Equity Considerations in Irrigation Design and Inequitable Distribution of Groundwater in LBDC Command

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RECEIVED ON 24.12.2009 ACCEPTED ON 08.06.2010

ABSTARCT

Climatic variability across the command of LBDC (Lower Bari Doab Canal) has pernicious impact on equitable usage of irrigation water from head to tail. The main thrust of this study is to highlight the need for rationalizing water allowance within the canal command so that joint equity of both the canal and ground water availability to the farmers is ensured. Tail reach areas receive only about 212mm annual rainfall which is 45% of the rainfall at head reach (472mm). Whereas, the crop delta increases from head to tail, with minimum difference of 13mm and maximum of 147mm for oilseeds and sugarcane crops respectively. For wheat/cotton rotation, combined annual difference in delta between tail and head reach areas comes out to be 133mm. Adding this difference in crop delta to rainfall difference (260.6mm), a total difference comes out to be 393.6mm which is 33% of field delta for wheat/cotton crop rotation at head reach of LBDC command. This difference in irrigated hydrology across the command is responsible for successively increased depth to groundwater towards tail of the command. Accordingly, the tail end farmers are forced to incur higher costs per acre for groundwater pumping. This is because groundwater pumping from deeper depths in tail areas is about 3.5 times more costly as compared to head reach. So there is dire need to ensure equitable irrigation water availability in terms of quantity and cost, rationalization of water allowance is recommended to achieve this equity.

Key Words: **Equity, Groundwater, Irrigation, Crop Water Requirement, Rationalization.**

1. INTRODUCTION

Frequently, diversions to irrigation are diminishing because of increased demands by cities and environment, and increased uses by the local population in the upper catchments. As a result, irrigation systems are under increased pressure to produce more with reduced supplies of water. Even more alarming situation is expected than currently being faced by Pakistan, since no additional water is expected to enter the system. It is imperative to improve the efficiency of existing water resources and land capabilities; otherwise the country will be facing acute shortage of food, fiber and edible oil in near future. The major issue facing Pakistan in the coming years is the lack of management regime for groundwater leading to exceptionally falling groundwater

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levels, pollution of both surface and groundwater in critical areas with depleted and saline groundwater pockets. All these issues have impact on agricultural production, food security and the overall ability of the nation to improve economic performance of irrigated agriculture.

Furthermore, because of increasing population of Pakistan, the availability of surface water per capita is declining, and is projected to be less than 1,000 cubic meters (m^3) per capita per year by 2010 as reported by Bricoe, et. al. [1]. Among the ADB member countries, Pakistan has the highest rate of utilization of the total available freshwater resources at 61%. In terms of groundwater withdrawal, Pakistan's annual rate of 489.5 m^3 per capita is also the highest by a wide margin as reported by Raymond, et. al. [2]. This information clearly indicates (i) the high reliance that Pakistan has on its available water resources for irrigation and (ii) the importance of increasing the efficiency of water use when there is limited scope for increasing the supply due to internal political division between the provinces for construction of storage dams.

In our irrigation systems, all groundwater recharge originates from the surface irrigation system, river flows and rainfall. River flows and rainfall contribution to groundwater recharge is greatly variable. Main canals generally run from north to south parallel to natural surface slope. This is also the direction of decreasing rainfall particularly in upper and central parts of the Punjab province. That is why; the recharge to groundwater from rainfall is also decreasing towards tail of canal commands resulting in increasing depth to watertable from head to tail. This creates inequity of water availability to the farmers particularly from groundwater which accounts about 60% for meeting the crop water requirements as reported by Halcrow, [3]. More over the quality of underlying groundwater varies considerably in different parts of canal commands. But the present canal water allocations have been designed without considering the variable rainfall and groundwater depth and quality distribution. Resultantly farmers suffer to varying degrees of total cost and quality of irrigation water supplied to the crops.

This climatic variability in the form of decreasing rainfall and increasing tempratures form north to south normally results in higher potential evapotranspiration (ET_o) in this direction. Thus the irrigation system design has ignored the difference in crop water requirement while allocating canal water accross canal commands. This flaw, along with variation in depth and quality of groundwater accross most of the commands has created anomaly in the total water availabilty to the farmers inspite of being advocated of having equal rights in this regard. This inequity of water avaiabilty accross the command has caused considerablly decreasing net income of farmers in head to tail direction as reported by Latif, et. al. [4]. This is because in areas where canal water is insufficient, groundwater has beocme a major factor underlying raisning agricultural production in the past two decades. The reason being that mostly increase in cropwater requirement is due to increased croping intensities as a result of increasing population.

Therefore, reduced water delivery along with increasing demands by irrigation sector requires two actions: a change in agriculture practice combined with rationalization in water allocation. These efforts have the potential for increasing agriculture productivity per unit of water in the existing setup of crop and water management in the country. Because in the past improper managemnet of groundwater extraction and its use have resulted in several hydrological, environmental and economical issues. Therefore, rationalization must go for appropriate and equitable irrigation water management that ensures equity, not just for the surface water but groundwater also which is at par with canal water in meeting crop water demands in Punjab province of Pakistan. This water allocation, being more equitable and hydrologically sustainable would lead to improve overall efficiency and productivity of the irrigation system.

