IRRIGATION AND DRAINAGE EFFORTS IN INDUS BASIN – A REVIEW OF PAST, PRESENT AND FUTURE REQUIREMENTS

Muhammad Basharat[1] and Sultan Ahmad Rizvi[2]

ABSTRACT

Indus Basin Irrigation System (IBIS) is contributing20.9% to gross domestic product (GDP), 43.5% of total employment and more than 60% of foreign exchange earnings through its agriculture sector. Until now, the irrigated agriculture growth had been well-paced in providing the increasing food requirements of the country. This had been possible with the implementation of 61 Salinity Control and Reclamation Projects (SCARP), in addition to improving irrigation system in IBIS. But maintenance of these systems could not be institutionalized, resulting in their poor performance. Although, waterlogging was reduced from 16% to 8% in Punjab, firstly with these projects, but later on, increasing groundwater abstraction was main facilitator. But in Sindh, waterlogging still fluctuates between 25 to 60 % of the irrigated area. Sustainability of current production levels is doubtful because it had been achieved at the cost of depleting the aquifers and ecosystem. Streams and lakeswhich were once fresh water sources, are noweither dryor heavily polluted, e.g. Ravi River and Hudiara Drain in Punjab; Hamal and Manchar Lakes in Sindh. In our opinion, lack of legislation and its implementation are the major factors.This paperpoints out deficiencies and lessonslearnt from the past irrigation and drainage management and recommends steps for further improvement.

Keyword: IBIS, irrigation, drainage, waterlogging, groundwater, SCARPs

1. INTRODUCTION

The geography of Pakistan comprises diverse and extensive regions, covering an area of 79.6 million hectare (Mha), out of which 32.08 Mha have good potential for agriculture. The country lies in the subtropical region with a semi-arid to arid climate. Rainfall is sparse and scanty, not reliable for reasonable agriculture. However, the region is blessed with fresh water sources in the form of Indus River and its tributaries.Buildingof irrigation canals was initiated during eighteenth century. Ensuing to this,widespread waterlogging and salinity appeared, which is still a major issue, particularly in the Lower Indus area.

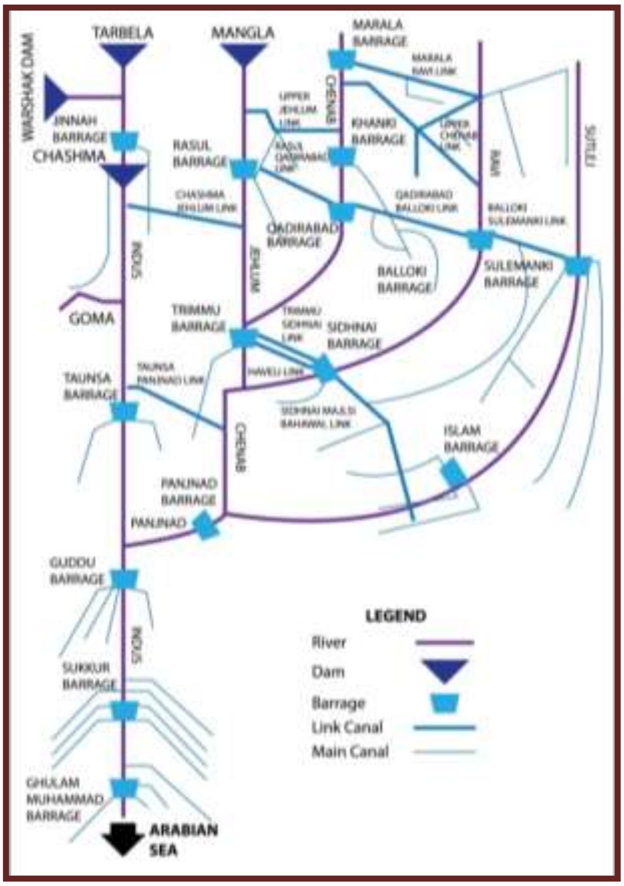
Until now, the irrigated agriculture growth is well paced for providing the increasing food and fiber requirements of the country. Besides, gradual structural developments, groundwater developments also contributed significantly. The theme of this paper is to point out deficiencies and draw lessons from the past irrigation and drainage management in IBIS andthus, recommending further steps for achieving potential production levels, matching with future food requirements.

