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Groundwater Management in Pakistan: An Analysis of Problems and Opportunities

LEAD Pakistan

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List of Abbreviations and Acronyms

ADB	Asian Development Bank
ADRRN	Asian Disaster Reduction and Response Network
ART	Alternative Risk Transfer
AusAID	Australian Agency for International Development
BISP	Benazir Income Support Program
CAT	Catastrophe
CC	Climate Change
CCA	Climate Change Adaptation
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CDKN	Climate and Development Knowledge Network
CLIS	Crop Loan Insurance Scheme
CME	Chicago Mercantile Exchange
CRED	Centre for Research on the Epidemiology of Disasters
DM	Disaster Management
DRIF	Disaster Risk Insurance Framework
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DRF	Disaster Risk Financing
ERC	Emergency Relief Cell
GCISC	Global Change Impact Study Centre
GDP	Gross Domestic Product
GEORISK	Geophysical Risk and Sustainability
GFDRR	Global Facility for Disaster Risk Reduction and Recovery
GHG	Green House Gas
GIS	Geographic information Systems
GLOF	Glacier Lake Outburst Flood
ICT	Information and Communication echnology
IBLI	Index Based Livestock Insurance
IFAD	International Fund for Agriculture Development
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan international Cooperation Agency,
LEAD	Leadership for Environment and Development
LIIP	Livestock Insurance Indemnity Pool
MCR	Minimum Capital Requirement
MFI	Micro Finance Institutions
MNAIS	Modified National Agriculture Insurance Scheme
MPCI	Multiple Peril Crop Insurance
NAT CAT	Natural Catastrophes
NDMA	National Disaster Management Authority
NDMC	National Disaster Management Commission
NDRMF	National Disaster Risk Management Framework
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organization

NOAA	National Oceanic & Atmospheric Administration
PARC	Pakistan Agriculture Research Council
PCRWR	Pakistan Council of Research in Water Resources
PDMA	Provincial Disaster Management Authority
PDNA	Post Disaster Needs Assessment
PFI	Pakistan Forest Institute
PINSTECH	Pakistan Institute of Nuclear Science and Technology
PIEAS	Pakistan Institute of Engineering and Applied Sciences
PMD	Pakistan Meteorological Department
RS	Remote Sensing
SECP	Securities and Exchange Commission of Pakistan
SBP	State Bank of Pakistan
UN	United Nations
UNDP	United Nations Development Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
UNISDR	United Nations International Strategy for Disaster Reduction
USAID	United States Agency for International Development
V&TCs	Volunteer and Technical Communities
WAPDA	Water and Power Development Authority

Foreword

The benefits of groundwater in Pakistan are multidimensional and range from drinking water supplies for urban and rural population to sustainable economic development. Despite the fact that groundwater has played a crucial role in meeting Pakistan's growing demand for food and fiber, the strategic value of Indus basin aquifer has not been fully recognized.

The nature of occurrence of groundwater coupled with complexity of the aquifer, and historic development approaches have seriously threatened the sustainability of Indus basin aquifer from which most of our groundwater is derived. It is now widely recognized that continued lack of focus on this issue would be disastrous for Pakistan's water security.

This paper, the second publication in our Occasional Papers series on water issues, presents a comprehensive review of problems and opportunities faced by ground water management in Pakistan. It brings to fore, the nature and extent of groundwater development in the Indus Basin aquifer and examines the benefits it has generated for sustaining irrigated agriculture in Pakistan. By reviewing the geographic and temporal dimensions of groundwater use and the range of technological and institutional approaches which have been applied in the past, this paper will examine why the resource and its source has proven so difficult to manage. This paper also addresses the overarching concern of sustainable aquifer management aquifer and suggests options for achieving it.

It is high time that we must work hard to address this challenge of managing a complex and hidden resource, which though regional in nature, has deep and wide ranging local impacts. Raising awareness at the government level about ground water issues and policy reforms must go hand in hand with collecting relevant information about each area specific groundwater concerns that need to be addressed. Capacity-building and engagement with planners and policy-makers must be enhanced and new 'out of the box' ideas like a few shared in this study must be tested.

It is hoped that this paper will serve as an important step towards the better management of ground water in all parts of Pakistan.

Ali T. Sheikh

CEO, LEAD Pakistan

Executive Summary

In the absence of sufficient surface storages and declining capacity of existing reservoirs due to sedimentation, coupled with fast decreasing flows in the western rivers, it is the Indus basin's alluvial aquifer that has historically rescued Pakistan from food insecurity and ensured economic development and national security. The benefits of groundwater in Pakistan are multidimensional and range from drinking water supplies for urban and rural population to sustainable economic development. Despite the fact that groundwater has played a crucial role in meeting Pakistan's growing demand for food and fiber, the strategic value of Indus basin aquifer in thwarting water shortages that would have caused untold harm to our agrarian economy has not been fully recognized. The nature of occurrence of groundwater coupled with complexity of the aquifer, and historical development approaches have seriously threatened the sustainability of Indus basin aquifer from which most of our groundwater is derived. It is now widely recognized that continued lack of focus on this issue would be disastrous for Pakistan's water security.

The uncontrolled and excessive exploitation has led to uneven decline in groundwater level with serious implications for groundwater quality, and consequent impacts on human health and the environment. In addition, the increased energy use and enhanced emission of greenhouse gases (GHG) have put a question mark on the sustainability of Pakistan's irrigated agricultural economy. During the last four decades, the policy focus has been on 'resource development' than 'resource management'. Considering the nature and occurrence of Indus basin aquifer, its management has been a complex issue and there is no single straightforward solution. This paper looks at the nature and extent of groundwater development in the Indus Basin aquifer and examines the benefits it has generated for sustaining irrigated agriculture in Pakistan. By reviewing the geographic and temporal dimensions of groundwater use and the range of technological and institutional approaches which have been applied in the past, this paper will examine why the resource and its source has proven so difficult to manage. This paper also addresses the overarching concern of sustainable aquifer management and suggests options for achieving it.

The paper suggests that management of groundwater in the Indus basin requires multifaceted actions focusing both on supply and demand side solutions. Increasing recharge to balance groundwater discharge to stabilize aquifer, rethinking management of conjunctive use of surface and groundwater resources, increasing productivity of groundwater use, increasing aquifer storage to create resilience against climate change and improving governance in the light of international experiences are some of the workable options which can help Pakistan to manage its groundwater resources which are of strategic importance for the future food security. These options require various levels of stakeholder interaction ranging from policy makers to user level. It is likely that this exercise will provide a basis for suggesting sound policy and institutional reforms agenda that can be shared with policy makers.

Policy reforms are also needed to address the management and organizational issues of existing institutions, with increased clarity in their roles and responsibilities. The evaluation of strategic options and monitoring of the implementation of national policies for the public water sector will remain a challenge in the absence of proper institutional arrangements. There is also a need to work on creating awareness through educational programs for all stakeholders.

1. Introduction

Under the semi-arid to arid conditions prevailing in most of the Indus basin, the availability of surface water resources is only marginally sufficient to meet the evapotranspiration demand of crops for basin wide, year-round high intensity cropping (Bhutta and Semdema, 2007). This 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 overexploitation of the groundwater. In addition, there is likelihood of a further reduction in surface supplies through capacity losses in the major reservoirs due to siltation and climate change (Leghari, 2012). Under these circumstances, it is the Indus basin's alluvial aquifer that has offered hope and which has the demonstrated potential to rescue Pakistan from food insecurity, economic development and ultimately national security.

Despite the fact that groundwater has played a crucial role in meeting Pakistan's growing demand for food and fiber, the strategic value of Indus basin aquifer has not been fully recognized in thwarting water shortages that would have caused untold harm to our agrarian economy. The nature of occurrence of groundwater coupled with complexity of the aquifer, and historical development approaches have seriously threatened the sustainability of Indus basin aquifer from which most of our groundwater is derived. If the lack of focus on this issue continues, the results may be disastrous for Pakistan's water security. Therefore, there is a strong need to give special attention to the management of this precious resource base at all levels from policymakers to actual users of water.

This paper looks at the nature and extent of groundwater development in the Indus Basin aquifer and examines the benefits it has generated for sustaining irrigated agriculture in Pakistan. By reviewing the past work, it examines why groundwater and its source have proven so difficult to manage. It also attempts to draw meaningful conclusions regarding future planning for sustainable development and management of the Indus aquifer and identify strategic areas for policy makers to intervene. This paper also highlights the importance of the management of the Indus basin aquifer for sustaining irrigated agriculture in Pakistan. If it had not been for storage it provided to the Indus River system in the absence of construction of dams, the perennial water requirement for year round agriculture would not have been met and the level of food security we find now would have been seriously reduced. In the end, the paper suggests policy and institutional reforms that can be shared with policy makers.

1.1 Surface Water Availability and Challenges

The Indus River and its tributaries (Indus Basin), on an average, bring 190 billion cubic meters (BCM) of water annually. This includes 179 BCM from the three Western Rivers (Indus, Chenab and Jhelum) whereas three Eastern rivers contribute only 11 BCM. Most of this, about 129 BCM, is diverted for irrigation. About 50 BCM flows to the sea and 11 BCM is lost as system losses, which include evaporation, seepage and spills during floods. Currently, 93% of the total water withdrawal (176.7 BCM) is allocated to the agricultural sector, 4 percent (7.6 BCM) is used for domestic purposes and the rest 3 percent (5.7 BCM) 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 BCM) (USAID, 2009).

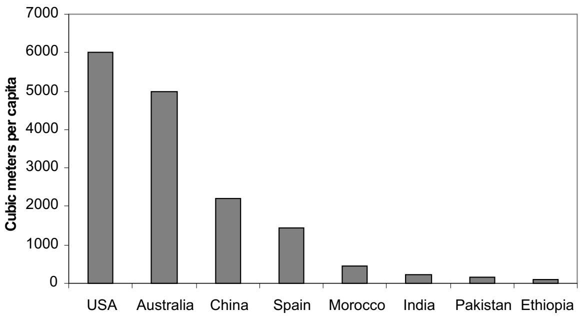

Figure 1: Comparison of per capita storage capacity in different semi-arid countries

The water requirements for irrigation in the Indus Basin are estimated at 250 BCM in 2025 against the estimated availability of 185 BCM. Even by exploiting the full groundwater resources, the water availability will not be more than 190 BCM. This large shortfall in water availability will lead to serious food shortages and rising food prices in future.

