Chapter 43
Challenges and Opportunities of Groundwater Management in Pakistan

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Abstract Groundwater is playing a critical role in supporting irrigated agriculture which is producing about 90% of the total grain production in Pakistan. However, uncontrolled and unregulated exploitation of this resource has questioned its ability to feed the rising population. This demands an urgent action to bring a balance between recharge and discharge components. The challenge is to work on both supply-side and demand management solutions. Effective implementation of governing laws is needed to manage groundwater abstraction. Adoption of water conservation practices, introduction of micro-irrigation technologies, and using groundwater to grow high-value crops can assist in boosting groundwater economy. There is also a strong need to rationalize cropping patterns keeping in view food demands of the country and the sustainable supply of groundwater. Educational programs should be initiated to create awareness for all groundwater users to maximize economic returns by growing high-value crops and adopting water conservation practices to minimize groundwater extraction.

43.1 Introduction

Pakistan is the third largest consumer of groundwater with about 9% of the total groundwater extraction in the world (Giordano 2009). The cropped land occupied by groundwater irrigation in Pakistan is 4.6% of the world's total groundwater irrigated area (Siebert et al. 2010). Increased use of groundwater in Pakistan helped in the expansion of irrigated area after the 1960s' Green Revolution, which increased irrigation water demand by about three times (Ahmad et al. 2004). In subsequent years, the reduction in surface water supplies and the urge to increase irrigated area kept the water demand on rise. This prompted farmers to increase groundwater exploitation (Leghari 2012). Presently, Pakistan is among those

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countries where groundwater withdrawals exceed renewals and the groundwater resources are not enough to meet the unimpededly outpacing irrigation water demands (Wada et al. 2010; Qureshi 2015).

The surface water availability in Pakistan is not sufficient to support year-round basin-wide intensive cropping systems. In addition, there is a possibility of additional reduction in surface water supplies because the storage volume of the major reservoirs is decreasing due to sedimentation. This deficit between demand and supply of surface water is usually rendered through groundwater abstraction. During the last three decades, groundwater has played a crucial role in thwarting water shortages and to guarantee food security for the increasing population of Pakistan. However, the nature of occurrence of groundwater coupled with complexity of the aquifer, and historic development approaches have seriously threatened the sustainability of Indus basin aquifer from which most of our groundwater is derived. It is increasingly realized that negligence on this issue could be disastrous for the economy of the country. Therefore, there is a strong need to give special attention to the management of this valuable resource base at all levels from policymakers to actual users of water.

The large-scale groundwater exploitation in Pakistan has helped in combating hunger, reducing poverty, and achieving economic growth. In water short areas of Pakistan, unrestricted access to groundwater has helped farmers in attaining high crop yields and creating opportunities to diversify cropping patterns and to overcome miseries of low rainfall years. However, unregulated and uncontrolled groundwater exploitation has raised serious concerns about the sustainability of irrigated agriculture because it produces more than 90% of the total grains in Pakistan. The dependence of two-thirds of the rural population on groundwater for food security and to earn their livelihood has further compounded the problem. Therefore, it is now broadly realized that Pakistan needs to take serious steps to create an equilibrium between groundwater discharge and recharge. As the scope for increasing water supplies is limited, controlling demand by optimizing water use in agriculture should be given more attention.

This chapter reviews the role of groundwater in increasing the productivity of irrigated agriculture in Pakistan. It also discusses difficulties in managing groundwater in the sociocultural environment of Pakistan and attempts to identify strategic areas for policymakers to intervene to ensure sustainable management of groundwater resources. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

43.2 Water Resources of the Indus Basin

The Indus basin has the largest irrigated area on any one river system. The total area of the Indus basin is 1.17 million km^2 with an annual water availability of 244 billion m^3. Out of this total area, 632,954 km^2 is in Pakistan, 373,887 km^2 is in India, 86,432 km^2 is in China, and 76,542 km^2 is in Afghanistan. The flows originated from the Indus River and its tributaries (Jhelum, Chenab, Ravi, Sutlej, Beas, and Kabul) are the major source of surface water in Pakistan. The rainfall in the catchment areas and the water obtained from the snow and glaciers melt is the major source of inflow for these rivers. The small ephemeral streams outside the Indus basin flow only during the rainy season and are of less importance in terms of overall water availability. The Indus Basin Treaty of 1960 permitted Pakistan full use of Indus, Jhelum, and Chenab rivers, whereas India was authorized to use flows of Ravi, Sutlej, and Beas rivers. Because of this treaty, Pakistan constructed a huge network of link canals, barrages, and dams, which makes the Indus basin largest contiguous irrigation system in the world (Chap. 1, Fig. 1.3). The network of Indus basin comprises of 4 storage dams (Warsak, Chasma, Mangla, and Tarbela), 16 barrages, 12 link canals, and 44 canal commands (23 in Punjab, 14 in Sindh, 5 in Khyber Pukhtunkhwa, and 2 in Baluchistan). Main features of the Indus Basin Irrigation System (IBIS) are shown in Fig. 43.1.

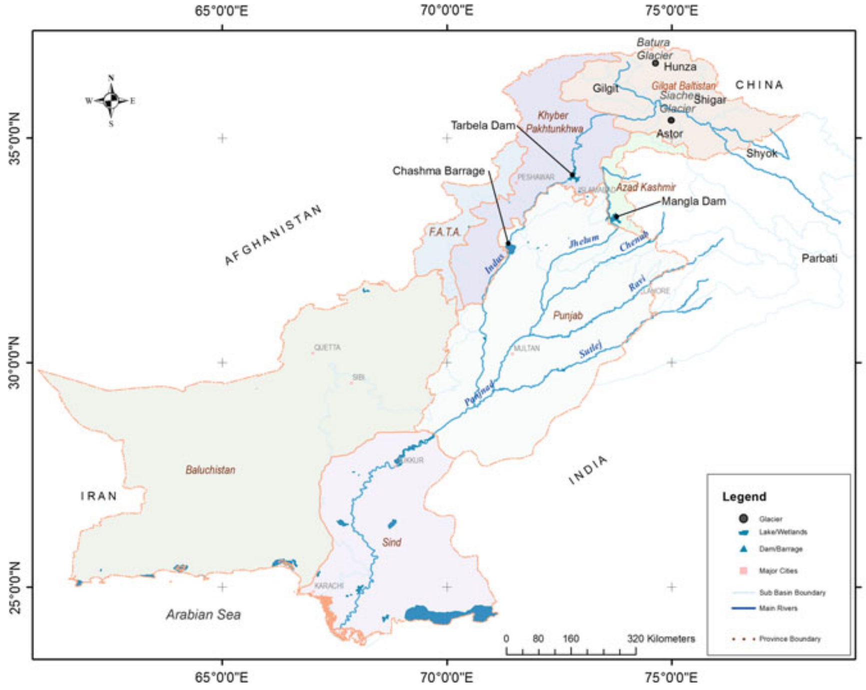

Fig. 43.1 Main features of the Indus Basin Irrigation System (IBIS)

The average annual flow brought in by the Indus River and its tributaries is 190 billion cubic meters (Bm^3), of which 179 Bm^3 comes from the Indus, Chenab, and Jhelum rivers, whereas the rest 11 Bm^3 is contributed by Ravi, Sutlej, and Beas rivers. About 130 Bm^3 is diverted for irrigation, 50 Bm^3 flows to the sea, and 10 Bm^3 is wasted due to soil evaporation and seepage losses from the canal network. Presently, out of 190, 177 Bm^3 is allocated for agriculture, 7.6 Bm^3 for domestic purposes, and the rest 5.7 Bm^3 for industrial purposes (Bakshi and Trivedi 2011).