1.1 Indus Basin Irrigation System

The Indus River originates in a spring located on the northern side of Himalayan range in Kaillas Parbat, Tibet, at an altitude of 5488 m above mean sea level. The total length of the river is 3,199 km.Five main tributaries i.e., Jhelum, Chenab, Ravi,

[1] Additional Director, IWASRI, WAPDA, Lahore (53770), Pakistan; email: basharatm@hotmail.com; Ph.: +92-3334492610.
[2] Agricultural Engineer, Soil and Water Conservation Research Institute (SAWCRI), Chakwal, Pakistan.

Beas and Sutlejon the eastern side and River Kabul on the western side jointhe Indus River.The Indus basin irrigation system (IBIS) comprises of three major reservoirs, 16 Barrages, 2 headworks, 12 inter-link canals, 44 canal systems (Figure 1) and 107,000 watercourses. The total length ofcanals is 56,073 kmandthat of the watercourses is1.6 million km. The total area being irrigated with canals and wells is about 17.97 Mha and another 4.17 Mha with wells only (Basharat et al., 2014).



The irrigated agriculture contributes 90% of the total agriculture production; about 20.9% of GDP, 43.50% of employment and 60% of export revenue (Government of Pakistan, 2015). The average annual canal water diversions were 129.2 billion cubic meter (BCM) in the past, have now been reduced to about 125.9 BCM. About 50-60 BCM of groundwater is abstracted per annum through over one million tubewells. Average escapage to the sea is 39BCM, which is highly variable between 3.7 (2004-05) to 113.3 (1994-95) BCM.The IBIS has proved to be functioning with quite low irrigation efficiencies, about 45-49% (Basharat, 2012), leading to poor water conservation, waterlogging and salinity. On the other hand, water shortage for the present cropping intensity is of the order of 38%.

Figure 1. Schematic Layout of Indus Basin Irrigation System of Pakistan.

1.2 Historic Developments in Irrigation, Waterlogging and Drainage

Regular irrigation in IBIS began in 1875 with the completion of the Upper Bari Doab Canal (UBDC) from Madhopur Headworks (now in India) on Ravi River. The last inundation canals were connected to weir controlled supplies in 1962 with the completion of Guddu Barrage. In consequence to this large scale water diversion, watertable came close to land surface,within a few decades.The comprehensive history of Irrigation and drainage developments in IBIS is given in Table 1.

Table 1. Sequence of irrigation, waterlogging and drainage developments in IBIS.

Period	Irrigation, Waterlogging and Drainage Developments
17th-18th century	• Inundation canals dug in17th century; • Weir controlled irrigation started late in the 18th century.
1800 to 1940s	• Majority of the existing irrigation systems were developed. Twin menace of waterlogging and salinity also appeared in many areas.
1950s to	• Waterlogging reached to its peak till 1960;

Period	Irrigation, Waterlogging and Drainage Developments
1960s	• Water and Power Development Authority (WAPDA) establishedin 1958; • SCARP projects were launched.
1970s	• Extensive surface drainage and canal lining measures were taken; • 1977-79 soil salinity survey showed reduction as compared to 1950s.
1980s	• Public wells privatized and more than 200,000 private wells installed, enhancing groundwater use and drainage.
1990s	• High floods in 1988, 1992 and 1994 further aggravatedwaterlogging; • Left Bank Outfall Drainage (LBOD) project in Sindh initiated in 1990.
2000	• In Upper Indus, groundwater contribution came at par with surface water; • In Lower Indus, surface irrigation still contributed the largest, due to abundant surface supplies and underlying saline groundwater.
1999-2002	• A severe drought enhanced watertable lowering in Punjab, in Bari Doab groundwater mining was triggered, that is still going on at alarming rates; • In Lower Indus, temporary lowering of watertable was observed.
2010	• Heavy flooding, recharged the aquifer in adjoining areas and enhanced waterlogging in lower Indus.
2011	• Heavy flood in Lower Indus due to high intensity rainfall, particularly in south-eastern parts,further aggravated waterlogging and salinity.
Present condition	• In Upper Indus, pumping for irrigation is larger than recharge,leading to declining groundwater levels to various extents. • In Lower Indus, SCARP tubewells and tile drainage is hardly functioning. Waterlogging and Salinity problems persist on wider areas.

2. STUDY APPROACH

A concrete review of past irrigation and drainage infrastructure development and management is carried out. Lessons are drawn from the past policies on irrigation and drainage management for future planning.