Water availability in the IBIS (Indus Basin Irrigation System) is highly seasonal with 85 percent 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***) to winter (***rabi***) season for meeting crop requirements. The stored water is mostly used during the winter season when main staple food of wheat is grown. Summer season is equally important because most of the cash crops such as cotton, rice and sugarcane are grown during this season. It is estimated that storage capacity of Pakistan reservoirs will be reduced by 57 percent by the year 2025. The recent estimates show that to meet the future water requirements, 22 BCM of more water will be needed (World Bank, 2008). This will need at least doubling of the existing storage capacity, which is only 15 percent of the annual river flow.

The per capita water storage capacity in Pakistan is 150 cubic meters (m3) compared to over 5,000 m^3 in USA and Australia and 2,200 m^3 in China (Figure 1). The dams of the Colorado and Murray Darling rivers can store 900 days of the river runoff, South Africa can hold 500 days' in the Orange River and India between 120-220 days' in the Peninsular Rivers. In contrast, Pakistan can hardly store 30 days of water (World Bank, 2005). If no new storage is built in future, canal diversions will decrease and the shortfall will increase by 12 percent by 2025. It is unfortunate that after the completion of Tarbela dam forty years ago, the construction of new storages could not be decided. It is therefore worth noting again the important role that the Indus basin aquifer has played in providing interim alternative to surface storage. Admittedly without this facility, Pakistan would have been in the grip of chronic water shortages and food insecurity.

The carrying capacity of the extensive network of irrigation canals has also been reduced over time due to siltation and poor maintenance. From the scarcity by design and intensive irrigation practices by farmers, the canal water availability per unit of irrigated land has become even more limited. This has prompted farmers to extract more groundwater. Moreover, most of the water supplies for domestic and industrial uses in major cities also come from this source. In the extreme drought conditions during the period 1996-2001, the surface water availability in Punjab was reduced by 46 percent and the groundwater was the only source of survival for humans and animals. This led to a 59 percent increase in private tube wells over the same period (Qureshi & Akhtar, 2003) to save the crops and livestock. Most of these tube wells were installed by farmers while some community wells were funded by NGOs but all this happened in an unplanned fashion with its associated consequences on the aquifer.

1.2 Characterization of Groundwater

Aquifer in the Indus Basin

The Indus plain is underlain with rich alluvial deposits more than 300 meters deep. The alluvium of aquifer varies in texture from medium sand to silty clay, but sandy sediments predominate. The alluvium has a heterogeneous character in the uppermost 200 meters, which was saturated to within a few feet of land surface till the early sixties. Despite this heterogeneity, the alluvial deposits of the Punjab form a unified highly transmissive aquifer, in which ground water occurs for the most part under water-table conditions. The uppermost 100 meters of the compacted aquifer is the most productive zone. Small capacity tube wells (2-4 cubic feet per second) can theoretically be developed almost everywhere. This shows that alluvial aquifer underlying the Punjab is a resource of enormous economic value, because it is highly amenable to flexible operation and scientific management.

The underlying aquifer covers about 16 million ha (Mha) of surface area, of which 6 Mha are fresh and the remaining 10 Mha are saline (Qureshi et al., 2010). The alluvium beneath about two-thirds of the Punjab is saturated to an average depth of 200 meters or more, with water of acceptable quality for irrigation supply. The average concentration of dissolved solids in these supplies is less than 1,000 ppm; the upper limit of concentration of acceptable supplies is placed as 1,800 to 2,000 ppm on the assumption that it is feasible to blend groundwater with canal water at a ratio of 1:2. 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.

In any event, assuming an effective porosity of 20 percent for the saturated sediments, the volume of usable ground water in storage is of the order of 2 billion acre-feet (2470 BCM). The safe groundwater yield is estimated to be about 68 BCM, whereas the extraction for agriculture, domestic and industrial sectors is already approaching to about 51 BCM. This means that this resource is almost exhausted. Furthermore, the remaining potential is located in areas where groundwater quality is poor or in areas where it is economically not feasible to extract, such as in hard rock areas of Balochistan.

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

Earlier, it was thought that the salt and fresh water interface caused mixing due to molecular diffusion which is a very slow process. But later scientific studies indicated that the mixing was taking place due to dispersion, which is thousands of times faster process depending on aquifer characteristics. As already witnessed, the unchecked and unplanned growth of private tube wells will exacerbate mixing and cause untold harm to sustainability of the aquifer and long term use of groundwater.

1.3 Contours of Groundwater Development in Pakistan

As everywhere, the question for the water sector in Pakistan is also of supply and demand. Due to arid and semi-arid conditions prevailing in most parts of the country, irrigated agriculture is the most economical and remunerative form of agriculture. Direct rainfall provides for less than 15 percent of the total crop water requirements and the rest has to be covered through irrigation (Qureshi *et al.*, 2004). The surface water resources of Pakistan are only marginally sufficient to support year-round cropping and high evapotranspiration demand of crops. Therefore, the gap between crop water requirements and surface water availability is usually met through the exploitation of groundwater. In fact, much of the groundwater that is pumped for irrigation is actually the water "recharged" from the surface systems. Given this inter-connectivity, estimating the total available water resources needs much caution.

Large-scale extraction and use of groundwater in the Indus basin started in 1960s with the launching of Salinity Control and Reclamation Projects (SCARPs) when 16,700 wells (supplying an area of 2.6 Mha) with an average capacity of $0.080\ m^3\ s^{-1}$ were installed to address waterlogging and salinity problems (Bhutta and Smedema, 2007). The pumped groundwater was discharged into the canals to increase irrigation supplies at the farm gate. Subsidized electricity and introduction of locally made diesel engines provided an impetus for the massive development of private tube wells with an average discharge capacity of $0.028\ m^3\ s^{-1}$. Currently, about 1.2 million small capacity private tube wells are working in Pakistan (Qureshi et al., 2008), out of which, over 800,000 are located in Punjab alone (Figure 2).

Currently, only 13% of the tube wells are operated by electric motors whereas the rest 87% are run by diesel engines and the total extraction of groundwater is about 52 BCM (Qureshi, 2014). Out of this, about 14 BCM is extracted using large capacity public electric pumps and the remaining 38 BCM using private diesel pumps. The investment

on private diesel tube wells is of the order

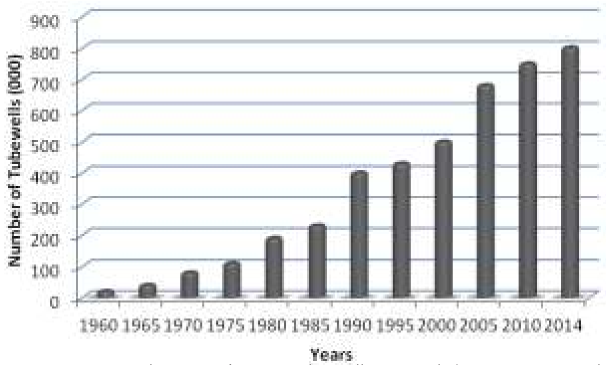

Figure 2: Development of private tube wells in Punjab (Data source: Punjab Agriculture Department)

of 30–40 billion rupees (US$ 400 million) because their low installation and operational costs makes them attractive for farmers. Diesel tube wells are also more feasible for small and fragmented land holders.

In 1960, groundwater contribution was only 8 percent of the total farm gate water supplies in Punjab. This increased to 40 percent in 1980s, and at present groundwater use for agriculture accounts for more than 60 percent of the water at the farm gate and 75 percent of the value of water delivered, with the flexibility of its availability as and when needed. During the last 25 years, 75 percent of the increase in water supplies is due to groundwater exploitation. In the process, the great canal system became less of a water delivery mechanism, and more of a groundwater recharge mechanism. In Punjab, for example, 80 percent of the groundwater recharge is from the canal system.

1.4 Economic Returns and Social Impacts of Groundwater Irrigation Development in Pakistan

The access to relatively cheap groundwater was a dividing line between poverty and well being for millions of poor farm families, for whom the long dry season is a trying time of one meal a day. The development of groundwater in Pakistan played a crucial role in combating hunger, reducing poverty, and achieving economic growth. In many water short areas of Pakistan, accessibility to groundwater not only ensured predictable and increased crop yields, but also created opportunities for smallholder farmers to diversify their income base and reduce their vulnerability to external shocks such as droughts. The estimated number of users is over 2.5 million farmers, who exploit groundwater directly or hire the services of tube wells from their neighbors (Shah, 2007). Farmers having access to groundwater also attain 50-100% higher crop yields as compared to those fully dependent on canal water (Shah et al. 2003; Shah, 2007). Farmers have also started growing high water demanding crops such as sugarcane and rice, resulting in increased farm incomes due to high market prices of these crops. The annual benefits of groundwater in the form of agricultural production are estimated to be in the range of 200 billion rupees (US$ 2.0 billion) (World Bank, 2006).

The benefits of groundwater in Pakistan are multi-dimensional 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. Qureshi and Akhtar (2003) have shown that more than 70% of the farmers in the Punjab depend directly or indirectly on groundwater to meet their crop demands. This clearly indicates that without groundwater availability, not only Punjab but the whole country would face food shortages as Punjab produces more than 90% of the total grains. Therefore management of this resource requires attention and commitment both from government agencies and the agricultural and domestic users. However, this can only happen if a better and more scientific understanding of the aquifer and its characteristics is developed with the urgent attention of policy makers, which unfortunately does not appear to be the case so far.

Groundwater offers a significant value addition to the farmers practicing dry land and irrigation farming which is entirely based on surface water. In the Pakistani context, this value addition comes from its 'stabilizing effect' and 'diversification effect' (Tsur, 1990). The stabilizing effect is groundwater's buffer role during droughts and dry spells when surface supplies run short. This role of groundwater was witnessed during the drought period (1998 to 2002) when surface water availability was 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).

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. With the increased groundwater accessibility, the cropping intensities have increased from 70 percent to over 150 percent (Shah, 2007). 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 (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 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.

