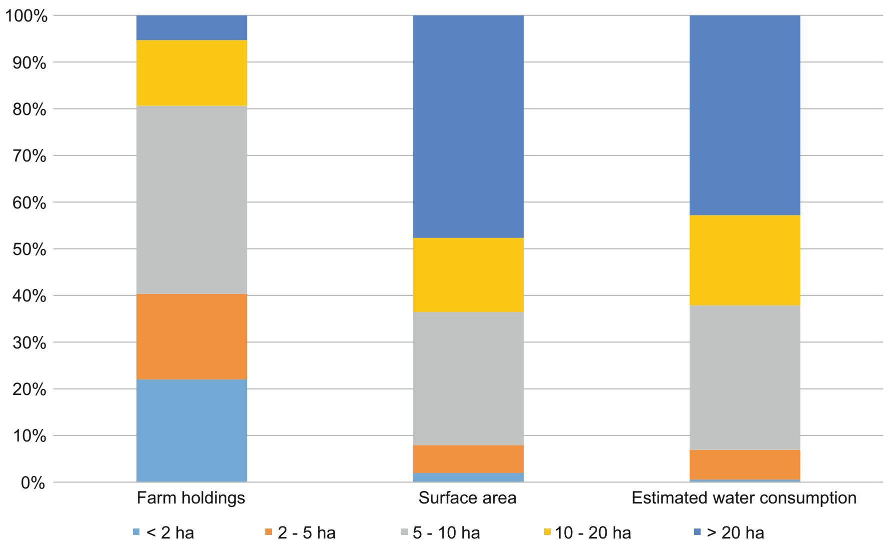

Fig. 23.6 Estimated water consumption (in %) per class of farm holding in the study area, located in the Saiss

whole. Distinguishing the contribution of the different categories of farmers to overexploitation is not easy due to complex agrarian structures and the mobility of farmers, and farmers' irrigation practices, which may lead to fourfold differences in irrigation volumes per ha (Benouniche et al. 2014). This explains the question mark in Fig. 23.6, which we are addressing in our on-going research. In the context of groundwater overexploitation, the question is then, who benefits from groundwater use, and who loses out?

23.5 Three Issues Related to the Rapid and Massive Development of Groundwater Use

23.5.1 Will Overexploitation Continue? Current Groundwater Use Practices in North Africa's Groundwater Economies

Current groundwater use practices have led to overexploitation of a large number of North Africa's aquifers, including some non- or little renewable aquifers. Due to the interplay between the different pathways of local groundwater economies, and the hydraulic characteristics of specific aquifers supporting them, groundwater practices will evolve differently in different situations.

Three main types of groundwater economies can be identified. First, the established medium-sized groundwater economies in northern and central Morocco, Algeria and Tunisia are based on renewable, but overexploited, groundwater resources, sometimes in addition to surface water resources which are exploited in existing irrigation schemes. Most of these groundwater economies have existed for more than 30 years, and each supports several tens of thousands of ha of irrigated agriculture. The groundwater economy of the Souss (Morocco) is probably the oldest and most threatened of all due to the marginalization of certain types of farming and social conflict (Popp 1986; Houdret 2012), brought about by a long history of intensive agriculture (orange trees, horticulture), and limited rainfall and recharge. But tensions have appeared even in more recent groundwater economies with higher precipitation rates like the Mitidja, in Algeria (Imache et al. 2010), Merguellil, in Tunisia (Leduc et al. 2007) or the Saiss (this study).

Second, the burgeoning groundwater economies of the Saharan areas, for example Nefzaoua (Tunisia) and Biskra (Algeria), are based on the exploitation of huge mostly non-renewable groundwater resources. Water is mined in quite a similar way as in the nearby oil fields (Margat 2008), while the local groundwater economy incorporates increasing numbers of farmers and other supporting actors in the current agricultural boom (Côte 2002; Mekki et al. 2013).

Third, minor volatile groundwater economies depend on often-overexploited small aquifers. They can be distinguished from the first type by their smaller size, which brings the tipping point beyond which a groundwater economy enters in a crisis situation much closer. Coastal horticultural groundwater economies are a typical example. Taking advantage of temperate climatic conditions, light soils and shallow groundwater, horticulture is widespread in many locations along the Atlantic and Mediterranean coasts. This led to many critical situations, particularly seawater intrusion, for example around Casablanca (Morocco) in the 1950s, around Azemmour (Morocco) in the 1980s (Berahmani et al. 2012), and north of Sfax (Tunisia) in the 1990s (Trabelsi et al. 2005). So far mainly individual adaptive strategies have been observed. Farmers reacted by piping good quality water in from nearby areas to continue horticulture, but in many cases had to change cropping systems by switching to more salinity tolerant crops or even quit (Berahmani et al. 2012). Local actors also looked to the State to save these groundwater economies, by providing additional surface water resources. However, as yet, there have been no 'success stories' concerning the restoration of the balance of such groundwater economies.

