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Spatial and Temporal Appraisal of Groundwater Depth and Quality in LBDC Command-Issues and Options

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Abstract

Pakistan's Irrigation system is more than a century old, the distribution system within any canal command is designed to distribute the canal water equitably ignoring rainfall patterns and underlying groundwater resources. Now, the groundwater contribution in meeting crop water requirement has even crossed the canal water supply in the existing scenario of increased cropping intensities. The underground reservoir that was recharged during 1st half of the 20th century by newly built irrigation system with low cropping intensities is now being overexploited due to increased cropping intensity. So, the current scenario has become now a major challenge in terms of its sustainability. In this context, groundwater elevation, depth and quality have been analyzed in space and time for Lower Bari Doab Canal (LBDC) command in Punjab, Pakistan. Tail end of the command is facing severe groundwater depletion rates, whereas, in certain parts, groundwater quality deterioration has also been detected and may pose a threat for sustainable irrigated agriculture. The paper describes the water quality and delineates the areas where saline water is present in the form of zones and depths. Also, possible rates and mechanisms of saline intrusion within the aquifer are described. Possible management alternatives for integration of canal and groundwater are discussed for providing relief to badly hit areas in terms of deeper depths and deteriorating groundwater quality.

Key Words: groundwater reservoir; groundwater quality; conjunctive use; aquifer mining; saline intrusion.

1. Introduction

Pakistan is an agrarian country where irrigation is used on 75% of agricultural land, mainly in Indus Basin. Like many other developing countries in South Asia, agriculture in Pakistan is heavily dependent on groundwater irrigation for sustainability of current crop production levels. Because, canal irrigation systems do not provide farmers with adequate water or enough control over irrigation deliveries, majority of them have turned to groundwater as a sole or supplemental source of irrigation. Sale and purchase of groundwater through informal water markets offer other farmers the opportunity to use groundwater particularly by non-owners of private tubewells. "The factors affecting private tubewell development and the emergence of groundwater markets are complex and interlinked" [1] including physical, economic and social factors.The increase in private tubewells has increased the total water availability for crop production and also provided with on demand control over irrigation supplies at farm level. This increased supplement to canal water is at stake due to over development and quality deterioration in many of the irrigated areas of Indus Basin, particularly the Punjab Province is facing unprecedented groundwater depletion rates. The same has been pointed out for LBDC command by Shakir et al. [2]. "Sustaining the massive welfare gains groundwater development has created without ruining the resource is a key water challenge facing the world today" [3].

1.1 Increasing Groundwater Use

Indus Basin Irrigation System (IBIS) was designed for an annual cropping intensity of about 75 percent with the intention to spread the irrigation water over as large an area as possible to expand the settlement opportunities [4]. Now, the increasing demand for food to cope with the ever increasing population has caused the annual cropping intensities to rise to 150 to 180 percent in different canal commands. This has been possible only with increasing contribution of groundwater for meeting additional water requirement but has resulted in both mining and quality deterioration of the aquifers. Large-scale groundwater irrigation demonstrated under Salinity Control and Reclamation Projects (SCARPs)in 1960s led to a proliferation of private tubewells with a capacity of about one cusecs (cfs) and less by farmers in the 1970s, 1980s and onward. The cropping intensity was 102.8, 110.5 and 121.7% during 1960, 1972 and 1980 respectively [5], and now operating at about 150% and even higher in different areas. As a result, groundwater mining due to higher abstraction rates as compared to the corresponding recharge is well reported in the literature[2, 6, 7, 8 and 9].

1.2 Lower Bari Doab Canal Command (LBDC)

The LBDC command, lying in Bari Doab, covers a GCA of 0.80 million hectares (Mha) and out of this, commands CCA of 0.70 Mha. The main canal with a design discharge of 278 m^3/s off takes from left bank of the Ravi River at Balloki Barrage and flows for 201 km, supplying water to its 65 Nos. off-taking channels as shown in Figure 1. These consist of 53.5 Km branch canals and 2261 Km of distributaries, minors and sub-minors. The canal irrigation is managed through four irrigation divisions, i.e. Balloki, Okara, Sahiwal and Khanewal (Figure 1). Agriculture in the area is sustained through surface water supplies from Balloki Barrage and pumped groundwater from the underlying unconfined aquifer. The canal water supply is the most important, less costly and dependable prime water resource, both for crop water requirement and groundwater recharge, with recent average annual (2001-09) deliveries of about 4849 million cubic meters (MCM) at canal head [9]. However, the sustainability of this increased food security is most importantly linked to the sustainability of groundwater reservoir.

1.3 Soils and Aquifer Characteristics

The area is part of a vast stretch (about 10,000 km^2) of alluvial deposits worked by the tributary rivers of the Indus, i.e. Ravi and Sutlej rivers. General slope of the area is mild towards the south-westerly direction (tail end), average ranging from 1 in 4,000 to 1 in 10,000. The predominantly agricultural land is at an elevation of 120 to 195 m above mean sea level. Area consists of two distinct physiographic/landform units, i.e. the Bar upland (high elevation area) in the upper half of command and the abandoned flood plain (Ravi and Sukh Beas) area (towards tail end) separated mostly by a sharp river cut escarpment locally known as "Dhaya". The soils of the Bar upland are of brighter colours (mostly silty), deeply developed and show definite profile development (horizons). The soils of abandoned flood plain are characterised by greyish colours, with weak or little profile development in the sub-soil and layering of different textures in the substratum.

The alluvial sediments that comprise of the aquifer exhibit considerable heterogeneity both laterally and vertically. Despite this, it is broadly viewed that the aquifer behaves as a single contiguous, unconfined aquifer. Study of the lithologic logs of test holes (180 to 300 m depth) and test tubewells (30 to 110 m depth) indicates that Bari Doab consists of consolidated sand, silt and silty clay, with variable amounts of kankers. Re-evaluation of the original data [10] and geological sections [11] suggests that in the area between Balloki and Okara, there is a moderately persistent and alternate layers of finer materials (clay, silt) of about 15-30 m thickness without any regularity/continuity, and that these finer materials are more prevalent towards the Balloki side i.e. head of the irrigation system. The near surface layer of clay/silt, 6-15m thick, is also prominently evident. However, thick layers (40 m of very fine to medium sand) were also found at deeper depths of the aquifer. Within the Middle Zone, as represented by the cross section near Sahiwal, silt/clay layers tend to be thinner and distributed unevenly, both vertically and horizontally. More importantly, the section shows that the aquifer characterises tend to be very much sandy towards Harrapa town. Also, detailed study of lithologic logs of bore holes on left side of LBDC canal have shown sandy aquifer with out any marked clay layers. The Lower Zone, as represented by the cross section near Mian Channu (Chichawatni to Khanewal), appears to be as described above, with a greater predominance of sand, and rare clay/silty materials. Except for a few local lenses, a few feet thick beds of hard rock, compact clay are rare in the area. Gravels of hard rock are not found within the alluvium and coarse or very coarse sands are uncommon.

1.4 Aquifer Response to Irrigation and Groundwater Development in LBDC

In the natural environment that existed before the inception of perennial canal irrigation, the groundwater hydraulic system was in state of dynamic equilibrium, i.e. there was no long term rise or decline of the watertable. However, the groundwater adjacent to rivers was at a higher level as compared to that in the middle of Doabs due to river seepage.Whereas, after the inception of irrigation system recharge pattern totally changed, more or less it became uniform in the lateral direction from the rivers. The groundwater levels in the aquifer had risen much with passage of time in response to spreading of irrigation supplies starting one century earlier.

Originally, the LBDC irrigation system was designed for a relatively low cropping intensity of about 67%. Peak crop water demand is about 8mm/d at farm head (30 years normal ETo by Pakistan Meteorological Department for Multan [12]), indicating a net peak flow requirement of about 1liter per second perhectare (lps/ha).