1.1 Irrigation System Performance

Molden, et. al. [5] has provided a basic conceptual framework for the use of performance assessment in support of irrigation service, and provided methodologies and indicators for its use. Special emphasis is placed on performance assessment as a tool for helping to alleviate poverty in irrigation and drainage system. The paper has quoted that the simplest and yet probably the most important, operational performance indicator is the DPR (Delivery Performance Ratio) defined as the ratio of actual flow of water to intended flow of water. The DPR enables a manager to determine the extent to which water is actually delivered as intended during a selected period and at any location in the system. The author has pointed out another indicator particularly for strategic performance assessment of any irrigation system defined in Equation (1):

$$\textit{Depleted Fraction} = \frac{ET_a}{P_e + Q_{in}} \tag{1}$$

Where ET_a is actual evapotranspiration from the gross command area, P_e is precipitation on the gross command area, Q_{in} is volume of surface and subsurface water flowing into the command area. This probably new indicator can assess changes that may be occurring gradually over time (for example rise/fall in groundwater levels, salinity or pollution loads). Water depleted within the area of study is not available for use in other areas of the system. The depleted fraction is concerned with water balance within an irrigated area which makes the indicator particularly useful for diagnostic purposes in water-scarce areas. Low values indicate a possibility of depleting more water after taking care that downstream needs are met. A very high depleted fraction , say above 0.70, means that very little or no more should be depleted within the area to avoid problems of salinity buildup within the area. A depleted fraction of 1.0 would generally not be desirable, but is often found with the result of falling groundwater tables. Since a few years back, in most parts particularly central and southern Punjab, the depleted fraction has perhaps gone beyond 1.0. So the irrigation system performance in the country needs to be assessed from strategic point of view and corrective measures are needed accordingly for sustainability of the irrigated agriculture.

1.2 Irrigation System Design Features in Pakistan

The development in the irrigation field in Pakistan started in about the middle of 19th century under British rule. The irrigation system was initially designed with the objective of bringing as much land under canal command as possible. The designed annual cropping intensities were generally kept low, at 60-80%, and the diversion capacity of canals were aimed at spreading the water thinly over large areas equitably with minimum O&M costs. However, as a consequence of population growth over time, the water requirements have increased beyond the designed capacities by many folds. The mainly stressed objective of canal operations now is to achieve as much equity as possible and to ensure supplies to the tail-end farmers. Exploitation of groundwater is managed by the farmers and they are free to share and manage this freely available water resource with out any conjunctive management policy at canal command or irrigation system level.

1.2.1 Irrigation and Equity

Equity can be emphasized in a variety of different angles depending upon different perspectives and scenarios; each dealing with specific situations i.e.

(i) Equity in distribution of available canal water.

(ii) Equity in meeting crop water demands under varying crop water requirements due to variability of ET_o and rainfall in the irrigation command area.

The need to adopt 2nd scenario above is being highlighted in this paper and seems to be essential for long term sustainability of the irrigated agriculture particulalry at tail end of the commands. Equitable distribution of water is the basic principle of any irrigation conveyance system. In the current scenario, equity in irrigation water distribution is considered to have been attained when the amount of water distributed to every outlet along a distributary is in proportion to the outlet's design discharge that approximately matches the proportion of water delivered at the distributary head to its design discharge as qouted by Bhutta, et. al. [6]. The contiguous irrigation system in the Indus Basin was designed to achieve maximum equity within the canal command. The system's inherent rigidity towards meeting potential crop water requirements was accepted in the design in order to assure an equitable distribution of available irrigation water supplies even during periods of water shortage. This has been assured by operating the distributaries on rotation basis during low discharges in the main canal. Canal operational practices are, therefore, conceived to allow channels to run at designed full supply level while maintaining equitable water supply to each unit of the cultureable command area. This has been achieved by accounting for seepage losses in the course of channel and adding this seepage loss upto the outlet (here the depatrtmets jurisdiction ends) in the water duty of the channel.

However, the equity claimed in the system design has also been doubtful in the past due to low levels of monitoring of the irrigation system at different levels. The combined effect of this poor equity across the canal commands along with increasing crop water demands towards tail has created the alarming situation for the tail reach farmers. Impacts of poor equity among different command areas are emerging more and more in the form of degradations, such as falling groundwater tables, deterioration of groundwater quality, river desiccations, and intense competition for water. So, further improvements in equity particularly the equity of meeting crop water demands can help to improve and optimize water productivity.

1.2.2 Equity and its Established Impacts in the System

In Pakistan the inequity of water distribution, among water users located at head middle and tail reaches has been reported by many [7-12] and is closely correlated to decreasing crop yields and increasing land salinzation as recently highlighted by Latif, et. al. [4]. Further the inequity of canal water along the channel arises from the tempering of Mogha system and cutting of channels for addituonal canal water through criminal means. In their study in central Punjab, Latif, et. al. [4] proved that farmer's location on the irrigation network has significant impact on their income in spite of the fact that water rights are same for all water users. Farmers located at upper reaches of the irrigation canals get higher income and it progressively decreases downstream. He pointed out the difference in income was due to higher use of groundwater towards tail reaches, the reason being that pumping groundwater is very costly. Another issue of groundwater quality variation along the canals was analyzed in the same study. The results revealed that salts in groundwater increase progressively from head to lower reaches of almost all the tertiary canals. In the paper, the difference has been attributed only to lower recharge of groundwater by inequitably available canal water and higher discharge in the form of groundwater pumping towards tail reaches of the canals. However, the effect of climatic variability in the form of decreasing rainfall and increasing crop water requirements towards the tail has been overlooked. This, being the major weakness of irrigation system design in Pakistan has created detrimental and strategic impacts on the life of tail end farmers of most of the canal commands.