3. IRRIGATION SYSTEMS DEVELOPMENT AND MANAGEMENT

3.1 Irrigation Systems Developments

After independence, the irrigation system, conceived originally as a whole, was divided between India and Pakistan regardless of irrigation boundaries. This resulted in an international water dispute in 1948, which was finally resolved by the Indus Waters Treaty (IWT) in 1960 under aegis of the World Bank. The treaty assigned the three eastern rivers (Ravi, Beas, Sutlej) to India, with an estimated total mean annual flow of 40.7BCM and the three western rivers (Indus, Jhelum, Chenab) to Pakistan with the transfer of irrigation supplies from the western rivers to the eastern deprived areas. This water transfer was made possible with construction of Mangla and Tarbela dams, five barrages, one syphon and eight inter-river link canals, during 1960-76.After partition, Kotri, Taunsa and Guddu Barrages were completed on the Indus River to provide controlled irrigation to areas previously served by inundation canals. Jinnah Barrage was built in 1946, and the Thal canal was commissioned in 1960. To bring an additional area of 1.075 Mhaunder irrigation, three canals, namely the Greater Thal (Punjab), Kachhi (Baluchistan) and Rainee (Sindh) are under construction since 2002, although at a very slow pace.

3.2 Operation and Management

Until now, the maintenance of the canal systems has been the responsibility of the Provincial Irrigation Departments (PIDs), under provincial budget. The beneficiaries pay a fee called 'Abiana', which is crop specific and is not reflective of the actual operation and maintenance (O&M) costs, and it goes directly to the Provincial Financial Departments. In an effort for improvement, the provinces passed a legislation whereby the PIDs were to be converted into financially self-sustaining autonomous Provincial Irrigation & Drainage Authorities (PIDAs). Under the PIDAs, the O&M of individual canal systems was to be entrusted to autonomous self-accounting Area Water Boards (AWBs), which could delegate the O&M of the distributaries and minor canals to Farmers Organizations (FOs). However, this plan could not be brought into action and matters continue to run like before.

Farmers had the responsibility for O&M of the watercourses and the field ditches but there were technical difficulties. The government intervened to carry out improvements through the On-Farm Water Management (OFWM) under the Provincial Agriculture Departments (PADs). Water User Associations (WUAs) were promoted and registered with the PADs. However, progress on developing WUAs and FOs remained slow.

4. DRAINAGE SYSTEMS DEVELOPMENT AND MANAGEMENT

4.1 Drainage System Developments

To combat the issue, various types of drainage projects were executed successively, from 1960s onward, as described below.

4.2 Surface drainage and canal lining

Large scale construction of storm water drains was initiated in 1933 and by 1947, nearly 2,270 miles of such drains had been constructed, mostly in Rechna and Chaj Doabs. Outfalls were poor and the drains remained ineffective during the monsoon. A number of seepage drains were also constructed along main canals to intercept seepage, but did not provide significant relief. Canal lining was first attempted in 1943 over a portion of Jhang Branch with a double layer of bricks. Some other canals such as Haveli, BRBD, Balloki-Sulemanki, and Sidhnai-Mailsi-Bahawal links were also constructed as lined canals. However, it was not considered an economical solution for large scale adoption, but still it is being tried in various shapes.

4.3 SCARP Projects

Since its creation in 1958, WAPDAhas completed almost 61 SCARPs,consisting of a network of surface and subsurface drainage systems (Figure 2).In fresh groundwater (FGW) areas,tubewells were installed fortwin purposes of drainage and additional irrigation supplies. While in saline groundwater (SGW) areas, drainagetubewells were installed. On the left bank in Sindh, Scavenger Wells (ScW) were installed, pumping separately, both the fresh and saline water for irrigation and drainage, respectively.In areas where tubewells were not feasible sub-surface tile drainage system was opted e.g. East Khairpur Tile Drainage project (EKTD) in 1970.Similarly, Fourth Drainage Project,Mardan SCARP, Khushab tile drainage and Fordwah Earstern Sadiqia (South) projects were launched in Upper Indus.