These North African aquifers can be positioned in the successive temporal stages of the rise and fall of groundwater economies, if adopting the frameworks of Shah et al. (2003) and Llamas and Martinez-Santos (2005). These frameworks propose a sequence in the life cycle of a groundwater economy, starting with a first stage in which the groundwater economy slowly emerges ("silent" revolution). The second stage corresponds to an era of groundwater-based agricultural prosperity. In the third stage, the first signs of groundwater overdraft or degradation become apparent, but farmer lobbies generally successfully defend the considerable interests generated by the groundwater economy. During the fourth stage, the decline in the groundwater economy causes social conflict. Conservation lobbies may prevent the groundwater economy entering this stage.

Most established medium-sized, partly renewable, groundwater economies are already positioned beyond the middle of the curves, meaning that there are early symptoms of groundwater overdraft with farmer lobbies defending their share and pushing the government to look for additional supplies, as is the case in the Saiss (Morocco), in the Mitidja (Imache et al. 2010) and in the Merguellil (Leduc et al. 2007). In the case of the Souss, clear signs of decline and social conflict are already apparent (Popp 1986; Houdret 2012). As in South Asia, these groundwater economies generally reached the later stages of the curves in less than 40 years. In these established groundwater economies, overexploitation will probably continue for the time being, while coalitions of privileged farmers and the State actively search for additional water resources, for example through desalination or inter-basin water transfer.

The Saharan groundwater economies appear to be stably positioned in an earlier stage of the curves, that is in the stage of the groundwater-based agrarian boom. In these aquifers, there are signs of overexploitation; in some confined aquifers the water tables have dropped as much as 100 m in the past 20 years (MRE 2009). However, the water reserves are huge, and few actors appear to be worried about the finite nature of groundwater resources. It is hard to see how, in the context of the alignment of interests between the States promoting agricultural growth, and the different private actors with direct economic and social interest in these new irrigation frontiers, overexploitation will even remain at current levels. As with other mining resources, the question will then be how the benefits of such unsustainable groundwater economies will be reinvested.

Finally, some of the minor groundwater economies, such as the coastal horticultural systems, have already reached the final stages of their life cycle. Dealing with overexploitation in such situations could be a good test case for managing groundwater resources sustainably, as the size of these economies is limited. Technical solutions (artificial recharge, pumping barriers) that exist to deal with this issue will need to be embedded in a larger management framework negotiated with all the actors. Otherwise short-term water use practices are likely to continue (Llamas and Martinez-Santos 2005).

While farmers and public institutions agree on the general overdraft in the different aquifers,[2] no supporting coalitions have emerged to deal with groundwater overexploitation (Faysse et al. 2012). Groundwater overdraft had dramatic short-term consequences in some specific aquifers, but actors reacted individually or looked to the State to supply more water. In all other groundwater economies, to most local actors the crisis appeared far away. Proposed measures to deal with the crisis, through aquifer contracts for instance, mostly concerned increasing water supplies, through desalination units, inter-regional water transfer, or the construction of dams. Water saving in agriculture was promoted by subsidizing irrigation technologies such as drip irrigation. In reality, drip irrigation may even increase water demand as farmers turn to more intensive agriculture or extend the irrigated area (Berbel et al. 2013; Batchelor et al. 2014). The question is what will be the consequences of current water use practices, and how long will it take to deal with the looming groundwater crisis?

Alley and Leake (2004) took a long-term and multi-perspective view of "sustainable" groundwater development, including the environmental, economic and social consequences. They showed that groundwater use might go through stages that are environmentally unsustainable, but that propel social and economic development which would not have been possible without such use. This means that groundwater use should be thought out and, perhaps more importantly, negotiated in all the different stages in the life cycle of a groundwater economy. This is very difficult due to the State interest in increasing agricultural productivity, the inherent characteristics of the rapidly expanding and diffuse groundwater economy, and existing social power relations. However, putting off dealing with these issues may lead to extremely difficult situations, given the economic, social and political proportions that groundwater economies have taken.

