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Abstract

In Pakistan, on-demand availability of groundwater has transformed the concept of low and uncertain crop yields into more assured crop production. Increased crop yields have resulted in food security and improved rural livelihoods. However, this growth has also led to problems of overdraft, falling water tables, and degradation of groundwater quality, and yields generally remain well below potential levels. Over the last three decades, Pakistan has tried several direct and indirect management strategies for groundwater management. However the success has been limited. This paper argues that techno-institutional approaches such as introducing water rights, direct or indirect pricing, and permit systems are fraught with difficulties in Pakistan because of its high population density and multitude of tiny users. Therefore, there is a need to develop frameworks and management tools that are best suited to Pakistani needs. Pakistan should follow both supply and demand management approaches. For demand management, adoption of water conservation technologies, revision of existing cropping patterns, and exploration of alternate water resources should be encouraged. For supply management, implementation of the groundwater regulatory frameworks developed by Provincial Irrigation and Drainage Authorities (PIDAs) and introduction of institutional reforms to enhance effective coordination between different organizations responsible for the management of groundwater resources should be given priority.

Keywords: groundwater management, Pakistan, institutional reforms, groundwater development, regulatory framework

1. Introduction

Groundwater has emerged as an exceedingly important water resource, and its increasing demand in agriculture, domestic, and industrial uses ranks it as a resource of strategic importance. Global estimates show that approximately 4,430 km^3 of fresh water resources are abstracted annually, of which 70% are used in agriculture, 25% in industry, and 5% in household (Kinzelbach et al. 2003). On the whole, annual groundwater abstracted for the world can be placed at 750–800 km^3, which is about one-sixth of the total freshwater abstraction (Shah 2000). The amount of groundwater contribution to agriculture is less as compared to surface water on the global scale, yet its unique advantages like reliability, accessibility, on-demand availability, less capital investment, and high productivity outweighs the volumetric access of surface water.

Indus Basin Irrigation System (IBIS) of Pakistan was designed about a century ago with an objective to expand settlement opportunities, prevent crop failure, and avoid famine (Jurriens and Mollinga 1996). IBIS is a gravity-run system with minimum management and operational requirements, which is an advantage with an inherited disadvantage of inflexibility. The operation of IBIS is based on a continuous water supply and is not related to actual crop water requirements. Irrigation canals are usually not allocated more than their design capacity, of which a typical value is about 2 mm day^{-1}. Despite significant increases in storage capacities, it is essentially a supply-based system. Hence, it cannot accommodate changing water demands during the crop season. Figure 1 shows the Pakistan map with provincial boundaries and Indus basin irrigated area.

The total surface water availability in the Indus Basin is 137×10^9 m^3 with a total served area of 16.7 million ha (Bhutta and Smedema 2007), which implies, on average, about 820 mm of surface water is available for each irrigated hectare. Effective rainfall retained in the root zone adds an estimated 200–300 mm to the crop water availability in the north of the Pakistan portion of the Indus basin and some 50 mm in the south. The average annual evapotranspiration in the major irrigated areas of the Indus basin ranges from 1,000 to 1,300 mm per year. Therefore irrigated farming is the most economical and remunerative form of agriculture. Irrigated lands supply more than 90% of the total agricultural production and are major user of the water resources. The difference between the crop water requirements and surface water supplies, combined with the generally unreliable nature and relatively inefficient delivery systems, has led to the exploitation of the groundwater, where conditions allow. In fact, much of the groundwater that is pumped for irrigation is actually surface water "recharged" from the surface systems. Given this interconnectivity, caution needs to be exercised in estimating the total available groundwater resources.

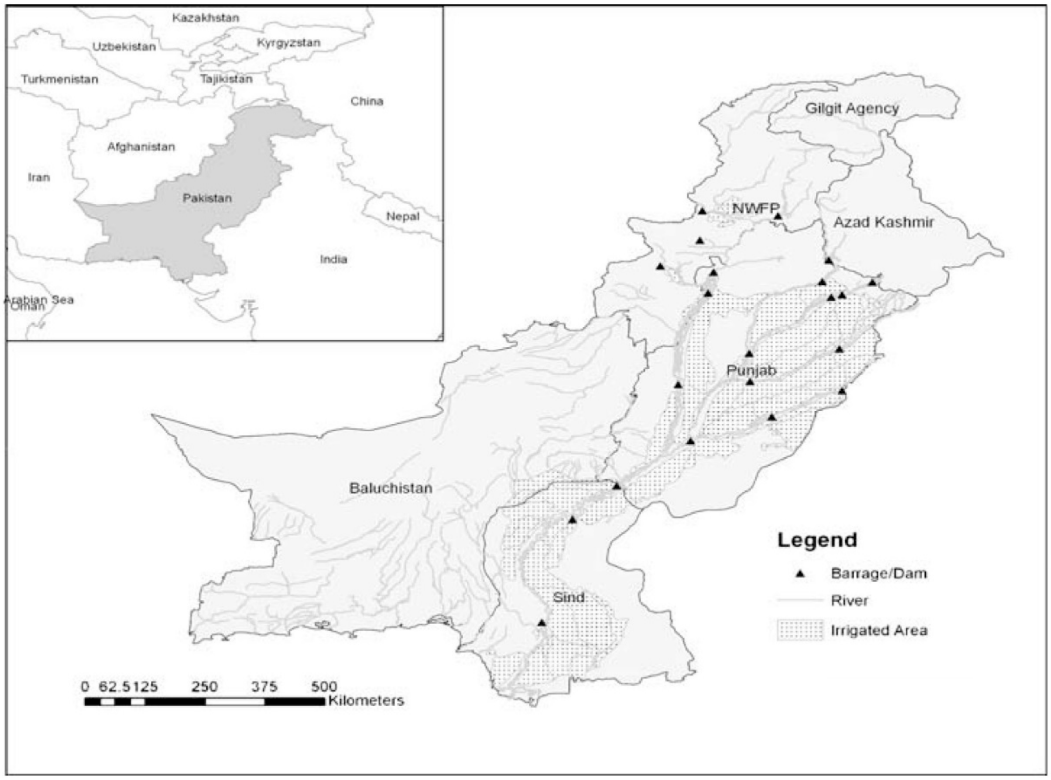

Figure 1. Map of Pakistan with provincial boundaries and Indus basin irrigation network.