To account for water use from both surface and groundwater various new irrigation performance indicators have been developed e.g. depleted fraction by Molden, et. al. [5]. Also, remote sensing has offered totally a new scenario for irrigation system performance assessment on command area basis of any size of interest. Ahmad, et. al. [13] has concluded through remote sensing analysis of actual evapotranspiration (ET_a) in Rechna Doab Irrigation System in Punjab, Pakistan, that the adequacy and reliability of combined surface water and groundwater deliveries decline towards the tails of the canal and towards the central and downstream parts of the Doab. The average ETa over Rechna Doab was estimated as 850mm/year which is almost double the average rainfall and almost 60% of the reference crop evapotranspiration. Another interesting fact is that the areas close to the main canals or river have higher ET_a, due to better access to canal and groundwater for agriculture. However, from upper Rechna to lower Rechna, there is slightly declining trend with ET_a variations of 64mm between different subdivisions in the same direction for Rabi season. This declining trend of ET_a from the upper to lower Rechna was much more profound in Kharif season and governs the annual variations. Accordingly the author's has suggested enhancing the overall system productivity through changed water allocation for long term perspectives.

1.3 Justice and Equity: A Critical Perspective

It is a commonly used concept that evapotranspiration is critically important because it is essential for crop production. In this regard, Ullah, et. al. [14] has highlighted the spatial variation of potential crop water requirements due to variation of ET_o from north to south in IBIS (Indus Basin Irrigation System). Basharat, et. al. [15] has highlighted the fact that already committed water allocations to canal commands in the IBIS did not have taken into account the underlying groundwater resources of the respective canals. There are many canal commands in Pakistan, in which share of canal water is equal, ET_o is increasing and rainfall decreasing towards the tail as compared to head reach areas. Consequently, farmers within the tail reach areas are forced to reduce area under crops or cultivating less water delta crops or pump more groundwater at a very high cost as compared to canal water, or even as a last resort leave the crop to face water stress even during critical growth stages. This causes an injustice between head and tail reach farmers where, in the tail reach farmers are suffering from continued increase in depth to watertable along with deterioration of the resource base. Detrimental impacts of this scenario on future of the irrigated agriculture in general and the farming community in tail areas of the canal commands in particular is clearly evident on strategic basis. This inequity of water availability across the command has two prong impacts on farmers' i.e.

(a) *Short term Impact:* Considerably decreasing crop yields towards tail areas for most of the farmers particularly the poor ones with small land holdings.

(b) *Longterm Impact:* Over exploitation of groundwater beyond safe yield, thus making depleted fraction over 1.0 and threatening the sustainability of poor economies.

This is because, in areas where canal water is insufficient, groundwater has become a major factor underlying raising agricultural production in the past two decades. The reason being mostly increase in crop water requirement due to increased cropping intensities as a result of increasing population. Therefore, the major issue for the tail end farming community in many of canal commands in IBIS is managing canal water so that overall equity of canal and groundwater is ensured across whole of the canal command.

2. MATERIALS AND METHOD

2.1 Study Area

The LBDC command area lying in Central Punjab (Fig. 1) is selected for highlighting the inequitable and unsustainable irrigation management in the long term perspective. The canal with a design discharge of 278m^3/s, off takes from the left bank of the river Ravi at Balloki head works and flows for 201 km along the length of the command area. In addition to the main canal, there are 53.5 Km branch canals and 2261 Km of distributaries, minors and sub-minors. The canal irrigation is managed through four canal irrigation divisions (Fig. 1), headed by Executive Engineers. Its command lies in Bari Doab covering an area of over 0.80 million hectares, lying between 29° 53' 0" to 31° 13' 6" Latitudes North and 71° 34' 49" to 73° 51' 56" Longitudes East . The general slope of the area is mild towards the south-westerly direction with average slopes ranging from 1 in 4,000 to 1 in 10,000. The predominantly agricultural land is at an elevation of 130-19 m above mean sea level. Agriculture in the study area is sustained through surface water supplies in the LBDC and pumped ground water. The most important, less costly and dependable prime water resource is the canal water supply both for crop water requirement and groundwater recharge, with an average recent annual deliveries to the LBDC command of about 4934 MCM (4 MAF). Constructed in 1911-1913, the irrigation system was designed for a cropping intensity of 67% which has steadily increased to the present level of about 160%. The sustainability of this increased cropping intensity is most importantly linked to the sustainability of underground reservoir.