[2] Issues related to groundwater pollution in North Africa are widely acknowledged in scientific studies and in government documents but, except for salinity problems, are rarely mentioned by local actors.

23.5.2 Groundwater as the Enabler of a Socio-economic Transition: Who Are Left Behind?

The different North African States, the private sector, and farmers alike acclaimed groundwater as an enabler of more productive agriculture, and a safety net for small-scale agriculture threatened by droughts. Groundwater is associated with 'modern' agriculture, improving the social status of farmers. Quarouch et al. (2014) showed that farmers look on groundwater as a means of gaining access to "unlimited horizons," where water no longer censors their existence. This can be compared with observations made in large-scale irrigation schemes, where farmers experienced access to groundwater as emancipation from *State water* (Kuper et al. 2009).

The recent boom in agricultural production was supported by a recent cycle of ambitious public policies aimed at agricultural productivity. The opportunities offered by the rapid development of the groundwater economy attracted many newcomers. In Morocco, the Green Morocco Plan had the clearly stated objective of facilitating access to land and water for 'modern' investors, who would be able to exploit these resources in line with new ambitions. The State granted substantial subsidies for irrigation (tube-wells, drip irrigation) and plantations to stimulate private investment by new *entrepreneurs*. There is even a discourse claiming that certain categories of farmers, such as the former assignees of agrarian reform cooperatives, do not "*participate in the economic development of the Nation*" (Papin-Stammose et al. 2013). In Algeria, the Saharan 'Eldorado' attracted many newcomers; investors who were keen to take advantage of the interesting returns of the Saharan farming systems, but also young people for whom the rapid socio-economic promotion represented an exciting opportunity.

While the groundwater economy brought undeniable social and economic progress to some, other groups of actors were marginalized. We have shown three orders of inequality in groundwater access and use. Firstly, large numbers of farmers did not obtain access to groundwater. In the Tadla irrigation scheme (Morocco), only 50 % of the farmers have access to groundwater. It is mainly small-scale farmers (<2 ha) who are left behind (Kuper et al. 2012). A recent study in the Cheliff irrigation scheme (Algeria) showed that only 38 % of farmers had access to groundwater, while the remaining farmers were "*trapped in a process of impoverishment*" (Amichi et al. 2012). The second source of inequality is the pump equipment as we showed for the Saiss. Farmers with poorly equipped wells, which are running dry, have difficulty competing with those who drill deep tube-wells and invest in high-value agriculture. The third source of inequality is the economic status of different categories of farmers in the skewed access and use of groundwater (ibid.). This may lead to similar social and economic differentiation to that reported in Gujarat (Prakash 2005). Social inequity may also undermine the development of local agriculture, as the majority of farmers (and their offspring) may be tempted to give up farming. Finally, the trend to increasing socio-economic inequality is a threat in the strained political context of North Africa, as most groundwater economies rely on overexploited aquifers.

However, different, often informal, mechanisms exist to deal with unequal access to groundwater. This contradicts common perceptions, as the groundwater economy is always presented as a private affair. "A farmer, a well" farmers in Morocco replied when asked whether they would be willing to share a (tube-) well (Quarouch et al. 2014). In India, Shah (1993) showed how thriving informal water markets provide access to those that do not have their own tube-well. Shah and Bhattacharya (1992) reported another interesting mechanism – the 5–7,000 informal 'tube-well companies' in Gujarat where farmers jointly invest in deep tube-wells. In North Africa, such mechanisms can also be found. In Biskra, we observed informal tube-well associations that reminded us of the Gujarati tube-well companies. More importantly, informal water markets, often intertwined with access to other production factors (land, capital, labour) ensure the integration of large numbers of small-scale farmers in the groundwater economy (Ammar Boudjellal et al. 2011). Unlike in South Asia, selling water directly and independently from a larger contractual but informal arrangement is generally (still) not done. Investigating these different mechanisms and their evolution may be an interesting way to contribute to the debate on how to deal with mounting inequalities. Finally, there are still areas where collective access to groundwater enables more generalized access to groundwater. These are mainly community-managed irrigation schemes and public tube-well schemes. In Tunisia, for instance, almost 30 % of the groundwater-based irrigated area depend (in part) on public tube-wells. However, both types of systems appear to be declining, because of diminishing investments in collective irrigation schemes, resulting in degraded equipment, and the proliferation of private tube-wells in these schemes, as farmers want to obtain a more secure access to groundwater.

