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Full Length Research Paper

Improving food security and livelihood resilience through groundwater management in Pakistan

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Extensive groundwater extraction has helped Pakistan to achieve food security, economic development and reduction in rural poverty. However, the problems of groundwater over-exploitation are now threatening the continuation of Pakistan's groundwater irrigation economy. This paper reviews the groundwater development, examines the benefits it has generated, institutional approaches applied and discusses why the resource has proven so difficult to manage. This study reveals that management of groundwater in Pakistan requires multifaceted actions focusing both on supply-side and demand-side solutions. These include stabilizing aquifer; re-visiting conjunctive water use; increasing productivity of groundwater use, and improving governance considering local socio-cultural factors.

Keywords: Conjunctive water use, policy reforms, food security, water table depth, soil salinization

INTRODUCTION

In South-Asia, decreasing surface water supplies has prompted farmers to exploit more and more groundwater to meet crop water requirements to ensure food security for the increasing population. In India and the Northern China Plain, for example, more than 50% of the total agricultural water use is contributed by groundwater (Shah et al., 2003). Pakistan is the third largest groundwater consumer in the world accounting for approximately 9% of the global groundwater withdrawals (Giordano, 2009). The continuous increase in the irrigated area over the last three decades and the expansion of cultivated area for sugarcane and rice crops were the main drivers in increased groundwater demand (Ahmad et al., 2004; Qureshi et al., 2010). Under the semi-arid to arid conditions prevailing in most of the Indus basin, surface water availability is only marginally sufficient to support basin wide, year-round high cropping intensity. Furthermore, more than 30% of the surface water storage capacity has been lost due to siltation of major reservoirs and climate change (Qureshi, 2014). Under these circumstances, Indus basin's alluvial aquifer has played significant role to salvage Pakistan from food insecurity, economic development and ultimately national security. Presently, more than 60% of the irrigation water available at the farm gate is contributed by groundwater (Chaudhry, 2010).

Like many other water stressed countries of the South-Asia, Pakistan is also faced with a serious imbalance in water supply and water demand. In the Indus basin, rainfall contributes less than 15% of the total crop water requirements and the rest has to be covered through irrigation (Bhutta and Smedema, 2007). Due to shortage and inconsistencies in surface water supplies, the gap between crop water requirements and surface water availability is usually met through the exploitation of groundwater. Currently Pakistan irrigates about 4.6% of the global groundwater-fed cropland (Siebert et al. 2010). The

Figure 1: Map of Pakistan

accessibility to groundwater has helped smallholder farmers in boosting crop yields, stabilizing production capacities and broadens their crop choices to increase their profit margins. This has positively impacted the livelihood of poor rural communities and the agricultural economy of the country at large (Shah 2007).

The benefits of groundwater in Pakistan are multidimensional and range from drinking water supplies for urban and rural population to sustainable economic development. On the other hand, continuing groundwater irrigation is also replete with serious consequences as energy costs are increasing, water levels are declining in the intensive irrigated areas, and groundwater quality is deteriorating. Due to increasing financial and environmental concerns, the large-scale development of surface water resources in Pakistan will remain a challenge in near future. Groundwater irrigation will therefore remain crucial to sustain agrarian growth to meet future food requirements.

Despite the fact that groundwater has played a crucial role in meeting Pakistan's growing demand for food and fibre, the strategic value of Indus basin aquifer has not been fully recognized in thwarting water shortages that would have caused untold harm to the agrarian economy. It is now widely recognized that continued lack of focus on this issue would be disastrous for Pakistan's water security. The major problems related to groundwater management in Pakistan are that the robust information on aquifer reserves and their withdrawal patterns is lacking, and the consequences of groundwater use for irrigation are poorly understood. This paper fills this gap by looks at the nature and extent of groundwater development and examines the benefits it has generated for supporting irrigated agriculture in Pakistan as well as the problems associated with groundwater use and future challenges. This paper also examines why groundwater and its source has proven so difficult to manage and conclude with policy recommendations for the rational management of groundwater resources. This paper uses the Pakistan groundwater situation as a study case however the findings will be equally valuable for other regions facing similar groundwater management challenges.

STUDY AREA AND DATA ANALYSIS

Study area

Pakistan is located between latitudes 24^o and 37^o North and longitudes 61^o to 76^o East. It is bordered by India in the East, China in the northeast, Afghanistan in the north, Iran in the southwest and the Arabian Sea to the South (Figure 1). The agriculture sector is dominant in the economy of Pakistan. The sector not only meets the food demand of the growing population but also provides the raw material for the industrial sector, notably cotton and sugarcane for the textile and sugar industry. As pointed out earlier, the sector employs 45% of the total labour force,

Table 1: Agricultural and irrigated areas by Provinces of Pakistan (Million ha)

Location	Total area	Agricultural land	Cultivated area	Rain fed area
Pakistan	57.06	33.63	21.20	4.95
Punjab	17.48	14.51	12.42	1.60
Sindh	14.09	7.35	4.88	1.43
Khaberpukhtunkhwa (KPK)	8.34	4.45	1.91	1.07
Balochistan	17.15	7.32	1.99	0.85

Table 2: Farm size distribution in Pakistan

Farm Size (Ha)	Farms (%)	Average size of farms (ha)
<0.5	23.1	0.28
0.5-1.0	17.5	0.74
1.0-2.0	20.5	1.37
2.0-5.0	25.1	3.10
5.0-10.0	7.8	6.71
10.0-20.0	4.0	12.73
20.0-60.0	1.7	35.14
>60	0.3	144.52

support 70% of the population directly or indirectly and earn 60% of the total foreign exchange. Pakistan's total cultivated area is about 21.2 million ha, out of which 6.65 million ha or 23.3% of the total cultivated area of the country is rain-fed (Table1). About 56% of the total cultivated area is allocated to food crops, 18% to cash crops, 6% to pulses and 3% to oil seeds. The left over area is covered with orchards, vegetables and condiments (GoP, 2013). A significant part of the land is allocated to seasonal fodders and minor crops.