The groundwater has different dynamics for different regions. For example, in the US and Spain, groundwater is used for commercial farming and agricultural exports while in the Middle East, groundwater is the only source of irrigation. The marginal value product of groundwater is modest because it is the basis of livelihood for large section of the society. In high income countries, groundwater irrigation is generally associated with cultivating high-value market crops. In China, groundwater is a major source of irrigation for cash crops, accounting for 70 percent of the cotton crop, 62 percent of the oil crop, and 67 percent of the vegetable crop (Wang et al., 2009). In Spain, for example, groundwater users achieved higher gross water productivity – US$3.24/$m^3$ compared to US$0.97/m for surface water (Hernandez-Mora et al., 2010). 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). Understanding this economic dynamics is critical to success in eliciting farmer participation in the sustainable management of aquifers. Technical interventions that fail to factor in this dynamic will have little chance of success.

2.Threats To Groundwater Irrigation Economy

As early as 1960s, it was realized that despite advantages of groundwater use for agriculture, it is inevitable that large-scale groundwater withdrawals would again disturb the hydrologic regime. Therefore exploitation of the groundwater resources must be based on regional hydrologic factors rather than on local demand factors. Groundwater supplies must be developed where they are available both in terms of quantity and quality. In the water stressed areas, water conservation programs such as reducing the intensity of cultivation or modifying the cropping pattern should be introduced. Otherwise, groundwater development will be unbalanced, which might create problems of overdevelopment of the aquifer. The second most important aspect was the maintenance of a favorable salt balance. This did not happen because of policy change towards private tube wells. Resultantly, water levels in the fresh groundwater areas started falling at an unprecedented rate and incipient secondary salinization emerged as the biggest threat to the sustainability of groundwater economy in Pakistan.

2.1 Depleting Aquifers due to Overdraft

The trend of continuous decline of the groundwater table has been observed in many areas of the Indus basin, which illustrates the serious imbalance between abstraction and recharge. 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 3 shows the changes in groundwater table depths over a period of 10 years (1993-2003) in the Punjab province. The changes in water table depths in the Sindh province are less significant because of lower abstraction rates of mostly poor quality ground water. Although no recent estimates exist, it is believed that under the ***business as-usual*** scenario, the water inaccessible area is expected to increase to 15% in Punjab and 20% in Balochistan by 2020 (PPSGDP, 2000; Qureshi et al., 2010).

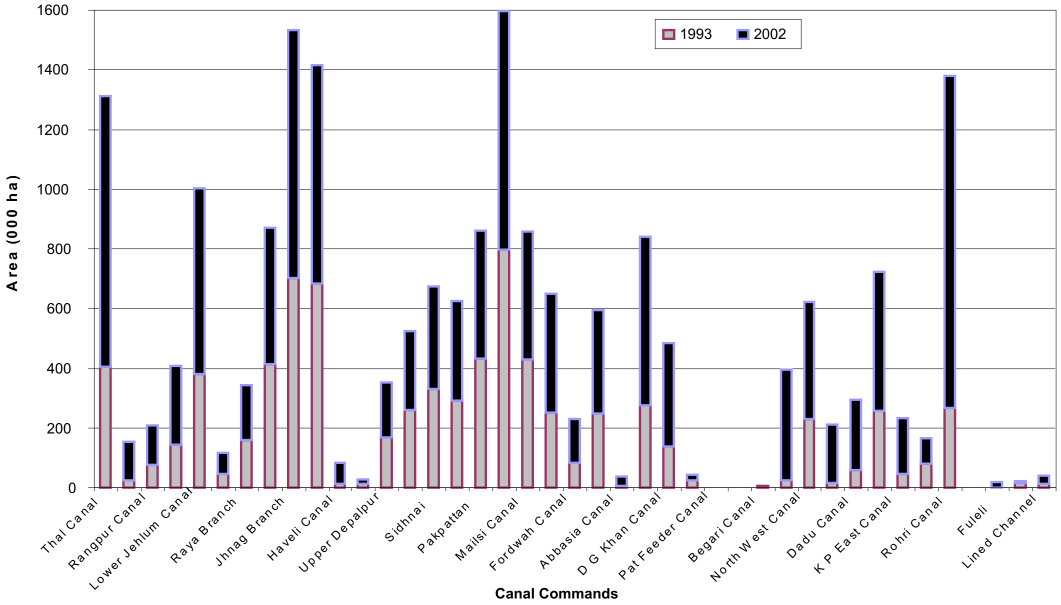

Figure 3: Increase in area with a water table depth of 300 cm during 1993 and 2003 in different canal commands of Punjab and Sindh provinces (Data Source: WAPDA).

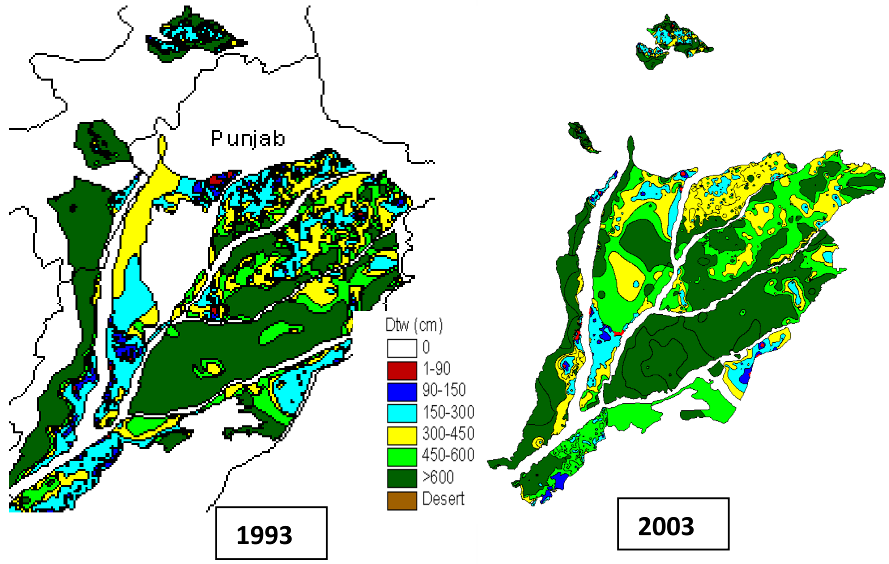

Figure 4: Comparison of water table depth between 1993 and 2003 in the Punjab province.

2.2 Climate Change Impacts on Future (Ground) Water Availability

In addition to existing challenges, groundwater management is now facing a new and emerging challenge: how to adapt to the potentially negative impacts of climate change on groundwater and its use. Climate change impacts are expected to increase existing pressure on groundwater resources by (i) impeding recharge capacities in some areas; and (ii) being called on to fill eventual gaps in surface water availability due to increased variability of precipitation. Groundwater contamination is also expected in low elevation coastal zones due to sea level rise. In some vulnerable areas, such impacts on groundwater resources may render the only available freshwater reserve unavailable or unsuitable for use in the near future (IPCC, 2007).

Considering the fact that the bulk of the Indus water is derived from snow and ice melt, Pakistan is more vulnerable to climate change impacts (Immerzeel et al., 2010). World Bank (2005) has predicted 50 years of glacial retreat, which will exacerbate flooding and drainage problems. After this period, river flows are likely to be reduced by 40% in the Indus basin, which will have serious consequences for the environment and food security. However, Archer and Fowler (2008) argue that summer temperatures have been falling despite rise in winter temperatures. Hewitt (2005) noted that there is an ample evidence of glacial expansion mainly in high level glaciers in the central Karakoram. This shows that the effects of climate change on glaciers and on river flow in the western HKH (Hindukush Karakoram Himalayas) are not clear (Archer et al., 2010). These conflicting views on the impact of climate change on the glaciers of HKH will have serious implications on the availability of (ground) water in the Indus Basin. Therefore it requires investigations to improve our understandings regarding uncertainties about origins of climate trends, linkage between climate change and glacial accumulation, ablation and runoff.

Climate change is also expected to affect the South Asian monsoon. The IPCC in its Third Assessment Report has reported that there will be increase in South Asian monsoon by 8-24%, which will bring additional water causing floods and damages to the infrastructure (Rasul et al., 2008). This requires that Pakistan should start preparing itself for possible future changes in climate change and its impact on Pakistan. Better (ground) water management would probably be the best strategy to cope with the projected climate changes and their impact on Pakistan's agricultural economy and environment. To maintain the advantages of groundwater as an important resource for sustainable development and also as a reserve freshwater resource for current and future generations, groundwater management should be more strategic and proactive to cope with potential impacts of climate change. Pakistan also needs to respond to the effects of climate change on their water management plans.

2.3 Increasing Pumping Costs and Environmental Concerns

Excessive lowering of the groundwater table has made pumping more expensive and energy intensive. Increasing water table depths (> 15 m) have left farmers with no choice except to drill deeper wells, which has increased their installation and operational costs due to high energy use. The annual cost of canal water is US$ 3.5/ha compared to annual groundwater cost of US$ 167/ha. Increasing water table depths have increased the pumping cost from US$ 4.2/1000 m^3 for shallow tube wells to US$ 12/1000 m^3 for a deep tube well (Qureshi et al., 2010). These costs keep on changing due to changing energy prices.

Beyond 20 m depth, turbine/ submersible pumps are installed which costs US$ 10,000 in Baluchistan and maintenance of these deep tube wells is generally beyond the capacity of poor farmers. Although electricity is heavily subsidized in Baluchistan, the benefits are restricted to only rich farmers who own deep tube wells while small poor farmers continue to suffer (Ahmad, 2009). Declining water tables in Baluchistan have resulted in the desertification of lands and drying up of high value fruit orchards. Urgent measures are required to balance groundwater discharge and recharge. Energy pricing for agriculture is largely seen as a political agenda in most countries e.g. India, Pakistan and China. The subsidized electricity in Baluchistan and KPK is exacerbating the problems of groundwater over-draft therefore this policy needs careful review. Subsidies should strictly be targeted to poor small farmers who practice agriculture for their livelihood and not to large commercial farmers.

The increasing use of energy (electricity and diesel) for agriculture is also causing serious green house gases (GHG) problems in Pakistan. Each year about 6 billion kWh of electricity and 3.5 billion liters of diesel are used to pump groundwater for irrigation. Carbon emissions attributed to this energy use amount to 3.8 million metric tons (MMT) of CO2 per year (Qureshi, 2014). Of this figure, which is roughly 1.2 percent of Pakistan's total carbon emissions, 1.4 MMT of CO2 is emitted through electricity consumption and 2.4 MMT of CO2 through diesel combustion. This implies that, on an 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.