23.5.3 The Groundwater Economy Is an Informal Economy, Should It Remain So?

The global groundwater economy emerged in a period when rural development was no longer considered to be the sole responsibility of the State. "Less state, more market" aptly described the general opinion of how development should take place, and the State was basically asked to get out of the way of private initiative (Shah 2009). Since the initiative, investment and management of the groundwater economy is mainly a private affair, the State's "*writ does not run*" in such informal water economies (Shah 2009). The groundwater economy that emerged in Algeria, Morocco and Tunisia is dominated by informal arrangements for access to water, land and other resources, and by actors whose role is not formally acknowledged (Ammar Boudjellal et al. 2011). If farmers remain in the invisible world of informal groundwater economies, this may increase the risk of domination by opportunist investments, which are both socially and ecologically unsustainable (Errahj et al. 2009). On the other hand, State intervention will not necessarily lead to improved social, economic and environmental sustainability of the groundwater economy. Formalizing access to groundwater could cement existing inequalities, and should thus be considered with caution (Mukherji 2006).

In North Africa, groundwater is now firmly associated with productive irrigated farming. By extension, groundwater became an important part of what remained a national priority for North Africa's political economies (Allan 2007). Interestingly, our results showed that the State was an active but not always very visible actor in the groundwater economy through different (in) direct mechanisms. First, the State provided water to a substantial number of farmers through public tube-wells, although the importance of these schemes has declined. Second, the three States have made considerable efforts to provide basic infrastructure in rural areas, thus facilitating the deployment of the groundwater economy. The electrification of rural areas, for example, enabled the spread of more powerful tube-wells. Third, many authors deplored the fact that the existing regulations on groundwater use were not applied. We do not entirely agree. The "tolerant" State allowed the private sector to appropriate access to groundwater resources (Brochier-Puig 2004). However, the rules-in-use were continuously evolving in a negotiated process between the State and the private actors. In Morocco for instance, this led to an increasing number of tube-wells registered by river basin agencies. On the other hand, the volumes extracted are not regulated anywhere, thereby revealing the limits of the on-going negotiations. Fourth, the different states subsidized the groundwater economies directly (through tube-wells) and indirectly (through energy, drip irrigation, fruit trees).

We have shown, in particular, that the subsidies for micro-irrigation were an important stimulus for the groundwater economy. Fifth, experience shows that the protagonists of groundwater economies who are in peril will sooner or later call on the State to find solutions (Houdret 2012). Private actors look for public protection by claiming, for instance, to include their land in a public irrigation scheme; the State thus becomes co-responsible for finding solutions to declining water resources. This happened in the Souss (Morocco) where citrus farmers had overexploited groundwater resources, and (by calling on the State) managed to obtain access to surface water by means of a 90 km pipeline, thereby marginalizing a large number of small-scale farmers (Houdret 2012). This appears to contradict earlier tough talk by the administration, as documented in the 1974 Water Master Plan of the Souss: "*If the private sector should continue to disregard bans on planting (orchards) or pumping, it should be prepared in the future to fully support the most disastrous consequences*" (Nhrira 2011).

In sum, while at first sight the groundwater economies in North Africa appear to be based on private initiative, the presence of the State remains important through different formal and informal channels. However, there are very few examples in the region of substantial discussions between the different actors on the future of the different groundwater economies.

23.6 Conclusions: Privatization of Groundwater?

Groundwater is now an important resource in North Africa – for farmers, the private sector, and the State. Over the past 30 years it has gradually become a lifeline for farmers engaged in irrigated agriculture. It saved farmers from structural droughts, and enabled them to intensify farming systems. It created many jobs in the grey support sector which developed in the wake of, and contributed to, the mounting groundwater economy. It enabled the different States to continue promoting irrigated agriculture as a national priority and a credible rural development option, for as long as the overexploited aquifers will continue to provide water.

The groundwater economy in the region emerged during a period of State disengagement following structural adjustments in the 1980s. It is tempting to define this as a transition from State-led surface irrigation development to private groundwater exploitation, amounting to a "privatization" of this resource. Groundwater access did end up in the hands of a minority of farmers, who are overexploiting the aquifers. However, we argue that there is also continuity in this transition or, in other words, that the trajectory of change is path-dependent. This explains why the State remained (and was held) legally but also morally 'responsible' for groundwater by users who had become dependent on groundwater. It intervened in many (in-) direct ways in what at first sight may appear to be private exploitation of groundwater. When private wells ran dry, the State even looked for additional water resources for the rolling groundwater economies, ignoring water demand management options.