Groundwater exploitation has enabled many farmers to supplement their irrigation requirements and to cope with the vagaries of the surface supplies. The access to groundwater has helped poor farmers to not only increase their production and incomes but also enhance their opportunities to diversify their income base and reduce their vulnerability against seasonality of agricultural production and external shocks such as droughts. The benefits of groundwater in Pakistan are multidimensional and ranged from drinking water supplies to urban and rural population to economic development as a result of higher agricultural production. The flexibility provided by groundwater largely supported employment generation, rural development, and poverty alleviation. However, the current rates of exploitation are unsustainable in many regions. Falling water tables and increasing salt contents in the pumped groundwater attest that, in future, groundwater will become more expensive and inferior in quality, which will have serious consequences for Pakistan's capacity to feed its growing population.

In Pakistan, about 10% of the total groundwater exploitation (4×10^9 m^3) is used to meet domestic and industrial requirements. In the most populous province of Punjab, about 90% of the population depends on groundwater for their daily domestic needs. In Balochistan province, about 4% of the population depends on groundwater, but it is estimated to reach 50% in the next 10 years. Because of increasing urbanization, improved living standards, and industrialization, the share of groundwater for nonagricultural uses is expected to increase further, which will have a direct impact on the availability of groundwater for agriculture.

Recognizing the important role that groundwater is playing to meet Pakistan's growing demand for food and fiber, its proper availability needs to be ensured. Therefore, it is imperative to understand the issues regarding groundwater management in Pakistan and to suggest possible pathways for systematic management and regulation of this precious resource. This paper gives an overview of groundwater development and its associated problems in Pakistan. The paper also discusses challenges facing groundwater management and suggests possible pathways to ensure sustainability of this resource in the Pakistani context.

2. Groundwater Development in Pakistan—Historical Perspective

The use of groundwater for irrigated agriculture in Pakistan has a long history. In the early days, the groundwater abstraction was done by means of open wells with rope and bucket, Persian wheels, karezes,[1] reciprocating pumps, and hand pumps. Large-scale extraction and use of groundwater for irrigated agriculture in the Indus basin started during the 1960s with the launching of Salinity Control and Reclamation Projects (SCARPs). Under this public sector program, 16,700 tube wells (supplying an area of 2.6 million ha) with an average discharge of 0.09 $m^3\ s^{-1}$ were installed to lower the groundwater table to create favorable crop growth conditions in the root zone and reduce the risk of soil salinization (Bhutta and Smedema 2007). The pumped groundwater was discharged into the existing public canal system to increase irrigation supplies (Qureshi et al. 2008).

The demonstration of SCARP tube wells was followed by an explosive development of private tube wells with an average discharge of 0.03 $m^3\ s^{-1}$. The provision of subsidized electricity by the government and introduction of locally made diesel engines provided an impetus for a dramatic increase in the number of private tube wells. Currently, about 0.8 million small capacity private tube wells are working in Pakistan, out of which more than 90% are used for agriculture (Qureshi et al. 2008). Investments on the installation of private tube wells are of the order of Rs. 25 billion (US$400 million) whereas the annual benefits in the form of agricultural production are to the tune of Rs. 150 billion (US$2.5 billion) (Shah et al. 2003). The groundwater is currently providing more than 50% of the total crop water requirements with the flexibility of its availability as and when needed (Shah 2007).

Figure 2 illustrates that Punjab province has taken the biggest lead in the development of private tube wells (PWP 2001; GOP 2000). As a result, groundwater abstraction from 1965 to 2002 has increased from $9 \times 10^9\ m^3$ to $45 \times 10^9\ m^3$ (Bhutta 2002; World Bank 2007). The quantum jump in the population of private tube wells during the last decade is linked to severe drought conditions in the country during the period 1998 to 2002. During this period, the surface water availability reduced by 26% and groundwater became the source of last resort for irrigation and drinking water for humans and livestock registering an increase of 59% in the growth of private tube wells (Bhutta 2002). With the improvements in surface water supplies after 2001, groundwater pumping from private tube wells was slightly reduced.

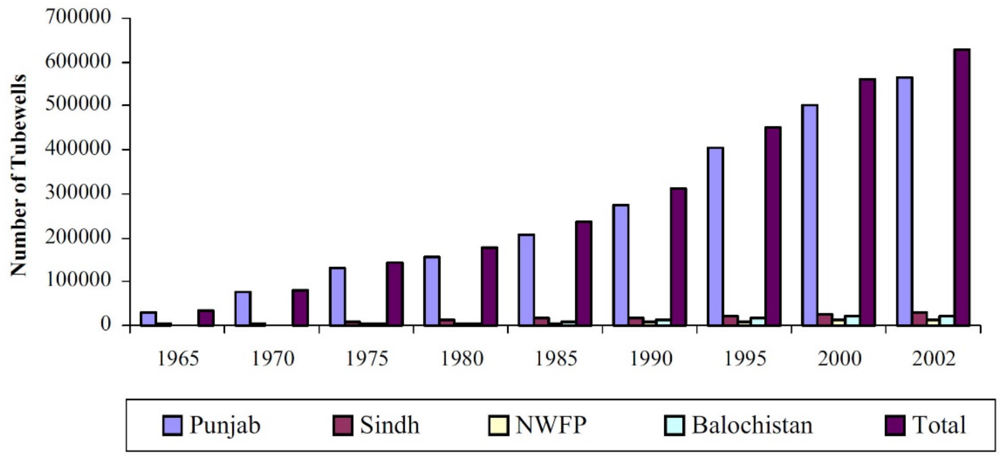

Figure 2. Historical development of tube wells in the four provinces of Pakistan (GOP 2000; PWP 2001).