2.4 Deteriorating 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. 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. About 77% (4 million ha) of the area in Punjab province has access to fresh groundwater. As stated earlier, saline waters are mostly encountered in central Doab areas. Cholistan area in the southern Punjab is well known for highly brackish waters, which cannot be used for drinking purposes. In some parts of Punjab, high fluoride (7-12 mg/l) and arsenic (50 g/l) concentration in the groundwater has also been reported.

Spatial distribution and comparison of groundwater qualities over a period of 25 years (1977-2003) in the Punjab province is shown in Figure 5. In the lower Indus Basin, about 28 percent of the area, mainly confined to a narrow and shallow strip along the Indus River, has fresh groundwater. Other areas are underlain by brackish groundwater. Indiscriminate pumping in these areas has already resulted in the contamination of the aquifer at different places where salinity of pumped water has increased beyond useable limits (Qureshi et al., 2004).

2.5 Soil Salinization

The use of poor quality groundwater for irrigation has resulted in large scale salinization of agricultural lands in the Indus basin. Latest estimate of WAPDA confirm that 4.5 million ha of irrigated lands are salinized (WAPDA, 2007). Surface salinity trends in four provinces of Pakistan are shown in Figure 6. The problems of soil salinity are much more severe in the tail-end areas of the canal commands where surface water availability is very low and groundwater quality is very poor.

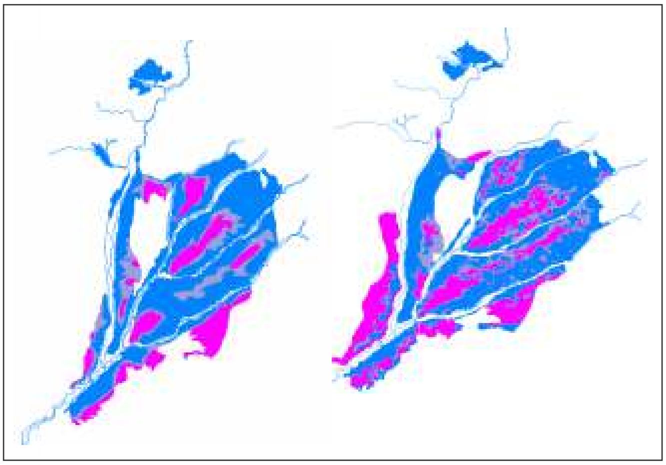

Figure 5: Changes in Groundwater Quality between 1977 and 2003 in the Punjab Province

Due to differences in annual rainfall and geo-morphological conditions, the extent of soil salinization in the Sindh province is much more than in Punjab. About 50% of the total irrigated land is affected from different levels of salinity in Sindh. 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 the coming decade unless better management measures are introduced.

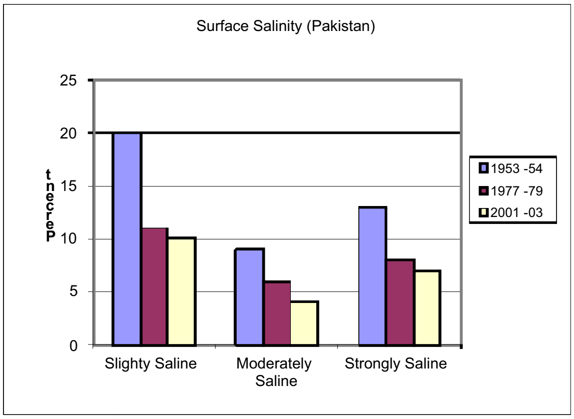

Figure 6: Surface salinity trends in four provinces of Pakistan (WAPDA, 2007)

2.6 Dilemmas of Groundwater Management in Pakistan

The large-scale development of groundwater in Pakistan helped in expanding irrigated area, increasing crop yields and cropping intensities, increased access to drinking water, and enhanced ability to hedge against the vagaries associated with surface water supply. The spectacular expansion of groundwater-based agriculture helped in achieving food security and alleviating millions out of poverty. However, the management of groundwater could not keep pace with its development. Due to these enormous socio-economic benefits and an apparent abundance of the resource, the focus has largely been on the 'resource development', and very little attention has been given to 'resource management'. The situation has now turned serious because unregulated groundwater exploitation has brought key aquifers under severe stress, threatening the sustainability of irrigated agriculture in Punjab where more than 90% of the total food production of Pakistan happens. The fact that more than 70 percent of population still lives in rural areas and earn their living through agricultural activities further complicates the matter.

Due to growing concerns that the groundwater-irrigation economy of Pakistan cannot be sustained without increasingly negative consequences on water resources, Pakistan has tried several direct and indirect management strategies to control the overexploitation of groundwater. Over the last three decades, the government has introduced many laws for regulating groundwater in Pakistan. These include licensing system to restrict installation of private tube wells in the critical areas, groundwater regulatory frameworks, re-drafting of Provincial Irrigation and Drainage Authority (PIDA) acts and groundwater rights ordinance for Baluchistan (Halcrow-ACE, 2003). Despite plethora of laws and policies developed by the government, no serious efforts have been made for enforcing laws, installing licensing and permit systems and establishing tradable property rights. Furthermore, the allocation of human and financial resources for groundwater management has been very small compared to the management of surface water resources (Lohmar et al. 2003) and no single body has been made responsible for managing the entire resource.

The large number of groundwater users was the major reason for the ineffectiveness of licensing policy in the Pakistani context. For example, in the Murray-Darling basin in Australia, groundwater users are only in 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 (Shah et al. 2003).

Shah (2007) argued that energy pricing policies provided a potent tool kit for indirect management of groundwater in India. However, despite similar socio-economic conditions, energy pricing policies for agriculture has not yielded any favorable results in Pakistan for controlling groundwater overdraft. This is probably due to the fact that these policies were traditionally aimed at generating more revenue rather than controlling groundwater overdraft. During the last three decades, governments in Pakistan has been changing their energy pricing policies for agriculture continuously. The subsidies provided in 1970s to boost agricultural production were withdrawn in 1980s, which resulted in the replacement of large number of electric tube wells to diesel tube wells. From 1990s onwards, energy pricing policies have mainly revolved around flat rate to actual charging and vice versa. However, these tactics only forced 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 to meet the increasing demand for food, the farmers continue to extract groundwater for meeting their crop water demands. This clearly demonstrates the need to search for more innovative ways to solve the problem of groundwater over-exploitation while maintaining the current levels of agricultural production in view of the increasing population.

3. Opportunities For Groundwater Management In Pakistan

Pakistan needs more concerted efforts 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.

3.1 Supply-side Solutions

3.1.1 Stabilizing aquifers by balancing aquifer recharge and discharge

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 to recover groundwater reserves. For example, 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). In recent years, India and Pakistan have also taken serious steps to use harvested rainwater to recharge aquifers. Indian experience of community rainwater harvesting ponds at the village level and introduction of check dams in the Baluchistan province of Pakistan are good workable examples (Shah 2007; Qureshi et al. 2010).

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. Connecting storm water drain lines to tanks and rivers can greatly improve the groundwater position with little effort and maintenance (Qureshi et al. 2008).). 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). Sharma and Smakhtin (2006) have suggested the establishment of groundwater protection zones according to the safe yield of the aquifer to avoid negative consequences such as water level decline, land subsidence, and increased salinity. These protection zones may be classified according to the level of vulnerability to groundwater extraction.

As noted above, the distribution of groundwater salinity in the Indus Basin is relatively well known. The problem affects the groundwater in large parts of Sindh, Punjab, Baluchistan and southern Khyber Pukhtunkhwa Province. In Punjab and Sindh, groundwater salinity is related closely to the river morphology. Salinity in shallow groundwater of Punjab is relatively low. However, salt concentrations are generally higher (often >3000 mg/l) in groundwater of the interfluve ('Doab') areas between the major river and canal tracts. Salinity is lower (<1000 mg/l) in groundwater below the active river channels as a result of dilution by local river and canal recharge to the aquifers (PHED, 2009). Occasional zones of saline groundwater in Punjab contain dissolved salts of 20,000 mg/l or more.

The fresh groundwater occurs in lenses below the rivers. The thicknesses of these lenses are decreasing with distance away from the river. Particularly saline waters are present in the Thal desert and Cholistan region. Salinity is even more widespread in the lower reaches of the Indus Plain in Sindh. As in Punjab, salinity increases away from the course of the lower Indus and large parts of the aquifer have groundwater of poor quality. Additional severe salinity problems related to seawater intrusion occur in coastal areas of Sindh, especially to the north and west of Karachi.

From the management perspective, Indus basin aquifer can be divided into three distinct zones as shown in Figure 7. In Punjab, natural groundwater is deep and saline because of marine origin of the aquifer. Percolation of rainfall and irrigation water has created a thin layer of fresh groundwater in these areas. The thickness of this layer varies from a few meters to over 150 m. In general these fresh water layers are found close to rivers and saline groundwater are present in the central and lower doabs – the area between two rivers. In fresh groundwater areas, the thickness of fresh groundwater is about 40 meters whereas in saline groundwater areas, it is less than 40 meters (Qureshi et al., 2004). In these areas, groundwater extraction should be done carefully to avoid disturbance of fresh and brackish groundwater interface. The use of skimming well technology can be an effective way of extracting fresh groundwater from thin lenses without disturbing the underlying saline groundwater layers.

In the central parts of Punjab where groundwater is fresh and shallow, overdraft is the major issue which is causing drastic water table declines, increased energy use and deterioration in groundwater quality. In these areas, groundwater extractions need to be brought in balance with the recharge to ensure sustainability of this resource. This can be done by rationalizing cropping patterns, introducing and enforcing governing laws and effective monitoring. In the lower parts of the Indus Basin (Sindh province), groundwater is mainly shallow and of very poor quality. Therefore to avoid further increase in soil salinization and loss of agricultural productivity, drainage of this brackish water and its safe disposal is most important. For this purpose, installation and revival of old drainage tube wells and effective management of LBOD (Left Bank Outfall Drain) and RBOD (Right Bank Outfall Drain) is required.