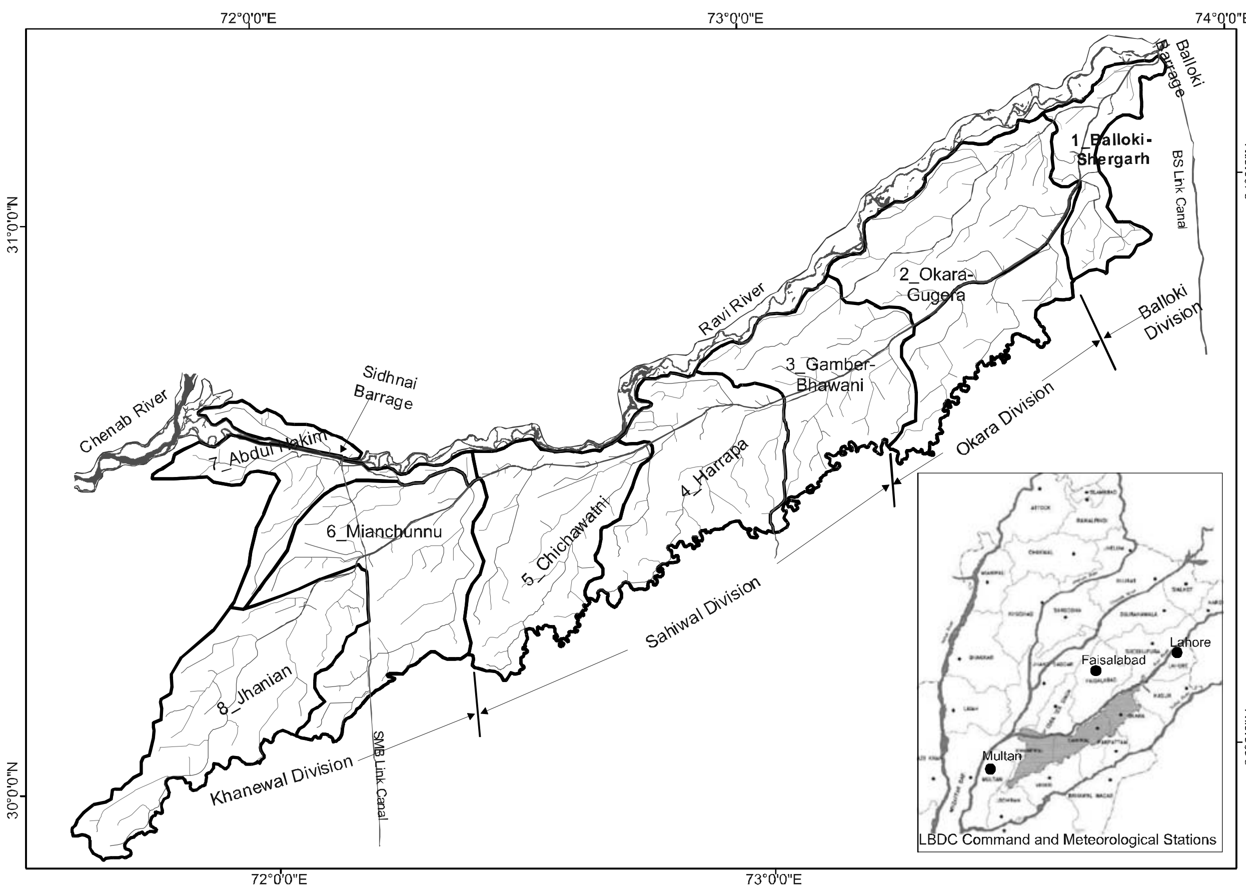

FIG. 1. LBDC COMMAND AREA SHOWING IRRIGATION DIVISIONS AND HYDROLOGICALLY SIMILAR UNITS AND LOCATION OF METEOROLOGICAL STATIONS

2.2 Methodology Adopted

The theme of the paper is to explore the causes of declining groundwater table from head to tail of the selected canal command. As almost all the rechrage to groundwater in our irrigation system is taking place from canal water, rainfall and meager amount of contribution from river seepage that too in adjoing areas to the rivers. For the purpose, temporal change in groundwater level has been calculated on the basis of irrigation divisions in the head to tail direction showing that inequity regarding availability and cost of using groundwater for supplimenting the canal water supply is increasing with passage of time.

The inequity of water distribution, among water users located at head middle and tail reaches has been reported by many [7-12] and is closely correlated to decreasing crop yields and increasing land salinzation as discussed by Latif, et. al. [4]. While highlighting the impact of climatic variability in the canal command, it was necessary to look into if there is any inequity regarding canal water diversion on main canal level. For the purpose volume of water (2006-2007) diverted to the distributaries from the main canal was calculated and compared to show if there is any decreasing trend in canal water distribution in head to tail direction along the length of main canal.

2.3 Field Data Collection

To overcome the doubts if any about the equitable water distribution or otherwise from both the sources (canal and groundwater) across the LBDC command, a fresh field data collection was carried out during the water year 2008-2009. In this attempt four water courses were selected at random in the command well spread from head end to tail end. The actual discharge being drawn by each outlet during the time that parent channels were flowing at full capacity was measured by using cut throat flume for earthen and float method for lined watercourses at each watercourse head. Data of canal water supplies and groundwater pumping on individual basis for each farmer was recorded for one complete year for the four watercourses. The results with respect to water use (2008-2009) on seasonal basis i.e. Kharif (April-September) and Rabi (October-March) seasons were calculated.

2.4 Crop Water Requirement

Ullahm, et. al. [14] has highlighted the spatial variation of ETo from north to south in IBIS and Ahmad, et. al. [13] has proved through remote sensing analysis that actual evapotranspiration (ET_a) decreases from upper to lower Rechna doab i.e. north to south direction. Keeping in view these facts and elongated shape of LBDC command, crop water requirement for the canal was calculated by dividing the command into sub-areas called HSUs (Hydrologically Similar Units). These HSUs were marked in GIS keeping in view the hydrological boundaries served by distributaries grouped into these units.

3. RESULTS AND DISCUSSION

3.1 Groundwater Declining trend and Inequity Across the Command

The depth to groundwater in LBDC command is about 3-8m in head reaches as compared to 12-20m in tail reaches. It is anticipated that this difference in groundwater depth will continue to increase if present scenarios of surface and groundwater use patterns persist. In depleting groundwater areas, farmers are forced to deepen their pump sumps in order that centrifugal pump remains functional with deepening groundwater. While deepening of the sumps, 1-3 deaths due to caving in of the sumps are frequently reported in print and electronic media in Khanewal and Multan (adjacent to Khanewal towards South) districts. Areal view from head to tail of command reveals the highest annual water consumption in upper and middle reaches of the canal command where depth to groundwater being shallow so the groundwater supplies are plentiful and farmers can pump as much as required with low pumping costs. In contrast, the farmers lying at the tail reaches of the canal command are spending high share of their crop production on groundwater pumping due to deeper depths to groundwater in these areas.