3. Patterns of Groundwater Use

In Pakistan, about 70% of the private tube wells are located in the canal command areas where groundwater is used for irrigation both in isolation and in conjunction with the canal water. Although evidence exists that mixing of saline and nonsaline irrigation water is less effective in keeping soil salinity levels lower (Hussain et al. 1990; Shalhevet 1994; Kumar 1995), this strategy is widely practiced in Pakistan. This implies that groundwater use is probably more widespread than is thought. Many farmers in irrigated areas use groundwater only when surface water system is not functioning, not delivering water on time, or the amount of delivered water is not enough to grow sensitive crops. Therefore careful selection of groundwater and proper crop rotations are preconditions for adopting a blending strategy.

The conjunctive use of surface water and groundwater is now practiced on more than 70% of the irrigated lands of Pakistan. Figure 3 shows that over the last 10 years, a further million hectares in the Punjab has adopted conjunctive use (Qureshi et al. 2004). The area irrigated by groundwater alone has increased from 2.7 million to 3.4 million ha, whereas the area irrigated by canal water alone has decreased from 7.9 million to 6.9 million ha. In Pakistan the production of major crops such as wheat, cotton, rice, and sugarcane is sustainable only because of the use of groundwater for irrigation.

The quality of groundwater in the Indus basin varies from fresh to saline, depending on its origin, the source of recharge, and the pattern of groundwater movement in the aquifer. In the Punjab province, groundwater quality varies from 0.5 to 4.5 dS m^{-1}, whereas in the Sindh province it goes up to 9.0 dS m^{-1}. The groundwater quality in NWFP and Baluchistan provinces is generally good (0.3 to 1.5 dS m^{-1}) (Bhutta 2002). The secondary salinization associated with the use of poor quality groundwater in Punjab and Sindh provinces is a major threat to the sustainability of the irrigated agriculture. Therefore farmers need to be educated about suitable crops that can be grown under the conjunctive management of surface water and groundwater resources.

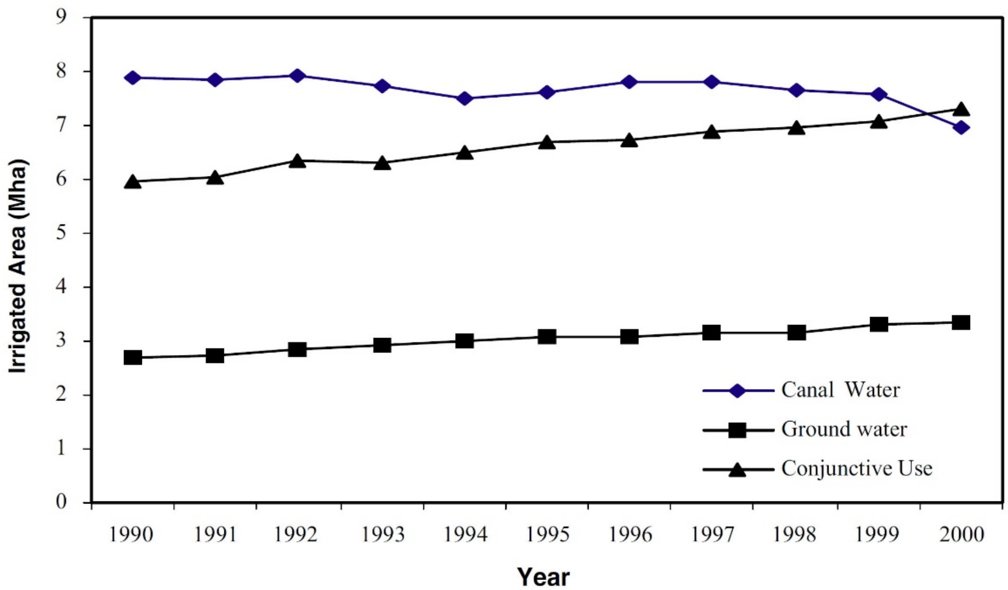

Figure 3. Trends in the use of groundwater for irrigation in the Punjab, Pakistan.

In Pakistan, the average cost of irrigating with groundwater is 30 times higher than that of surface irrigation (World Bank 2007). The cost of canal water per year per hectare is US$5.5, whereas the groundwater is sold as US$167/ha/year. The optimal farm-level production performance is achieved where farmers are able to use the less expensive surface water and supplement with groundwater to fill the shortfalls. Data collected from 521 canal irrigators across Pakistan revealed that farmers with access to groundwater were able to cultivate 90% of their total area as compared to only 63% for those who were fully dependent on canal water. Moreover, access to groundwater allows these farmers to grow high-water-demanding crops such as sugarcane and rice, which resulted in increased farm income because of high market prices of these crops (Shah et al. 2003; Shah 2007). Farmers having access to groundwater also attained 50–100% higher crop yields as compared to those fully dependent on canal water. Meinzen-Dick (1997) has also shown that farm incomes of farmers with access to both surface water and groundwater resources are about five times higher than those limited to surface water only, and argued that owning a tube well in Pakistan and having access to canal water assures a farmer of adequate and timely water supplies in most situations, sharply increasing earnings.