So what conclusions can be drawn regarding the pathways of North Africa's groundwater economies, and the Janus nature of groundwater use (liberation or anarchy)? In our opinion, these pathways did not lead to 'anarchy' but rather to negotiated disorder in which the different interests of the farmers, the private sector, and the State were continuously realigned through various (in)formal channels. This disorder explains why groundwater continues to be overexploited in the short- or medium-term interest of those who use groundwater, those who provide services to the booming groundwater economies, and that of the permissive State looking for food security, social stability and economic development. At the same time, groundwater 'liberated' farmers only partially from *State water*. Groundwater was available for only a minority of farmers, with many inequalities. And even farmers who were able to obtain groundwater access were quickly confronted with other challenges, including harsh agricultural markets. In times of crisis, these farmers therefore often turned towards the State for support.

Finally, in a context of structural overexploitation of aquifers, crisis situations are likely to occur frequently in the next decade or so. This is not only the case in North Africa, but in many other parts of the world. Most actors depending on groundwater are well aware of these imminent crises. However, there are few examples of concerted and negotiated strategies to deal with such crises. Perhaps, the wider implications of this study relate to giving more visibility and importance to the short and medium-term effects of current dynamics and the impending decline of groundwater economies in order to create "space for change" (Leeuwis and Aarts 2011). This may in particular entail building coalitions of actors around the definition and analysis of scenarios of change pertaining to how the groundwater economy may evolve in the future. Research has certainly a major role to play in enabling such reflections.

Acknowledgments Research for this study was carried out in the framework of the 'Groundwater Arena' project, funded by the French National Research Agency (CEP S 11/09), and the Sirma collaborative agreement.

References

Akesbi N (2014) Le Maghreb face aux nouveaux enjeux mondiaux. Les investissements verts dans l'agriculture au Maroc. IFRI, Paris. http://dev.ocppc.lnet.fr/sites/default/files/IFRI_noteifriocpnakesbi.pdf

Akesbi N, Guerraoui D (1991) Enjeux agricoles: évaluation de l'expérience marocaine. Editions le Fennec, Casablanca

Al Atiri R (2007) Evolution institutionnelle et réglementaire de la gestion de l'eau en Tunisie: Vers une participation accrue des usagers de l'eau. In: Bouarfa S, Kuper M, Debbarh A (eds) L'avenir de l'agriculture irriguée en Méditerranée. Nouveaux arrangements institutionnels pour une gestion de la demande en eau. 3rd Wademed seminar. Cirad, Montpellier

Allan JAT (2007) Rural economic transitions: groundwater uses in the Middle East and its environmental consequences. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threats to development, vol 3. CABI, Wallingford, UK

Alley M, Leake SA (2004) The journey from safe yield to sustainability. Ground Water 42 (1):12–16

Amichi H, Bouarfa S, Kuper M, Ducourtieux O, Imache A, Fusillier JL, Bazin G, Hartani T, Chehat F (2012) How does unequal access to groundwater contribute to marginalization of small farmers? The case of public lands in Algeria. Irrig Drain 61(S1):34–44

Amichi F, Bouarfa S, Hartani T, Lejars C, Belhamra M, Daoudi A, Amichi H, Kuper M (2013) Le maraîchage au service de la phoeniciculture pour développer de nouvelles frontières agricoles à El Ghrouss. In: Hartani T, Kuper M, Belhamra M (eds) Proceedings of the seminar on the governance of groundwater in the Maghreb. ENSA-CRSTRA-Cirad, Biskra

Ammar Boudjellal AA, Bekkar Y, Kuper M, Errahj M, Hammani A, Hartani T (2011) Analyse des arrangements informels pour l'accès à l'eau souterraine sur les périmètres irrigués de la Mitidja (Algérie) et du Tadla (Maroc). Cah Agric 20(1–2):85–91

Batchelor C, Reddy VR, Linstead C, Dhar M, Roy S, May R (2014) Do water-saving technologies improve environmental flows? J Hydrol 518:140–149

Bekkar Y, Kuper M, Errahj M, Faysse N, Gafsi M (2009) On the difficulty of managing an invisible resource: farmers' strategies and perceptions of groundwater use, field evidence from Morocco. Irrig Drain 58(S3):252–263

Benblidia M (2011) L'efficience d'utilisation de l'eau et approche économique. Plan Bleu, Sophia Antipolis