The total area irrigated by the Indus Basin Irrigation System (IBIS) is 16 million hectares (mha), out of which only 8.6 mha has year-round access to surface water supply while the rest gets water during the summer season only. The water availability in the IBIS may vary between 230 and 120 Bm^3 depending on the year. This makes the storage critical for agriculture in Pakistan particularly during the winter season because 85% of the flow occurs during the summer season.

The water quality of Indus River (Chap. 1, Fig. 1.3) and its tributaries is suitable for irrigation. The river water quality degraded toward the tail reaches of the canal system. It varies from 200 ppm at the head reaches to 400 ppm at the tail reaches. The discharge of drainage effluents into the rivers and canals is considered as the major reason for this degradation of water quality. The BOD values in most river systems range between 2 and 5 mgl^{-1}. The River Ravi is by far the most polluted river (BOD = 77 mgl^{-1}) because it accrues 47% of the total pollution load discharged into the rivers of Pakistan. The DO contents in most of the rivers are higher than the threshold levels of 4 mgl^{-1} (Halcrow 2003).

The groundwater quality in major parts of Sindh, Punjab, Baluchistan, and south Khyber Pakhtunkhwa provinces is not suitable for irrigation and drinking purposes. The quality of groundwater in Punjab and Sindh is closely linked to the river morphology. The salt concentrations in the shallow groundwater of Punjab are often higher than 3000 mgl^{-1} (PHED 1999). However, in some areas of Punjab, salt concentration in the groundwater may go up to 20,000 mgl^{-1} or more. The fresh groundwater occurs in lenses below the rivers. The thicknesses of these lenses are decreasing with distance away from the river. In the Thal Desert, Cholistan region, and the lower reaches of Indus plain in Sindh, groundwater is even more saline. Generally, large parts of the southern Pakistan have groundwater of poor quality. In the coastal areas of Sindh, groundwater is extremely saline due to seawater intrusion.

43.3 Characterization of the Indus Basin Aquifer

The dominant physiographic units are the alluvial plain of the Indo-Gangetic Plain, which consists of sand and silt and minor amounts of gravel and clay. In accordance with their mode of deposition by large constantly shifting rivers, the alluvial deposits are heterogeneous, and individual strata have limited horizontal and vertical continuity. The alluvium of the Punjab plains has been deposited by the present and ancestral tributaries of the Indus River. The Indus plain is underlain with rich alluvial deposits more than 300 m deep. The alluvium of aquifer has medium sand to silty clay texture with predominance of sandy sediments. The lithology of the alluvium shows a series of geologic sections in each doab, with the heterogeneous character of the uppermost 200 m of the alluvium in downstream and sloping directions and the arbitrary spreading of clay zones. The alluvial deposits of the Punjab, in spite of their heterogeneous composition, form a unified highly transmissive aquifer, in which groundwater occurs for the most part under water table conditions. The uppermost 100 m of the compacted aquifer is the most productive zone. Small capacity tubewells (50–100 l per second) can theoretically be installed almost everywhere.

The underlying aquifer in IBIS covers an area of 16 mha, of which 6 mha is covered by good quality groundwater and the remaining 10 mha with poor-quality groundwater (Qureshi et al. 2010). The alluvium beneath about two-thirds of the Punjab is saturated to an average depth of 200 m or more, with water of acceptable quality for irrigation supply. The average concentration of dissolved solids in these supplies is less than 1,000 ppm. The upper limit of concentration is fixed at 1,800–2,000 ppm, which allows to mix groundwater with canal water at a ratio of 1:2. The aquifer is recharged from precipitation and leakage from the rivers, unlined canals, and percolation from the cropped lands.

In any event, assuming an effective porosity of 20% for the saturated sediments, the available volume of groundwater is estimated at 2470 Bm^3. The safe groundwater yield is about 68 Bm^3, whereas the groundwater extraction has already reached to 51 Bm^3. The remaining groundwater potential is in mountainous areas (e.g., Balochistan) where exploitation of groundwater is not economically feasible. This means that groundwater resource in Pakistan is almost exhausted.

This rapid growth of private tubewells for the extraction of groundwater for irrigation proceeded without consideration of its impact on the aquifer, which as has been said is both complex structurally and in terms of quality of water it holds in storage. Obviously uncontrolled and unregulated extraction got concentrated closer to the rivers and away from the center of *doabs* that are underlain with highly salinized water. This led to migration of saltwater to sweet water areas in many places.

Earlier, it was thought that the saltwater and freshwater interface as it moves caused mixing due to molecular diffusion which is a very slow process. But later scientific studies indicated that the mixing was taking place due to dispersion, which is thousands of times faster process depending on aquifer characteristics. As can already be seen unchecked and unplanned growth of private tubewells will exacerbate mixing and cause untold harm to sustainability of the aquifer and long-term use of groundwater.

43.4 Development of Irrigation in the Indus Basin

The major objective of the development of IBIS was to provide water over large areas to facilitate the settlement and agricultural prospects for the disintegrated population (Jurriens and Mollinga 1996). However, even today, the system is gravity run supply-based and has no relevance with the crop water demand during different growing seasons. The system requires minimum operational and management skills, but with an intrinsic disadvantage of inflexibility. The system was designed for an annual cropping intensity of 70%, which has now increased to 150% due to rising demand for food. The consistent poor maintenance of the system has reduced its efficiency to 35–40%, which has further reduced the surface water availability per unit of irrigated land (Tarar 1995). The Indus plain does not have a well-defined drainage system. The differences in topography helps in generating surface runoff during the monsoon and flooding season. Due to poor drainage conditions, flooding of agricultural lands during the monsoon season has become a permanent feature in many parts of the Indus basin.

The groundwater table levels at the time of IBIS development were 20–30 m below the soil surface; therefore, provision of subsurface drainage system was not realized. However, due to continuous seepage from network of canals and consistent percolation losses from irrigated fields, groundwater table started rising resulting in large-scale waterlogging and salinity problems. These issues became worse in saline groundwater areas because pumping was restricted owing to quality concerns. Figure 43.2 shows the groundwater levels before and after the introduction of IBIS in the Punjab Province.

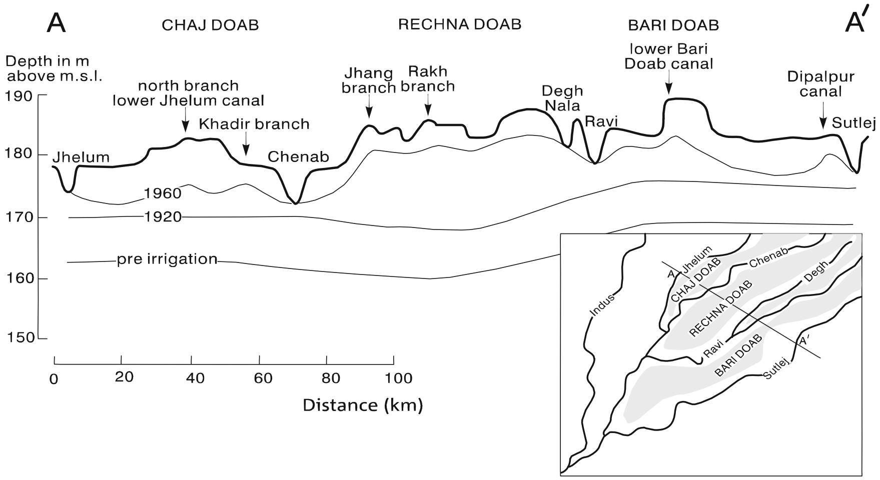

Fig. 43.2 Comparison of groundwater levels before and after (1920 and 1960) the introduction of irrigation system in the Punjab, Pakistan (Wolters and Bhutta 1997)