Deepest depth to groundwater in the Khanewal Division (tail end) has been reported as 20.73m (October 2008). Hydrographs of observation wells from all the four Divisions of LBDC (Fig. 1) are plotted in Fig. 2 and calculated declining rates given in Table 1. The Table 1 and Fig. 2 show the highest depletion rate of groundwater table in Khanewal Division (0.34m/year), then Sahiwal Division (0.18m/year) whereas the groundwater position in Balloki and Okara Divisions (upper reaches) is stable.

3.2 Tubewell Irrigation and Increasing Costs with Deepening Groundwater

About 48,000 tubewells were working in the LBDC command in 2005 as reported by NESPAK, [16] with varying density, capacity and pumping modes due to gradually increasing depth to groundwater from head to tail. As the groundwater level drops, the cost of pumping increases, if it falls much further then the need arises to change technologies from centrifugal pumps to more expensive turbine pumps. Thus tubewell irrigation has

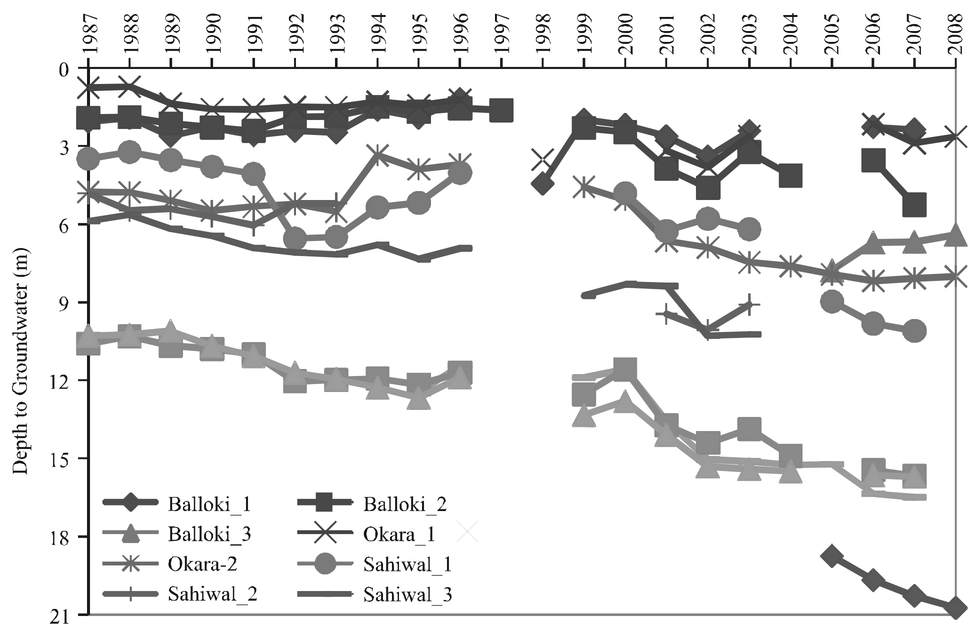

FIG. 2. DEPTH TO GROUNDWATER HYDROGRAPHS FOR SOME OF THE OBSERVATION WELLS IN FOUR DIVISIONS OF LBDC COMMAND

TABLE 1. CHANGE IN DEPTH TO WATERTABLE (DTW) PER YEAR OVER DIFFERENT PERIODS IN IRRIGATION DIVISIONS OF LBDC

LBDC Division	1987-1996		1998-2002 (Drought)		2005-2008	
	No. of Observation Wells	Change (m)	No. of Observation Wells	Change (m)	No. of Observation Wells	Change (m)
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						

brought reliability in meeting crop water demand at critical stages and during the events of reduced canal supplies but maintaining this reliability is becoming increasingly costly for the tail reach farmers. To highlight this inequity with regard to groundwater pumping cost, the data collected by Halcrow, [3] from drillers in the area about costs of drilling and installing a tubewell in the LBDC command has been used. The data covers well different modes of pumping i.e. by centrifugal pumps or turbines and electricity or diesel primed. In tail reach areas, centrifugal pumps are installed in a dug well (8-17m deep) or the turbine has become the only chance at a very high cost. Also, the drilling depth is another variable in cost of the well due to vertical location of fresh water availability.

Considering the unit costs and the quantities required, the total cost for drilling and assembly of a 1-cusec capacity tubewell (drilling depth of 100-130m) is of the order of Rs. 130,000/- on average. Whereas for a 4-stage turbine with same 1-cusec discharge, the total average cost is Rs. 304,750/-. Adding the electricity hook-up charges, the total was about Rs. 230,000/- for the tubewell and Rs. 500,000/- for the turbine. Whereas the total cost of diesel driven tubewell with drilling depth 50-60m, in the head reach areas is not more than Rs. 120,000/-.

The groundwater pumping cost after the installation also increases with depth to watertable. Average pumping hours of a 1-cusec capacity tubewell has been assumed as 900 per year and 10 years as its working life. With Rs. 4.0 as cost of 1 KWH of energy, the operation cost after adding to the capital cost for various depths to groundwater has been plotted in Fig. 3. From Fig. 3, it is apparent that cost per cubic meter of groundwater pumped increases about 3.5 times as the depth to watertable varies from 6-21m from head to tail in LBDC command.