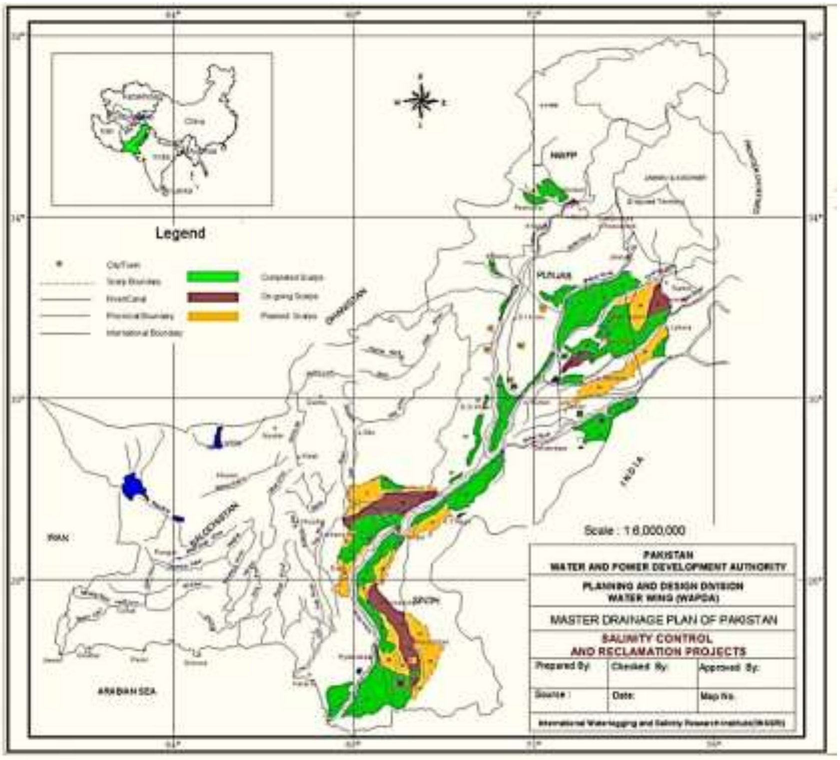


Figure 2. SCARP projects implemented in IBIS.

The initial results of tile drainage system were quite encouraging. But later on problems of non-functioning of sumps and choking of surface drains emerged. The concerted efforts made for more than four decades helped to arrest the problem and reclaim more than 12.6 million acres (Ma). Summary of completed SCARP projects is given in Table 2.

Table 2. Existing drainage facilities (WAPDA, 2004).

Province	Gross Area (Ma)	CCA (Ma)	Surface Drains (km)	Subsurface Drainage						
				Tubewells (Nos.)			Interceptor Drains (km)	Tile drainage		
				FGW	SGW	ScW		Length (km)	Area (Ma) GCA	Area (Ma) CCA
Punjab	10.357	9.220	3402	8065	1985	-	6	2810	0.235	0.164
Sindh	6.732	5.710	9031	4190	1587	361	154	2046	0.105	0.089
KP	0.884	0.884	971	491	-	-	-	7756	0.658	0.137
Baluchistan	0.177	0.161	322	-	-	-	-	-	-	-
Total	18.150	15.793	13726	12746	3572	361	160	12612	0.998	0.390

4.4 Operation and Management

After construction and operation for two years, WAPDA handed over the drainage projects to PIDs of the respective provinces. However, conflicts between WAPDA and PIDs on taking over these systems and carrying out operation and maintenance remained unsettled. No separate charge was levied for the drainage services, except for a drainage cess in some areas, resulting in poor post-construction maintenance.

Although the systems initially worked well and a significant area was rehabilitated, with time, the disposal systems of sumps malfunctioned.Similarly the surface drains got choked and drainage effluent could not be disposed of (Figure 3). Now almost all the systems are stagnant and no further improvements are being made, except very little O&M, and that also due to the interests of farmers.

Figure 3. Poorly maintained sumps, drains, standing water in EKTD Project.

4.5 SCARP transition

SCARP Tubewells achieved the objectives of drainage and salinity control but have been only partially successful in providing supplemental irrigation supplies on sustainable basis because of progressive reduction in pumpage, due to poor O&M, with heavy financial burden. Water rates levied for the use of SCARP tubewell water were almost negligible as compared to the costs incurred.To rectify this huge loss,the SCARP tubewellswere gradually phased out and replaced by private tubewells. This transition concept did not meet favour in Sindh but in Punjab was tested through a pilot project envisaging the transition of 216 Public tubewells in the KhanqahDogran unit of SCARP-I. But as it was too cost intensive, the idea was dropped. Thus, when the farmers were not spoon-fed, they took the initiative and started to develop groundwater resources on their own for supplementing irrigation demands.