Benmouffok B (2004) Efforts de l'Algérie en matière d'économie de l'eau et de modernisation de l'irrigation. In: Hammani A, Kuper M, Debbarh A (eds) Proceedings of the seminar on the modernisation of irrigated agriculture, Rabat, 19–22 April 2004. 1st Wademed seminar. IAV Hassan II, Rabat

Benouniche M, Kuper M, Hammani A, Boesveld H (2014) Making the user visible: analyzing irrigation practices and farmers' logic to explain actual drip irrigation performance. Irrig Sci. doi:10.1007/s00271-014-0438-0

Benziouche SE, Cheriet F (2012) Structure et contraintes de la filière dattes en Algérie. New Medit 11:49–57

Berahmani A, Faysse N, Errahj M, Gafsi M (2012) Chasing water: diverging farmers' strategies to cope with the groundwater crisis in the coastal Chaouia region in Morocco. Irrig Drain 61 (5):673–681

Berbel J, Pedraza V, Giannoccaro G (2013) The trajectory towards basin closure of a European river: Guadalquivir. Int J River Basin Manag 11(1):111–119

Bouchedja A (2012) La politique nationale de l'eau en Algérie. In: Euro-RIOB 2012, 10ème Conférence Internationale, Istanbul, 17–19 Oct 2012

Brochier-Puig J (2004) Société locale et État face aux limites de la ressource eau (Nefzaoua, Sud-Ouest tunisien). In: Picouët M et al (eds) Environnement et sociétés rurales en mutation, Approches alternatives. Éditions IRD, Paris, pp 307–321

Célérier J, Charton A (1925) Les grands travaux d'hydraulique agricole au Maroc. Annales de Géographie 34(187):76–80

Chevalier L (1950) Le plan de modernisation et d'équipement pour l'Afrique du Nord. Population 5(1):166–170

Côte M (2002) Des oasis aux zones de mise en valeur: l'étonnant renouveau de l'agriculture saharienne. Méditerranée 99(3–4):5–14

Daoudi A, Wampfler B (2010) Le financement informel dans l'agriculture algérienne: les principales pratiques et leurs déterminants. Cah Agric 19:243–248

El Alaoui M (2006) Développement de l'agriculture irriguée, dispositif juridique et institutionnel et stratégie de gestion de l'eau au Maroc. In: Bouarfa S, Kuper M, Debbarh A (eds) L'avenir de l'agriculture irriguée en Méditerranée. Nouveaux arrangements institutionnels pour une gestion de la demande en eau. 3rd Wademed seminar. Cirad, Montpellier

El Gueddari A (2004) Economie d'eau en irrigation au Maroc: Acquis et perspectives d'avenir. Hommes, Terre et Eaux 130:4–7

Errahj M, Kuper M, Faysse N, Djebbara M (2009) Finding a way to legality, local coordination modes and public policies in large-scale irrigation schemes in Algeria and Morocco. Irrig Drain 58(S3):358–369

Faysse N, Hartani T, Frija A, Tazekrit I, Zairi C, Challouf A (2011) Agricultural use of groundwater and management initiatives in the Maghreb: challenges and opportunities for sustainable aquifer exploitation. AfDB Econ Brief 1–24. http://www.afdb.org/en/documents/document/economic-brief-agricultural-use-of-groundwater-and-management-initiatives-in-the-maghreb-challenges-and-opportunities-for-sustainable-aquifer-exploitation-25496/

Faysse N, El Amrani M, El Aydi S, Lahlou A (2012) Formulation and implementation of policies to deal with groundwater overuse in Morocco: which supporting coalitions? Irrig Drain 61(S1):126–134

Hammani A, Hartani T, Kuper M, Imache A (2009) Paving the way for groundwater management: transforming information for crafting management rules. Irrig Drain 58(S3):240–251

Houdret A (2012) The water connection: irrigation and politics in southern Morocco. Water Altern 5(2):284–303

Imache A, Hartani T, Bouarfa S, Kuper M (2010) La Mitidja, 20 ans après: réalités agricoles aux portes d'Alger. Editions Alpha, Algiers

Jus H (1878) Les forages artésiens de la province de Constantine: résumé des travaux exécutés de 1856 à 1878. Impr. Nouv., Paris

Khiari A (2002) Une région pionnière dans le Sahara algérien: El Ghrouss. Méditerranée 99 (3–4):27–30

Konikow LF, Kendy E (2005) Groundwater depletion: a global problem. Hydrogeol J 13 (1):317–320