There are 6.3 million farms with an average holding of 3.2 ha. About 86% are small land holders (0.5 to 10 ha), medium farms are 7.8% (10 to 25 ha), whereas the large farms are only 6% (60 ha and above) (USAID, 2009; GoP, 2013). Farm size distribution in Pakistan is given in Table 2.

Due to arid and semi-arid climate prevailing in most parts of the country, food security is directly linked with the sustained progress of the irrigated agriculture. On the other hand, the viability of irrigated agriculture in the Indus basin is threatened by waterlogging and soil salinization. These problems are the result of a multitude of factors, including seepage from the canals system, inadequate provision of drainage, poor on-farm water management practices, insufficient surface water supplies and use and management of poor quality groundwater for irrigation. The problems like depleting soil fertility, soil erosion, water logging and salinity are making the situation more complicated.

The Indus River and its tributaries (Indus Basin), on an average, bring 190 billion cubic meters (Bm^3) of water annually. This includes 179 Bm^3 from the three Western Rivers (Indus, Chenab and Jhelum) whereas three eastern rivers contribute only 11 Bm^3. Most of this, about 129 Bm^3, is diverted for irrigation. About 50 Bm^3 flows to the sea and an estimated 11 Bm^3 are the system losses, which include evaporation, seepage and spills during floods. Currently, 93% of the total water withdrawal (177 Bm^3) is allocated to the agricultural sector, 4% (7.5 Bm^3) is used for domestic purposes and the rest 3% (5.5 Bm^3) goes to industrial use (Bakshi and Trivedi, 2011). The population of Pakistan is expected to increase to 250 million in 2025, which will double the demand for municipal and industrial supplies (14 Bm^3) and irrigation water will face increasing competition from these two sectors (USAID, 2009). The water requirements for irrigation in the Indus Basin are estimated at 250 Bm^3 in 2025 against the estimated availability of 185 Bm^3. Even by exploiting the full groundwater potential, the water availability will not be more than 190 Bm^3 (Qureshi et al., 2010). (Figure 1)

Water availability in the Indus Basin Irrigation System (IBIS) is highly seasonal with 85% of the total river flows occur during the summer season (July-September). This makes the storage critical for Pakistan for inter-seasonal transfer of water from surpluses in summer (kharif) season to meet shortages in winter (rabi) season for meeting crop water requirements. The recent estimates suggest that to meet the future water requirements, 22 Bm3 of more water will be needed by the year 2025 (World Bank, 2008). This will need to at least double the existing storage capacity, which is only 15% of the annual river flow.

Furthermore, many canals can no longer convey their official design capacity due to siltation and poor maintenance. From the scarcity by design and intensive irrigation practices by farmers, over time canal water availability per unit of irrigated land has further reduced. Due to age and poor maintenance, overall irrigation efficiency is only about 36 percent (Bhutta and Smedema, 2007). In practical terms, therefore, much surface water is lost en-route, which is of particular concern in areas underlain with saline ground water. Seepage in areas underlain with good quality groundwater however contributes to groundwater recharge which is then pumped through mostly private tubewells. The lower Indus Basin, however, is largely deprived of recoverable recharge because of underlying saline groundwater. Despite the shortage of water, over irrigation is a major problem in Pakistan. The impact of this is not only wastage of water, but it also leads to water-logging and salinity (Qureshi et al., 2010).

Data analysis

The results presented in this paper are based on a mix of literature review and analysis of primary data. A comprehensive literature review was conducted taking into account the available peer-previewed articles and reports on different aspects of groundwater development and management in Pakistan. The long-term data on groundwater development, changes in groundwater table depth and quality and energy use for groundwater extraction were collected from Water and Power Development Authority (WAPDA). Data on tubewell population and their distribution across the country were collected from the Punjab Agricultural Department. Information on total irrigated area for different crops, irrigation patterns, irrigation water use efficiencies and economics of groundwater, were collected from yearbooks of Pakistan Bureau of Statistics (GoP, 2013; GoP, 2014) These data were summarized and analyzed to generate GIS maps to understand the spatial and temporal changes in groundwater table depth and quality, in addition to the impact of increasing energy prices on the cost of irrigation.

RESULTS AND DISCUSSION

Groundwater occurrence and development in Pakistan

The 300 meters deep alluvium of the Indus basin has a heterogeneous character and form a unified highly transmissive aquifer. The underlying aquifer covers 16 million ha (Mha) of surface area, of which 6 Mha are fresh and the remaining 10 Mha are saline (Qureshi et al., 2010). Small capacity tubewells (0.03-0.06 m^3s^{-1}) can theoretically be developed almost everywhere. The aquifer receives its direct recharge from natural precipitation, river flow, and the continued seepage from the unlined canals, distributaries and watercourses and application losses from the irrigated fields. This shows that alluvial aquifer of the Indus basin is a resource of enormous economic value, because of its highly amenable flexible operation and scientific management.

Large-scale extraction and intensive use of groundwater in the Indus basin started in 1960s with the induction of Salinity Control and Reclamation Projects (SCARPs) when 16,700 wells (supplying an area of 2.6 Mha) with an average capacity of 0.080 m^3s^{-1} were installed to control water table and salinity problems (Bhutta and Smedema, 2007). The pumped groundwater was discharged into the irrigation canals to augment irrigation supplies. Subsidized electricity and introduction of locally made diesel engines provided an impetus for the massive development of private tubewells with an average discharge capacity of 0.03 m^3s^{-1}. Currently, about 1.2 million private tubewells are working in Pakistan with an estimated investment of US$ 0.5 billion (Qureshi et al., 2008). Out of these, over 0.80 million are only located in the Punjab Province (Figure 2). The safe yield is estimated to be 68 Bm^3, whereas the total extraction is already approaching to 52 Bm^3 (Qureshi, 2014). This virtually means that this resource is almost exhausted because the remaining potential is located in areas where groundwater quality is poor or where it is economically not feasible to extract, such as in hard rock areas of Baluchistan. (Figure 2).