5. EFFICACY OF PAST DRAINAGE INTERVENTIONS

Engineering solutions in the form of tubewells, tile drains and surface drains systems really solved the waterlogging problems over much of the area. However, there had been sustainability issue of varying degree with all interventions applied so far, due to poor O&M and lack of farmers' participation. For example, in majority of saline areas inPunjab i.e. Fordwah,Sadiqia, DG Khancanals,some of the central areas of Chaj and Rechna Doabs, waterlogging is again on the rise (Figure 4). However, in fresh groundwater areas of Punjab the groundwater balance progressively became negative due to increasing groundwater irrigation. Thus, in these areas, the drainage benefits that were supposed to be provided by interventions implemented via SCARP projects were then triggered due to secondary benefits of groundwater irrigation.That is why in many areas where drainage projects were implemented, the watertable now stands below the tile drainage base. On the other hand, in Sindh, drainage projects did not function properly, particularly due to theft of transformers installed for drainage tubewells and lack of O&M allocations (Figure 3).

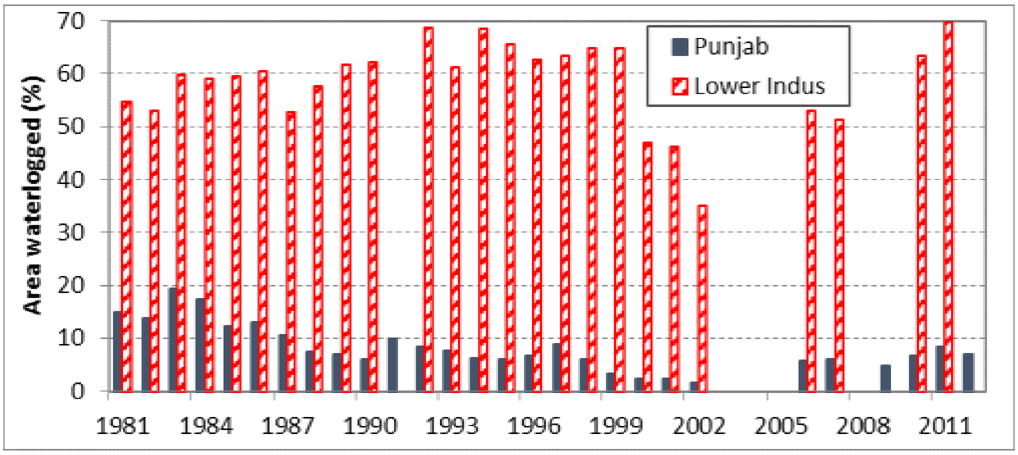


Figure 4. Post-monsoon waterlogged areas in Punjab and Lower Indus.

5.1 Drainage imperative of Conjunctive-use in Upper vs. Lower Indus

In Punjab the number of tubewells were 944,649 in 2009-10 (Government of Pakistan, 2012), and are now exceeding one million, pumping about 50 to 60 BCM annually. This tubewell growth promoted irrigation-cum-drainage and supported gradual increase in cropping intensities i.e., 102.8, 110.5 and 121.7% during 1960, 1972 and 1980, respectively (Ahmad, 1995), which is now operating at about 172% (Mirza and Latif, 2012) and even higher in certain areas. The most recent assessment of overall groundwater abstraction in Sindh places it at 4.3 BCM by Hal crow-ACE (2003) and 2.5 BCM by IWMI (Qureshi et al., 2003). In other words groundwater use stands at less than 4-8% of surface water use in Sindh, whereas in Punjab it is about 50%.

There are three interrelated factors that explain the modest use of groundwater in Sindh, i.e. the groundwater prevalent in large part of canal command; the high surface water supplies and the widespread waterlogging and surface salinity. The waterlogging is further aggravated because main natural drains over the years have been encroached upon and have been blocked by the construction of roads and other infrastructure. Consequently, waterlogging is again on the rise (Figure 4). As of June 2011, 20% of the irrigated area of Punjab had DTW at more than 12 m, whereas 99.5% area of Lower Indus falls within 4.5m DTW. Out of this, 53.7% falls in the waterlogged category i.e. within 1.5m (Figure 5).