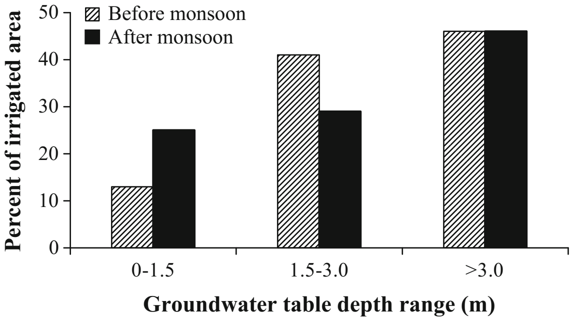

Fig. 43.3 Groundwater table depths in the Indus Basin before and after the monsoon season

The groundwater levels are deepest in the dry month of May and lowest after the rainy season (i.e., September). It is estimated that 30% of the cultivated area (4.7 mha) has a groundwater table within 1.5 m of the soil surface (severely waterlogged) after the summer rainy period (Wolters and Bhutta 1997). Before the rainy season, this area is deceased to 13% (2 mha). Currently, about 25% of the irrigated area in Punjab and 60% in Sindh are severely waterlogged, abandoning about 40,000 ha annually due to salinity problems (WAPDA 2010). Figure 43.3 shows that regardless of the season, 46% of the cultivated area in the Indus basin has groundwater tables deeper than 3 m.

43.5 Contours of Groundwater Development

Like many other dry regions of the world, the major problem of the water sector in Pakistan is also of low supply and high demand. The rainfall in the Indus basin accomplishes only 15% of the total agricultural water demand, and the rest needs to be provided through irrigation (Bhutta and Smedema 2007). As the surface water availability is only partially sufficient to meet evapotranspiration demand of crops, the gap is met through the exploitation of groundwater. The groundwater pumped for irrigation is essentially the water "recharged" from the irrigation network. Due to this interconnectivity, estimating the total available water resources needs much caution (Leghari 2012).

Historically, groundwater abstraction in Pakistan was started using open wells, hand pumps, karezes, and Persian wheels. However, extensive groundwater exploitation started in 1960s when 16,700 large capacity (0.080 m^3s^{-1}) tubewells were installed in the Indus basin under the Salinity Control and Reclamation Projects (SCARPs). These wells were installed to control waterlogging and salinity problems in 2.6 mha of irrigated area and increase water supplies at the farms by using the extracted groundwater for irrigation alone in conjunction with the canal water. Realizing the initial benefits, farmers started installing private wells of smaller capacities (28 ls^{-1}) in the 1980s. Since then, private wells are increasing at the rate of about 9.6% per year (Qureshi 2014) and the population of private wells

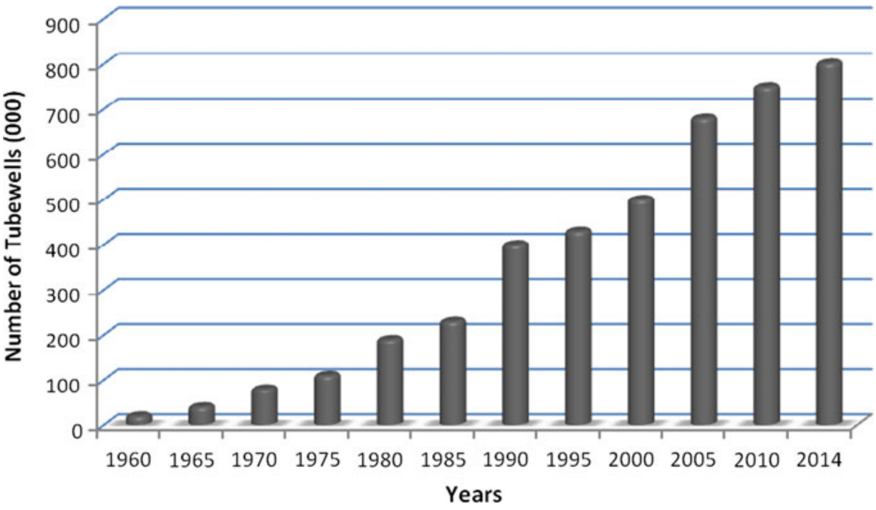

Fig. 43.4 Expansion of private wells in the Punjab Province of Pakistan

has reached to 1.2 million with 800,000 only working in Punjab (Qureshi et al. 2004). Provision of subsidized electricity and easy access to small diesel engines provided the much-needed incentive for this dramatic increase of groundwater wells over the last three decades (Fig 43.4).

Currently, in Pakistan, 52 Bm^3 of groundwater is extracted annually (Qureshi 2014). Of this, 14 Bm^3 is pumped using electric motors and the remaining 38 Bm^3 using small capacity private diesel engines. Due to increasing prices of electricity, farmers are more attracted to diesel pumps. Today, 87% wells are operated by diesel pumps compared to only 13% by electric motors (Qureshi 2014). Diesel pumps are preferred due to their feasibility for small and fragmented land holdings and low installation and operation and maintenance costs compared to electric wells (Shah 2007). Farmers have invested over US$400 million in groundwater wells, which has increased groundwater contribution in Punjab from 8% in 1960 to 60% in 2015. During the last two decades, groundwater has contributed more than 70% of the total increase in irrigation supplies. This has benefited national economy by US $2.0 billion in the form of agricultural production (World Bank 2008). Due to this process, the canal system is only recharging groundwater instead of delivering irrigation water. For example, canal system in Punjab contributes 80% of the groundwater recharge (Bhutta and Smedema 2007).

43.6 Socioeconomic Benefits of Groundwater Development

The groundwater development in Pakistan was accelerated due to the pressure to grow more food for the increasing population and to handle the decreasing surface supplies because of depleting storage capacity of reservoirs and changing rainfall patterns in the wake of climate change. The smallholder farmers could achieve predictable crop yields and diversify their income base, thereby creating more jobs and reducing poverty. Studies have shown that farmers with groundwater access attained 50–100% better crop yields than those who were fully reliant on canal water (Shah et al. 2003; Shah 2007). Farmers having access to groundwater also started growing water thirsty crops such as sugarcane and rice. This has helped increase the production of these crops and improve livelihood of farmers. At present, about 2.5 million farmers in Pakistan are using groundwater to supplement irrigation supplies (Qureshi 2011). However, most of these farmers understand very little about any adverse effects of unsystematic groundwater extraction on groundwater quality and soil salinization.

Groundwater has helped Pakistani farmers in stabilizing crops by creating a buffer during droughts and dry spells (Tsur 1990). During the extraordinary drought of 1998–2002, the surface water supplies were reduced by 26% and the growth of groundwater wells was increased by 59% because this was the only choice for irrigation and drinking water for humans and livestock (Bhutta 2002). Farmers having access to both surface water and groundwater earn five times higher than those limited to surface water only (Latif and Tariq 2009). This demonstrates that access to groundwater guarantees a farmer of increased income due to timely availability of irrigation water.

43.7 Challenges to Groundwater Economy in Pakistan

43.7.1 Depleting Aquifers Due to Overdraft

Despite unique benefits, unchecked groundwater pumping has resulted in dropping groundwater levels in many irrigated areas. Due to declining water tables, smallholder farmers on 5% irrigated area in Punjab and 15% in Baluchistan have lost access to fresh groundwater. In the *business as usual* scenario, this area may increase to 15% in Punjab and 20% in Baluchistan by 2025 (Qureshi et al. 2010). Comparison of changes in groundwater levels from 1993 to 2013 in the Punjab Province is shown in Fig. 43.5. In Sindh Province, changes in groundwater levels are less pronounced due to restricted exploitation pertaining to poor quality (Khan et al. 2008).