4. Problems of Groundwater Development

4.1. Groundwater Overdraft

The availability of inexpensive drilling technologies allows even poor farmers to access groundwater to increase their crop production and improve livelihoods. Unreliability of surface water supplies turned more and more farmers to use groundwater without a full awareness of the hazard represented by its quality. However, due to unregulated and uncontrolled use, the relative accessibility has diminished. The trend of continuous decline of the groundwater table has been observed in many areas of the Indus basin, which illustrated the serious imbalance between abstraction and recharge. In fresh groundwater areas of Punjab and Baluchistan provinces, falling groundwater tables is a major issue. Excessive lowering of the groundwater table has made pumping more expensive. As a result, many wells have gone out of production, yet the water tables continue to decline and salinity increases. As a typical example, increase in the area with a groundwater table depth of 300 cm between 1993 and 2002 in different canal commands of Punjab and Sindh provinces is shown in Figure 4. In many areas of Balochistan, groundwater tables are dropping at a rate of 2 to 3 m per year. As a result, about 15% of the area in the Baluchistan province has been restricted for farmers (Punjab Public Sector Groundwater Project (PPSGDP) 2000).

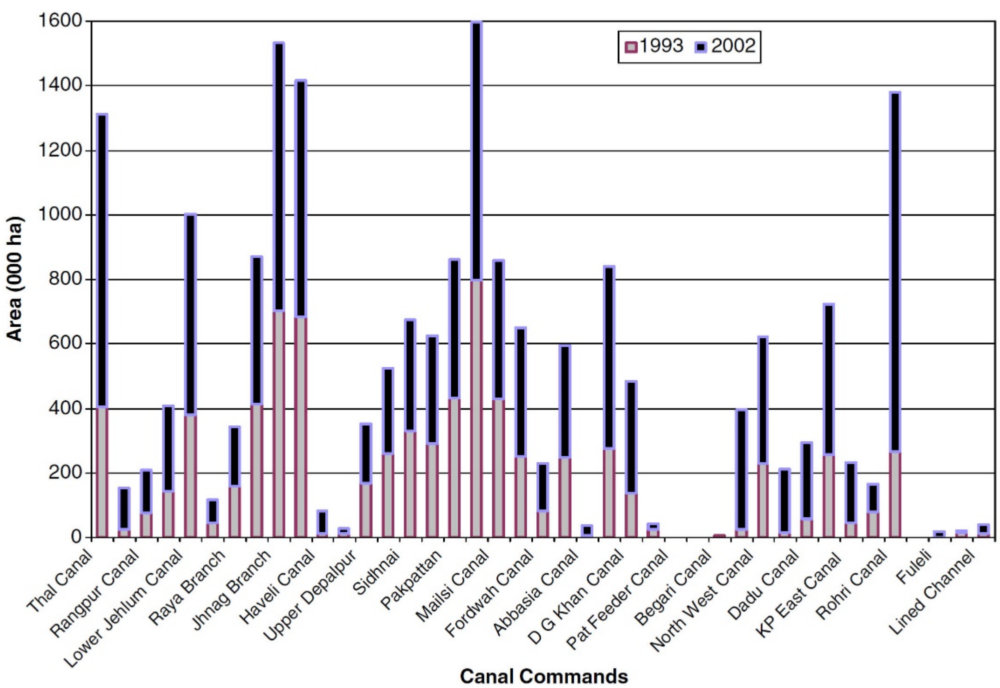

Figure 4. Increase in area with a groundwater table depth of 300 cm over a period of 10 years (1993–2002) in different canal commands of Punjab and Sindh provinces.

More than 80% of the groundwater exploitation in Pakistan takes place through small-capacity private tube wells. These shallow tube wells (up to 6 m depth) were initially installed by farmers to capture the seepage from unlined canals to supplement irrigation supplies for meeting crop water requirements. Therefore their installation and operational costs were very low and farmers were enjoying their benefits without much financial burden. Because of excessive mining of aquifers in fresh groundwater areas, groundwater table depths started falling at a rate of 2–3 m annually. As a result, the groundwater dropped to depths that were inaccessible in 5% and 15% of the irrigated areas of Punjab and Balochistan provinces, respectively. Under the business-as-usual scenario, this area is expected to increase to 15% in Punjab and 20% in Baluchistan in the next decade (PPSGDP 2000).

With the increasing groundwater table depths (> 15 m), farmers were left with no choice but to drill deeper wells. This transformation led to increased installation and operational costs. The construction cost of a deep electric tube well (> 20 m) is US$5,000 as compared to US$1,000 for a shallow tube well (< 6 m). The present cost of pumping groundwater from a shallow tube well is US$4.2 per 1,000 m^3 as compared to US$12 per 1,000 m^3 from a deep tube well. Of course all these costs are affected by the increasing energy prices. Beyond 20 m depth, turbine/submersible pumps are needed to extract groundwater. The average cost of installation of such a pump is about US$10,000 in Balochistan, and maintenance of these deep tube wells is generally beyond the capacity of poor farmers. Under these conditions, access to groundwater was restricted to only large and rich farmers who could afford this price, and the sufferings of poor small farmers were further compounded. In Balochistan the installation of more than 20,000 deep private tube wells over the last 10 years has negatively affected the traditional karezes and spring systems. The declining groundwater table has resulted in the desertification of lands and the drying up of high value fruit orchards.

4.2. Deterioration of Groundwater Quality

Another effect of falling groundwater tables was the deterioration of groundwater quality. The quality of groundwater in the Indus Plains varies widely, both spatially and with depth and is related to the pattern of groundwater movement in the aquifer (Qureshi et al. 2008). Areas subject to heavier rainfall and consequently greater recharge, in the upper parts of Punjab, are underlain with waters of low mineralization. Similarly recharge occurring from the main rivers and canals has resulted in the development of wide and deep belts of relatively fresh groundwater along them. The salinity of the groundwater generally increases away from the rivers and also with depth. There are large numbers of saline groundwater pockets in the canal command areas of Punjab and Sindh provinces. In Punjab province, 23% of the area has poor groundwater quality, while it is 78% in Sindh province (Haider 2000).