The groundwater issues pose two very major

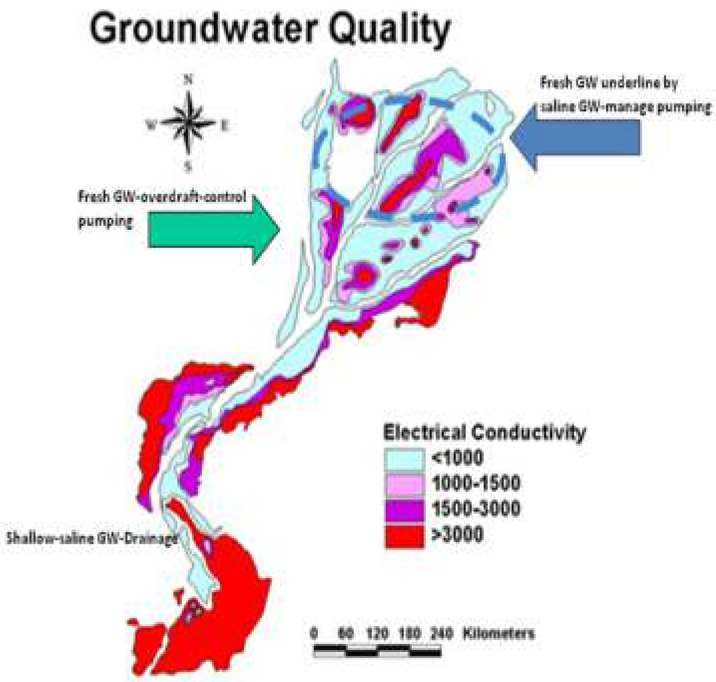

Figure 7: Three distinct groundwater zones of the Indus Basin

challenges to the State. First, the performance of currently operational surface water supply systems needs to be improved. Secondly, groundwater will have to be managed – for related reasons of quantity and quality – much more aggressively than has been the case in the past. In derivative traditional irrigation philosophy, recharge to groundwater is considered as a by-product of irrigation, though, in today's world, groundwater recharge should be considered paramount for making groundwater sustainable (IWMI, 2010). Therefore, it is important that Pakistan work both on increasing groundwater recharge to maintain strategic storage (especially in the absence of any increased surface storages) and at the same time regulate groundwater pumping according to hydro-geological conditions prevailing in different parts of the basin. These actions are absolutely necessary to stabilize aquifers both in terms of quantity and quality to ensure contribution of groundwater for achieving future food security and reducing rural poverty.

A balance between recharge and discharge can be ensured by defining groundwater protection zones. Once implemented, this will help policy makers to use it as an instrument to restrict boreholes and dug wells, imposing groundwater withdrawal limits and extraction fees, and other incentives. Groundwater protection zones can be classified according to the level of vulnerability to groundwater extraction and these should be protected from some potentially polluting activities, viz. urbanization, solid waste dumping, and chemical disposal, mining and quarrying (Qureshi et al., 2015). Groundwater protection zones can also be used to initiate more complementary approaches such as public information campaigns and groundwater user groups.

3.1.2 Increasing groundwater storage as a resilience against climate change

Pakistan is highly dependent on its water resources originating in the mountains of the upper Indus for sustaining its irrigated agriculture. Hence any changes in the available water resources through climate changes or other human interventions will lead to serious challenges of food security and livelihood of millions of poor. Since aquifers are replenished by effective rainfall, rivers, and lakes, a change in the amount of effective rainfall will alter recharge patterns. Climate change is likely to affect ground water due to changes in precipitation and evapotranspiration. Increased temperatures will result in soil deficits which will increase irrigation demands. Pakistan also has a history of droughts and will continue to experience in the coming years due to climatic changes, which are occurring in the region. Given the vulnerability to drought, water availability for agriculture is likely to be a subject of debate both for rainfed as well as for irrigated agriculture. Due to decreasing availability of surface water as a result of climate change, dependence on groundwater will further increase in future. Therefore, increasing aquifer storage and exploiting groundwater according to aquifer capacity in different agro-ecological zones can provide the much needed resilience against the negative effects of climate change. In addition, efficient use of groundwater must be the foundation for a fully productive agriculture sector.

3.1.3 Re-thinking conjunctive water management

In 1960s, when the decision was taken to develop groundwater to lower the water tables and increase water supply at the farm gate, it was realized that in order to rationalize use of water from all sources in the spirit of conjunctive use, water would be required to move from groundwater access areas (i.e. from doabs) to areas where it is short or quality is not suitable. However, this could not happen because groundwater development went into the hands of the private sector. The conjunctive use of surface water and groundwater water is now practiced on more than 70% of the irrigated lands of Pakistan. This does not mean that this practice is effective and optimal. The area irrigated by groundwater alone has increased from 2.64 Mha to 3.69 Mha whereas, the area irrigated by canal water alone has decreased from 7.9 Mha to 6.78 Mha (Leghari et al., 2012). During the last 10 years, another million hectares in the Punjab has adopted conjunctive use (Figure 8). Therefore it is necessary that farmers are aware of the management of surface water and groundwater resources so that maximum benefits can be achieved.

Under current circumstances, groundwater plays more important role in irrigation than surface water, ranging from 65% dependence on groundwater in head-end areas to over 90% dependence in tail-end areas. This means that groundwater is no longer supplemental to surface water, but has become an integral part of the irrigated agricultural environment. In Punjab, conjunctive use of surface water and groundwater is equally practiced in head and tail reaches of the canal systems. Prudence demands that head-end farmers should use less groundwater as their canal water allocations are higher than the tail-end farmers and the quality of groundwater is superior. However, contrary to this common wisdom, head-end farmers use more groundwater in an attempt to maximize their crop production.

The key disadvantages of this uncontrolled conjunctive use is that upstream areas are subjected to rising water tables whereas tail-end farmers continue to grapple with increasing salinity problems due to excessive use of poor quality groundwater. The groundwater table depth in the head reaches of the system fluctuates around 1-m during the cropping season. In the middle reaches, groundwater table depth remains below 2-m whereas in tail-end areas it is well below 3-m (Qureshi et al., 2014).

The groundwater quality deteriorates as we move from head to tail reaches of the system. The groundwater quality at the head reaches of the system is less than 1 dS/m that may reach to 5.0 dS/m as we move towards the tail-end of the system. Due to cost of pumping and poor quality of groundwater, tail end farmers use less water per unit area, thereby reducing the leaching requirements and increasing soil salinity. The net income of the farmers using poor quality groundwater to supplement canal water is 43% to 59% less than those fully dependent on good quality canal water (Latif and Ahmad, 2009).

The head-end farmers should be encouraged to use more groundwater to meet their crop water requirements as the quality of groundwater at the head of canal is good and recharge is sufficient to replenish the groundwater withdrawals. In the existing fixed rotational canal system, provision of additional surface supplies for tail-end farmers may not be an easy solution. Therefore, there is a strong need to make a thorough investigation of the 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. These information need to be generated separately for fresh, marginal and saline groundwater zones. This can provide an opportunity to divert additional canal water to the areas where groundwater is of poorer quality and the need for fresh water resources is more pressing.

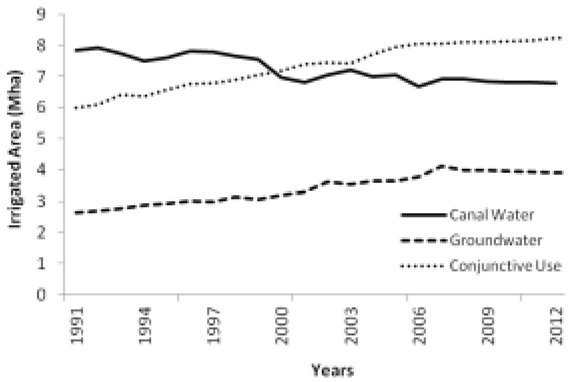

Figure 8: Trends of different modes of irrigation in the Punjab Province

3.1.4 Revisiting canal allocations for rationalizing groundwater use

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. On an average, the surface water availability is about 0.21 liters/sec/ha. This water amount is usually insufficient to irrigate the entire farm in one irrigation turn therefore farmers can decide whether to under-irrigate all land or leave a fraction un-irrigated (Latif and Ahmad, 2009). This situation prompted farmers to use groundwater for irrigating their crops.

The canal water is allocated without considering the seepage loss along the channel and is the major cause of inequitable water distribution at a tertiary level.

Resultantly, the tail-enders get 20 percent less water than middle-enders, who in turn get 20 percent less water than the farmers located at the head reaches of the canal. Similar trends are observed in the productivity levels of head, middle and tail reached of the same canal system. The issue of bringing transparency in running an equitable water distribution system therefore remains a challenge.

To improve salinity management in the canal command areas where head and tail ends of the same system have varying soil and groundwater qualities, existing water allocation criteria needs to be revisited. Canal water allocations should be made considering cropping patterns, groundwater quality and soil salinity levels. For this purpose, existing water allocation criteria of providing equal access to canal water regardless of location along the canal and soil and groundwater quality (*warabandi* system) needs serious debate. The canal water supplies should be allocated 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 should 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.

Implementation of this option requires a well thought strategy and incentives to convince head-end farmers to agree on surface water reallocation. This objective may be achieved 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. In the watercourse located at the tail-end of the canal system, use of poor quality groundwater for irrigation should be strictly prohibited to avoid the risk of soil salinization. In addition to technical changes, this would also require policy level interventions to enforce suitable cropping patterns to avoid over-exploitation of groundwater resources.

In case, head end farmers agree to forego their right for canal water or accept less percentage of their share and increase their groundwater pumping, the possible consequence could be that they will start pumping more groundwater to maintain their profitable cropping patterns. In areas where groundwater quality is good this option will be intuitively attractive. Through this excessive use of groundwater, head end farmers may face salinity problems similar to those of tail end farmers due to increase in salinity of groundwater. On the other hand, tail end farmers might start changing their cropping patterns in lieu of more fresh water availability. As fresh water will not be available to meet their full crop demand, they might still go for excessive groundwater pumping resulting in increased salinity problems.

This shows that simply changing water allocations will not be enough to ensure sustainability. For this purpose, policy interventions regarding cropping patterns and amount of groundwater that can be pumped to remain acceptable salinity levels need also to be introduced. For the implementation of proposed water allocation plan, intensive monitoring of systems needs to in place. 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 is required. In the existing set up, water user associations can be engaged to start the dialogue process to make farmers agree on this new paradigm shift in managing surface water and groundwater resources in Pakistan.

Until water allocation strategies are revised, tail-end farmers should be encouraged and facilitated to use the little amount of surface water available through high efficiency techniques (drip and/or sprinkler) and restrict groundwater use of poor quality. In order to overcome the uncertainty in canal water supplies, farmers should store their weekly canal water share in naturally occurring depressions near their fields or artificially constructed on-farm storage ponds. These depressions and ponds can also be used to harvest rain water. This stored water can then be used for irrigation as and when required using drip or sprinkler systems.