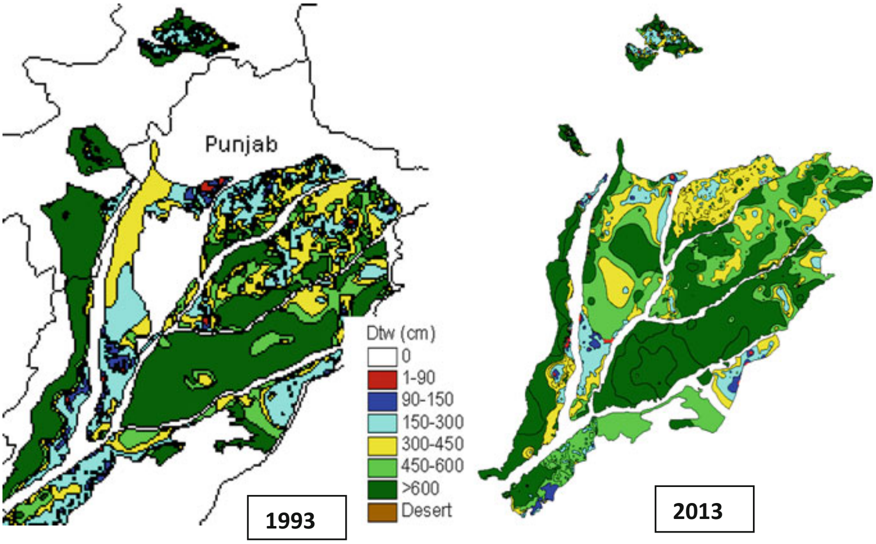

Fig. 43.5 Changes in groundwater levels in the Punjab Province of Pakistan (*Source* Qureshi et al. 2004)

43.7.2 Increased Energy Use and Environmental Concerns

The average annual groundwater extraction in Pakistan is about 52 Bm^3. This amount of groundwater is pumped through 1.0 million diesel wells (38 Bm^3) and 200,000 electric wells (14 Bm^3) (Qureshi 2014). In the Baluchistan Province where water table depths have gone much deeper than the capacity of diesel engines (>20 m), pumping has become costlier and energy intensive. Increased water table depth requires deeper drilling and installation of turbine/submersible pumps, which costs US$10,000 for each well. Due to surge in energy prices, the cost of pumping 1000 m^3 of groundwater has reached to US$4.2 for shallow wells and US$12 for a deep well (Qureshi et al. 2008). To make these costs affordable for smallholder farmers, electricity is heavily subsidized in Baluchistan. However, there are evidences that the subsidized electricity is exacerbating the problems of groundwater overdraft and mainly benefiting large farmers as they own most of the deep wells (Ahmad 2009). Therefore, urgent measures are needed to halt excessive groundwater extraction.

The annual extraction of groundwater for irrigation in Pakistan consumes 6 billion kWh of electricity and 3.5 billion liters of diesel, which releases 4.2 million metric tons (MMT) of CO_2 (Qureshi 2014). This amount is equivalent to 1.4% of total carbon emissions in Pakistan. Out of the total, 1.6 MMT of CO_2 is produced through electric pumps and 2.6 MMT of CO_2 from diesel pumps. This means that the extraction of each cubic meter of groundwater consumes 0.82 kWh of energy and emits 80 g of CO_2. This shows that increasing water use efficiency in agriculture will reduce energy use, stabilize aquifers, and help in controlling carbon emissions.

43.7.3 Deficient Recovery of Energy Costs

Increasing energy prices, poor mechanism of cost recovery and changing energy subsidy policies of the government has been a matter of grave concern for the groundwater irrigation economy. It was generally argued that diminishing energy subsidies may help reducing groundwater extraction because direct management through authorization permits will not be effective in the Pakistan (Shah 2007). Learning from the Indian experience, Pakistan also decided to use energy pricing policies as a surrogate for groundwater management.

The electrification of groundwater pumps started in 1970s when the government decided to facilitate farmers by bearing all capital installation costs for wells and electricity tariffs were subsidized. This initiative increased the number of wells from 37,000 to 84,000 within 5 years. However, this created huge burden for the government to monitor electric meters to collect electricity charges from farmers (Qureshi and Akhtar 2003). In 1990s, government withdrew subsidies due to rising energy costs, which resulted in the replacement of large numbers of electric wells with the diesel wells. Smallholder farmers preferred diesel wells due to low installation and operational costs (Qureshi and Akhtar 2003).

The analysis done by the World Bank (2007) reveals that the changing energy prices in Pakistan forces farmers to shift from electric to diesel form of energy without any significant decline in groundwater overdraft. Currently, the electric wells are about 10% of the total private well population and their contribution is only 20% of the total groundwater extraction in Pakistan. This suggests that changing energy prices would not be a robust tool to manage groundwater overdraft in Pakistan, as has been the case in many parts of India. Therefore, there is a strong need to search for more innovative solutions to match with the sociocultural environment of Pakistan.

43.7.4 Deteriorating Groundwater Quality

The groundwater salinity in Pakistan is closely related to the river morphology. The shallow groundwater in Punjab is of low salinity (<1000 ppm), whereas the deep groundwater has higher salt concentrations (>3000 ppm). The deep groundwater is generally present in the areas located between the major rivers and canals. The groundwater quality in 77% of the irrigated area in the Punjab (4 mha) is suitable for irrigation. In the upper parts of Punjab where areas are subjected to heavier rainfall, groundwater has low mineralization. The groundwater in the dry areas of southern Punjab is not fit for drinking and agricultural purposes due to high salinity. In many parts of Punjab, groundwater also contains high fluoride (7–12 mgl^{-1}) and arsenic concentrations (50 µgl^{-1}). In fresh groundwater areas of Punjab, quality of pumped groundwater has also degraded due to disproportionate pumping. According to recent estimates, about 70% of the wells extract saline groundwater, which is aggravating salinity problems in the irrigated areas. (Bhutta and Alam 2012). The distribution of saline groundwater area in four provinces of Pakistan is shown in Fig. 43.6.

The problems of groundwater quality in the lower parts of the Indus plain are more serious. In the Sindh Province, only 28% of the area is underlain by fresh groundwater, whereas the rest 72% is underlain by brackish groundwater. The fresh groundwater is confined to a small strip along the Indus River (Leghari et al. 2012). The coastal areas of Sindh and Makran coastal zone have saline groundwater (>3000 ppm) due to seawater intrusion. The groundwater in the Khyber Pakhtunkhwa Province tends to be fresher. In the saline groundwater, sodium and chloride ions are more common, whereas the presence of sulfate, magnesium, and potassium has also been observed in drinking water (Khan et al. 2013).