The expansion of groundwater irrigation in Punjab registered a 70 percent increase in the irrigated area i.e. 8.65 Mha in 1960 to 14.7 Mha in 2014 (Government of Pakistan, 2014). During the same period, groundwater contribution to overall irrigation water supplies increased from a merely 8 percent to over 60 percent, with the flexibility of its availability as and when needed (Qureshi, 2014)). During the last three decades, 75 percent of the increase in water supplies has come from groundwater exploitation. In the process, the great canal system of the Indus basin has become less of a water delivery mechanism, and more of a groundwater recharge mechanism. In Punjab, for example, canal system contributes about 80 percent of the total groundwater recharge (Khan et al., 2008).

Socio-economic impacts of groundwater irrigation in Pakistan

The on-demand availability of groundwater was a deviding line between poverty and welfare for millions of poor farm families for whom the long dry season is a trying time of

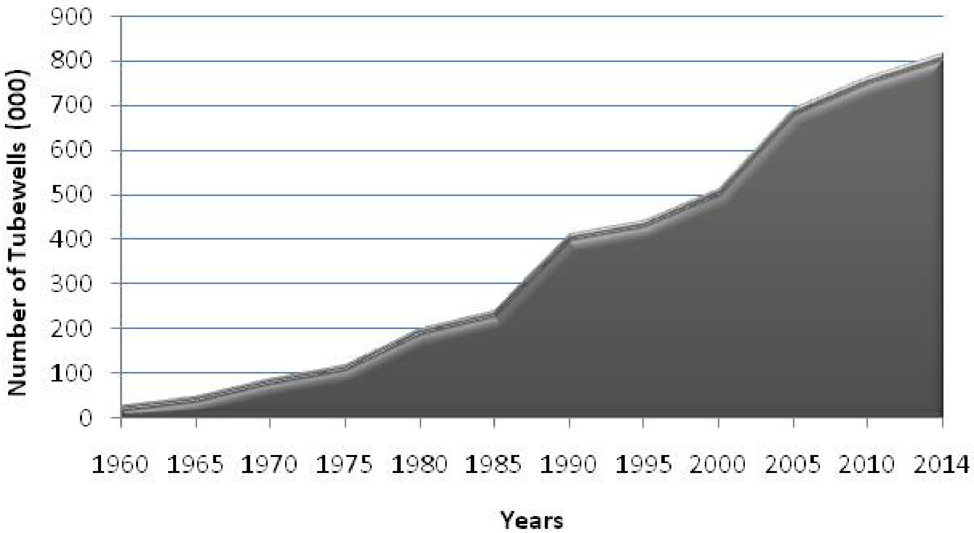

Figure 2: Historical development of private tubewells in the Punjab Province of Pakistan

one meal a day. Groundwater exploitation in Pakistan played a vital role in fighting hunger, tumbling poverty, and achieving higher economic growth. The increased accessibility to groundwater not only ensure predictable and increased crop yields, but also created opportunities for smallholder farmers to diversify their income base and reduce their exposure against external shocks such as droughts The estimated number of groundwater users in Pakistan is over 2.5 million farmers, who exploit groundwater directly or buy groundwater from their neighbors (Shah, 2007; Qureshi, 2014). Farmers having access to groundwater managed to attain 50 to 100 percent higher crop yields compared to those fully dependent on canal water (Shah et al. 2003; Shah, 2007). Farmers also started growing water intensive crops such as sugarcane and rice, resulting in increased farm incomes due to high market prices. The annual benefits of groundwater irrigation in the form of agricultural production are estimated at US$ 2.0 billion (World Bank, 2006).

The flexibility provided by groundwater offered a significant value addition to the farmers over dry land and surface water irrigation farming. In the Pakistani context, this value addition comes from its '*stabilizing effect*' and '*intensification effect*' (Tsur, 1990). The stabilizing effect is groundwater's buffer role during droughts and dry spells when surface supplies run dry. This role was witnessed during the severe drought during 1998 to 2002 when surface water availability was reduced by 26 percent 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 tubewells (Bhutta, 2002; Qureshi et al., 2010).

The "*intensification effect*" refers to the capacity of groundwater users to intensify land use by cultivating two, three, or more crops each year. In Pakistan, like most of South Asia and China, the economic value of groundwater irrigation comes from intensifying land use as the cropping intensities increased from 70 percent to over 150 percent with the increased groundwater accessibility (Shah, 2007). Data collected from 521 canal-irrigators across Pakistan has also revealed that farmers having access to groundwater were able to cultivate 90 percent of their total area as compared to 63 percent for those who were fully dependent on canal water (Shah et al. 2003; Shah, 2007). Meinzen-Dick (1997) has also shown that farm incomes of farmers with access to both surface water and groundwater resources are about 5 times higher than those limited to surface water only, and argued that owning a tubewell in Pakistan and having access to canal water assures a farmer of adequate and timely water supplies in most situations, sharply increasing earnings.