The canal flow of 0.23 lps/ha (3.3cfs/1000acres) at watercourse head, for a present cropping intensity of about 160 % cannot meet peak demand, leading to complementary tubewell irrigation. There has been an exponential growth of tubewells within the last three decades in LBDC command. The reported number of tubewells in LBDC command in 1994-95 was about 20,000 rising to 48,102 in 2005 [13]. This phenomenal increase in the number of tubewells has also been the prime driver in increasing cropping intensity. It means the farmers in LBDC have transitioned over the last 30 years to become heavily reliant on groundwater to supplement the canal water supplies. Now, the groundwater levels are going deeper and deeper. That means the underground reservoir that was recharged by newly built irrigation

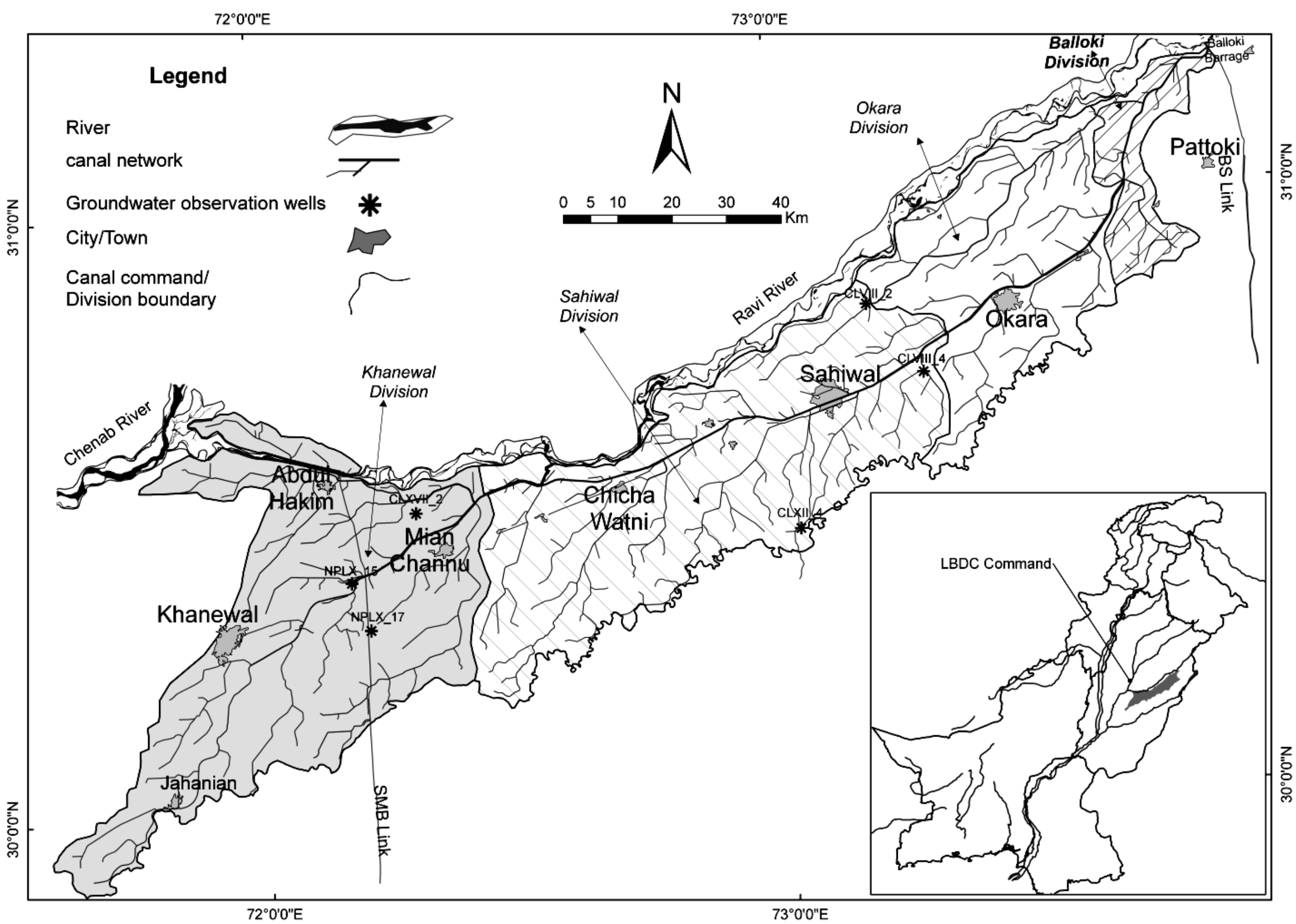

Fig. 1: LBDC canal irrigation network managed through four Irrigation Divisions.

system with low cropping intensities, is now being overexploited due to increased cropping intensity. The 9% area of the LBDC command that was termed waterlogged in 1979-80 on the basis of depth to watertable (DTW), i.e. up to 3 meters, had vanished [14].

The changes in aquifer levels encompassing over one century in response to above mentioned scenarios are shown in Figure 2 for individual observations, well spread in LBDC command. The average rate of groundwater rise was 0.77 ft. per year for these six observation wells. The period from 1987 to 2008 indicates a decline rate of 1.03 ft/year, i.e. even faster depletion rate than it rose to the surface.

2. Methodology

2.1 Groundwater Depth and Quality Analysis

Depth to groundwater observations are carried out twice a year, the groundwater quality is sampled after quite a long interval of 4 to 20 years by SMO of WAPDA The depth to watertable data since 1960 and water quality data for three different periods has been analyzed. Water level data discrepancies were removed by plotting hydrographs of DTW data.

The observation points being monitored by SMO and DLR were marked in GIS of the LBDC command. The depths to watertable values were converted to groundwater elevations using actual survey data or Shuttle Radar Topography Mission (SRTM)elevation data with 90 m^2 resolution (where actual survey was not available). The maps of depth to groundwater and elevation contours were prepared using Surfer software and converted to GIS format. The groundwater quality data presented herein is based on chemical analysis of the groundwater samples collected in 1961-62, 2001-02 and 2006-07 by WAPDA. The water samples have been collectedwithin a depth of 300 cm during profile augering or deeper depths of the order of 50 meters in case of tubewells and shallow depth hand pumps. The data was classified on the basis of the laboratory analysis done for Total Dissolved Solids (TDS), Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC). For the purpose of classification and ease in description, the groundwatersamples have been expressed as usable, marginal and hazardous for irrigation purposes as determined by the most adverse value of any of the afore-stated three parameters, using the criteria adopted by WAPDA for Indus Plains of Pakistan as given in Table 1[15]. At the first stage, the samples were classified as hazardous depending upon if according to any one of the three parameters (TDS, SAR and RSC) the sample falls within the hazardous range and then similar approach was adopted for marginal quality. The remaining points were declared as fresh as they met all the three criteria of TDS, SAR and RSC for fresh water. This was done in ArcMap using quarry and analysis techniques. Groundwater quality maps were developed for 1961-62, 2001-02 and 2006-07 and different zones (keeping in view the command of distributaries) were identified in LBDC command. The water quality of these zones was further analyzed in space and time to identify possible extant of saline intrusion.

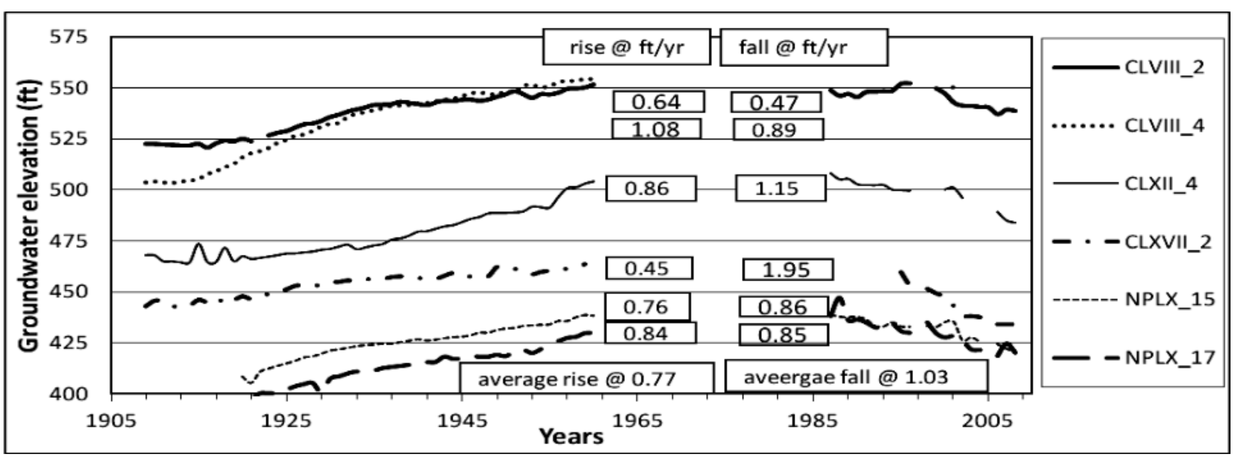

Fig. 2: Groundwater hydrographs spanned over one century, showing reservoir filling and depletion in LBDC command (1961 to 1986 is data gap).