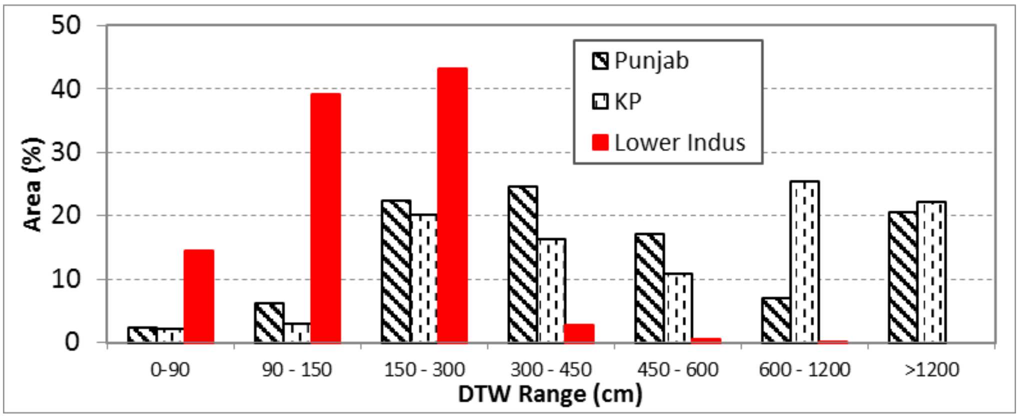


Figure 5. Comparison of DTW amongst the provinces (June, 2011).

5.2 Why Drainage Failure in Lower Indus?

Out of the 4100 SCARP tubewells installed since the mid-1960s, only a small portion (less than 10%) is now operational – often under de facto joint farmer management efforts. In the Guddu Barrage command area (Begari, Ghotki and Desert), wells, for instance, are virtually non-existent, except a few SCARP wells (or very few private wells), even though the shallow groundwater in many areas is fresh. Low tubewell densities also apply to saline zones; here there are hardly any tubewells. This is mostly due to higher canal supplies, e.g. average annual supply to rice command is 1723 mm (Van Steenbergen et. al., 2015).Other reasons for waterlogging are that almost 50% of the cultivable command area does not have drainage facilities (Table 1). The present surface drainage density is usually not more than 3-7 m/ha. This leaves much of the land without a drainage system. Thus, the limited use of groundwater and high surface irrigation allowances in Sindh generate very high effluent disposal requirements than were provided under the different drainage projects. The picture is further distorted within the canal commands by unregulated direct outlets, tampered or closed off-takes (Figure 6) or in some areas extensive canal seepage, creating local area overabundance of water.

Figure 6. Farmers use full authority to divert (or otherwise) water to their outlets.

5.3 Shortcoming of previous approaches

Continuous improvement in the performance of irrigated agriculture can be approached by revisiting past policies. On the basis of review, following shortcomings are identified:

- Lack of farmers' involvement in planning, design, construction and O&M
- Irrigation inequity, ensuing to political involvement through irrigation officials;
- Lack of participation by the private sector and water users themselves, especially for construction of field drains and improving water use efficiency lead to lack in capacity building at field scale;
- Since the inception of PIDAs in 1997, irrigation departments and PIDAs are active in parallel and the irrigation system could not take any side i.e. solo flight by the government or complete participation and authority sharing by FOs;
- Lack of Linkage between Research and Development;
- Emphasis was given only to engineering approaches. Bio drainage or saline agriculture was not tried at large scale;
- Deep drainage by saline SCARP tubewells has badly polluted the environment and lead to salinity build up, especially in Lower Indus;
- Untreated urban and industrial effluent disposal into the rivers and drains posed abig threat to agriculture water;

- Rationalized allocation of operational and maintenance funds and fresh drainage investments were discontinued;
- Irrigation and drainage services are not efficient and charged very minimally, the collection levels for 'abiana' have been around 50 to 60% of the assessed levels.

6. EMERGING ISSUES – CONCLUSIONS AND RECOMMENDATION

The IBIS, being more than a century old, is now facing a variety of issues, like over/under use, with respect to water supply and pollution loads. Thus, with the passage of time, integrated management needs for this mega irrigation system are increasingly being felt. It is concluded that present technical control through hierarchically sequenced rivers/canals and structures be combined and institutionalized with vigorous land and water use planning, as discussed below.