Challenges to Groundwater Irrigation Economy

Depleting aquifers due to overdraft

Due to uncontrolled and unregulated exploitation of groundwater, trends of continuous decline of the groundwater table have been observed in many areas of the Indus basin, which illustrates the serious imbalance between abstraction and recharge (Figure 3). Excessive mining of aquifers in fresh groundwater areas has resulted in falling water tables and groundwater has become inaccessible in 5% and 15% of the irrigated areas of Punjab and Balochistan provinces, respectively. Figure 2 shows the changes in groundwater table depths over a period of 20 years (1993-2013) in the Punjab province. The changes in water table depths in the Sindh province are

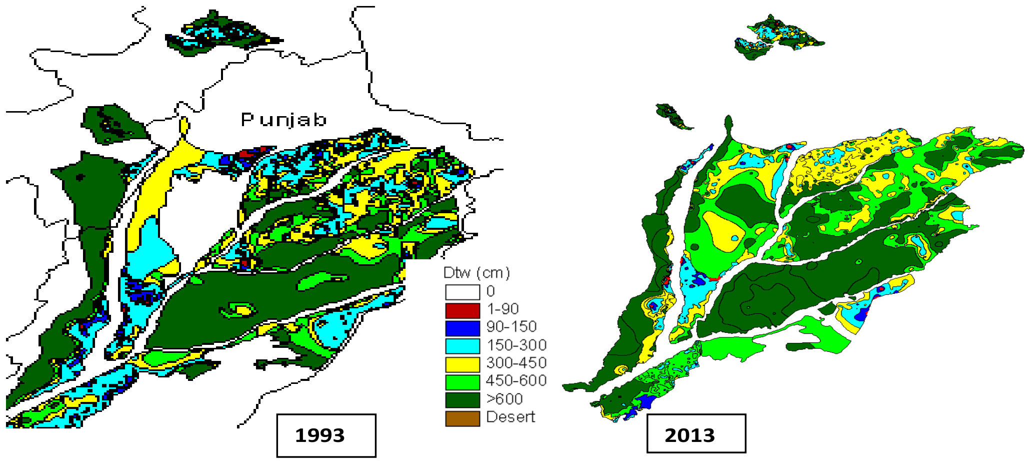

Figure 3: Comparison of water table depth between 1993 and 2013 in the Punjab province

less significant because of lower groundwater rates due to quality concerns. Although no recent estimates exist, it was estimated that under the *business as-usual* scenario, this area is expected to increase to 15% in Punjab and 20% in Balochistan by 2020 (PPSGDP, 2000).

Increased pumping costs and environmental threats

The management challenge is to stabilize the groundwater table at levels where the cost of pumping is affordable. Excessive lowering of the groundwater table has left farmers with no choice than to drill deeper wells, which has made pumping more costly and energy intensive. The annual cost of canal water is US$ 3.5/ha compared to annual groundwater cost of US$ 167/ha. Increasing groundwater table depths have increased the pumping cost from US$ 4.2/1000 m^3 for shallow tubewells (< 15 m) to US$ 12/1000 m^3 for a deep tubewell (> 15 m) (Qureshi et al., 2010). These costs keep on changing due to changing energy prices and installation expenses.

In Pakistan, only 13% of the tubewells are operated by electric motors whereas the rest 87% are run by diesel engines of various capacities (Qureshi, 2014). In 2012, farmers extracted 52 Bm^3 of groundwater, of which about 14 Bm^3 was extracted using electric pumps and the remaining 38 Bm^3 using private diesel pumps (Qureshi, 2014). Each year about 6 billion kWh of electricity and 3.5 billion liters of diesel are used for extracting groundwater for irrigation. Carbon emissions attributed to this energy use amount to 3.8 million metric tons (MMT) of CO_2 per year (Qureshi, 2014). Of this figure, which is roughly 1.2% of Pakistan's total carbon emissions, 1.4 MMT of CO_2 is emitted through electricity consumption and 2.4 MMT of CO_2 through diesel combustion. This implies that, on average, the extraction of every cubic meter of groundwater contribute 80 g of carbon emissions. Therefore reducing water use for agriculture by improving water productivity could help in decreasing energy use, stabilizing aquifers and reducing carbon emissions.

Deteriorating groundwater quality

The quality of groundwater in the Indus basin 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 are underlain with waters of low mineralization. The salinity of the groundwater generally increases away from the rivers and also with depth. There are saline groundwater pockets in the canal command areas of Punjab. Figure 4 shows that about 77% (4 Mha) of the area in the Punjab province has access to fresh groundwater with an average concentration of dissolved solids less than 1000 ppm. In the lower Indus Basin (Sindh province), about 28% of the area, mainly confined to a narrow and shallow strip along the Indus River, has fresh groundwater whereas the rest 72% is underlain by brackish groundwater (Leghari et al. 2012). In Pakistan, water up to1000 ppm is considered fresh, from 1001-1500 ppm, marginally fresh, and from 1500-3000 ppm marginally fresh, and above 3000 ppm groundwater is considered hazardous for irrigation. Indiscriminate pumping in the fresh groundwater areas of the Punjab province has also resulted in the contamination of the aquifer at different places where salinity of pumped water has increased beyond useable limits (Bhutta and Alam, 2012). About 17% area of Punjab and 75% in Sindh is underlain by saline groundwater (TDS>3000 ppm). About 70 percent of tube

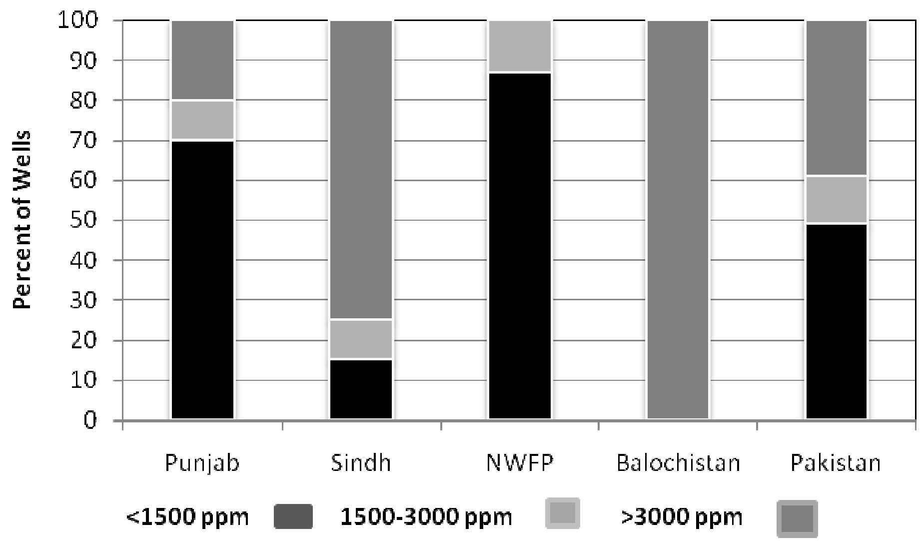

Figure 4: Groundwater quality in the four provinces of Pakistan

wells pump saline water for irrigation, which is escalating secondary salinization. Problems are not only due to salinity but also sodicity.