In the lower parts of the Indus plain, the area of fresh groundwater is confined to a narrow strip along the Indus River. Similar situations can also be found in central areas of Punjab province where a layer of fresh groundwater floats over the saline water. Due to excessive pumping of this thin fresh groundwater layer, the downward gradients are increasing, thereby inducing saltwater intrusion into fresh groundwater areas. As a result of saline groundwater intrusion, about 200 public tube wells installed in the fresh groundwater zone of Punjab and Sindh provinces (EC = 1–2 dS m^{-1}) had to be abandoned because of increase in groundwater salinity (EC = 10–12 dS m^{-1}).

4.3. Soil Salinization

The salt-affected soils associated with the use of poor-quality groundwater for irrigation have become an important ecological entity of the Indus basin, yet according to the latest estimates, the extent of salt-affected lands has decreased to about 4.5 million hectares from about 6 million hectares in the 1980s (WAPDA 2007). Because of differences in annual rainfall and geomorphological conditions, the problem of salinity is much more severe in the lower part of the Indus basin (Sindh province), where about 56% of the total irrigated land is affected with salinity. This is mainly because of the presence of marine salts, poor natural drainage conditions, and the use of poor-quality groundwater for irrigation because surface water supplies in the Sindh province are not enough to meet the actual crop water and leaching requirements. Furthermore, leaching opportunities are also very limited because of highly saline soils at shallow depths and highly saline groundwater at deeper depths (Bhutta and Smedema 2007). These problems have brought into question the sustainability of the system and the capacity of Pakistan to feed its growing population.

4.4. Socioeconomic and Environmental Impacts

Declining groundwater tables and land degradation as a result of poor-quality groundwater use for irrigation has seriously affected the social fabric of Pakistani society. Drying of karez systems in Balochistan has increased the livelihood burden on women because of out-migration of spouses for income supplementation. On average, a woman must carry more than 200 l of water every day, which creates an enormous burden on her time and physical capacities. Similar conditions also exist in the Cholistan areas of Punjab, where women have to walk miles to bring fresh drinking water from natural streams, as groundwater is very deep and hazardous to health, as it contains heavy metals.

Soil salinity remains a hazard for the Indus basin and threatens the livelihood of farmers, especially the small-scale ones. Land degradation is reducing the production potential of major crops by 25%, valued at an estimated loss of US$250 million per year (Haider et al. 1999). Groundwater overdraft has also led to seawater intrusion in the coastal areas of the Indus basin, which is threatening the ecology of wetlands. Important aquatic resources, mangrove forests, and coastal areas need to be protected. Mangrove forests cover 130,000 ha and are an important source of firewood and provide the natural breeding ground for shrimps.

5. Problems of Groundwater Management

Until recently the management of groundwater in Pakistan has been neglected because of an apparent abundance of the resource and full attention being given to its development. Inexpensive drilling technology allowed farmers to exploit groundwater extensively to irrigate their crops, which resulted in a spectacular expansion of agriculture and helped lift millions out of poverty. However, the management of groundwater could not keep pace with its development. Over the last three decades, Pakistan has tried several direct and indirect management strategies to control the overexploitation of groundwater, but pragmatic and viable solutions have proven elusive.

5.1. Direct Management

Over the last three decades, government has introduced many laws for regulating groundwater in Pakistan. In the 1980s, a licensing system was introduced to restrict installation of private tube wells in the critical areas (where groundwater was falling at a faster rate and/or where groundwater quality was deteriorating). However, enforcing laws, installing licensing and permit systems, and establishing tradable property rights have so far proved to be ineffective in Pakistan. At the provincial level, the groundwater regulatory framework for Punjab province was prepared in the mid-1990s with the assistance of the World Bank. The national groundwater management rules were also drafted under the Provincial Irrigation and Drainage Authority (PIDA) act in 1999–2000 and included in the Canal act of 2006. Similar law was developed by the Balochistan government (Balochistan Groundwater Rights Administration Ordinance, 2001). These rules suggest demarcation of critical areas, provision of licenses for the installation of tube wells especially in critical areas, and registration of all tube wells (Halcrow-ACE 2003). However, provincial governments failed to implement this framework because of political pressures.

Despite a plethora of laws and policies developed by the government, no serious effort was made for implementing them. In addition to historical neglect, the delegation of human and financial resources for the groundwater management is very small. Moreover, unlike the management of surface water resources (Lohmar et al. 2003), there has been no effort to manage aquifers that span beyond administrative provincial boundaries. Another complication in the management of groundwater was that no single body was responsible for controlling the entire resource. In the absence of a single authority, it becomes difficult to implement policies that attempt to manage the resource in a long-term sustainable way (Negri 1989).

In addition to a lack of respect for the law and corruption in the public sector, a large number of groundwater users was also the major reason for the ineffectiveness of licensing policy in the Pakistani context. For example, in the Murray-Darling basin in Australia, groundwater users number only in the thousands, and enforcement of regulatory laws is relatively easy. In the Murray-Darling basin, permits are mandatory for all large groundwater users. However, small users (2 ha or less) are allowed to extract groundwater without a permit for domestic gardens and livestock needs. If such an exemption were to be applied in Pakistan, more than 90% of the irrigators would be exempted. These incompatibilities between the concept of permit systems and the realities of their application within the specific setting have also been demonstrated in India and China (Shah et al. 2003). In Jordan, where the scale of the development is between that of Australia and the situations in Asia, there has been some success with issuing permits and enforcing regulations in the deeper aquifers where the relative investments in installing pumps are high. However, where the water table is closer to the surface and the risk to the farmer of losing his investment is lower, such systems have proven more difficult (Chebaane et al. 2004).

Shah (2007) argued that energy-pricing policies provided a potent toolkit for indirect management of groundwater in India. However, despite similar socioeconomic conditions, energy-pricing policies for agriculture do not yield any favorable results in Pakistan for controlling groundwater overdraft. This was probably because energy-pricing policies were aimed at generating more revenue rather than controlling groundwater overdraft. Changing tactics of the government only forces farmers to shift from one mode of energy to another but could not help resolve the real issue of groundwater overdraft (Qureshi et al. 2008) because groundwater was crucial for meeting the increasing demand for food, and farmers continue extracting groundwater to meet their crop water demands.