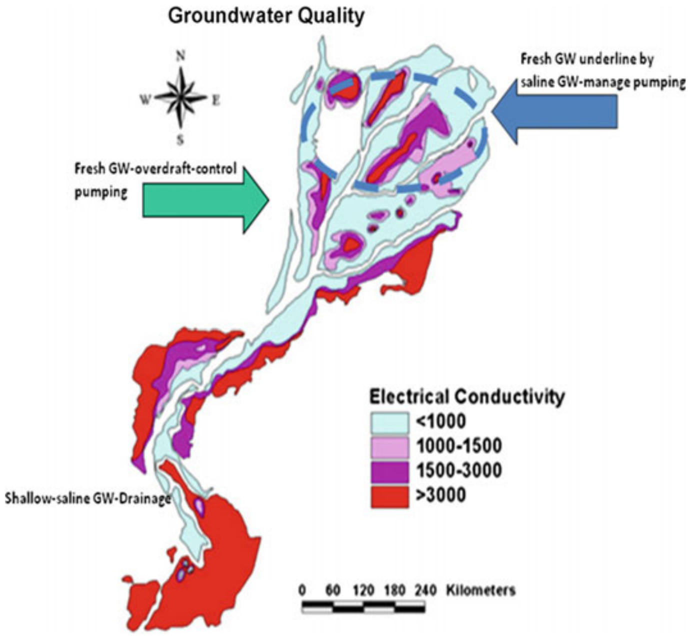

Fig. 43.6 Distribution of saline groundwater along the Indus Basin of Pakistan

The discharge of untreated wastewater into rivers and canals is the main source of pollution. The recent evaluations have shown that most of the groundwater is biologically contaminated (JICA 2010). The analysis of wastewater samples collected from 25 different localities of the Lahore city has shown concentrations of Cu, Mn, Ni, and Cd above the permissible WHO limits (Khan et al. 2013). The water from highly polluted River Ravi is posing a serious health risk for the large population who used it for drinking purposes (Basharat and Rizvi 2011; Ejaz et al. 2011).

43.7.5 Degradation of the Resource Base—Soil Salinization

The large network of canal system deposits salts in the Indus River. The total salts brought in annually are about 33 million tons (Mt). Out of this, 16.4 Mt outflows to the sea, while the rest 16.6 Mt is added to the system. Considering 16 mha of irrigated area in the Indus basin, one ton of salts is added to each hectare of land annually. Currently, about 4.5 mha is affected with soil salinity (WAPDA 2010). The extent of soil salinity is higher in the tail-end areas of the canal system where poor-quality groundwater is used for irrigation. The trends of surface salinity in four provinces of Pakistan are shown in Fig. 43.7. In the Sindh Province, 54% of the total irrigated land is salinized due to poor drainage conditions, lack of leaching opportunities, and existence of shallow saline groundwater (Bhutta and Smedema 2007). The seawater invasion is detrimental for the wetlands in the coastal areas. The mangrove forests over 130,000 ha are under serious threat and need to be protected.

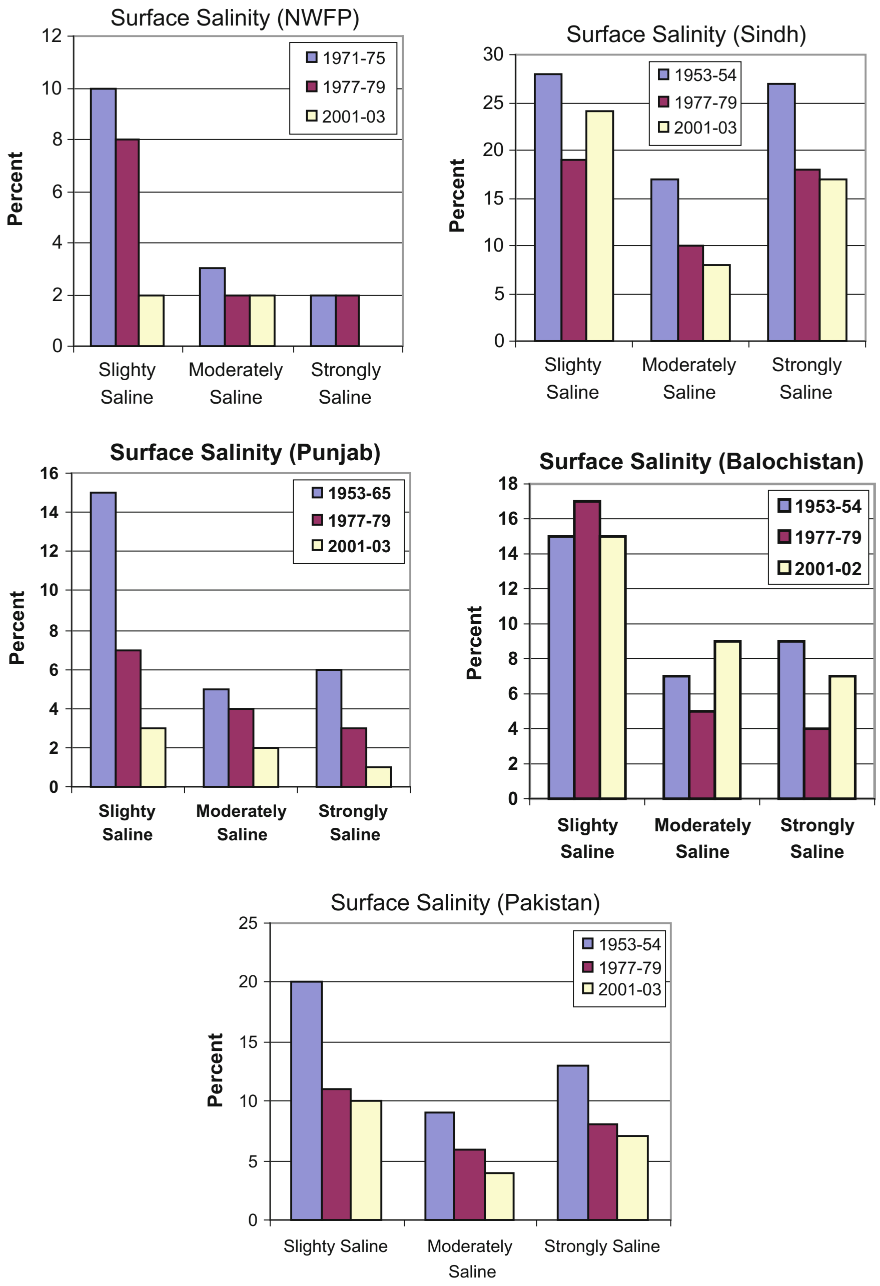

Fig. 43.7 Trends of surface salinity in four Provinces of Pakistan (*Source* WAPDA 2010)

43.8 Opportunities for Improving Groundwater Management

43.8.1 Stabilizing Aquifers

The emergence of groundwater challenges demands that the performance of existing surface water supply systems is enhanced, and groundwater management is given more attention. Generally, recharge to groundwater is taken as by-product of irrigation, whereas it should be considered necessary for sustainable groundwater management. Therefore, increasing recharge to groundwater is necessary to maintain strategic storage and at the same time regulate pumping according to hydro-geological conditions prevailing in different parts of the Indus basin. In many parts of the world, artificial groundwater recharge is used as an effective tool for stabilizing aquifers. The artificial recharge to total groundwater use varies from 12% in England to 30% in Germany (Li 2001). The rainwater harvesting community ponds at the village level in India and check dams in different parts of Pakistan are commonly used as artificial recharge structures (Shah 2007; Qureshi 2015).

For sustainable groundwater management in the Indus basin, aquifer can be divided into three zones. In Punjab, a thin layer of fresh groundwater is present above deep saline groundwater. The thickness of this layer varies from a few meters to over 150 m and is found close to rivers and *the area between two rivers.* In fresh groundwater areas, this layer is about 40 m thick, whereas it is less than 40 m in saline groundwater areas (Leghari 2012). This situation demands careful groundwater extraction to avoid mixing of fresh and brackish interface. The use of skimming well technology has proven successful in extracting groundwater from thin lenses without disturbing the underlying saline groundwater.