Increased soil salinization

The Indus Basin is faced with a considerable salt balance problem. The salts are brought in by rivers and their tributaries. Presently water diverted from the Indus River to canal system for irrigation brings in about 33 million tons (Mt) of salts while the outflow to the sea is only 16.4 Mt. This means an average annual addition of some 16.6 Mt to the salt storage in the Indus Basin. Of this, only 2.2 Mt is deposited in a series of evaporation ponds located in the desert area outside the irrigated plain in southeast Punjab; the remainder accumulates in the irrigated land and its underlying strata and aquifer (Nespak/MMI, 1993). In short, an average of 1 ton of salts is added to each hectare of irrigated land. This accumulation is the main cause of land salinization. Salt-affected soils have become an important ecological problem in the Indus Basin—an estimated 4.5 million ha are already afflicted, about half of which are located in irrigated areas (WAPDA, 2010). Of course, the scale of the problem of salt accumulation in the root zone would be even greater if saline groundwater is used for irrigation.

The consistent use of poor quality groundwater for irrigation has resulted in large scale salinization of agricultural lands in the Indus basin. The problems of soil salinity are much more severe in the tail-end areas of the canal commands where surface water availability is low and groundwater quality is very poor. Due to differences in annual rainfall and geo-morphological conditions, the extent of soil salinization in the lower Indus basin (Sindh province) is much more than Punjab where about 54% of the total irrigated land is affected from different levels of salinity (Figure 5). This is mainly because of the presence of marine salts, poor natural drainage conditions and the use of poor quality groundwater for irrigation. Furthermore, leaching opportunities are limited due to 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 in future unless better management measures are introduced.

Prospects for Groundwater Management in Pakistan

The main drivers of groundwater development in Pakistan has been increasing population, the pressure to grow more food, risk-aversion, the Government's national policy of achieving food security in the face of potential disasters (e.g., floods, droughts), and the energy subsidies in the agriculture sector. As discussed before, the large scale groundwater exploitation helped Pakistan in expanding irrigated area, increasing crop yields and cropping intensities, improving access to drinking water, and enhancing ability to hedge against the vagaries associated with surface water supply. Most importantly, groundwater extraction has helped to lift millions out of poverty. However, the situation has nonetheless now turned serious

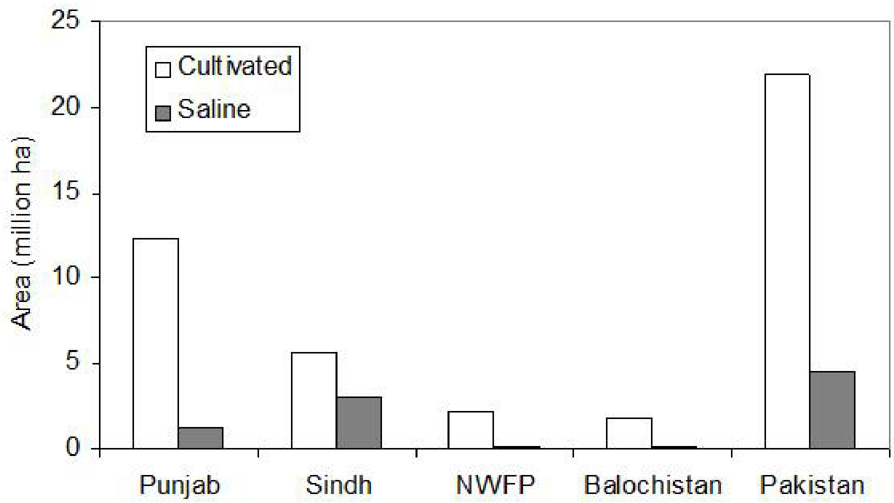

Figure 5: Province-wise distribution of cultivated area and salt-affected area (WAPDA, 2010).

because unregulated exploitation of groundwater has brought Indus basin aquifer under stress, threatening the sustainability of irrigated agriculture which produces more than 90% of the total food production in Pakistan.

The management of groundwater in Pakistan is further complicated due to the fact that more than 70% of the population still lives in rural areas and earn their living through agricultural activities. It is now widely recognized that groundwater-based irrigation economy of Pakistan cannot be sustained without increasingly negative consequences. As such, more concerted efforts are needed to bring a balance between aquifer extraction and recharge, and to find alternative ways to reduce the intensity of energy use in irrigation development, requiring work on both supply- and demand-side solutions. The potential solutions that can help Pakistan sustain groundwater irrigation economy are briefly discussed below.

Stabilize aquifers by balancing aquifer recharge and discharge

Like many industrialized countries, establishing a balance between discharge and recharge components could be an effective way of aquifer management in Pakistan. To recover groundwater reserves, artificial groundwater recharge contributes to total groundwater use at the rate of 30% in Western Germany, 25% in Switzerland, 22% in the USA, 22% in Holland, 15% in Sweden and 12% in England (Li, 2001. Indian experience of community rainwater harvesting ponds at the village level to recharge groundwater and introduction of check dams in the Baluchistan province of Pakistan are also good workable examples (Shah 2007; Ahmad, 2009). Rainwater harvesting can also be introduced in public and community wells situated near slums and in villages, draining water from nearby rooftops and seepage infrastructure. However, the efficacy of investments in rainwater harvesting on a wide scale with regards to the impact on basin availability of water for downstream farmers and costs involved needs to be evaluated (Venot et al. 2007).