3.3 Surface Water Equity

In order to judge equity of water distribution to off-taking channels from head to tail along the main canal, the daily discharge data for the period March 2006 to December 2007 was used to calculate DPR and total water diverted during the period. DPR was calculated on daily basis for each channel for the days data is available. Daily values varied from zero to about one, so to get a representative value of DPR, averages were calculated for the whole period for each channel as shown in Fig. 4. The resulting DPR statistics indicate an average of 0.78, coefficient of variation as 0.15, minimum DPR of 0.43 and maximum of 1.04. The channel with minimum DPR is a non-perennial channel lying at the head reach and that with maximum DPR are those with small design discharges falling mostly towards tail of main LBDC canal. As shown in Fig. 4, most of the channels have DPR values close to the average of 0.78 with out any decreasing trend towards tail except those four in number having high DPR values but having small discharges.

Resulting water withdrawals for 2006 and 2007 in the form of water depth distributed over the respective CCA are also plotted in Fig. 4. It is seen that in general, the equity of water distribution is much doubtful. But, at present there is not any considerable decrease in surface

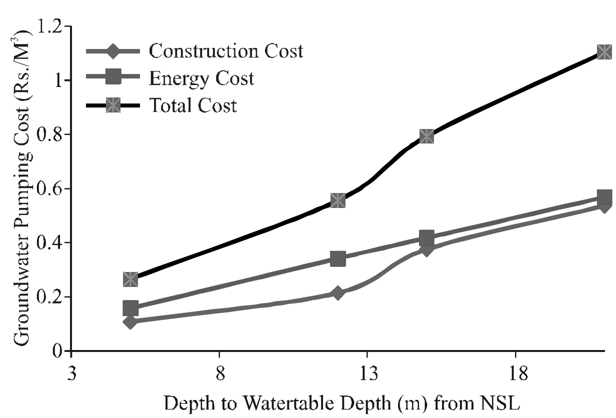

FIG. 3. INCREASE IN COST OF GROUNDWATER PUMPING WITH DROP IN GROUNDWATER LEVE

water diversion from head to tail in general. Trend lines drawn in Fig. 4, for canal water diversion do indicate a decrease of the order of 3.0cm/year from head to tail which is not considerably inequitable. The spikes and dips in the figure are for those channels having less discharge and CCA, depicting possibility of higher %age inaccuracy of discharge data collection as compared to large channels. The CoV (Coefficient of Variation), also known as "relative variability", i.e. standard deviation divided by the mean has also been calculated for the canal diversions to off taking channels and found to be 0.179 and 0.183 for 2006 and 2007 respectively. Whereas the mean canal water diversions are 65.3 and 64.6cm and the corresponding standard deviation is 11.71 and 11.84 respectively for 2006 and 2007. So, data analysis for the two years show that there is not any considerable decrease in surface water diversion from head to tail nor any profound variation of canal diversions along the main canal.

3.4 Water Availability and Usage Across LBDC Command

To overcome the doubts if any about the equitable water distribution or otherwise across the LBDC command, a fresh field data collection was carried out during the water year 2008-2009. In this attempt four water courses were selected at random in the command to find if there is any trend of decreased canal water availability in the downstream direction. The additional purpose is to judge water availability and use patterns in space and time by the farmers from both the sources i.e. canal and groundwater. Design data of watercourse and its command was obtained from the concerned Irrigation Divisions (Table 2). The results obtained, with respect to water use (2008-2009) on seasonal basis i.e. Kharif (April-September) and Rabi (October-March) seasons are given in Table 3.

No measurements were conducted in head reach Division (Balloki). Water usage in Table 3 has been plotted in Fig.