Table 1: Irrigation water quality criteria adopted for groundwater quality mapping.

Quality	TDS (ppm)	SAR	RSC (meq/L)
Safe/useable	< 1000	<10	< 2.5
Marginal	1000 - 2000	10–18	2.5 – 5.0
Hazardous	> 2000	>18	> 5

2.2 Groundwater Travel Times in the Aquifer

Fresh water from rainfall and surface water in the form of canal irrigation percolates into the aquifer storage. At the fresh-saline aquifer interface, the groundwater storage is liable to have encounter and there is potential for mixing of saline groundwater with fresh due to hydraulic gradient, particularly in the downstream direction of the irrigation system. In order to have an estimate of extent of the phenomenon taking place in the study area, groundwater travel times were calculated using Darcy law (Equations 1 and 2) and porosity values based on average lithology as depicted during 1961-62 hydrogeological investigations.

$$Hydraulic\ gradient = t = \frac{\Delta h}{\Delta L} \quad (1)$$

$$V = \frac{Kt}{n} \quad (2)$$

Where; V is the groundwater traveling rate (m/day), kis aquifer permeability (m/day), and n is the porosity of the aquifer sediments.

2.3 Groundwater Pumping in LBDC Command

Total groundwater abstraction in the LBDC command based on the 2005 data was estimated as 4674 MCM by the NESPAK [13]. Whereas, on the basis of the same data, the Halcrow consultants for LBDC has calculated revised estimates of groundwater abstraction for the year 2005 as given in Table 2 i.e. 4796 MCM[8], which is little higher than estimated by NESPAK. Last column of Table 2 has been added to get true picture of the spatial distribution of groundwater pumping across the LBDC Command. Such a big difference in groundwater pumping across the LBDC Divisions, particularly the 3.42 ft. depth of groundwater pumped over the Okara Division also being too high, gave the idea to reanalyze the whole data in order to find any discrepancies in the analysis or the data itself, as given in the following section.

Table 2: Comparison of groundwater abstraction in LBDC command in 1994 [14] and 2005 [8].

Division	CCA (acres)	1994			2005			
		No. of	Abstraction MC	MA	No. of	Abstraction MC	MA	Depth (ft)
Balloki	88116	5700	440	0.36	2019	121	0.09	1.11
Okara	34603				1393	1459	1.18	3.42
Sahiwal	66024	7220	1030	0.83	1917	1528	1.23	1.87
Khanew	64450	6740	1240	1.00	1296	1688	1.36	2.12
Total	17389	1966	2710	2.19	4810	4796	3.88	2.23

According to NESPAK [13],the calculations using individual tubewell pumping hours as collected through field staff,were considered not representative. The consultants estimated the total number of tubewells and average pumping hour on Kharif and Rabi basis for each Division by using a revised sample survey. Then, average discharge for different dia category tubewells and the corresponding pumping hours were used for estimating total pumpage on division basis. By having a look on the average discharges of individual tubewells in Table 3 (column 2), it seems that the discharges adopted for these tubewells were on higher side resulting in over estimation of annual groundwater abstractions. As part of this paper, the average tube well discharges for different dia categories of tubewells were revised based on actually measured discharges by the author during field visits. The original and revised tubewell discharges for different delivery dia categories are given in Table 3. By using the new individual tubewell discharge for each delivery pipe category and the number of tubewells falling in each category for the four Divisions of LBDC command, the new weighted average discharge was computed for each category of tubewell delivery pipe. Both the weighted average discharge, i.e. the developed by consultants and the revised one, are give in Table 4. By using the same data of number and operation hours of the tubewells but adopting the new discharge values of the different categories of tubewells resulting in new weighted average discharge of tubewells for each Division, the fresh estimates of tubewell pumpage were completed.

2.3.1 *Freshanalysis of groundwater pumping data*

According to NESPAK [13],the calculations using individual tubewell pumping hours as collected through field staff,were considered not representative.The consultants estimated the total number of tubewells and average pumping hour on Kharif and Rabi basis for each Division by using a revised sample survey. Then, average discharge for different dia category tubewells and the corresponding pumping hours were used for estimating total pumpage on division basis. By having a look on the average discharges of individual tubewells in Table 3 (column 2), it seems that the discharges adopted for these tubewells were on higher side resulting in over estimation of annual groundwater abstractions. As part of this paper, the average tube well discharges for different dia categories of tubewells were revised based on actually measured discharges by the author during field visits. The original and revised tubewell discharges for different delivery dia categories are given in Table 3. By using the new individual tubewell discharge for each delivery pipe category and the number of tubewells falling in each category for the four Divisions of LBDC command, the new weighted average discharge was computed for each category of tubewell delivery pipe. Both the weighted average discharge, i.e. the developed by consultants and the revised one, are give in Table 4. By using the same data of number and operation hours of the tubewells but adopting the new discharge values of the different categories of tubewells resulting in new weighted average discharge of tubewells for each Division, the fresh estimates of tubewell pumpage were completed.

Table 3: Individual Tubewell average discharge (cfs).

Deliver	Q adopted by	Q adopted
8	2.00	2.00
7	2.00	1.75
6	1.55	1.30
5	1.20	0.90
4	0.72	0.50
3	0.45	0.35

Table 4: Revised weighted average discharges (cfs) for groundwater pumping estimation.

Discharge	Division			
	Khanewal	Sahiwal	Okara	Balloki
Calculated by	1.20	1.16	1.16	0.97
Adopted by	1.32	0.99	0.95	0.83
Adopted	0.91	0.87	0.88	0.71

2.3.2 *Groundwater consumption for human and livestock*

The Public Health Engineering Department does not cover the whole urban and rural areas for domestic water supply, so, an alternate approach based on liters per capita per day (lpcd) was applied based on the actual population both for humans and livestock in the study area.Upadhyay (2004) has quoted that the better-off residents of cities around the world typically consume around 200 liters per capita per day (lpcd). Upadhyay [16] conducted a village-level case-study in Gujrat (India) to find actual water use for livestock purposes. The area is water scarce where droughts are considered every 3 years on an average. Thus, the total per capita water use for a buffalo and a cow was 71.1 and 53.6 lpcd, respectively. Using urban and rural population estimates [17] (Table 5) and by adopting 200 and 140 lpcd for urban and rural population and 62 lpcd for animals (total number of animals, 19,33,633), total groundwater pumping was calculated. Also, half of this was assumed as return flow recharging the local aquifer.

Table 5: Urban and rural population in LBDC [17].