Institutional solutions to groundwater management have also proved to be far more complex than was originally thought. The government is usually under pressure to produce adequate food to feed the population and reduce poverty, especially in rural areas where more than 70% of the population lives. As the availability of public funds for major investments in surface water and irrigation systems had declined sharply, facilitating the development of the groundwater resource allowed the expansion of irrigated agriculture to continue. With many farm families now highly dependent on groundwater for their livelihoods, the national government was reluctant to implement the regulatory laws.

5.2. Indirect Management

Direct management of an economy with such a large number of farmers through enforcing laws, installing licensing and permit systems and establishing tradable property rights did not prove to be effective in Pakistan (Shah 2007). Drawing on the models used in India where energy-pricing policies provided an entry point for indirect management of groundwater (Shah 2007), Pakistan also explored indirect management of groundwater through manipulation of energy prices, realizing that the characteristics of the relationship between groundwater and energy in Pakistan are somewhat different from that of India.

In Pakistan, the use of electricity for groundwater pumping started in the 1970s when the rural electricity grid was expanded and the government provided much-needed incentives for farmers to install tube wells to boost agricultural production. During this period, all capital installation costs were borne by the government, and electricity tariffs were based on a metering system with each farmer paying according to what he consumed. In the 1980s, the population of tube wells surge from 37,000 to 84,000, making it difficult for the government to collect revenue through the metering system (Qureshi and Akhtar 2003). On the other hand, because of increasing electricity costs, the government withdrew subsidies on electricity tariffs in the Punjab and Sindh provinces. As a result, large numbers of electric tube wells were replaced with diesel tube wells, and the ratio of electric to diesel pumps was increased to 1:4, which had been 1:1 in 1970s (GOP 2000). Diesel tube wells were especially preferred by small farmers (< 5 ha) because of low installation costs, easy handling, and no requirement of any reserved money (Qureshi and Akhtar 2003).

This clearly shows that changing energy prices only forced farmers to shift from one mode of energy to another but could not help resolve the real issue of groundwater overdraft because groundwater was crucial for meeting the increasing demand for food, and farmers continued the extraction of groundwater. This is evident from the fact that total groundwater abstraction in 1990 was 43×10^9 m^3 (NESPAK/SGI 1991), which increased to

48 × 10^9 m^3 in 2000 (Qureshi and Akhtar 2003; Bhutta 2002) and jumped to 51 × 10^9 m^3 in 2006 (World Bank 2007). Furthermore it should be noted that the electric tube wells are now less than 10% of the total private tube well population in Pakistan and their share of total groundwater abstraction is about 20%. Therefore, changing electricity-pricing policies, as was the case in parts of India, would have a minor impact on controlling the groundwater overdraft. This clearly demonstrates the need to search for more innovative ways to solve the problem of groundwater overexploitation while maintaining the current levels of agricultural production in view of the increasing population.

6. Prospects of Groundwater Management

The problems of groundwater management in Pakistan are complex and no single solution is available. The direct and indirect strategies have not yielded the desired results, and the extent of overexploitation keeps increasing. A major barrier that prevents the transition from resource development to resource management mode is the absence of a robust information base. Despite hectic efforts by different national and international organizations, the available information on groundwater availability, quality, withdrawal, and other variables is very limited and not properly synthesized. Therefore, there is a strong need to develop a comprehensive database regarding information on users, uses, groundwater abstraction, aquifer conditions, water table depth, and groundwater quality. This information is central to understanding the areas where groundwater resources are underdeveloped and where it is overdeveloped. The dynamics of socioeconomic conditions of these regions also need to be studied for future planning. The potential interventions that might be helpful for reducing demand are briefly discussed next. Recently, Provincial Irrigation Departments (PIDs) and Water and Power Development Authority (WAPDA) has initiated several projects for the development of an integrated database. The successful completion of these projects will be a big step forward toward achieving the goal of groundwater management.

7. Demand Management Interventions

7.1. Managing Conjunctive Use of Surface and Groundwater

In most of the canal command areas, conjunctive use of surface water and groundwater is equally practiced in head and tail ends of the canal system. In Pakistan, the canal water delivered to the head-end farmers is generally 32% and 11% more than to the farmers of tail-end and middle-end, respectively (Haider et al. 1999). The unmanaged conjunctive use of surface and groundwater at the head ends of the canals causes water tables to rise, resulting in waterlogging, whereas at the tail-ends salinity problems are increasing because of excessive use of bad-quality groundwater for irrigation. Therefore planned conjunctive use should be encouraged whereby the upstream farmers make better use of the surface supplies in the canals, which are more reliable for them. For this purpose, the canal department needs to regulate the canal flows to match the requirements. Farmers also need to be educated on proper mixing ratios of surface water and groundwater resources in order to keep the salinity of irrigation water within permissible limits to avoid the risk of secondary salinization.

7.2. Improving Water Productivity

Despite the overall shortage, present irrigation practices of farmers include a tendency to over-irrigate, whereas the opposite should be accomplished. Water is delivered to old traditional irrigation canals and on-farm conveyance and the use of irrigation water is generally rudimentary and wasteful. The use of earth bunds, unlined canals, and poor leveling combined with low water charges have resulted in very low levels of water conveyance and use efficiencies (30% as a national average) and caused the emergence of serious drainage problems (Bhutta and Smedema 2007). Even though much of this lost water is now captured by the extensive groundwater pumping, this does not apply to the saline groundwater zone, and the pumping involves extra costs. The productivity of water in Pakistan is among the lowest in the world. For wheat, for example, it is 0.6 kg m^{-3} as compared to 1.0 kg m^{-3} in India (IWMI 2000). Maize yields in Pakistan (0.4 kg m^{-3}) are nine times lower than those in Argentina (2.7 kg m^{-3}) (Bastiaanssen 2000). This reveals a substantial potential for increasing the productivity of water.