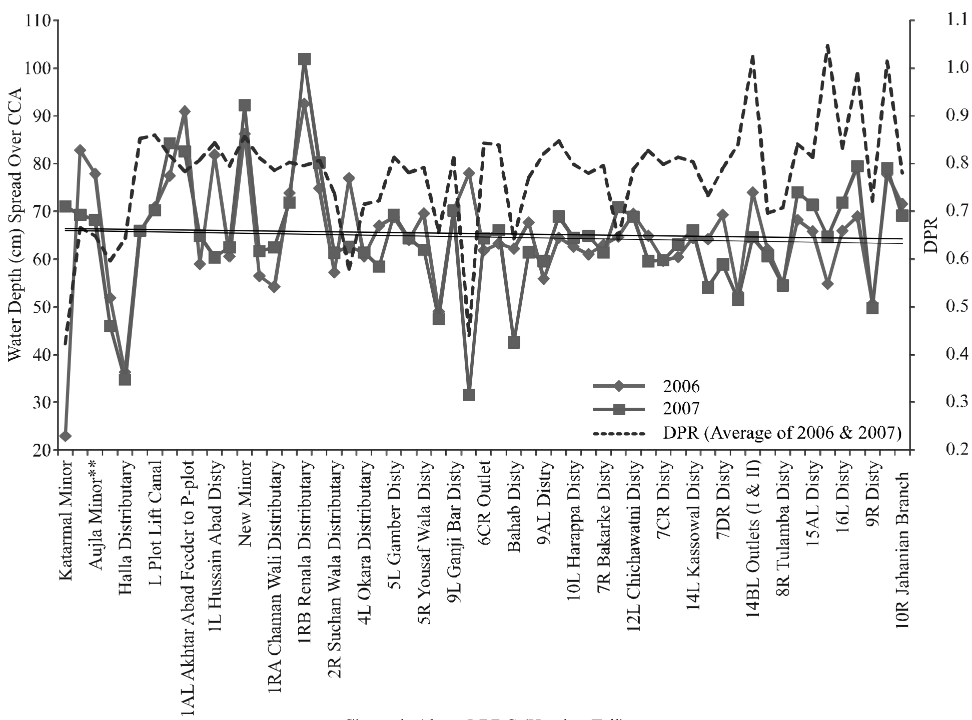

FIG. 4. EQUITY OF CANAL DIVERSIONS TO OFF-TAKING CHANNELS FROM LBDC MAIN CANAL

5. From the results, it is clear that total water usage (canal and ground water) decreases from head to tail of the LBDC command. Looking separately at canal withdrawals by the watercourses, there is not any trend (decreasing or increasing) in the downstream direction. 1st and 3rd watercourses are drawing their design share, while 2nd and 4th (last one) are drawing more. These anomalies in discharge of the watercourse are considered to be normal practice in Pakistan's irrigation system. It often happens that watercourse discharge increases upon payment (or otherwise) of bribery to the concerned irrigation officials. These results form watercourse level measurements are in agreement to that as already shown in Section 3.3 about water diversions to LBDC off taking channels that there is no decreasing trend in canal water supply from head to tail end. However, other factors such as poor maintenance due to long term shortage of funds may cause some tails of a few secondary channels to be permanently dry or receiving less share as quoted by Halcrow ,[12] for tails of Jandraka and 15L distributaries in LBDC command.

From Fig. 5, it is clear that for Kharif season, tubewell water usage is highest for the upper reach areas due to watertable being shallow and low pumping cost. This is also supported by high density of tubewells and more rice cultivation in Okara Division as reported by NESPAK [16]. Therefore, it is clear that groundwater usage is higher at upper reaches as compared to tail reach areas, specifically due to shallow groundwater depth and growing of high delta rice crop.

3.5 Variability of Crop Water Requirement Across LBDC

The data of 30 years normal (1971-2000) rainfall and ET_o computed by Pakistan Meteorological Department [17] is available for three meteorological stations outside the LBDC canal command, i.e. Lahore in North-East, Faisalabad in the West and Multan in South-West (Fig. 1), each of them about 50 Km away from canal command boundary. The maximum difference of rainfall for these stations is 442 mm and ETo difference is 176.7mm. The Blanney-Criddle

TABLE 2. SALIENT FEATURES OF SELECTED WATERCOURSES (HEAD TO TAIL OF LBDC COMMAND)

Watercourse No.	Reduced Distance (Km)	Canal Division	Parent Channel		Watercourse Discharge		CCA (Acres)
			Name	Discharge (ft^3/s)	Designed (ft^3/s)	Measureed (ft^3/s)	
26030R/1R	48.39	Okara	1R	81.6	1.46	1.43	438
31200L/5L	94.96	Sahiwal	1R/5L	37.0	1.72	2.58	517
60750R/1R-12L	161.98	Sahiwal	1R/12L	171.0	1.86	1.69	504
60630R/2L-10R	237.24	Khanewal	2L/10R	109.0	1.88	2.21	562.7

TABLE 3. WATER USAGE (cm/HECTARE) AT WATERCOURSE LEVEL OF FOUR SELECTED WATERCOURSES ACROSS LBDC (CALCULATED FROM FIELD MEASUREMENTS)

Watercourse	No.Water Usage (cm/Hectare)								
	Kharif		Rabi		Kharif Total	Rabi Total	Annual Total	Annual Canal	Annual Tubewell
	Canal	Tubewell	Canal	Tubewell					
26030R/1R	33.2	60.4	19.8	12.5	93.3	32.3	125.9	53.0	72.8
31200L/5L	55.2	15.5	32.0	21.6	70.4	53.6	124.1	86.9	37.2
60750R/1R-12L	34.1	32.0	24.4	22.9	66.4	47.5	113.7	58.8	55.2
60630R/2L-10R	39.3	32.2	-	-	72.8	-	-	-	-

method had been used for estimating ET_o by the meteorological department. These ET_o values have been adopted for calculating crop water requirement for the LBDC command. The total canal command area was divided into eight sub-areas called HSUs as shown in Fig. 1, assuming similar hydrological conditions i.e. rainfall and ET_o within the HSUs. The boundaries of these sub-areas were marked in GIS keeping in view the hydrological boundaries governed by distributary canals. For interpolation of these hydrological parameters (rainfall and ET_o), the most commonly used method called IDW (Inverse Distance Weighting) interpolation was used as given in the Equation (2).

$$Z_p = \frac{\sum_{i=1}^{n} Z_i W_i}{\sum_{i=1}^{n} W_i} \tag{2}$$

Where Z_p is interpolated value at the desired location, Z_i is parameter value at the known point, W_i is weight assigned to the known location, and n is no of sample points. The weighting function used for the above equation is given in Equation (3):

$$W_i = \frac{1}{d_i^2} \tag{3}$$

Interpolated monthly rainfall and ET_o for the HSUs are given in Tables 4-5, respectively. From the Tables 4-5 it can be seen that annual rainfall decreases from head to tail, the maximum annual difference between sub-areas is 260.6mm/annum. But in contrary, potential evapotranspiration (ET_o) increases from head to tail of the command, the maximum annual ET_o difference between HSUs is 138.9mm/annum.