Division	Tehsil	Population	
		Urban	Rural
Balloki	-	-	223696
Okara	Okara	339378	698314
	Renala	40296	371584
Sahiwal	Chichawatni	88487	872556
	Sahiwal	278976	1017503
Khanewal	Khanewal	189457	472271
	Mian Channun	111199	282118
	Jahanian	31082	582409
LBDC Total		10,78,875	45,20,451

3. Results and Discussions

3.1 Groundwater Depth and Elevation

The depth to watertable continuously increases towards the tail of the command as shown in DTW map for June 2008 (Figure 3A). The groundwater elevation map (Figure 3B) shows, generally, a steep groundwater gradient (1 in 3060) as compared to natural ground slope (1 in 3715) in downstream direction of the LBDC command.Also, with passage of time, groundwater depletion (Figure 2) is taking place in the command but to different extent in different areas. The resulting depletion rates of groundwater levels have been computed for the period 1987 to 2008 on the basis of Irrigation Divisions in head to tail directionas given in Table 6. The period from 1987 to 2008 was divided into three intervals i.e. 1987-1996 (pre-drought), 1998-2002 (drought period) and 2005-2008. The highest depletion rate of 0.94 m/ year was found in Okara Division during the drought period.This highest depletion rate in Okara Division during drought also shows the relatively more contribution of rainfall both in meeting crop water requirement and groundwater recharge. On an average, for Sahiwal and Khanewal Divisions of LBDC command, the rate of groundwater depletion was 0.36 m/year for the period from 1987 to 2008. The volume of groundwater depleted in these two irrigation divisions (GCA 0.599 Mha) for the above period, using 25% specific yield is 11320 MCM (9.17 MAF).Whereas, groundwater levels are stable both in Balloki and Okara Divisions without any remarkable depletion. According to Basharat and Tariq [9], spatial climate variability within the irrigation system in Indus Basin has created differential variations in rainfall and as a result, in irrigation water demand. For the LBDC command, they concluded that annual normal rainfall decreases towards tail (212 mm) as compared to head (472 mm). Increasing groundwater depletion rate towards tail end of the command was attributed to decreasing recharge to groundwater in the downstream direction of the canal command as result of decreasing rainfall in this direction.

The current situation of groundwater depletion in tail reaches of LBDC indicates that water demand exceeds supply. This deficit is currently being met by overexploitation/mining of groundwater resources, resulting mainly with dropping of groundwater levels particularly in tail reaches. Interviews with farmers in Khanewal Division indicated that they used to dig 7-8 m deep sump to place their centrifugal pump near the groundwater level in 1990. Since then, they had to deepen their sumps gradually in the past and now the depth of sumps is 14 m on an average and the depth to watertable varies as 15-20 m in depleted areas of the Division. Further deepening is very risky as several wells collapsed during digging and resulted in fatal accidents. The centrifugal pump being used is not going to be effective anymore in an increasing area with passage of time. Therefore, most of the farmers are replacing centrifugal units with turbine pumps primed by electricity at very high cost. The situation is almost similar in Sahiwal Division but less severe due to the watertable depth being comparatively shallower by about 5 m, ascompared to Khanewal Division.

Table 6: Change in depth to watertable (m/year) over different periods in LBDC.

LBDC Division	1987 to 1996		1998 to 2002		2005 to 2008	
	No. of Wells	Change	No. of	Change	No. of	Change
Balloki	4	-0.04	4	0.34	8	-0.09
Okara	5	-0.01	4	0.94	21	0.04
Sahiwal	7	0.16	6	0.53	43	0.18
Khanewal	3	0.19	6	0.53	36	0.34

- *Note: negative (-) means rising watertable.*

3.2 Groundwater Quality

Groundwater quality for the three surveys is shown in Figure 4 and compared in Figure 5 and Table 7, in terms of useable, marginal and hazardous classes. It is observed that percentage of observations with hazardous groundwater quality has decreased with passage of time. On the other hand, fresh and marginal quality percentages have increased. The possible reasons are explained as below:

- Mixing of fresh and saline groundwater has been taking place since inception of irrigation causing increase in marginal quality groundwater; and
- Deep percolation of fresh irrigation water is causing dilution of underlying marginal and hazardous groundwater due to groundwater flow processes caused by natural hydraulic gradients in downstream direction. Groundwater pumping by tubewells further induces these gradients and causes local but mostly vertical turbulence enhancing mixing of fresh and saline resources.

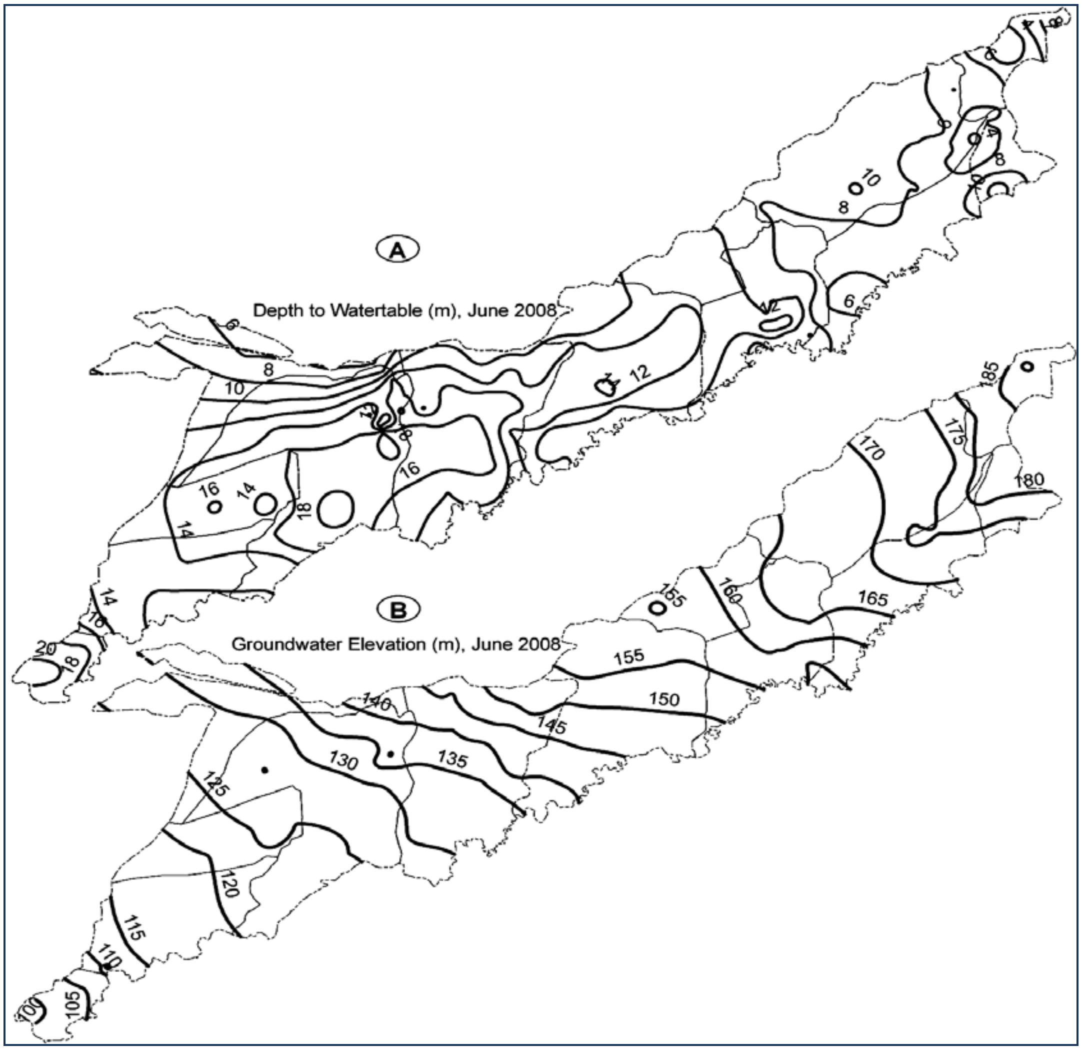

Fig.3: Depth to groundwater (A); and elevation (B), for June 2008 in LBDC command.

The limitations to the data and interpretation of results are that the samples are from the open-hole section of the borehole and represent a composite of water from one or more water-producing zones of varying water quality, particularly in areas where the groundwater quality varies with depth.

Table 7: Shallow groundwater quality in LBDC.