6.1 River Water Quality and environmental flow requirements

Water pollution is being caused by untreated wastewater disposal from both industrial and municipal systems and also from agricultural drainage. The pollution in Ravi River is the highest compared to all the other rivers. Maximum waste is being discharged in the river reach between Lahore and Balloki, a length of 62 km. In this reach, the river is completely devoid of dissolved oxygen (DO) under low flow conditions and simply acts as a sewage drain. Furthermore, there is a decreasing trend in DO level and an increasing trend in BOD and TDS levels. Hudiara drain is also a major source of pollution for Ravi. The drain carries mainly industrial and agricultural waste from both India and Pakistan. Similarly, Hamal and Manchar Lakes in Sindh are now increasingly polluted with saline effluent. Therefore, current level of enormous pollution being fed into the lakes and river system is an additional burden on the ecosystem. Thus, in addition to effluent treatment, environmental flows are required for round the year in dry river reaches.

6.2 Drainage Disposal

Except LBOD and RBOD (under construction) in Lower Indus, most of the drainage effluent is disposed-off into the rivers or ponds. No comprehensive effort has been carried out to treat the industrial effluent before its disposal into drains or rivers. None of the current methods of disposal within the system seem environmentally acceptable on a large scale or on a permanent long-term basis. Disposal outside the system can only be achieved by taking the effluent to the sea via a “National Surface Drainage System”. However, this has already been discouraged by the Sindh Government. Efforts should, therefore, be made to regulate the disposal according to river flow and keeping water quality less than 500 ppm.

6.3 Groundwater governance and rationalization of water allocations

Increasing deficit between groundwater recharge and extraction is causing groundwater depletion to the tune of 0.15-0.55 m/year in central and lower parts of Bari Doab, causing a groundwater mining of 2.33 BCM/year. The allocation of river water to different canal commands both in Punjab and Sindh has no rationale. Similarly, declaration of perennial and non-perennial areas has become outdated due to many of the changes in the past, e.g. changing depth to groundwater, desiccation of eastern rivers and provision of additional canal supplies after the Mangla and Tarbela Dams (Basharat et al., 2014a). Many people advocate groundwater governance to control resource mining, but in the presence of overall poor governance in the society, controlling above one million tubewells is not possible at all. Therefore, it is recommended to initiate groundwater recharge projects in depleted areas and rationalizesurface water allocations throughout the irrigation systemfor indirect control on waterlogging and groundwater mining, simultaneously.

6.4 Increasing Water Demands for Domestic and Industrial Sectors

A majority of the main urban centres in Pakistan historically depend almost exclusively on groundwater (Lahore, Quetta, Peshawar, and Faisalabad); others have recently augmented surface supplies (Rawalpindi, Karachi, and Faisalabad). Although the importance of groundwater in urban water supply is increasing, there is no management or planning for the future. On the other hand, urban population and water demand is increasing due to migration from rural to urban areas.It has been projected that urban water requirement for the 25 major cities of Pakistan would be 6.34 and 8.67 BCM, for year 2030 and 2050, respectively, against the current supply of about 4.0 BCM (Basharat et al., 2015).Similarly, in the majority ofirrigated areas, domestic water needs were increasingly fulfilled via groundwater pumping. Now this irrigation-enhanced groundwater reliance is not dependable due to quality deterioration in many areas. Therefore, communities should be stressed on demand management and resource conservation, both at supply and consumer ends.

6.5 Cost Recovery and institutional issues

The most crippling problem that irrigation and drainage in Pakistan is facing is that the revenue generated by the irrigation sector is not adequate to meet O&M. This is due to low water charges as well as low recovery of the assessed amounts. Many users and polluters of drains do not even pay for the use of drainage infrastructure. For example, urban community centres and industries dispose of municipal waste and toxic effluents in canals and drains without payment or regulation. Meanwhile, the capacity and efficiency of key drainage institutions has deteriorated significantly over the years. Capacity utilization of drainage O&M machinery varies between 30 and 50 percent. These low levels of recovery make the irrigation and drainage system highly unsustainable and dependent on government subsidy. Existing irrigation and drainage systems need to be made financially sustainable. Thus, decentralized management of IBI Scan accrue far reaching positive impacts as claimed by Molinga and Veldwisch (2016) that it is possible for mega irrigation systems as well.