The second option can be to use poor quality groundwater for irrigating crops through drip and sprinkler systems. This will minimize the inflow of salts in the soil profile due to reduced water application. The stored canal water can then be used for leaching the salts on occasional basis. The problem with this option could be clogging of emitters due to salt inflow. However, this can be managed through regular flushing of drippers with the clean water. The advantage would be that tail-end farmers can bring more area under cultivation. This will be a great step towards improving livelihoods of the tail-end farmers.

The adoption of these irrigation techniques may increase the threat of soil salinization due to reduced leaching activity. Therefore, the evaluation of these options for different agro-climatic conditions within a canal command is inevitable. Successful implementation of these concepts will also require financial assistance for small farmers to shift from flood irrigation to drip and sprinkler irrigation systems and improve leveling of their fields to control field application losses. The farmers should also be provided technical and financial assistance for establishing on-farm water storage ponds and extension services for the maintenance of drip and sprinkler systems. Farmers might also need assistance in developing new cropping systems to match with the water availability both in terms of quality and quantity. All these options would require necessary changes in the government policies, institutional arrangements and wide scale dialogue with farmers. For this purpose, network of existing water user associations may play a vital role. These policy decisions have to be taken if we are serious in minimizing poverty and improve livelihoods of farmers and ensure future food security for the country.

3.2 Demand-side Solutions

3.2.1 Increasing economic productivity of groundwater

In most irrigated areas of world, groundwater is generally associated with cultivating high-value market crops. In China, groundwater is a major source of irrigation for cash crops, accounting for 70 percent of the cotton crop, 62 percent of the oil crop, and 67 percent of the vegetable crop (Wang et al., 2009). The value added to farming from groundwater use is best demonstrated in the Mediterranean countries. In Andalusia, Spain, groundwater users apply less water per hectare compared to surface water irrigators – 3,900 m3 of groundwater compared to 5,000 m3 for surface water. The gross water productivity of groundwater is US$3.24/m3 compared to US$0.97/m3 for surface water, with economic productivity of US$9.94/m3 for groundwater compared to US$4.6/m3 for surface water (Hernandez-Mora et al., 2010). In Spain, groundwater productivity is 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). 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 percent of the country's exports of high-value orchard and vegetable crops.

The major concerns regarding performance of irrigated agriculture in Pakistan are low crop yields and low water use efficiencies. The average yields in Pakistan are low for wheat and rice, being 2276 kg/ha and 1756 kg/ha, respectively. Contrary to the rest of the world, groundwater in Pakistan is being used to grow traditional crops such as wheat, maize, rice and sugarcane. 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 where 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), so restricting the rice production to its domestic needs and converting to less water intensive crops could reduce the pressure on groundwater.

The productivity of water in Pakistan is also about the lowest in the world. For wheat, for example, it is 0.5 kg/m^3 compared to 1.0 Kg/m^3 in India and 1.5 Kg/m^3 in California. The comparison of yields and water use efficiency between India and Pakistan suggest that we are 12 percent less efficient in using water for wheat. The nitrogen use in India is also double than Pakistan. These are the major factors behind increased crop yields and productivity of water in India. Therefore, Pakistan needs to think seriously to grow high value and low water intensive 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.

3.2.2 Promoting sustainable groundwater use

Farmers having access to groundwater in addition to canal water tend to apply more water compared to those who are fully dependent on canal water. Studies have shown that reducing water applications to wheat and cotton by 40-50 percent can produce optimal crop yields without increasing salinity levels in the soil (Prathapar and Qureshi, 1999; Qureshi and Bastiaanssen, 2001). Adoption of innovative 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). Table 1 compares the irrigation amounts, total water use and water savings for current and optimized irrigation practices.

In the Indus Basin, adoption of improved irrigation practices could save up to 24 BCM of water, which is about 14% of the total renewable water available in the Indus basin. Under the current surface water conditions of the Indus basin, this water is contributed through groundwater extraction. Reducing groundwater extraction by 24 BCM will also reduce the diesel consumption by 2.2 billion liters (62%) and CO^2 emissions by about 1.5 million mt of C (40%) (Qureshi, 2014). These savings can be achieved by implementing optimized irrigation schedules together with other farm management options.

Using water-saving technologies, such as piped water and pressurized micro-irrigation, to replace flood irrigation are the widely accepted means of promoting sustainable groundwater use. The advantage claimed is that delivering water on-demand to the root-zone of plants can improve application efficiency by saving water lost to evaporation and the seepage associated with other methods. However, it is also argued that at the basin scale, only water saved by reducing evaporation and flows to 'sinks' qualifies as a real saving and that most of the micro-irrigation techniques produce little real water saving in this sense. Farmers often use the water they 'save' to increase their irrigated areas and so the result of using water-saving technologies has little impact on reducing the groundwater overdraft at the basin scale.

Despite such counter-intuitive evidence, promoting water-saving technologies is still a popular policy instrument of groundwater governance in China, India, Mexico, Spain, and the USA. There is little denying the claim that micro-irrigation can save energy and labor, reduce salt-load, and improve crop yield and quality. The viability of micro-irrigation is more appealing where high value crops are grown under green houses because productions are many folds higher and so do the incomes. In Pakistan, micro-irrigations are also getting popularity with the initial support of government. However, their large scale adoption would require quality goods with access to lucrative international markets. In

Crop	Area (ha)	Current irrigation practices		Improved irrigation practices		Total water saving (BCM)
		Irrigation (mm)	Total water use (BCM)	Irrigation (mm)	Total water use (BCM)	
Wheat	8,578,000	480	41.2	300	25.7	15.5
Cotton	3,100,000	480	14.9	300	9.4	5.5
Rice	1,016,000	1600	16.3	1300	13.3	3.0
	Total		**72.4**		**48.4**	**24.0**

Table 1: Comparison of irrigation amounts, total water use and water savings for current and improved irrigation practices in the Indus Basin (Source: Qureshi, 2014).

the absence of such arrangements, their economic feasibility for small farmers will remain a challenge.

3.2.3 Improving productivity of water use in agriculture

Under the traditional irrigation practices, the use of earth bunds and poor field leveling results 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. Therefore, more efforts should be concentrated on adopting water conservation techniques in the irrigated agriculture because this is by far the greatest user of water.

Resource conservation technologies such as precision land levelling, zero tillage, bed and furrow planting have shown considerable reduction in water application at the field scale. Zero tillage technology is now widely practiced in many countries including the USA, Brazil, Argentina and Zimbabwe. Studies in India and Pakistan have shown many advantages of bed planting in rice-wheat systems (Hobbs and Gupta 2003a). Studies in Bangladesh also show that more than 40% water saving can be obtained compared to flood irrigation in case of bed planting, in addition to higher gross margins (Mollah et al. 2009). Another potential way to increase water use efficiency in the rice is the alternate wetting and drying (AWD) technique. With AWD, farmers allow ponded water to disappear from the field and infiltrate for several days until the perched field water table reaches 15–20 cm depth. Although, yield increases under AWD are rare, higher water productivity is commonly obtained (Bouman et al. 2007). There is also evidence that AWD may boost concentrations of essential nutrients, particularly zinc, in harvested rice (Price et al. 2013). Despite these benefits, the adoption of AWD in Pakistan is relatively poor. Fixed rotational irrigation system arrangements, non-availability of water on needed schedules and lack of understanding of complexities of AWD are considered as the major constraints in the wide scale adoption. This requires more work to finding ways to overcome the current barriers to promote large scale adoption of this technology.

3.2.4 Encouraging use of alternate water resources

The increasing gap between fresh water supply and demand along with the projected effects of climate change have put enormous pressure on agriculture to reduce its share of freshwater use and look for alternative sources to meet the requirements. Scientists around the globe are working on finding new ways to recycle water—through the reuse of urban wastewater, for irrigation and other purposes. This could make more clean water available for use in domestic and industrial sectors. The use of industrial or municipal wastewater (treated and untreated) in agriculture has become a routine practice in many arid and semi-arid countries because it offers environmental and socio-economic benefits such as reduction in effluent disposal problems, supply of nutrients as fertilizer and improvement in crop production during the dry season (Qadir et al., 2010).

The annual global wastewater production is roughly 1500 BCM and about 20 Mha of agricultural land is currently irrigated with wastewater (Jiménez and Asano, 2008). Farmers in Asia (China, Pakistan, India) and Africa (Ghana, Ethiopia, Kenya, and Morocco) deliberately use undiluted wastewater as it provides nutrients and is cheaper than other water sources. The use of wastewater for irrigation is also getting momentum in the Arabian countries. An estimated 11 BCM of wastewater is produced annually, of which 5.6

BCM is treated to various levels and 4.3 BCM of this treated wastewater is used for agricultural production (Qureshi and Shoaib, 2015). In Pakistan, the total annual quantity of wastewater produced is estimated at 4.5 BCM (Qureshi, 2011). Currently, a small amount of this wastewater is being used to grow vegetables in large cities whereas the rest is either disposed of in rivers or discharged into open areas on the outskirts of big cities. This practice is creating huge environmental problems. Therefore there is a need to make profitable use of this wastewater by growing valuable crops instead of discharging it in main water bodies to pollute fresh water resources.

Currently, wastewater use for agriculture is largely restricted to grow vegetables and cereals (Raschid-Sally and Jayakody, 2007). Smallholder farmers in Africa and Asia grow perishable crops such as leafy vegetables using wastewater to enhance their household income. For instance, in most West African cities, 60–80% of the vegetables consumed are produced in urban and peri-urban areas using wastewater (Drechsel et al. 2006). Besides crop farming, wastewater is used also for aquaculture in Africa, and in Central, South, and Southeast Asia (Bangladesh, Cambodia, China, India, Indonesia, and Vietnam) (Asano et al., 2007). 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. Brackish groundwater has been used successfully to irrigate wheat, cotton, pearl millet, sugar beet etc. 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.