Groundwater Quality Class	1961-62		2001-02		2006-07	
	No. of Obs.	%age	No.of Obs	%age	No.of Obs.	%age
Useable	150	47.7	443	43.5	170	49.7
Marginal	77	24.5	351	34.5	113	33.0
Hazardous	87	27.7	224	22.0	59	17.3
Total Obs.	314	100	1018	100	342	100

As discussed previously, concentrations of chemical constituents in water from the LBDC aquifer system varies both depth and location vise. Based on the results of the deep groundwater quality investigations carried out in 1961-62 (test locations are shown in Figure 4d), Greenman et al. [18] has concluded that the distribution of saline and fresh groundwater zones in Bari Doab is a result of past and present hydrologic, climatic, and topographic factors. Among these, the present and former positions of stream channels, representing sources of recharge, the high bluffs of the bar uplands in the upper part of the Bari Doab, and differences in the permeability within the alluvial aquifer are the most important. The deep groundwater quality data of 1961-62 has revealed that a strip of about 10 km wide between Pattoki and Chunian starting from Raiwind and ending at about the middle of Okara and Sahiwal has the highly saline groundwater.The water samples ranged up to 10,000 ppm up to a maximum depth sampled around 200 m as shown in Figure 6 for bore holes numbers (BR 8, 122, 21, 123 & 124, Figure 4d). This high salinity groundwater is a result of non existence of any tributary channels of Ravi River in this strip due to high bluffs of 10 to 15 m as compared to its surroundings. Hussain and Hamid [19] has similarly explained that saline groundwater in Bari Daob is found principally beneath the high-lying portion of the bar upland, in the upper part of the Doab, where bluffs are 11 to 15 m above the level of the rivers and thus, mark the limit of river meander and fresh water recharge from that source in historic times. A particularly extensive zone of fresh groundwater from downstream of Sahiwal to south of Multan apparently is related to a former channel of the Ravi River. Another saline zone of bit smaller extent is located in tail end, upstream of Jhanian town (Figure 4). Keeping in view the sufficient groundwater hydraulic gradient (Figure 3B) and distribution of saline groundwater (Figures 5 & 6), it appears that there are areas with on-going risk of lateral as well as vertical saline intrusion due to differential hydraulic gradients. Mostly, these areas with fresh groundwater are at risk from saline groundwater areas lying in the upstream direction of groundwater flows.

3.2.2 Saline intrusion and up-coning analysis

As seen in Figure 3B, there is high groundwater gradient in the downstream direction of LBDC irrigation system and existence of highly saline water in the head end from upstream of Shergarh to the middle of Okara and Sahiwal, however with decreasing salt contents. The area is therefore vulnerable to saline intrusion or up-coning depending upon distribution of salts horizontally as well as vertically along with depth and extraction rates of irrigation tubewells. Keeping in view the groundwater quality map developed for 2001-02, the LBDC command was divided into 13 sub-areas (Figure 4) as fresh or saline zones in general. Changes in water quality parameters (TDS, SAR and RSC) with time are examined regarding maximum and average values. According to the results (Table 8), it is proved that, at present, groundwater being pumped at Shergarh area has become more and more saline with passage of time. Possibly, this has been due to the presence of high salinity groundwater in the upstream direction (BR_8, BR_122 and BR_21, Figure 6) and prevalence of differential hydraulic head mostly due to the difference in natural surface elevation. In this way highly saline groundwater at deeper depths in upstream direction flows to shallow depths in downstream direction. However, any such conclusion cannot be drawn regarding Okara and Gamber sub-areas, because no trend is deduced with existing data of three periods in these areas. However, TDS and SAR both have increased with passage of time in Jahanian_L sub-area, being in the down stream direction of the more saline Jahanian_M sub-area.

The above interpretation concludes that the water quality situation is deteriorating with passage of time in areas which have high salinity groundwater underlying due to the combined effect of groundwater mining and saline up-coning, or those areas lying in downstream direction of these high salinity areas dueto lateral salt movement. Data used and results of travel time calculations using Darcy law are given in Table 9. Groundwater travels a distance of about 0.54 to 1.36 km during 100 years time span for the two locations in LBDC. So, due to slow moving rates of the groundwater, saline intrusion phenomenon has been slow, but even then has shown remarkable identification.

3.3 *Groundwater Pumping for Agriculture, Urban and Rural Population in LBDC Command*

The reported groundwater pumping in LBDC command in 1994-95 was 2710 MCM [14]. Whereas, based on 2005 tubewell survey data, revised annual groundwater pumping for agriculture purposes over the LBDC command has been estimated afresh as 3954 MCM (3.205 MAF) as given in Table 10. Thus, within a period of 10 years, 1244 MCM increase in annual groundwater usage has been found in LBDC command. This indicates 4.6 % annual growth rate in pumping which is even higher than annual population growth in the country. That means population growth resulting in increased water demand in the form of

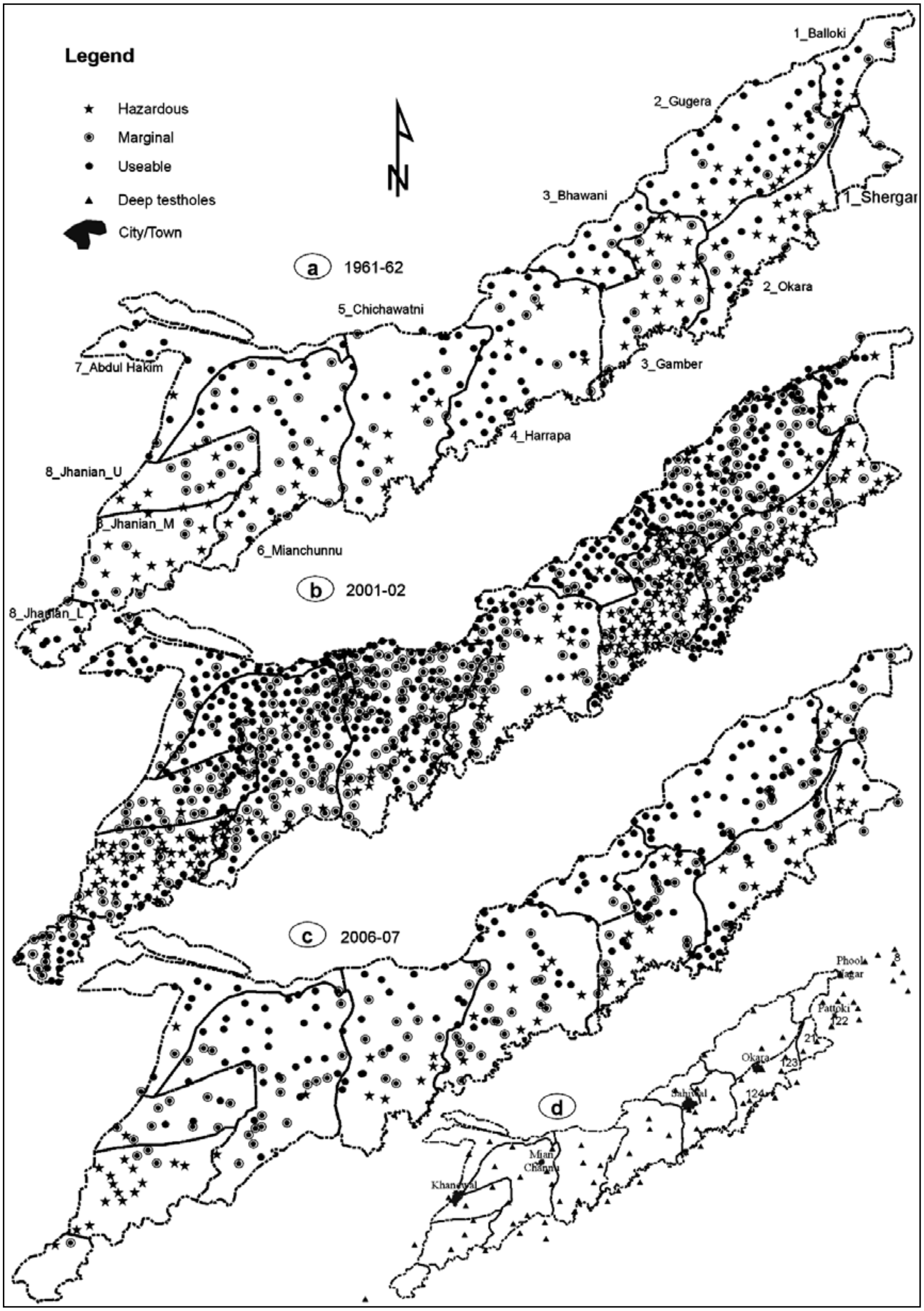

Fig. 4: Groundwater quality as observed on a:1961-62; b:2001-02; c:2006-07; & d:test hole locations (1961-62).