6.6 Role of Private Sector

The large scale irrigation and drainage systems in Pakistan, built and run by the state, are increasingly hampered by problems of low delivery efficiency, inequitable distribution of irrigation water and inadequate O&M. One possible way of easing these problems is to increase the involvement of the private sector and reduce dependency at the public sector. Both surface and sub-surface drainage at a local level are potential fields for private sector investment because the benefits go to a definable group of beneficiaries. An amended approach would be to replace the concept of cost recovery, where the state invests in infrastructure and then retrospectively attempts to recover a part of its costs from users, with the concept of cost sharing, where the farmers share in the investment, regarding the infrastructure as theirs rather than the state's and undertake O&M more willingly. This approach can have far-reaching consequences because of the importance of the feeling of ownership and its effect on motivation for good maintenance.

6.7 Involving Farmers in Planning and Design

The biggest mistake in LBOD was at the planning and design stage. The farmers were not consulted for setting out the location of SCARPS tubewell. These were placed at a regular grid, instead of locating them close to farmers' dwellings. This resulted in stealing of electric motors, transformers, and conductors. One of the best ways to judge the acuteness of a particular drainage problem is to consult the farmers and in particular, to find out if they are willing to own the investment and also share a part of this in the form of labour and money. If, for reasons of poverty or because of the partial public-good nature of drainage, they are only able and willing to commit part of the necessary resources, their relative willingness can still be a good guide as to the problem's urgency. One possible policy approach is, therefore, for the state to say to the farmers: "if you can: (a) organize yourselves in a FO; (b) identify the need and ask for help; (c) find a way to pay part of the cost or provide part of the labour; and (d) undertake to operate and maintain the facility afterwards, then the state should provide support in the forms of assistance with diagnosing the problem and designing the solution or the balance of the necessary resources."

REFERENCES

Ahmad, N. 1995. Groundwater Resources of Pakistan (Revised), 16B/2 Gulberg-III, Lahore.

Basharat, M. 2012. Integration of canal and groundwater to improve cost and quality equity of irrigation water in a canal command. PhD thesis, Centre of Excellence in Water Resources Engineer, University of Engineering and Technology, Lahore, Pakistan.

Basharat, M., Ali, S. U. and Azhar, A. H. 2014. Spatial variation in irrigation demand and supply across canal commands in Punjab: a areal integrated water resources management challenge. Water Policy journal 16(2) 397-421; doi:10.2166/wp.2013.060.

Basharat, M., Hassan, D., Bajkani, A. A., Sultan, S. J. 2014a. Surface water and groundwater nexus: Groundwater management options for Indus Basin Irrigation System; Pakistan Water & Power Development Authority (WAPDA): Lahore, Pakistan.

Basharat, M., Sultan, S. J. and Malik, A. S. 2015. Groundwater management in Indus Plain and integrated water resources management approach. IWASRI Publication No. 303. Lahore, Pakistan.

Government of Pakistan. 2012. Agricultural Statistics of Pakistan. Statistics Division, Pakistan Bureau of Islamabad, Pakistan.

Government of Pakistan. 2015. Pakistan Economic Survey -2014-15. Finance Division, Government of Pakistan, Islamabad.

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

Mirza, G. M. and Latif, M. 2012. Assessment of current agro-economic conditions in Indus Basin of Pakistan. In proceedings of International conference on Water, Energy, Environment and Food Nexus: Solutions and Adaptations under Changing Climate.

Mollinga, P.P. and Veldwisch, G.J. 2016. Ruling by canal: Governance and system-level design characteristics of large-scale irrigation infrastructure in India and Uzbekistan. Water Alternatives 9(2): 222-249.

Qureshi, A. S., Shah, T. and Akhtar, M. 2003.The groundwater economy of Pakistan. IWMI Working Paper No. 64. International Water Management Institute, Colombo, Sri Lanka.23 pp.

Rizvi, S. A. 2014.Performance characterization of irrigation system using remote sensing and GIS techniques.PhD thesis, Centre of Excellence in Water Resources Engineer, University of Engineering and Technology, Lahore, Pakistan.

Van Steenbergen, F., Basharat, M., Lashari, B. K. 2015. Key challenges and opportunities for conjunctive management of surface and groundwater in mega-irrigation systems: Lower Indus, Pakistan. *Resources* 2015, *4*(4), 831-856; doi:10.3390/resources4040831.

WAPDA.2004. Master Drainage Plan of Pakistan - Drainage Vision – 2025, pre-feasibility. WPADA, Lahore.