4. Groundwater Governance Practices

4.1 Global Experiences

Groundwater governance discourse worldwide is a product of the growing threat of water scarcity, which has stressed the need for a critical transition from resource development mode to resource management mode. Groundwater has proved to be particularly difficult to manage relative to other natural resources. The direct management of groundwater through the introduction of groundwater use rights and limitations on groundwater access by enforcing permit systems has only worked where the State is strong to ensure enforceability and accountability and number of groundwater users is small, such as in Oman. However, in the absence of political will and enforcement capacity, efforts to regulate groundwater extraction have failed such as in Jordan (Venot and Molle, 2008). China, under the 1988 National Water Law, introduced a system of permits, which could not be implemented in most villages (Wang et al., 2009). India has tried numerous groundwater laws and regulations for decades to regulate groundwater extraction but success so far has been very limited (Planning Commission, 2007). The aquifer management in the Murray-Darling basin in Australia through permit systems was successful because implementation was easy due to small number of groundwater abstractors (Shah et al. 2003).

Volumetric pricing of groundwater is generally considered a superior strategy of promoting efficient groundwater use. Pricing requires a robust system for the monitoring of groundwater abstractions.

This again is possible in situations where abstractors are few and large and where the culture of a metered water supply has formed deep roots. Where groundwater abstractions are small, numerous, and dispersed such as in Pakistan, groundwater pricing becomes difficult to administer. Even in Europe, individual metering for the monitoring of groundwater abstraction has proved costly and almost impossible to implement (Zoumides and Zachariadis, 2009).

In many countries where groundwater is excessively used for agriculture, energy prices are used as a surrogate for groundwater pricing. Since the electricity generation and distribution networks are controlled by governments, manipulating energy prices could discourage groundwater overdraft. However, in China, India and Iran, electricity prices are heavily subsidized, either to protect livelihoods, food security, or both. These subsidies are often the prime drivers of the groundwater overdraft. Chinese farmers in many provinces are charged only 25 percent of the normal electricity rates for pumping water (COWI, 2013). In Iran, farmers pay only 20 percent of the actual cost of electricity (FAO 2009b; Soltani and Saboohi 2008). Mexico offers farmers a 20 percent 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, using energy prices to control groundwater abstraction could face resistance from farmers. In the Mediterranean region, energy prices are easier to manipulate however they are unlikely to have much impact, unless raised several-fold (Zoumides and Zachariadis, 2009). Studies done in India also reveal that a 25 percent increase in electricity price would reduce groundwater use by only 1.6–3.3 percent (Badiani and Jessoe, 2010). Similarly, in Pakistan, increasing electricity prices during the last two decades only forced farmers to shift from electricity to diesel engines (Qureshi et al. 2010). As a result, groundwater exploitation continued because it was crucial to meet increasing cereals demands.

This suggests that solutions offered 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 therefore not likely to succeed in Pakistan due to its peculiarities and socio-cultural environment. Therefore a well thought-out, pragmatic, patient and persistent strategy is needed to address the issue of groundwater management. Some of 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 less water-demanding crops, and the development of enabling policies and decision support systems.

4.2 The Pakistan Case

In Pakistan, the focus has been on the development of groundwater and not much attention was given to the management of aquifers because the resource was in abundance and the negative impacts of this development were not fully understood. However, the situation has now become serious because unregulated exploitation of groundwater has brought many aquifers under stress and sustainability of irrigated agriculture is under severe threat. Uncontrolled development of groundwater was largely overlooked because the policy makers remained under pressure to produce more food to reduce poverty, especially in rural areas. Furthermore, reduced reach of the State into rural areas, weak accountability and enforcement of laws and regulations, and the sheer number of tube well users were the major reasons for the ineffective governance of groundwater (Shah et al. 2003; Shah 2007; Qureshi et al. 2010). Moreover, declining investments in surface water development and maintenance of existing irrigation system left governments with no options other than to allow the expansion of irrigated agriculture through groundwater development. Due to this dependence on groundwater for rural livelihoods, government has been reluctant to implement stringent regulation.

Pakistan has introduced many laws for regulating groundwater in Pakistan. In 1980s, licensing system was introduced to restrict installation of private tube wells in the critical areas (where groundwater was lowering at faster rate and/or where groundwater quality was deteriorating). 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 Provincial Irrigation and Drainage Authority (PIDA) act in 1999-2000 and included in the Canal act of 2006. Similar law was developed by the Baluchistan government (Balochistan Groundwater Rights Administration Ordinance, 2001). These rules suggested demarcation of critical areas, provision of licenses for the installation of tube wells especially in critical areas and registration of all tube wells (ACE-Halcrow, 2003). This regulatory framework was submitted to the provincial governments for implementation. However, like many other laws, these recommendations could not get the attention of the government and the problem of groundwater management remains a challenge.

The problem so far has been the absence of effective implementation of existing laws and regulations. Historically, in Pakistan, the provision of human and financial resources for the management of groundwater has remained very limited compared to surface water resources (Lohmar et al., 2003). Another complication was that no single organization was responsible for managing the total resource base which is the Indus basin aquifer. In addition to the general lack of respect for law and prevalence of corruption in the public sector, the 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 are in thousands only and enforcement of regulatory laws is relatively easy. There 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).

Agriculture in Pakistan is changing fast. Contract farming seems to be increasing, more progressive and commercial farmers are emerging, high value crops are displacing food grains and increased prices of agricultural commodities are attracting people towards agriculture. But all this cannot happen without assured water supply. It is going to require a very different type of state machinery at both Federal and Provincial levels to meet these challenges. In constructing this "new water state", the focus must be primarily on instruments which govern the relationships of different users with the water, and with each other. For this to happen, Pakistan needs to invest in institutions to enable them to take on the future challenges of water management. In the past, reform process has been extremely slow with implementation almost missing.

The capacity of institutions should be developed 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 make necessary institutional arrangements for the formulation and evaluation 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.

5. Conclusion

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.

In the ***business as usual scenario***, the projected water requirements for the 2025 are 250 BCM whereas supplies will not exceed 190 BCM even if full potential of groundwater is exploited. This shortfall of water requirements would result in 70 million tons of food shortages by the year 2025 (ADB, 2002). On the other hand, anticipated climate changes are expected to bring more droughts which will affect both irrigated and rainfed agriculture. This will require significant improvement in water availability and its use and the introduction of new and sustainable methods of food production. Management of surface and groundwater resources is also important, especially in view of prolonged drought conditions witnessed at the turn of the century in Pakistan.

The groundwater aquifer of Indus Basin has huge storage capacity. In the absence of sufficient surface storage capacities, groundwater aquifer can act as a strategic resource to support irrigated agriculture in Pakistan. Over the last two decades, the water economy of Pakistan has survived largely due to the tapping of the unmanaged groundwater by millions of farmers, by towns and villages and industries. However, this era of "productive anarchy" is now coming to an end, since groundwater is now being over tapped in many areas. 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 informed and organized users.

An even more difficult task is the management of groundwater quality because reservoirs are already being mined in the "***barani***" and sweet water areas. In the northern part of the Indus basin, groundwater in the centre parts of the doabs is underlain with geologic saline water which tends to migrate with declining water tables in the adjoining good sweet water areas. In rain-fed areas, farmers have invested in rainwater harvesting structures for supplemental irrigation and for recharging aquifers. These structures have been built by individuals as well as by local groups and/or communities.

These initiatives have helped small farmers to get higher yields as compared to the time when these structures were not in place. Therefore supporting these initiatives of farmers and helping them to sustain them will be crucial to stabilize aquifers, produce more food and fight poverty.

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 leads to serious consequences. The action which was once considered as blessing is now widely criticized as a bad call. Therefore, a very well informed debate is needed about whether to pump its aquifers to the maximum and face the consequences later, 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 gets out of hand.

In addition to these supply-side solutions, demand for groundwater also requires management. In the Indus basin, irrigation efficiencies are low and the erroneous concept of "*more water-more yield*" still prevails among farmers. Adoption of water conserving crop management practices such as alternate wetting and drying, direct-seeded rice, and bed planting could help. Introduction of micro-irrigation technologies and using groundwater to grow high value crops can assist in boosting groundwater economy. Cropping patterns also need to be rationalized – starting with the promotion of feasible alternatives to rice – considering country needs and the availability and sustainability of aquifers.

There is also a need for creating awareness among farmers and other users through educational programs for all stakeholders, heavy promotion of alternative crops, and programs to develop strong output markets for these alternative crops. The options of using alternate water resources such as wastewater and drainage water resources also need to be explored. Use of these marginal water resources (after the adoption of appropriate measures) will help not only in solving water shortage problems but also in solving drainage and increasing environmental issues.

Needless to say that it is the management of the Indus Basin aquifer that will hold one of the important keys to sustainable absorption of climate shocks in future. Therefore planners and policy makers will have to make strategies to maintain sustainability of the Indus basin aquifer both in terms of quality and quantity to extract maximum benefits from the aquifer storage when it will be most needed. Managing the aquifer will require a well thought-out, pragmatic, patient and persistent strategy. The central elements will be heavy involvement of users, substantial investments in modern water and agricultural technology, and the State playing a vital role as developer of the enabling legislation, and regulator and provider of knowledge and decision support systems duly backed with appropriate research feeding into strategy, planning, designing and implementation stages of the required actions. Pakistan also needs to give due attention to the effective implementation of existing laws and regulations for sustainable groundwater management in Pakistan.