Water pricing structures which make water savings financially attractive are unlikely to be introduced in the near future. Therefore more efforts should be concentrated on adopting water conservation techniques in the irrigated agriculture subsector because this is by far the greatest user of water. Relatively modest increases in water productivity across the Indus basin would result in significant increases in food production without increasing the volume of water abstracted.

7.3. Introducing Resource Conservation Technologies

While it is recognized that water saved at the farm level is not necessarily water that can be used elsewhere (Ahmad et al. 2007), targeted water conservation measures can result in less water being lost to sinks and a decrease of the threat of waterlogging in parts of the Indus basin. Small farmers should be provided with subsidies to shift from flood irrigation to drip irrigation, improve leveling of their fields, and introduce mulching to conserve non-beneficial water loss through soil evaporation. There technological changes have proved successful in improving water productivity at the field level. However, these measures will be effective only if farmers do not at the same time expand their cultivated area or increase their cropping intensity (Ahmad et al. 2007).

Resource conservation technologies such as precision land leveling, zero tillage, and bed and furrow planting have also shown considerable reduction in water application at the field scale. Zero tillage technology is now widely practiced in many countries including the United States, Brazil, Argentina, and Zimbabwe. In Pakistan, its use is restricted to about 150,000 ha and needs to be expanded. The furrow-bed method of irrigation can save up to 40% of applied irrigation water as compared to the basin irrigation method (Qureshi et al. 2003). This water savings will have a huge effect on the current water use for agriculture, which in turn will reduce the groundwater extraction. Prathapar and Qureshi (1999) have also demonstrated that in the Indus basin, optimal crop yields can be obtained by applying an irrigation equivalent to 80% of the total crop evapotranspiration (deficit irrigation). Introduction of these techniques in (semi-)arid conditions of the Indus basin require careful irrigation planning as reduced irrigation applications may increase the threat of soil salinization. Therefore careful evaluation of the impact of these techniques at different scales for different agroclimatic conditions within a basin should be carried out before recommending them to farmers for large-scale adoption.

7.4. Rationalizing Cropping Patterns

The traditional crops such as rice and sugarcane have benefited from increased irrigation supplies. Since rice is a water-intensive crop, it is essential to review whether Pakistan should continue to grow rice for export or instead use this water for other crops for which the country has a comparative advantage. In the rice-growing areas of Pakistan, more than 70% of irrigation water is supplied through tube wells (Qureshi et al. 2006); restricting the rice production to its domestic needs and converting to less water-intensive crops could reduce the pressure on the groundwater.

Adoption of other irrigation water strategies such as alternate wet and dry irrigation (AWADI) used for rice can also help save groundwater. Direct seeded rice requires 23% less irrigation water as compared to traditional transplanted rice under Pakistani conditions (Qureshi et al. 2006). Similarly, strategies should be developed to replace sugarcane with low water-demanding and high market-value crops. Introduction of high-value crops like sunflower, pulses, vegetables, and orchards can also increase farm incomes substantially. Presently the country is importing more than one billion US dollars of edible oils (GOP 2007).

7.5. Promoting Rainwater Harvesting

The rain-fed areas of Pakistan contribute about 10% of the total agricultural production. However, production levels of rain-fed areas are very low (i.e., 1–1.5 t/ha). Oweis and Hachum (2001) argue that the production potential of these areas can be doubled by providing one or two supplemental irrigations at critical growth stages of the crop. Where farmers are already doing this, they are generally relying on groundwater extraction. However, they should be encouraged to harvest rain water and adopt watershed management strategies to both improve the productivity of rain-fed systems and reduce the demands on groundwater. Many fragmented efforts have been made in the past; however, there is a need to develop comprehensive policy at the government level to ensure continuity in this regard. Furthermore, farmers should be educated to optimize crop yields by using less water rather than maximizing their crop yields through excessive groundwater irrigation.

8. Supply Management Interventions

8.1. Artificial Recharging of Aquifers

Aquifer management is considered as the most effective way of establishing a balance between discharge and recharge components. This practice is widely used in industrialized countries such as Germany, Switzerland, the United States, the Netherlands, and Sweden, although only in the United States are there large abstractions from groundwater for irrigation. The share of artificial recharge to total groundwater use in these countries ranges between 15% and 25% (Li 2001, Groundwater recharge, unpublished). In recent years, India has also taken serious steps to use harvested rainwater for recharging their aquifers and recently allocated significant funds in the Union budget for further promotion of the practice. However, while there is evidence that groundwater recharge interventions have produced positive results on the groundwater availability, whether they can have the necessary impact on a broader scale and be cost-effective in the context of the Indus basin has yet to be established.

Investments to develop small-scale surface structures to facilitate groundwater recharge can be used to improve the availability of groundwater at the local level, and, possibly, farther downstream. There are, of course, two important cautionary points with promoting such investments on a wide scale. The first is with regard to the impact on the basin availability of water, with groundwater water recharge "diverting" surface water from existing downstream users, as has been shown in other parts of south Asia (Venot et al. 2007). The second important point is the effectiveness of such approaches, and while there are challenges with groundwater recharge, it is imperative that it be fully explored either as an alternative or complimentary facet to the further development of large-scale surface storage systems. As mentioned earlier, existing surface-water systems are significantly less reliable than groundwater and are not the farmers' preferred source for improving the productivity of Pakistan's irrigated agriculture.