From the management perspective, Indus basin aquifer can be divided into three distinct zones as shown in Figure 6. In Punjab, natural groundwater is deep and saline because of marine origin of the aquifer. Percolation of rainfall and irrigation fields has created a thin layer (up to 50 m) of fresh groundwater (Qureshi et al. 2004). In these areas, groundwater extraction should be managed in such a way so that the fresh and brackish groundwater interfaces are not disturbed. In the central parts of Punjab where groundwater is fresh and shallow, overdraft is the major issue and extractions need to be brought in balance with the recharge. This can be done by rationalizing cropping patterns, enforcing governing laws and effective monitoring. In the lower parts of the Indus Basin, groundwater is shallow and of very poor quality and soil salinity is the major concern. Therefore to avoid further soil salinization and loss of agricultural productivity, drainage and disposal of brackish water is most important.

Re-visiting conjunctive water management strategies

In Pakistan, canal water is allocated based on a fixed time per unit area without considering the seepage loss along the channel, which is a major cause of inequitable water distribution at a tertiary level. The rate of seepage loss

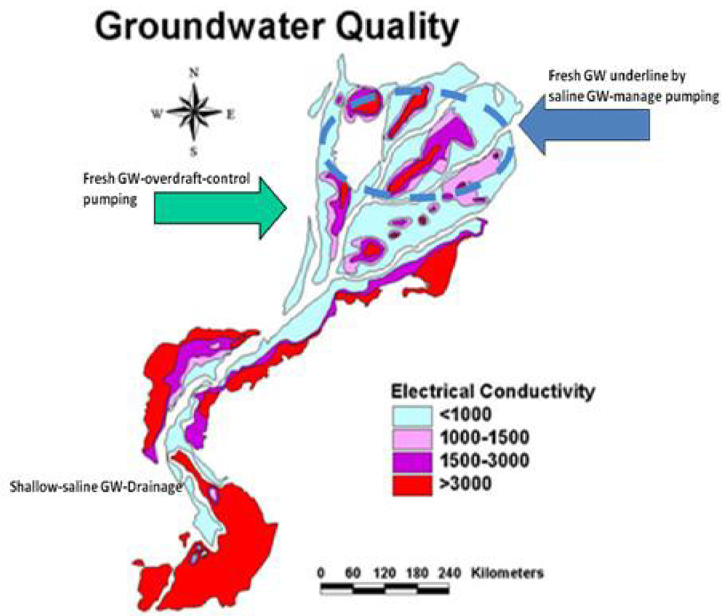

Figure 6: Three distinct groundwater zones of the Indus Basin of Pakistan

increases with increase in length canal thus the farmers in the lower reaches get much less water per unit area. The farmers located at the tail-end of the system get 20% less canal water than middle-end farmers, who in turn get 20% less water than the farmers located at the head reaches of the canal (Latif and Ahmed, 2009). Due to these discrepancies in the surface water distribution, dependence on groundwater is ranging from 65% in head areas to over 90% in tail areas. This shows that groundwater is no longer supplemental to surface water, but has become an integral part of the irrigated agricultural environment. Although evidences exist that blending of saline and non-saline irrigation water is less effective in keeping soil salinity levels lower than applying cyclic irrigations (Shalhevet, 1994; Kumar, 1995), this strategy is still widely practiced. By mixing groundwater with good quality surface water, farmers tend to decrease the salinity of the irrigation water in order to maintain favorable salt balance in the root zone.

The conjunctive use of surface water and groundwater is practiced on more than 70% of the irrigated lands of Pakistan. The area irrigated by groundwater alone has increased from 2.6 Mha to 3.7 Mha whereas the area irrigated by canal water alone has decreased from 7.9 Mha to 6.8 Mha. Over the last 10 years, a further million hectares in the Punjab has adopted conjunctive use (Figure 7). The major issue related to conjunctive use of surface water and groundwater is that it is equally practiced in head-end and tail-end of the canal systems. Prudence demands that head-end farmers should use less groundwater as their canal water allocations are much higher than the tail-end farmers. However, contrary to this common wisdom, head-end farmers use more groundwater in an attempt to maximize their crop yields. On the other hand, due to cost of pumping and poor quality of groundwater, tail-end farmers use less water, thereby reducing the leaching requirements and increasing soil salinity. Therefore net income of tail-end farmers is 43% to 59% less than those head-end farmers (Latif and Ahmad, 2009).

The key disadvantages of this unmanaged and unregulated conjunctive use is that upstream areas experience rising water tables whereas tail-end areas are exposed to increased salinity problems due to excessive use of poor quality groundwater (Qureshi 2014). Therefore unplanned conjunctive use of surface water and groundwater resources is therefore creating more problems than benefits. For the sustainability of irrigated agriculture across Indus basin, head-end farmers should be encouraged to use more groundwater due to better quality and sufficient recharge capacity to replenish the

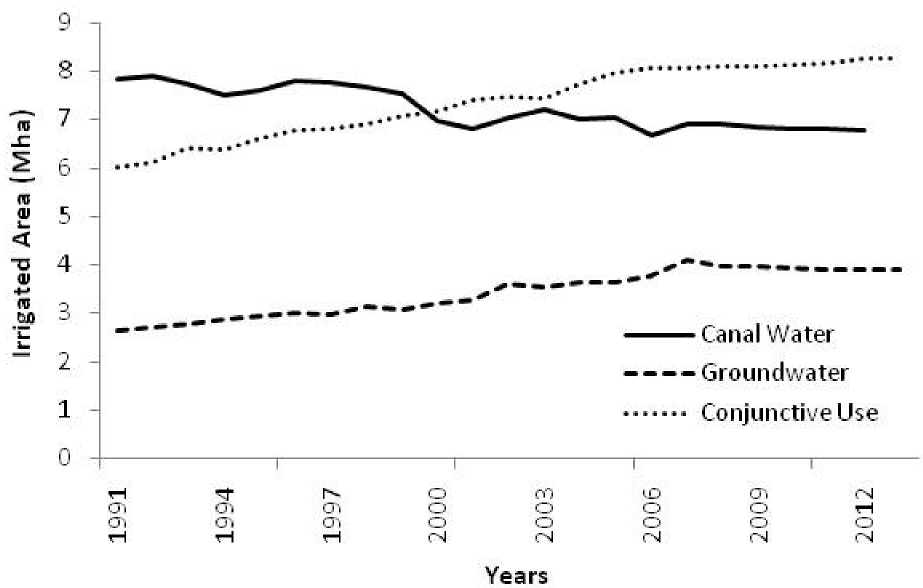

Figure 7: Trends of different modes of irrigation in the Punjab Province of Pakistan