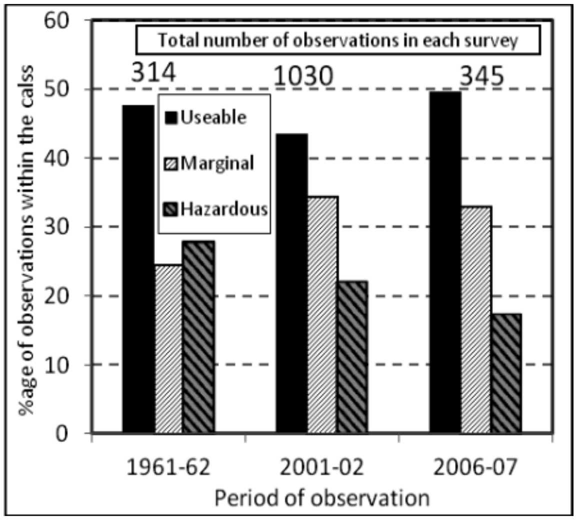

Fig. 5 Temporal comparison of groundwater quality.

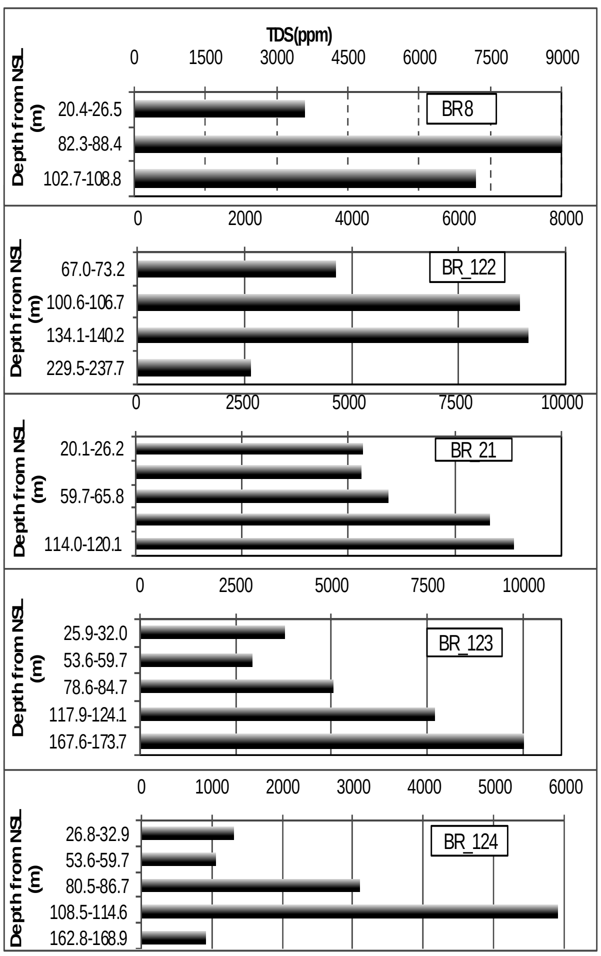

Fig. 6: Groundwater salinity profile for the strip from Raiwind to middle of Okara & Sahiwal (left side of Lahore-Multan road).

increasing cropping intensities and high living standards is mainly responsible for unprecedented groundwater depletion. Similarly, assuming 200 liters per capita per day (lpcd) for cities and half of this returning to groundwater, i.e. 100 lpcd being the net consumption, the annual net consumption for urban population in LBDC command is 40 MCM (32427 AF). Assuming 140 liters per capita per person and 62 liters per animal per day (also assuming half of this joining as recharge to groundwater), the yearly total net human and livestock water consumption for rural areas of LBDC command is 132 MCM (106695 AF). So, the total net annual groundwater use for domestic and livestock purposes is 172 MCM (139110 AF) in LBDC command.

Thus, the aquifer underlying LBDC command on an average is providing 4125 MCM (3.343 MAF) of groundwater annually. The source of recharge for this groundwater storage is on an average 4849 MCM (3.93 MAF) annually diverted to the LBDC command and an annual average rainfall of about 350 mm.

3.4 *Pumping Cost Inequity over the Command*

Division wise graphical presentation of watertable and tubewell boring depth is given in the Figure 7. Maximum drilling depth varies from 30 to 46 m in the head reach and 46 to 79 m in the tail. The tubewells are therefore, pumping from the aquifer at a minimum depth of 30 to 46 m and at maximum depth of 46 to 79 m from head to tail of the command. Cost of groundwater pumping with increase in depth to watertable has been estimated from data of drilling depth and pumping equipment commonly used across the LBDC command as reported by Halcrow [8]. Cost per cubic meter of groundwater pumped increases about 3.5 times as the depth to watertable drops from 6 to 21 m from head to tail in LBDC command as shown in Figure 8. The fact that farmers located at upper reaches of the canals get higher income and it progressively decreases downstream along all main, secondary and tertiary irrigation canals has also been highlighted in [20, 21].

Table 8: Groundwater quality and levelchanges in LBDC command [for water quality: maximum value without brackets and average values within brackets].

Sub_Area	1961-62				2001-02				2006-07				Groundwater Quality		Water level (m)	
	No. of obs.	TDS (ppm)	SAR	RSC	No. of obs.	TDS (ppm)	SAR	RSC	No. of obs.	TDS (ppm)	SAR	RSC	Average Present Condition	Temporal Change	Rise (1913-1960)	Depletion (1960-2008)
1_Balloki	12	2890 (786)	28 (6.85)	8.83 (2.6)	18	2118 (845)	29.3 (6.2)	12.5 (1.9)	14	2080 (1020)	17 (6.5)	4.0 (1.1)	Useable	Slightly deteriorated	3-6	0-1
1_Shergarh	4	1656 (1186)	19 (13.3)	7.35 (5.7)	13	8282 (2262)	269.1 (20.7)	14.8 (6.1)	7	12420 (4680)	54.8 (23.7)	6.6 (1.04)	Hazardous	Deteriorating	9-12	0-1
2_Gugera	55	2970 (930)	25 (5.64)	24.5 (2.2)	135	2662 (1052)	40.5 (5.5)	13.3 (2.0)	52	1472 (722)	9.7 (3.5)	3.2 (0.35)	useable	Improving	6-15	1-2
2_Okara	25	5840 (1558)	68 (12.5)	10.2 (1.9)	91	8621 (1800)	92.2 (14.1)	20.7 (2.5)	35	6365 (1415)	45.5 (8.6)	6.2 (0.9)	Marginal	No change	9-15	0-2
3_ Bhawani	16	2760 (788)	30 (4.79)	18.9 (2.0)	37	2061 (746)	12.0 (4.1)	3.3 (0.5)	15	1280 (589)	7.9 (2.7)	1.2 (0.2)	Useable	Improving	6-12	4-5
3_ Gamber	30	4790 (1824)	38 (14.2)	21.8 (5.3)	108	8448 (1653)	68 (15.5)	17.2 (4.2)	41	4488 (1149)	32.7 (7.8)	16.2 (2.1)	Marginal	Bit improved	9-15	2-3
4_Harrapa	44	2760 (906)	29 (6.48)	18.9 (1.8)	79	2739 (1099)	31.5 (9.6)	12.7 (2.6)	42	2047 (918)	37.8 (8.3)	14.9 (2.3)	Useable	TDS same. SAR increased	6-12	3-4
5_Chichawatni	52	4025 (953)	20 (5.99)	15.4 (2.5)	141	3040 (1105)	39.6 (7.6)	13.3 (1.2)	36	2827 (1102)	26.6 (8.4)	8.4 (1.2)	Useable to Marginal	No change	6-9	1-4
6_Mianchunnu	66	2980 (949)	26 (6.87)	10.1 (2.2)	161	2752 (993)	29.5 (6.3)	11.4 (1.2)	46	5585 (952)	24 (6.7)	8.3 (1.6)	Useable	No change	6-9	1-5
7_Abdul Hakim	11	1250 (525)	21 (3.9)	8.5 (1.1)	47	2848 (641)	8.08 (3.04)	3.2 (0.7)	9	1248 (645)	11.6 (3.7)	5.4 (0.6)	Useable	No change	6-8	1-2
8_Jahanian_U	18	1900 (1016)	24 (10.6)	10.8 (4.2)	52	2093 (951)	19.6 (6.8)	8.0 (2.2)	15	13082 (872)	13.4 (8.2)	6.7 (3.1)	Useable	No change	9	3
8_Jahanian_M	21	5528 (1790)	33 (15.4)	18.3 (6.1)	77	3264 (1296)	36 (12.3)	14.7 (5.2)	17	2600 (1535)	29.4 (16.8)	12.9 (5.9)	Marginal	TDS reduced SAR same	9	3-8
8_Jahanian_L	12	1784 (808)	35.3 (8.6)	11.6 (1.4)	25	2419 (1089)	16.6 (5.3)	6.6 (0.7)	2	3087 (2343)	14.3 (13.4)	1.9 (0.9)	Marginal	TDS and SAR both increased	9	8