Kuper M, Hammani A, Zemzam S, Bouarfa S, Thomas V (2003) Stratégies d'utilisation conjuguée des eaux de surface et souterraine pour l'irrigation: le cas du périmètre irrigué du Tadla au Maroc. In: Proceedings of the 3rd Pcsi seminar on the Integrated water management in river basins. Cirad, Montpellier

Kuper M, Dionnet M, Hammani A, Bekkar Y, Garin P, Bluemling B (2009) Supporting the shift from "state" water to "community" water: lessons from a social learning approach to design joint irrigation projects in Morocco. Ecol Soc 14(1):19

Kuper M, Hammani A, Chohin A, Garin P, Saaf M (2012) When groundwater takes over: linking 40 years of agricultural and groundwater dynamics in a large-scale irrigation scheme in Morocco. Irrig Drain 61(S1):45–53

Leduc C, Ben Ammar S, Favreau G, Béji R, Virrion R, Lacombe G, Tarhouni J, Aouadi C, Zénati Chelli B, Jebnoun N, Oï M, Michelot JL, Zouari K (2007) Impacts of hydrological changes in the Mediterranean zone: environmental modifications and rural development in the Merguellil catchment, central Tunisia. Hydrol Sci J 52(6):1162–1178

Leeuwis C, Aarts N (2011) Rethinking communication in innovation processes: creating space for change in complex systems. J Agric Educ Ext 17(1):21–36

Lightfoot DR (1996) Moroccan Khettara: traditional irrigation and progressive desiccation. Geoforum 21(2):261–273

Llamas MR (1998) Groundwater overexploitation. In: Proceedings of the UNESCO-IHP conference on world water resources at the beginning of the 21st century, Paris

Llamas MR, Martínez-Santos P (2005) Intensive groundwater use: silent revolution and potential source of social conflicts. J Water Resour Plan Manag 131(5):337–341

Lopez-Gunn E, Llamas MR (2008) Re-thinking water scarcity: can science and technology solve the global water crisis? Nat Res Forum 32(3):228–238

MacDonald AM, Bonsor HC, Dochartaigh BEO, Taylor RG (2012) Quantitative maps of groundwater resources in Africa. Environ Res Lett 7(2):024009

Mamou A, Kassah A (2002) Eau et développement dans le Sud tunisien: projet national mobilisateur 'potentialités et gestion de l'eau dans le Sud tunisien'. CERES, Tunis

Margat J (2008) Exploitations et utilisations des eaux souterraines dans le monde, vol 52. Unesco/BRGM, Paris

Margat J, Vallée D (1999) Vision méditerranéenne sur l'eau, la population et l'environnement au XXIème siècle. Plan Bleu, Sophia Antipolis

Mekki I, Jacob F, Marlet S, Ghazouani W (2013) Management of groundwater resources in relation to oasis sustainability: the case of the Nefzawa region in Tunisia. J Environ Manage 121:142–151

Mitchell M, Curtis A, Sharp E, Mendham E (2012) Directions for social research to underpin improved groundwater management. J Hydrol 448–449:223–231

Moench M (2007) When the well runs dry but livelihood continues: adaptive responses to groundwater depletion and strategies for mitigating the associated impacts. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threats to development. CABI Head Office, Oxford, pp 173–192

Monition L, de Lesguise MN (1954) Contribution à l'étude du drainage naturel des nappes aquifères. In: Proceedings Ass. Int. Hydrol. Sa., CR Assembl. Gén., Rome, pp 499–519

Mukherji A (2006) Political ecology of groundwater: the contrasting case of water-abundant West Bengal and water-scarce Gujarat, India. Hydrogeol J 14:392–406

Nhrira A (2011) La sauvegarde des eaux souterraines dans le Bassin du Souss Massa. In: Proceedings of the groundwater conference, 14–16 March 2011. Afeid, Orléans

Otmane T, Kouzmine Y (2013) Bilan spatialisé de la mise en valeur agricole au Sahara algérien Mythes, réalisations et impacts dans le Touat-Gourara-Tidikelt. Cybergeo: European Journal of Geography, Espace, Société, Territoire 632

Papin-Stammose C, Petit O, Kuper M (2013) Résilience des paysanneries marocaines dans un contexte de mutations de l'accès aux ressources productives: cas du Saiss. In: Hartani T, Kuper M, Belhamra M (eds) Proceedings of the seminar on the governance of groundwater in the Maghreb. ENSA-CRSTRA-Cirad, Biskra

Pascon P (1978) De l'eau du ciel à l'eau de l'état: psychosociologie de l'irrigation. Hommes, Terre et Eaux 8(28):3–10