groundwater withdrawals. For this purpose, thorough investigations are needed to estimate required amounts of canal water supplies that are needed to mix with the groundwater to mitigate the adverse effects of poor quality groundwater on soil salinization. This information is needed separately for fresh, marginal and saline groundwater zones.

Revise existing canal water allocation criteria

The distribution of canal water in Pakistan is done on a controlled rotational system called '*warabandi*'. This system allows each farmer to take an entire flow of the canal outlet once in seven days and for a period proportional to the size of his land holding. The water amount is usually insufficient to irrigate the entire farm in one irrigation turn, and the farmer can decide whether to under-irrigate all land or leave a fraction un-irrigated (Qureshi et al., 2008). This water allocation criterion of providing equal access to canal water regardless of location along the canal and soil and groundwater quality is not serving the purpose of salinity management in the canal command areas where head and tail ends of the same system have varying soil and groundwater qualities. Therefore existing water allocation criteria needs to be revised to allocate canal water supplies on variable time basis i.e. less at the head end and more for the tail-end farmers. Given the fact that groundwater access both in terms of quantity and quality at the head-end is plentiful, head reach farmers need be convinced to allow additional canal water to flow to the tail end of the system where groundwater quality is poor and canal water is of absolute importance to sustain crop production and livelihoods of farmers. Farmers located at the tail-end should not be allowed to use poor quality groundwater for irrigation. Instead they should be made aware to use surface water more wisely to avoid salinity development.

The proposed water allocation strategies within a canal system are technically possible but might have social implications as it will not be easy to convince head-end farmers to relinquish their share of surface water. However, if the head-end farmers are relieved of economic burden of pumping groundwater by providing water through public operated tube wells and charged water fee equivalent to canal water, their cooperation can be obtained. For this purpose, policy interventions regarding cropping patterns and amount of groundwater that can be pumped to remain within acceptable salinity levels need also to be introduced. To change water allocation laws, political understanding of the issue and government level interventions for changing the policies and realignment of the roles and responsibilities of public sector organizations would also be required. In the existing set up, water user associations can be engaged to start the dialogue process to make farmers agree on this paradigm shift in managing surface water and groundwater resources in Pakistan.

Increase economic productivity of groundwater

The major problem of irrigated agriculture in Pakistan is low water use efficiency and low crop yields resulting in poor economic returns. Groundwater is largely exploited and used for irrigating traditional crops such as wheat, maize and rice. The overall irrigation efficiency is only about 30%. In addition to water shortage, lack of inputs and poor irrigation practices, soil salinization are the other major factors for low crop yields (Bhutta and Smedema, 2007). The average yields in Pakistan are low for wheat and rice, being 2.7 t/ha and 2.2 t/ha, respectively. There is a great variability in crop yields with some farmers achieving yields of 3.8 t/ha for wheat and 3.5 t/ha for rice (Qureshi, 2014). Therefore, the marginal value product of groundwater is modest with the average income of 5,000 – 8,000 US$/ha with an economic productivity of US$ 0.20/m^3.

In high income countries, groundwater irrigation is mostly associated with cultivating high-value market crops. The groundwater productivity can be as high as US$5.52/$m^3$ for peppers and tomatoes compared to US$0.28/$m^3$ for field crops like corn, sunflower, and cereals (Garrido et al., 2006). In China, for example, groundwater is a major source of irrigation for cash crops, accounting for 70% of the cotton crop, 62% of the oil crop, and 67% of the vegetable crop (Wang et al. 2009). In Spain, economic productivity of groundwater is US$ 3.24/m^3 compared to US$0.97/$m^3$ for surface water (Hernandez-Mora et al., 2010). Farmers in the Jordan River valley earned net revenues from groundwater-irrigated farming of up to US$14,000–16,000/ha (Venot and Molle, 2008). In Morocco, the area irrigated by groundwater is one third of the irrigated area and contributes nearly 75% of the country's exports of high-value orchard and vegetable crops. Therefore, farmers in Pakistan need also to grow high value and less water demanding crops with groundwater. High value crops like sunflower, pulses, vegetables and orchards can increase farm incomes substantially and safe country's foreign exchange which is currently used to import these commodities to meet local demand.

Introduction of resource conservation technologies such as precision land leveling, zero tillage, bed and furrow planting can also help a great deal in improving on-farm water use efficiencies which are currently only 36% (Bhutta and Smedema, 2007). Studies done in Pakistan have shown the effectiveness of these techniques in reducing field application losses. Choudhary and Qureshi (1991) have also shown that improved irrigation management techniques such as furrow-bed and furrow-ridge can reduce irrigation requirements by 40%. Qureshi and Bastiaanssen (2001) has suggested that applying 300mmof water to wheat and cotton (instead of the current practice of 420mm) is enough to produce optimal crop yields without increasing salinity levels in the soil. Prathapar and Qureshi (1999) argue that irrigation applications can be reduced to 80% of the total crop evapotranspiration (deficit irrigation) without compromising on yields and soil salinization. Similarly improved irrigation methods for rice such as direct seeding also reduce irrigation amounts by 15–20% (Qureshi et al., 2006). High efficiency irrigation methods such as drip and sprinkler systems have also proved successful in increasing water use efficiency. However, in a country like Pakistan where continuous availability of water and energy are big issues, adoption of these technologies will remain a challenge, especially for small farmers (Qureshi et al., 2010). For this reason, on-farm water conservation techniques which are less costly and energy intensive should be encouraged more.