Table 9: Groundwater travel time calculations for two sites in LBDC command.

Area	Hydraulic head (m)		Horizontal Distance (km)	Hydraulic Conductivity (m/day)	Porosity	Groundwater Velocity (km/100 years)
	h_1	h_2				
South of Sahiwal	157.5	152.5	10.5	10	0.32	0.54
N-E of Jhanian	115	107.5	10.88	20	0.37	1.36

Table 10: Division wise tubewell numbers and pumping hours along with fresh calculated pumping volumes (2005).

Division	Average Q (cfs) used	Number of Tubewells			Average operation hours				Groundwater pumping (MCM)		
					Kharif		Rabi		Kharif	Rabi	Annual
		Fresh	Saline	Total	Fresh	Saline	Fresh	Saline			
Balloki	0.71	1,344	675	2,019	596	119	371	74	63.8	39.7	103.5
Okara	0.88	12,987	952	13,939	923	185	214	43	1091.1	253.0	1344.1
Sahiwal	0.87	13,545	5,630	19,175	628	125	405	81	816.9	527.0	1343.8
Khanewal	0.91	10,570	2,399	12,969	709	142	425	85	726.7	435.7	1162.4
Total		38,446	9,656	48,102	2,856	571	1,415	283	2698.5	1255.4	3953.8

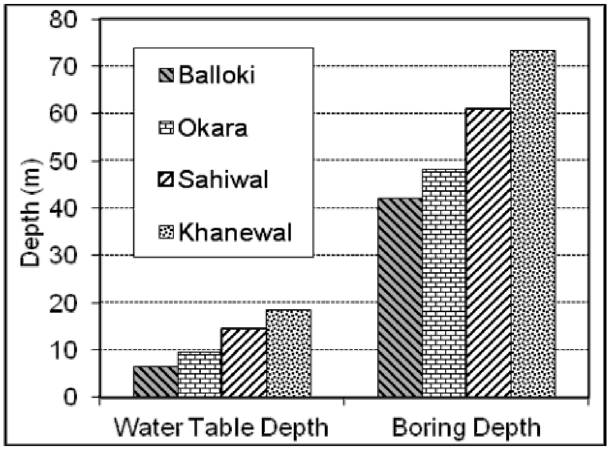

Fig.7: Increasing depth to watertable and boring depth towards tail of the LBDC command.

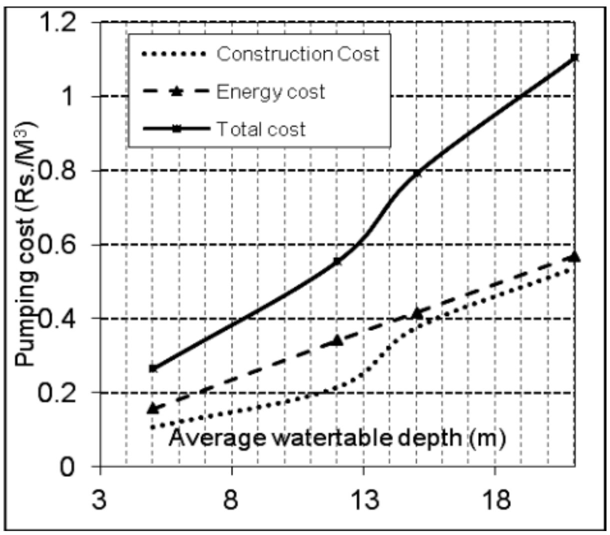

Fig.8: Increase in pumping costwith decline in depth to watertable.

3.5 Surface and Groundwater Balance Analysis

Recent average annual (2001-09) deliveries of about 4849 MCM were released to LBDC command against annual crop water requirement of 6953 MCM as calculated by Basharat and Tariq [9] using the crop coefficient (K_c) and reference crop evapotranspiration (ET_o) by dividing the area into eight sub-units. As detailed in [9], 48.75 % of these canal releases is available for crop consumptive use and 44.12 % adds to groundwater via canals and watercourses seepage, and field application losses. Thus, net canal supply available to crops is 2364 MCM which is about 33.8% of crop consumptive use requirements. The surface and groundwater balance of the command area is shown in Figure 9. Against crop consumptive use requirement of 6953 MCM, 2364 MCM is provided from canal supply, 2689 MCM from groundwater (68% as consumptive use out of 3954 MCM pumping) and 1406 MCM as effective rainfall from annual average rainfall which is about 472 mm at head end and 212 mm at tail end of the command. Thus a net shortage of 495 MCM of irrigation water is being faced by the farmers in addition to groundwater mining of the aquifer. Also, due to over use by many of the farmers especially in head end area, other farmers, particularly at the tail end, are facing even more shortage for crop consumptive use.

Recharge to groundwater from canal supply is 44.12 % of canal deliveries at head i.e. 2140 MCM and rainfall recharge 370 MCM (16 % of annual rainfall) and groundwater return flow of 948 MCM (24% of groundwater pumping). So, the total recharge to groundwater being 3458 MCM, whereas the groundwater pumping for agriculture and domestic purposes is 4124 MCM. Thus, a net loss in groundwater storage of 666 MCM (0.54 MAF) is occurring to the aquifer under LBDC command, which is equivalent to 36 cm (1.18 ft) per year drop in aquifer levels (assuming 0.25 as specific yield) over the GCA of 0.8 million hectares. Shakir et al. [2] has also estimated the lowering of groundwater tables at a rate of 30 to 40 cm per year in most parts of the LBDC command.