In the central Punjab where groundwater is fresh and shallow, overexploitation of groundwater is causing drastic water table drops and deterioration in groundwater quality. In these areas, unregulated groundwater extraction needs to be checked. This can be done by rationalizing crops, enforcing laws, and ensure consistent monitoring. In the lower parts of the basin, drainage of brackish groundwater should be given priority to lower groundwater levels below crop root zone. The establishment of groundwater safety zones may also help in controlling excessive groundwater pumping.

43.8.2 Rethinking Conjunctive Water Management

In 1960s when decision was taken to develop groundwater to lower the water tables and increase water supply at the farm gate, it was realized that for rationalizing use of water from all sources in the spirit of conjunctive use, water would be required to move from groundwater excess areas to groundwater short areas, or where groundwater quality is not suitable. However, due to heavy involvement of private sector in the groundwater development, this could not happen. Currently, surface water is used in conjunction with the groundwater on 70% of the irrigated area in Pakistan. This does not mean that this practice is effective and optimal. Over the last two decades, the groundwater irrigated area has jumped from 2.6 to 3.7 mha. On the other hand, area irrigated with the canal water has reduced from 7.9 to 6.8 mha (Fig. 43.8).

Contrary to common wisdom, groundwater is equally used by head-end and tail-end farmers. Logically, head-end farmers should use less groundwater than tail-end farmers because they have more access to surface water. This unmanaged groundwater use is causing waterlogging problems at the head-end of the canal system and increases soil salinization at the tail-end of the system because farmers continue to use poor-quality groundwater for irrigation (Qureshi et al. 2008). Consequently, crop yields and farm incomes of tail-end farmers are reduced to half compared to head-end farmers (Latif and Tariq 2009) (Fig. 43.8).

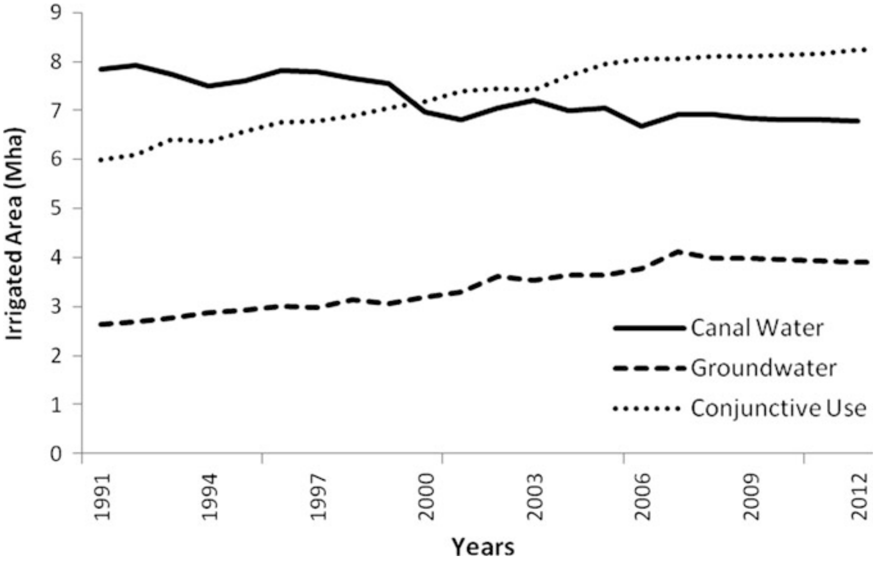

Fig. 43.8 Trends of different modes of irrigation in the Punjab Province of Pakistan

For salinity management in the Indus basin, existing water allocation criteria of providing equal access to canal water (*warabandi system*) needs serious debate. The canal water allocation to head-end farmers should be reduced to increase share of canal water for the tail-end farmers, and they should also be discouraged to use inferior quality groundwater for irrigation. The implementation of these water allocation strategies would require adjustments in policies to provide more access to groundwater to head-end farmers at the cost equivalent to canal water.

43.8.3 Increasing Economic Productivity of Groundwater

In most irrigated areas of world, groundwater is used to grow high-value crops. In China, for example, more than 60% of cotton, vegetable, and oil crops are grown using groundwater (Wang et al. 2009). In Mediterranean countries such as Andalusia and Spain, groundwater use efficiency is high because farmers apply only 3,900 m^3 per ha of groundwater compared to 5,000 m^3 per ha of surface water. Consequently, groundwater users in Spain attain higher economic return of US\$3.24 per m^3 compared to US\$0.95 per m^3 for surface water (Hernandez-Mora et al. 2010). By selecting proper crops, groundwater productivity can be increased. For example, groundwater productivity of peppers and tomatoes can go up to US \$5.52 per m^3 compared to only US\$0.25 per m^3 for crops like corn, sunflower, and cereals (Garrido et al. 2006). In the extreme dry regions such as Jordan River Valley, farmers have earned up to US\$16,000 per ha (Venot and Molle 2008). Similarly, in Morocco, 75% of the horticulture crops are grown with groundwater. This shows that understanding the economics of using groundwater for irrigation is very critical for managing groundwater.

In Pakistan, productivity of groundwater use is far lower than the regional standards. The productivity of groundwater for wheat crop is only 0.5 kgm^{-3} compared to 0.9 Kgm^{-3} in India and 1.6 Kgm^{-3} in California. Groundwater is used to grow high water-demanding crops such as rice and sugarcane. Considering the overall groundwater situation, Pakistan needs to decide whether to grow rice for export or replace it with other high-value crops to match the availability of groundwater. The sunflower, oil, fruit, and vegetable crops can help increase farm incomes and support national economy by reducing their import from other countries and saving huge foreign exchange.

43.8.4 Increasing Groundwater Use Efficiency

Farmers having access to groundwater tend to apply higher amounts of water for each irrigation event. Studies done in Pakistan have shown that irrigation amounts to wheat and cotton can be reduced by 40–50% without conceding yields and increasing soil salinity (Prathapar and Qureshi 1999; Qureshi and Bastiaanssen

2001). Adoption of water saving methods for rice such as direct plantation and alternate wet and dry irrigation technique can save substantial amount of irrigation water (Qureshi et al. 2006).

The sprinkler and drip irrigation techniques are widely used for promoting sustainable groundwater use. These methods improve application efficiency by reducing loss of water through soil evaporation and excessive deep percolation. However, impact of these technologies can only be achieved if farmers do not use the saved water to increase their irrigated area. The drip irrigation technique also saves energy and labor, reduces salinity, and increases crop yield, although these claims need more verification. The viability of micro-irrigation is more appealing where high-value crops are grown under greenhouses because productions are many folds higher and so does the incomes. In Pakistan, micro-irrigations are also getting popularity with the initial support of government. However, their large-scale adoption would require quality goods with access to lucrative international markets. In the absence of such arrangements, their economic feasibility for small farmers will remain a challenge.

Water conservation strategies such as improved land levelling, zero tillage, bed and furrow planting also have the potential to reduce water demand. Studies done in India, Pakistan, and Bangladesh have shown that up to 40% water can be saved by bed planting compared to flood irrigation (Hobbs and Gupta 2003); Mollah et al. 2009). The efficiency of water use for the rice crop can be increased by applying alternate wetting and drying method of irrigation (Bouman et al. 2007). This technique also has the capacity to increase concentration of zinc in the harvested rice (Price et al. 2013). However, fixed rotational irrigation system and lack of working knowledge are considered as the major limitations in the large-scale adoption of AWD in Pakistan.