Penov I (2004) The use of irrigation water in Bulgaria's Plovdiv region during transition. Environ Manage 34(2):304–313

Poncet J, Kuper M, Chiche J (2010) Wandering off the paths of planned innovation: the role of formal and informal intermediaries in a large scale irrigation scheme in Morocco. Agr Syst 103 (4):171–179

Popp H (1986) L'agriculture irriguée dans la vallée du Souss. Formes et conflits d'utilisation de l'eau. Méditerranée 59(4):33–47

Postel S (1999) Pillar of sand: can the irrigation miracle last? WW Norton, New York

Prakash A (2005) The dark zone: groundwater irrigation, politics and social power in North Gujarat. PhD thesis, Wageningen University and Research Centre

Quarouch H, Kuper M, Abdelaoui E, Bouarfa S (2014) Eaux souterraines, sources de dignité et ressources sociales. Cas d'agriculteurs dans la plaine du Saïss au Maroc. Cahiers Agricultures. doi:10.1684/agr.2014.0699

Riaux J (2013) Engager la construction d'un regard sociohydrologique: des archives catalyseurs de l'interdisciplinarité. Nat Sci Soc 21(1):15–23

Rojas R, Kahunde S, Peeters L, Batelaan O, Feyen L, Dassargues A (2010) Application of a multimodel approach to account for conceptual model and scenario uncertainties in groundwater modelling. J Hydrol 394(3):416–435

Shah T (1993) Water markets and irrigation development: political economy and practical policy. Oxford University Press, Bombay

Shah T (2009) Taming the anarchy: groundwater governance in South Asia. Resources for the Future Press, Washington, DC

Shah T, Bhattacharya S (1992) Farmer organisation for lift irrigation: irrigation companies and tubewell co-operatives of Gujarat. In: Singh K, Ballabh V (eds) Symposium on management of rural co-operatives. Institute of Rural Management, Anand

Shah T, Deb Roy A, Qureshi AS, Wang J (2003) Sustaining Asia's groundwater boom: an overview of issues and evidence. Nat Res Forum 27(2):130–141

Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Doll P, Portmann FT (2010) Groundwater use for irrigation – a global inventory. Hydrol Earth Syst Sci 14:1863–1880

Swearingen WD (1987) Moroccan mirages: agrarian dreams and deceptions, 1912–1986. IB Tauris Publishers, London/New York

Trabelsi R, Zaïri M, Smida H, Ben Dhia H (2005) Salinisation des nappes côtières: cas de la nappe nord du Sahel de Sfax, Tunisie. Comptes Rendus Geosci 337(5):515–524

Venot JP, Zwarteveen M, Kuper M, Boesveld H, Bossenbroek L, Van Der Kooij S, Wanvoeke J, Benouniche M, Errahj M, De Fraiture C, Verma S (2014) Beyond the promises of technology: a review of the discourses and actors who make drip irrigation. Irrig Drain 63(2):186–194

Ziyad A (2007) Renouvellement de la politique de l'eau au Maroc: quel apport du débat national sur l'eau? Hommes Terre Eaux 137:59–61

Official Data

Agences de Bassin Hydraulique (ABH) (2011) Plan directeur d'aménagement intégré des ressources en eau (PDAIRE), Rabat, Morocco

Direction Générale des Ressources en Eau (DGRE) (2005) Situation de l'exploitation des nappes phréatiques. Tunis, Tunisia
Direction Générale des Ressources en Eau (DGRE) (2008) Annuaire de l'exploitation des nappes profondes. Tunis, Tunisia
Direction Générale du Génie Rural et de l'hydraulique agricole (DGGREE) (2006) Computer data base, accessed on 23/9/2013. Tunis, Tunisia
High Planning Commission (HCP) (2007) Prospective Maroc 2030: Quelle agriculture pour le Maroc? Rabat, Morocco
Ministère de l'Agriculture et de la Pêche Maritime (MAPM) (2012) Situation de l'agriculture marocaine. Rabat, Morocco
Ministère des Ressources en Eau (MRE) (2009) Etude d'inventaire et de développement de la PMH. Algiers, Algeria
Ministère des Ressources en Eau (MRE) (2011) Note sur l'activité de l'hydraulique agricole. Algiers, Algeria
TICET (2009) Institutional framework and decision making practices for water management in Tunisia. Project report of the CITET. Tunis, Tunisia

Part V

Modeling and Decision Support