4. Opportunities And Challenges

Groundwater development in LBDC command, mainly after the 1960s, offered a permanent solution to the problem of leaking irrigation system by providing necessary drainage. So, this kind of irrigation system leakage and pumping has become an asset because it is offering demand-based irrigation service delivery as compared to canal irrigation which is supply-based system by virtue of its design. In areas where quality of groundwater is unsatisfactory, the tubewells only offer a compromise solution to the problems of canal leakage due to the marginal quality of groundwater being pumped. Assuming 6 m fluctuation in groundwater level and 0.25 as storage coefficient, the groundwater reservoir under the LBDC command has provided an alternative storage of the order of one mega reservoir i.e. 12,000 MCM (9.7 MAF). Unfortunately this huge

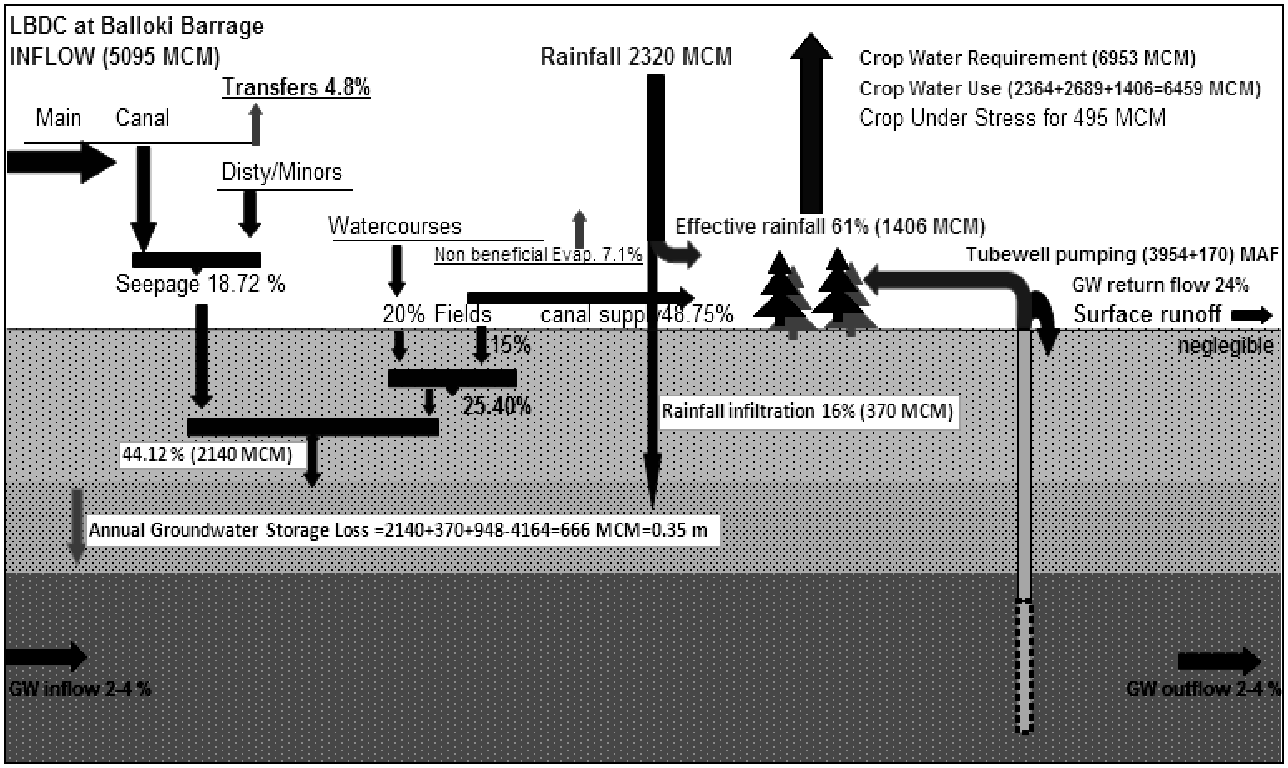

Fig.9: Crop water requirement, surface water and groundwater balance in LBDC command (irrigation system efficiencies adopted from [9].

reservoir is being over utilized with out any planning and management which has resulted in deterioration of pumped groundwater quality due to over use of the thin fresh layer in some parts of the upper left half of head end command. At the same time, lower half of the canal command is facing with groundwater mining problem and consequently farmers have to incur three to four times cost of pumping than if the depth to groundwater had been within 3to 10 m from land surface. So, there is a big challenge in optimally managing this huge groundwater reservoir with varying quality and depths to groundwater across the command. A major barrier that prevents transition from the present level of groundwater development to management mode is absence of any infrastructure and regulatory framework that allows the government agencies to take control over the mass scale groundwater abstraction. Moreover, the farmers are not being provided with necessary information and knowledge about the consequences of depleting the groundwater reservoir.**C**onjunctive use policy by the Government with respect to canal and groundwater resources allocation and management at canal command level is missing altogether. The changing situation in the command area due to non-existence of above management modeis discussed below.

4.1 Head End Command Area

In the head-end areas, canal supplies along with rainfall are enough for meeting increased crop water requirements in the present scenario, particularly, in fresh groundwater areas located between Ravi River and Lahore-Multan road. However, the area lying to the left of Lahore-Multan road up to Okara, had saline native groundwater by virtue of absence of historic river flow patterns in the area as pointed out by Greenman et al. [18]. The shallow groundwater occupies the interval between the native pre-irrigation watertable and that of maximum watertable level achieved as a result of additional leakage till 1960s since the commissioning of LBDC canal. Thus, in areas of predominantly saline native groundwater, supplies from shallow sources generally are also saline, but mineral concentrations in the shallow water are less because of dilution by ongoing canal and field irrigation seepage. Water from shallow irrigation or domestic supply wells in these areas contain generally less than 5000 ppm; the average range of concentration varies from 1653 to 2262 ppm (Table 8, survey 2001-02, sub-areas Shergarh, Okara and Gamber). In the area between Habibabad and Shergarh, farmers are pumping groundwater with increasing salt contents, due to both horizontal and vertical saline intrusion.

4.2 Tail End Command Area

In the tail-end areas, native groundwater was already of fresh quality except a few areas of very small extents. With the inception of canal irrigation, watertable had risen to the tune of 30 m or less depending upon proximity to river or otherwise. With increased cropping intensities, higher groundwater pumping as compared to corresponding recharge from the surface has resulted in long term mining trend of the resource. Current rate of over exploitation of groundwater can be very devastating to the environment and economic well being of the populace of the area. Current trends has induced water level drawdown to the levels where existing depths of wells do not support pumping and re-drilling of majority of wells is being implemented by the farmers in these areas. This has increased the investment of farmers and will not serve the purpose in the long run.

5. Conclusions & Recommendations

Along with increased cropping intensity, shortage in canal supplies due to relatively dry years in the past and the capacity constraint of the main canal has also been a factor in unprecedented lowering of groundwater levels. The situation is expected to bit improve with rehabilitation of LBDC system. In the current situation, on an average, contribution to crop consumptive requirement from groundwater is 2689 and from canal water is 2364 MCM. Thus, groundwater now contributes 18% more as compared to canal supplies in meeting crop consumptive use requirements. Therefore, it is needless to point out that there is an urgent need for conservation of this vital resource for the preservation of socio-environmental security and sustainability of existing level of agricultural development. Generally, results showed that deterioration of groundwater quality itself in LBDC is not very serious problem but discharging water from aquifer more than its potential (particularly in saline areas) can devastate groundwater quality in near future. Sustainability of groundwater irrigation is the major issue in the current scenario of increasing water demands.

- Canal water reallocation from fresh groundwater areas in head end to depleting areas in tail end is recommended to avoid continued depletion of groundwater in tail end and maximizing conjunctive use at canal command level.
- In depleting fresh groundwater areas, water withdrawal can be reduced by partly diversifying to low delta crops, and employing water saving technologies at a field scale. In Kharif, rice may be replaced with maize, pulses and oilseeds; whereas wheat may be replaced with oilseeds and gram.
- Both groundwater depth and quality are serious management issues. Therefore, water quality aspect has also to be incorporated in canal water allocations for integration of the two resources.
- Devise some groundwater management strategy in steps, first by registering the tubewells and then regulating their pumpage by imposing some quota and limiting their maximum pumpage.
- Involve farmers at village level and FOs at distributary level in groundwater depth and quality monitoring so as to enhance their knowledge and willingness for the times to come when a proper groundwater management will be in place.
- In the present scenario for saline groundwater areas in the head end, it is feasible to inhibit irrigation leakage particularly the watercourse losses by lining all the main lines of the watercourse, which at present the policy is to line 30 % and 15 % lengths for saline and fresh groundwater areas, respectively.
- To fulfil the groundwater recharge requirement in depleted areas, flood flows may be diverted to old bed of Sukh-Beas River.

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