43.8.5 Promote Use of Alternate Water Resources

Globally, 1500 Bm^3 of wastewater is produced every year and about 20 mha of land is irrigated with wastewater (Jiménez and Asano 2008). The Asian and African farmers intentionally use untreated wastewater because it contains essential nutrients needed by crops. The wastewater use for irrigation is also getting popular in the Arabian countries where 11 Bm^3 of wastewater is generated every year. Out of this, 5.6 Bm^3 is treated and 75% of this water is used for irrigation (Qureshi and Shoaib 2015). In Pakistan, 4.5 Bm^3 of wastewater is produced annually and only a small proportion of this is used to grow vegetables in peri-urban areas around the large cities, whereas the rest is discharged into rivers or thrown in open areas around cities (Qureshi 2011). This is causing huge environmental and health problems. Therefore, there is a strong need to develop a strategy for the profitable use of this resource and its environmentally safe disposal.

Currently, wastewater use for agriculture is limited to grow vegetables and fodder crops (Raschid-Sally and Jayakody 2007). However, by adopting proper management practices and selecting appropriate crops, wastewater can also be used to irrigate wheat, cotton, pearl millet, and many other crops. In deep groundwater areas, soil salinity can be managed through controlled seepage during the monsoon season. However, in shallow groundwater areas, installation of effective drainage systems is necessary for sustainable use of wastewater. The local governments should facilitate treatment of wastewater and devise effective policies for the safe use of this resource for agriculture. However, long-term impacts of wastewater use for agriculture on soil and human health need to be carefully evaluated.

43.8.6 Improving Groundwater Governance

Groundwater management has proven to be much more difficult relative to other natural resources. The direct management of groundwater (i.e., enforcing permit systems and extraction rights) has worked successfully where the State was strong to ensure implementation of governing laws and groundwater users are manageable, such as in Australia and Oman. Groundwater management has failed in countries where governments were relatively weak such as Jordan (Venot and Molle 2008), China (Wang et al. 2009), India (Shah 2007), and Pakistan (Qureshi et al. 2010). In Pakistan, India, and China, where users are numerous and dispersed, administration of groundwater becomes very difficult if not possible. For the similar reasons, even in Europe, monitoring of groundwater extraction by individual farmers has proved difficult to implement (Zoumides and Zachariadis 2009).

In many countries where groundwater is excessively used for agriculture, energy prices are used as a surrogate for groundwater pricing. In China, India, and Iran, electricity prices are subsidized. In China, for example, the electricity charges for agriculture wells are only 25% of the usual electricity rates (COWI 2013). In Iran and Mexico, energy charges for farmers are only 20% of the actual cost of electricity (FAO 2009; Soltani and Saboohi 2008). Generally, a flat rate of electricity is charged in India regardless of groundwater use (Shah 2007). In the Mediterranean region, manipulation of energy prices is possible, although it will not have any impact unless prices are raised significantly (Zoumides and Zachariadis 2009). Studies have shown that a 25% increase in electricity prices would have a marginal reduction (2–3%) in groundwater use in India (Badiani and Jessoe 2010). Pakistan has also miserably failed in controlling groundwater overdraft by regulating energy prices, and groundwater extraction keeps on rising because it was crucial to meet water demand (Qureshi et al. 2010).

Pakistan has presented plethora of laws for regulating groundwater extraction. Starting with the introduction of licensing and permit system in 1980s, the national groundwater management policy was drafted in 1999 under Provincial Irrigation and Drainage Authority (PIDA) Act. These rules suggested delineation of critical areas, licenses for tubewell installation in critical areas, and regular monitoring of all tubewells (Halcrow-ACE 2003). Despite all these efforts, effective implementation of these laws remained a challenge due to poor political will. The governance of groundwater has also become complicated because no single organization is responsible for managing this resource. Moreover, political governments intentionally allow farmers to extract groundwater to ensure rural food security as they could not fulfill their responsibility of maintaining the surface supply systems. Therefore, Pakistan needs to increase the capacity of institutions to effectively implement governing laws and organizational changes for the management of groundwater resources.

43.9 Conclusions

Groundwater is playing an important role in improving sustainability of irrigated agriculture in Pakistan. However, this luxury is now coming to an end because this resource is being over tapped in many areas, which has threatened the capacity of the Indus basin to feed its growing population. The deterioration of groundwater quality is even a more serious problem because large tracts of irrigated areas are becoming saline due to use of poor-quality groundwater for irrigation.

Pakistan should learn from its experience of groundwater development without proper planning and management. There is an urgent need to create balance between groundwater discharge and recharge. Pakistan requires a practical, persistent, and well-determined strategy for managing its groundwater resources with the active engagement of its users and increasing investments in promoting advanced water management techniques. The government needs to play a dynamic role as developer and implementer of the enabling laws and regulations and provider of well-tested decision support systems to facilitate the groundwater management process.

Pakistan needs to develop legal frameworks and tools suited to its needs. The major challenge is to increase supplies and decrease water demands. Water demands can be reduced by adopting water conservation technologies. The government policies should aim at encouraging the use of micro-irrigation technologies and using groundwater to grow high-value crops. Cropping patterns should be rationalized considering country needs and the availability of surface water and groundwater supplies. In addition, awareness raising campaigns about the management of groundwater resources and its impact on environment and crop production should be initiated.

Pakistan also needs to strengthen institutions by building their capacity and organizational changes to enable them to undertake challenging task of groundwater management. Pakistan should revisit its policies for the management of groundwater to make them more susceptible to local socioeconomic and cultural conditions. In addition, coordination and cooperation between organizations and institutes responsible for groundwater management need to be improved.

References

Ahmad S (2009) Water availability and future water requirements. Paper presented at the national seminar on “Water conservation, present situation and future strategy” organized by Ministry of Water and Power, Islamabad, Pakistan, May 2009

Ahmad I, Hussain SAS, Zahid MS (2004) Why the green revolution was short run phenomena in the development process of Pakistan: a lesson for future. J Rural Dev Adm 1–4:89–104

Badiani R, Jessoe KK (2010) Electricity subsidies, elections, groundwater extraction and industrial growth in India. Paper submitted to the pacific development conference 2010, Berkeley, University of California. Available at: http://mitsloan.mit.edu/neudc/papers/paper_194.pdf

Bakshi G, Trivedi S (2011) The Indus equation. Strategic Forsight Group C-306, Montana, Lokhandwala Complex Andheri West, Mumbai 400 053, India

Basharat M, Rizvi SA (2011) Groundwater extraction and wastewater disposal regulation—Is Lahore aquifer at stake with as usual approach. Pak Eng Congr 135–152

Bhutta MN (2002) Sustainable management of groundwater in the Indus basin. Paper presented at second South Asia Water Forum, Pakistan Water Partnership, Islamabad, Pakistan, Dec 14–16

Bhutta MN, Smedema LK (2007) One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: a historical review. Irrig Drain 56:581–590

Bhutta MN, Alam M (2012) Prospective and limits of groundwater use in the Indus Basin of Pakistan. Paper presented in the World Water Day symposium organized by the Pakistan engineering council, Lahore, Pakistan, 22 March 2012

Bouman BAM, Humphreys E, Tuong TP, Barker R (2007) Rice and water. Adv Agron 96:187–237

COWI (2013) Groundwater in China. Part 1—Occurrence and use. COWI, Kongens Lyndby, Denmark

Ejaz N, Hashmi NH, Ghumman AR (2011) Water quality assessment of effluent receiving streams in Pakistan: a case study of Ravi river. Mehran Uni Res J Eng Technol 30(3):383–396

Food and Agriculture Organization of the United Nations (FAO) (2009) Groundwater management in Iran. Draft synthesis report. FAO, Rome, Italy

Garrido A, Martínez-Santos P, Llamas MR (2006) Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience. Hydrogeol J 14(3):340–349