8.2. Use of Alternate Water Resources

The total annual quantity of wastewater produced in Pakistan is estimated at 4.5×10^9 m^3. Most of this water is either disposed of in rivers or discharged into open areas on the outskirts of big cities. A small amount of this water is being used to grow vegetables in large cities. There is a need to make profitable use of wastewater by growing valuable crops instead of discharging it in main water bodies to pollute fresh water resources.

Presently, the use of saline water is restricted to growing salt-resistant crops. Such crops as grasses for fodder and bushes and trees such as eucalyptus have proved successful in providing a reasonable economic return to the farmers of the saline areas. A large amount of work has been done in Pakistan; however, more should be done to improve the use of saline lands and saline waters. Studies done in Pakistan and India have shown that brackish water can be used for irrigating different crops under different soil types and environmental conditions (Sharma and Rao 1998; Qadir et al. 2001). Brackish groundwater has been used successfully to irrigate wheat, cotton, pearl millet, sugar beet, and so forth. Yield reductions of up to 15–20% were observed when compared with fresh water irrigation. In the deep groundwater areas, excessive accumulation of salts was well managed during the summer monsoon rains. In shallow groundwater areas, well-managed drainage systems are mandatory for successful use of brackish water for irrigation without causing soil degradation.

8.3. Policy Reforms

Because of the peculiarities of Pakistan's groundwater socioecology, a multidimensional approach is needed. In Balochistan province, for example, the policy of providing subsidies on electricity needs to be reviewed. Currently, the annual subsidy on agricultural tube wells is Rs. 8.5 billion (US$140 million). This subsidy is mainly provided to only 2.5% of the farmers who own deep electric tube wells. The majority of small farmers are deprived of this facility, which is creating serious equity concerns in the rural communities. Moreover, farmers should be educated to grow high-value crops with the expensive groundwater rather than continuing with traditional wheat and fodder crops. This will yield them good incomes and improve their livelihoods. After becoming well-off, they should start adopting more efficient irrigation systems.

In the Punjab province, more efforts are needed to review existing cropping patterns for areas where hydrological conditions suggest that additional groundwater resources are insufficient to support intensive agriculture. Separate strategies should be developed for large commercial farmers and for small poor farmers who are totally dependent on groundwater for protecting their livelihoods. Cropped areas for different crops should be fixed on the basis of the country's food requirements and the availability of water resources. In areas such as the Cholistan desert where groundwater resources are not yet tapped because of the lack of resources of the local population, groundwater still presents the opportunity to secure the livelihoods of the large population living in this region. Producing local food will reduce their dependence on adjacent agricultural areas.

For effective management of groundwater, laws and policies are in place. Now the government will is needed to bring about a change. The choice of formal and informal institutional setups depends on the hydrological regime and economic profile of the population. In the context of Pakistan, farmers need to be made aware of the increasing groundwater problems and taken into confidence to implement possible technical, scientific, institutional, and political tools to protect key strategic aquifers with regard to quality and quantity. Policies should also be formulated for the economic transition of the population that currently depends on intensive irrigated agriculture to earn their living. Doing this is essential for reducing pressure on groundwater resources and creating political space for direct management of the resource base. India is moving toward management of aquifers through groundwater user associations in an attempt to involve users in decision making. However this has to be done together with demand management strategies, as discussed earlier, to increase effectiveness.

9. Conclusions

This paper has shown that groundwater has acquired a pivotal role in the agricultural economy of Pakistan. Groundwater now accounts for almost half of all irrigation requirements. Although, there is clear evidence that groundwater is being overexploited, yet tens of thousands of additional wells are being put into service every year. In the rain-fed areas of Balochistan, farmers are pumping from depths of hundreds of meters and in the sweet water areas of the Indus Basin, depletion is now a fact in all canal commands. Furthermore, there are serious and growing problems with groundwater quality, a reality that is likely to get worse in the coming years. Therefore there is an urgent need to develop policies and approaches for bringing water withdrawals into balance with recharge, a difficult process that is going to require action by government and by informed and organized users. Since much groundwater recharge in the Indus Basin is from canals, this requires an integrated approach to surface and groundwater.

The governance and management of groundwater in Pakistan has proved much more complex for multiple reasons. The increasing dependence of irrigated agriculture on groundwater has helped ensure food security for the rising population and has been a fundamental linkage to the livelihood of millions of rural poor, which makes the groundwater management even more complicated. The traditional ways of managing groundwater through the introduction of groundwater use rights, direct and indirect pricing, limiting access to groundwater by enforcing permit systems and delivering groundwater on volumetric basis are not likely to succeed in Pakistan because of its high population density and exceedingly large number of users. These strategies are feasible where a given aquifer has very few users and the responsible authority has a very clear mandate and capacity. Therefore a well-thought-out, pragmatic, patient, and persistent strategy is needed to address the issue of groundwater management. The key to success will be heavy engagement of users, substantial investments in modern water and agricultural technology, and the development of the enabling policies and decision support systems.

Pakistan needs a serious debate about whether to pump their aquifers to the maximum and face the consequences thereafter, or be more proactive now, better manage abstraction, and invest in recharge today. For effective groundwater management, Pakistan is required to introduce frameworks and instruments that are suitable to its needs. The frontline challenge is not just supply-side innovations but to put in place a range of corrective mechanisms before the problem becomes either insolvable or not worth solving. The potential solutions presented in this paper need enabling policies and, more importantly, their effective implementation to complement existing efforts for the management of groundwater resources in Pakistan.

Note

1. The karez is one of the oldest traditional irrigation systems of Balochistan. The karez was devised as a means of tapping groundwater supplies using gravity flow. It is a gently sloping tunnel that conveys water from below the water table to the ground surface. It consists of a series of hand-dug wells and tunnels that collect rain and groundwater and discharge it into farmer fields. A karez can be used as a source of water for years. There are about 493 karezes in Balochistan (IUCN 2000). Some karezes are older than 100 years. An average karez has a discharge of 0.20 $m^3 s^{-1}$ and can irrigate 10–20 ha.

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