6. References

- Ahmad, S., 2009. Water availability and future water requirements. Paper presented at the National Seminar on "Water Conservation, present situation and future strategy" organized by Ministry of Water and Power, Islamabad, Pakistan. May, 2009.
- Archer, D.R. and Fowler, H.J., 2008. Using meteorological data to forecast seasonal runoff on the River Jhelum, Pakistan. J. of Hydrol., 361, 10-23.
- Archer, D.R., Forsythe, N., Fowler, H.J. and S.M. Shah, 2010. Sustainability of water resources management in the Indus basin under changing climatic and soio-economic conditions. Hydrology and Earth System Sciences Discussions, 7, 1883-1912.
- Asano, T., Burton, F., Leverenz, H., Tsuchihashi, R., Tchobanoglous, G., 2007. Water Reuse: Issues, Technologies, and Applications (McGraw-Hill). Metcalf & Eddy Inc..
- Badiani, R. and Jessoe, K.K., 2010. Electricity subsidies, elections, groundwater extraction and industrial growth in India. Paper submitted to the Pacific Development Conference 2010, Berkeley, University of California. Available at: http://mitsloan.mit.edu/neudc/papers/paper_194.pdf
- Bhutta, M.N., 2002. Sustainable management of groundwater in the Indus basin. Paper presented at Second South Asia Water Forum, 14-16 Dece. Islamabad, Pakistan: Pakistan Water Partnership.
- Bhutta, M. N., Smedema, L.K., 2007. One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: A historical review. Irrig. and Drain. 56:581-590.
- Bouman, B.A.M., Humphreys, E., Tuong, T.P., Barker, R., 2007. Rice and Water. Adv. Agron. 96, 187–237.
- Chebaane, M, El-Naser, H, Fitch, J, Hijazi, A, and Jabbarin, A., 2004. Participatory groundwater management in Jordan: Development and analysis of options. Groundwater: from development to management. Hydrogeology Journal. Vol. 12 No. 1. Paper 2009-03.
- COWI., 2013. Groundwater in China. Part 1 – Occurrence and Use. COWI, Kongens Lyndby, Denmark.
- Drechsel, P., Graefe, S., Sonou, M., Cofie, O.O., 2006. Informal irrigation in urban West Africa: an overview. In: Research Report 102, IWMI, Colombo, Sri Lanka.
- Food and Agriculture Organization of the United Nations (FAO)., 2009b. Groundwater Management in Iran. Draft Synthesis Report. FAO, Rome, Italy.
- Garrido, A., Martínez-Santos, P. and Llamas, M.R., 2006. Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience. Hydrogeology J., 14(3): 340–349.
- Halcrow-ACE, 2003. Exploitation and regulation of fresh groundwater—main report. ACEnHalcrow JV Consultants, Gulberg III, Lahore, Pakistan
- Hernández-Mora, N., Martinez, L., Llamas, R.M., and Custodio, E., 2010. Groundwater in the southern member states of the European Union: an assessment of current knowledge and future prospects. Country Report, European Academies Science Advisory Council. Available at: http://www.easac.eu/fileadmin/PDF_s/reports_statements/Spain_Goundwater_country_report
- Hewitt, K., 2005. The Karakoram Anamaly? Glacier Expansion and the "Elevation Effect".

Karakoram Himalaya, Mt. Res. Div., 25(4), 332-340.

- Hobbs P.R., Gupta R.K., 2003a. Resource-conserving technologies for wheat in the rice-wheat system. In: Improving Productivity and Sustainability of Rice-Wheat Systems: Issues and Impact. American Soc. Agron. Spec. Publ. 65, 149-171.
- Immerzeel, W.W., van Beek, L.P.H., and Bierkens, M.F.P., 2010. Climate Change will affect the 5 Asian Water Towers, Science, 328, 1382–1385, doi:10.1126/science.1183188, 2010.
- Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007 - Impacts, Adaptation
- and Vulnerability Working Group II contribution to the Fourth Assessment Report of the IPCC.
- Jiménez, B. Asano, T., 2008. 'Water reclamation and reuse around the world', in B. Jiménez and T. Asano (eds) Water Reuse: An International Survey of Current Practice, Issues and Needs, IWA Publishing, London, pp 648.
- Latif, M., Tariq, J.A. 2009. Performance assessment of irrigation management transfer from Government to farmer-managed irrigation system: a case study. Irrig. and Drain. 58: 275-286.
- Leghari, A.N., Vanham, D., and Rauch, W., 2012. The Indus Basin in the framework of current and future water resources management. Hydrol. Earth Syst. Sci. Discuss., 8: 2263–2288, doi:10.5194/hessd-8-2263-2011
- Li, Y., 2001. Groundwater recharge. Unpublished. Nanjing Institute of Hydro. and Water Resour. China.
- Lohmar, B., Wang, J., Rozelle, S., Huang, J. and Dawe, D., 2003. China's agricultural policy reforms: Increassing investment, resolving conflicts and revising incentives. Agricultural Information Bulletin # 782, Economic Research Service, USDA.
- Meinzen-Dick, R, 1997. Groundwater markets in Pakistan: Participation and Productivity. Research Report No. 105. International Food Policy Research Institute (IFPRI), Washington D.C., USA.
- Mollah MIU, Bhuyia MSU, Kabir MH, 2009. Bed Planting – A New Crop Establishment Method for Wheat in Rice-Wheat Cropping System. J Agric Rural Dev 7(1&2), 23-31.
- PHED, 1999. Hydrogeological map of Punjab, Public Health Engineering Department, Lahore.
- Planning Commission. (2007) Ground Water Management and Ownership –Report of the Expert Group. Government of India, New Delhi, India.
- PPSGDP, 2000. Legal and Regulatory Framework for Punjab Province. Punjab Private Sector Groundwater Development Project (PPSGDP). Technical Report No. 45. Lahore, Pakistan.
- Prathapar S.A., Qureshi, A.S., 1999. Modeling the effects of deficit Irrigation on soil salinity, depth to water table and transpiration in semi-arid zones with monsoon rains. J Water Resour Dev 15(1–2):141–159. doi:10.1080/07900629948989
- Price, A.H., Norton, G.J., Salt, D.E., Oliver Ebenhoeh, O., Meharg, A.A., Meharg, C., Islam, M.R., Sarma, R.N., Dasgupta, T., Ismail, A.M., McNally, K.L., Zhang, H., Dodd, I.C., Davies, W.J., 2013. Alternate Wetting and Drying Irrigation for Rice in Bangladesh: Is it Sustainable and has Plant Breeding Something to Offer? Food Energy Sec. 2, 120–129.
- Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P., Drechsel, P., Bahri, A., Minhas, P.S., 2010. The challenges of wastewater irrigation in developing countries. Agri. Wat. Manage. 97: 561-568.
- Qureshi, A.S., Bastiaanssen, W.G.M., 2001. Long-term effects of irrigation water conservation on

crop production and environment in semi-arid zones. ASCE Irrigation and Drainage Engineering. Vol. 127, No. 6:331-338.

- Qureshi, A.S., Akhtar, M., 2003. Effect of electricity pricing policies on groundwater management in Pakistan. Pakistan Journal of Water Resources. Vol. 7(2): 1-9.
- Qureshi, A.S., Asghar, M.N., Ahmad, S., Masih, I., 2004. Sustaining crop production under saline groundwater conditions: A case study from Pakistan. Aust. J. Agric. Scie. Vol. 54 (2): 421-431.
- Qureshi, A.S., Masih, I., Turral, H., 2006. Comparing water productivities of transplanted and direct seeded rice for Pakistani Punjab. Journal of Applied Irrigation Science. Vol. 41, No. 1: 47-60.
- Qureshi, A.S., McCornick, P.G., Qadir, M., Aslam, M., 2008. Managing salinity and waterlogging in the Indus Basin of Pakistan. Agricultural Water Management 95:1-10.
- Qureshi, A.S., Gill, M.A., Sarwar, A., 2010. Sustainable groundwater management in Pakistan: Challenges and opportunities. Irrig. and Drain. Vol. 59, Issue 2:107-116.
- Qureshi, A. S., 2011. Water Management in the Indus Basin in Pakistan: Challenges and Opportunities, Mount. Res. Dev., 31, 252–260, doi:10.1659/mrd-journal-d-11-00019.1, 2011.
- Qureshi, A.S., 2014. Reducing Carbon Emissions through Improved Irrigation Management: A case study from Pakistan. Irrig. And Drain. 63: 132-138.
- Qureshi, A.S., Shoaib, I., 2015. Evaluating benefits and risks of using treated municipal wastewater for agricultural production under desert conditions. Paper presented in the DT12 Conference, held in Cairo, November 16-19, 2015.
- Rasul, G. Dahe, Q., and Choudhry, Q.Z., 2008. Global warming and melting glaciers along southern slopes of HKH ranges. Pakistan journal of meteorology, 5(9), 63-76.
- Raschid-Sally, L., Jayakody, P., 2007. Understanding the drivers of wastewater agriculture in developing countries—results from a global assessment. In: Comprehensive Assessment Research Report Series, IWMI, Colombo, Sri Lanka.
- Shah, T., 2007. The groundwater economy of South-Asia: An assessment of size, significance and socio-ecological impacts. In: Giordano, M and Villholth, K.G. (Editors). The agricultural groundwater revolution: Opportunities and threat to development. CABI Publications. 7-36 pp.
- Shah, T., Debroy, A., Qureshi, A.S., Wang, J., 2003. Sustaining Asia's Groundwater Boom: An overview of issues and evidence. Natural Resource Forum: 27: 130-141.
- Soltani, G. and Saboohi, M., 2008. Economic and social impacts of groundwater overdraft: the case of Iran. Paper submitted to 15th ERF Annual Conference, Cairo, Egypt. 23–25 November 2008.
- Tsur, Y., 1990. The stabilization role of groundwater when surface water supplies are uncertain: the implications for groundwater development. Water Resources Research, 26(5): 811–818.
- USAID, 2009. Pakistan's Food and Agriculture Systems. Economic growth office of USAID's bureau of Economic growth. Islamabad, Pakistan. 102 pp. http://pdf.usaid.gov/pdf_docs/PNADO507.pdf)
- Venot, J. P., Turral, H., Samad, M. & Molle, F., 2007. Explaining Basin Closure Through Shifting Waterscape in the Lower Krishna Basin, South India. Research Report. International Water Management Institute, Colombo, Sri Lanka.
- Venot, J.P., Molle, F., 2008. Groundwater depletion in the Jordan highlands: can pricing policies regulate irrigation water use? Water Resources Management, 22(12): 1925–1941.

- Wang, J., Huang, J., Huang, Q., Rozelle, S.C., and Walker, H.F., 2009. The evolution of China's groundwater governance: productivity, equity and the environment. Quarterly Journal of Engineering Geology and Hydrogeology, 25(1): 141–158.
- WAPDA, 2007. Waterlogging, salinity and drainage situation. SCARP Monitoring Organization, Water and Power Development Authority, Lahore, Pakistan.
- WAPDA., 2010. Hydropower Potential in Pakistan. Lahore, Pakistan. www.wapda.gov.pk
- World Bank., 2005. Pakistan's Water Economy: Running Dry. Report No. 34081-PK. Washington DC: World Bank.
- World Bank, 2007. Punjab groundwater policy—Mission report. WB-SA-PK-Punjab GW Mission report, June 2007. www.worldbank.org/gwmate
- World Bank, 2008. World Development Report 2008, Washington, DC. P.96.
- Zoumides, C. and Zachariadis, T. (2009) Irrigation water pricing in southern Europe and Cyprus: the effects of the EU Common Agricultural Policy and the Water Framework Directive. Cyprus Economic Policy Review, 3(1): 99–122.

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