Giordano M (2009) Global groundwater? issues and solutions. Annu Rev Environ Resour 1:153–178

Halcrow-ACE (2003) Exploitation and regulation of fresh groundwater—main report. ACEnHalcrow JV Consultants, Gulberg III, Lahore, Pakistan

Hernández-Mora N, Martinez L, Llamas RM, Custodio E (2010) Groundwater in the southern member states of the European Union: an assessment of current knowledge and future prospects. Country report, European Academies Science Advisory Council. Available at: http://www.easac.eu/fileadmin/PDF_s/reports_statements/Spain_Goundwater_country_report

Hobbs PR, Gupta RK (2003) Resource-conserving technologies for wheat in the rice-wheat system. In: Improving productivity and sustainability of rice-wheat systems: issues and impact. American Society of Agronomy Special Publication, vol 65, pp 149–171

Japan International Cooperation Agency (2010) Preparatory study on Lahore water supply, sewerage, and drainage improvement project in Islamic Republic of Pakistan

Jurriens R, Mollinga, PP (1996) Scarcity by design: protective irrigation in India and Pakistan, ICID Journal 45(2):31–53

Jiménez B, Asano T (2008) Water reclamation and reuse around the world. In: Jiménez B, Asano T (eds) Water reuse: an international survey of current practice, issues and needs. IWA Publishing, London, p 648

Khan S, Rana T, Gabriel HF, Ullah M (2008) Hydrogeologic assessment of escalating groundwater exploitation in the Indus Basin, Pakistan. Hydrogeol J 8:1635–1654

Khan A, Javid S, Muhmood A, Mjeed A, Niaz A, Majeed A (2013) Heavy metal status of soil and vegetables grown on peri-urban area of Lahore district. Soil Environ 32(1):49–54

Latif M, Tariq JA (2009) Performance assessment of irrigation management transfer from Government to farmer-managed irrigation system: a case study. Irrig Drain 58:275–286

Leghari AN, Vanham D, Rauch W (2012) The Indus Basin in the framework of current and future water resources management. Hydrol Earth Syst Sci Discuss 8:2263–2288. https://doi.org/10.5194/hessd-8-2263-2011

Li Y (2001) Groundwater recharge. Unpublished. Nanjing Institute of Hydro and Water Resource, China

Mollah MIU, Bhuyia MSU, Kabir MH (2009) Bed planting—a new crop establishment method for wheat in rice-wheat cropping system. J Agric Rural Dev 7(1&2):23–31

PHED (1999) Hydrogeological map of Punjab. Public Health Engineering Department, Lahore

Prathapar SA, Qureshi AS (1999) Modeling the effects of deficit irrigation on soil salinity, depth to water table and transpiration in semi-arid zones with monsoon rains. J Water Resour Dev 15(1–2):141–159. https://doi.org/10.1080/07900629948989

Price AH, Norton GJ, Salt DE, Oliver Ebenhoeh O, Meharg AA, Meharg C, Islam MR, Sarma RN, Dasgupta T, Ismail AM, McNally KL, Zhang H, Dodd IC, Davies WJ (2013) Alternate wetting and drying irrigation for rice in Bangladesh: is it sustainable and has plant breeding something to offer? Food Energy Sec 2:120–129

Qureshi AS (2011) Water management in the Indus Basin in Pakistan: challenges and opportunities. Mount Res Dev 31:252–260. https://doi.org/10.1659/mrd-journal-d-11-00019.12011

Qureshi AS (2014) Reducing carbon emissions through improved irrigation management: a case study from Pakistan. Irrig Drain 63:132–138

Qureshi AS (2015) Improving food security and livelihood resilience through groundwater management in the Indus Basin of Pakistan. Global Adv Res J Agric Sci 4(10):687–710. ISSN: 2315-5094. Available online http://garj.org/garjas/home

Qureshi AS, Akhtar M (2003) Effect of electricity pricing policies on groundwater management in Pakistan. Pak J Water Resour 7(2):1–9

Qureshi AS, Bastiaanssen WGM (2001) Long-term effects of irrigation water conservation on crop production and environment in semi-arid zones. ASCE Irrig Drain Engg 127(6):331–338

Qureshi AS, Shoaib I (2015) Evaluating benefits and risks of using treated municipal wastewater for agricultural production under desert conditions. Paper presented in the DT12 conference, held in Cairo, 16–19 Nov 2015

Qureshi AS, Asghar MN, Ahmad S, Masih I (2004) Sustaining crop production under saline groundwater conditions: a case study from Pakistan. Aust J Agric Sci 54(2):421–431

Qureshi AS, Masih I, Turral H (2006) Comparing water productivities of transplanted and direct seeded rice for Pakistani Punjab. J Appl Irrig Sci 41(1):47–60

Qureshi AS, McCornick PG, Qadir M, Aslam M (2008) Managing salinity and waterlogging in the Indus Basin of Pakistan. Agric Water Manag 95:1–10

Qureshi AS, Gill MA, Sarwar A (2010) Sustainable groundwater management in Pakistan: challenges and opportunities. Irrig Drain 59(2):107–116

Raschid-Sally L, Jayakody P (2007) Understanding the drivers of wastewater agriculture in developing countries—results from a global assessment. In: Comprehensive assessment research report series, IWMI, Colombo, Sri Lanka

Shah T (2007) The groundwater economy of South-Asia: an assessment of size, significance and socio-ecological impacts. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threat to development. CABI Publications, pp 7–36

Shah T, Debroy A, Qureshi AS, Wang J (2003) Sustaining Asia's groundwater boom: an overview of issues and evidence. Nat Resour Forum 27:130–141

Siebert S, Burke J, Faures JM, Renken KF, Hoogeveen J, Döll P, Portmann FT (2010) Groundwater use for irrigation: a global inventory. Hydrol Earth Sys Sci 3:3977–4021

Soltani G, Saboohi M (2008) Economic and social impacts of groundwater overdraft: the case of Iran. Paper submitted to 15th ERF annual conference, Cairo, Egypt, Nov 2008, pp 23–25

Tarar RN (1995) Drainage system in Indus plains—An overview. In: Proceedings of national workshop on drainage system performance in Indus plains and future strategies, Vol. II. Tandojam, Pakistan, pp 1–45, 28–29 January

Tsur Y (1990) The stabilization role of groundwater when surface water supplies are uncertain: the implications for groundwater development. Water Resour Res 26(5):811–818

Venot JP, Molle F (2008) Groundwater depletion in the Jordan highlands: can pricing policies regulate irrigation water use? Water Resour Manage 22(12):1925–1941

Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP (2010) Global depletion of groundwater resources. Geophys Res Lett 20:L20402

Wang J, Huang J, Huang Q, Rozelle SC, Walker HF (2009) The evolution of China's groundwater governance: productivity, equity and the environment. Q J Eng Geol Hydrogeol 25(1):141–158

WAPDA (2010) Hydropower potential in Pakistan, Lahore, Pakistan. www.wapda.gov.pk

Wolters W, Bhutta MN (1997) Need for integrated irrigation and drainage management, example of Pakistan. Proceedings of the ILRI symposium, towards integrated irrigation and drainage management, Wageningen, The Netherlands

World Bank (2007) Punjab groundwater policy—mission report. WB-SA-PK-Punjab GW Mission report, June 2007. www.worldbank.org/gwmate

World Bank (2008) World development report 2008. Washington, DC, p 96

Zoumides C, Zachariadis T (2009) Irrigation water pricing in southern Europe and Cyprus: the effects of the EU common agricultural policy and the water framework directive. Cyprus Econ Policy Rev 3(1):99–122