Increase institutional capacities to improve groundwater governance

During the last three decades, Pakistan has introduced plethora of groundwater regulatory laws. In 1980s, licensing system was introduced to restrict development of private tubewells in the areas where groundwater tables were declining at faster rate and/or where groundwater quality was deteriorating. In the mid 1990s, groundwater regulatory framework for Punjab province was prepared with the technical assistance of the World Bank (World Bank 2007). The national groundwater management rules were drafted under Provincial Irrigation and Drainage Authority (PIDA) act in 1999-2000 and included in the Canal act of 2006 (Halcrow-ACE 2003). Despite these initiatives, the success in controlling uncontrolled groundwater exploitation has been limited (Lohmar et al. 2003). In addition to historical neglect, very little human and financial resources were allocated for the management of groundwater. 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, which makes it difficult to implement policies that attempt to manage resource in a long-term sustainable way.

Like much of South-Asia, unregulated exploitation of groundwater was overlooked because political governments were under pressure to feed the increasing population and reduce poverty, especially in rural areas. In addition to weak accountability and non conformity of existing laws and regulations, the sheer number of tubewell users was also the major bottlenecks for the ineffective governance of groundwater in Pakistan (Shah et al. 2003; Shah 2007; Qureshi et al. 2010). The direct management of groundwater through the introduction of groundwater use rights and by enforcing permit systems to regulate groundwater access has only worked where the State is strong to ensure enforceability and accountability and number of groundwater users is small, such as in Oman and Australia. In the absence of political will and enforcement capacity, efforts to regulate groundwater extraction have failed such as in Jordan, India and China (Chebaane et al. 2004; Venot and Molle, 2008; Wang et al., 2009). Volumetric pricing of groundwater has also proved unsuccessful due to lack of robust monitoring systems such as in Pakistan. Even in Europe, individual metering for the monitoring of groundwater abstraction has proved costly and almost impossible to implement (Zoumides and Zachariadis, 2009).

Shah (2007) argued that energy pricing policies provided a potent tool kit for indirect management of groundwater. However, in many countries such as China, India and Iran, heavily subsidized electricity is often the prime driver of the groundwater overdraft. Chinese farmers are charged only 25% of the normal electricity rates for pumping water (COWI, 2013). In Iran, farmers pay only 20% of the actual cost of electricity (FAO 2009b; Soltani and Saboohi 2008). Mexico offers farmers a 20% discount on electricity used for pumping groundwater during the night-time. In most Indian states, farmers are charged a flat rate for electricity regardless of use, thus the marginal pumping cost of energy is zero (Shah, 2009). In all these situations, increase in energy prices for groundwater extraction has faced resistance from farmers. Studies done in India also reveal that a 25% increase in electricity price would reduce groundwater use by only 1.6–3.3% (Badiani and Jessoe, 2010). Similarly, in Pakistan, increasing electricity prices during the last two decades only forced farmers to shift from electric to diesel engines but could not help resolve the real issue of groundwater overdraft (Qureshi et al. 2010). Because groundwater was crucial to meet the increasing demand for food and farmers continue extracting groundwater to meet their crop water demands.

In the fast changing environment, Pakistan needs to invest in institutions to enable them to undertake systematic sets of legislation and organizational changes to solve entitlement, pricing and regulatory issues. Reforms should aim at solving the management issues as well as delivering benefits to the people because without these strings chances of success will be very limited. Pakistan urgently needs to formulate and evaluate of strategic options and monitoring the implementation of national policies for the management of groundwater. Therefore in addition to technical solutions, effective coordination between different organizations involved in the management of surface water and groundwater resources need to be developed.

CONCLUSIONS AND RECOMMENDATIONS

Amongst global resources, water is emerging as the most critical but misused natural resource. It is an important input to agricultural production and an essential requirement for domestic, industrial and municipal activities. Increasing population and standards of living are contributing to steep rise in demand for fresh water. The consequent wastage, over-exploitation, pollution and depletion of available fresh water pose a threat to mankind. Pakistan, once a water surplus country due to extensive water resources of the Indus River and its tributaries, is now fast turning into a water scarce country.

The groundwater aquifer of Indus Basin has huge storage capacity. In the absence of sufficient surface storage capacities, this groundwater aquifer can be a strategic resource to support irrigated agriculture in Pakistan. Over the last three decades, the water economy of Pakistan has survived largely due to the tapping of the groundwater by millions of farmers, by towns and villages and industries. However, this era of "*productive revolution*" is now coming to an end, since groundwater tables are fast depleting, groundwater quality is deteriorating and energy demand and cost is increasing. Therefore, there is an urgent need to develop policies and approaches for bringing water withdrawals into balance with recharge, a difficult process which is going to require action by government and by users.

Pakistan must first accept and then learn from its experience that development of groundwater resources without proper planning and management of the Indus basin aquifer has had serious consequences. The action which was once considered as blessing is now widely criticized as a bad call. Therefore Pakistan needs a serious debate about whether to over-pump its aquifers and face the consequences later, or be more proactive now by managing abstraction and investing in recharge today. For effective groundwater management, Pakistan needs to introduce frameworks and instruments that are suitable to its context. 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 too costly to solve.

The solutions available and tried for groundwater management around the globe are still far from satisfactory. Conventional groundwater management through the introduction of permit systems and groundwater use rights, direct and indirect pricing, and delivering groundwater on a volumetric basis are not likely to succeed in Pakistan due to its peculiarities and socio-cultural environment. Therefore it needs a well thought-out, pragmatic, patient and persistent strategy. The potential drivers of success necessarily include the heavy engagement of users, refinements in water pricing structures, substantial investments in modern water and agricultural technology, provisions to encourage farmers' transition into high value and less water-demanding crops, and the development of enabling policies and decision support systems.

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