The monthly crop consumptive use has been calculated by multiplying crop coefficient of the particular crop with the ET_o during that calendar month. The calculated delta of the crops being grown in the LBDC command area on HSU basis is presented in Fig. 6 for comparison. The crop delta increases from head to tail in the LBDC command, with a minimum difference of 13 mm and maximum of 147mm for oilseeds and sugarcane crops respectively. For head reach HSU i.e. 1_Balloki-Shergarh, wheat cotton rotation has annual water demand of 376+806=1182mm. Tail reach HSU i.e. 8_Jhanian area, has crop water requirement of 403+912=1315mm for the same crop rotation. Adding this

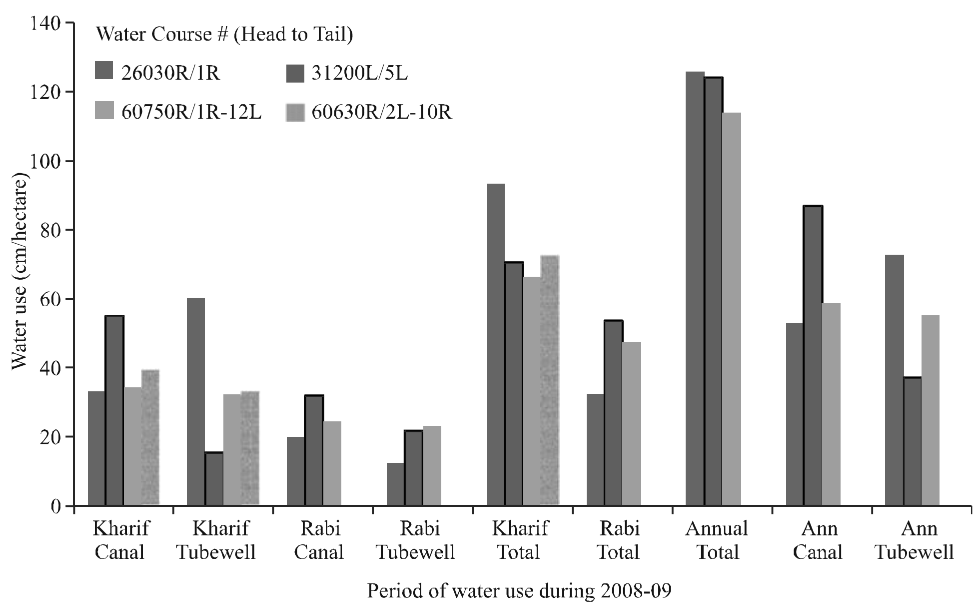

FIG. 5. WATER USAGE AT WATERCOURSE LEVEL OF FOUR WATERCOURSES DURING 2008-2009

difference in crop delta (1315-1182=133mm) to rainfall difference (260.6mm), a total difference comes out to be 393.6mm which is 33% of field delta for wheat/cotton crop rotation at head reach of LBDC command. The above analysis shows an increasing crop water requirement continuously from head to tail of the canal command due to climatic variation (Fig. 6).

3.6 Summary of the Results

(i) Canal water diversions data to off taking channels do indicate a decrease in canal water supply to tail channels of the order of 3.0cm/year but it is not that serious inequity when referred to head and tail of main canal.

TABLE 4. INTERPOLATED MONTHLY RAINFALL (mm) FOR THE HSUS IN LBDC COMMAND

Month	Hydrologically Similar Units							
	1	2	3	4	5	6	7	8
January	16.3	14.6	13.2	12.4	11.0	9.5	7.9	9.2
February	23.3	21.8	20.2	18.8	16.2	13.6	10.8	13.0
March	32.2	29.9	27.9	26.8	24.8	22.8	20.5	22.2
April	17.9	17.4	16.9	16.3	15.4	14.4	13.4	14.2
May	18.6	17.6	16.5	15.6	14.0	12.4	10.6	12.0
June	30.8	29.2	27.2	25.2	21.6	18.0	14.0	17.2
July	150.3	137.1	124.7	116.1	100.8	85.9	68.9	82.0
August	119.3	107.8	96.4	87.7	72.3	57.3	40.2	53.4
September	41.9	37.1	32.6	29.7	24.4	19.3	13.4	17.9
October	7.5	6.2	5.3	4.8	3.9	3.1	2.1	2.9
November	3.5	3.3	3.1	3.0	2.8	2.6	2.4	2.6
December	10.8	10.1	9.4	9.1	8.5	7.9	7.2	7.7
Total:	472.2	432.1	393.5	365.5	315.5	266.9	211.6	254.2

TABLE 5. INTERPOLATED MONTHLY ET_O (cm) FOR THE HSUS IN LBDC COMMAND

Month	Hydrologically Similar Units							
	1	2	3	4	5	6	7	8
January	63.5	63.2	63.1	63.4	63.9	64.4	64.9	64.4
February	74.2	73.9	73.8	74.0	74.5	74.9	75.4	75
March	122.7	122.5	123.0	123.9	125.7	127.5	129.4	127.8
April	163.6	163.4	163.5	164.1	165.3	166.3	167.5	166.5
May	209.5	209.3	209.8	210.7	212.5	214.3	216.2	214.6
June	231.3	231.5	231.9	232.6	233.9	235.1	236.4	235.3
July	172.1	178.9	185.9	191.3	201.1	210.7	221.5	213.1
August	154.5	159.5	165.7	171.7	182.8	193.4	205.5	196.0
September	171.3	171.5	171.9	172.6	173.9	175.1	176.4	175.3
October	150.8	147.7	146.1	146.3	147.2	147.9	148.6	147.9
November	102.5	99.8	98.3	98.3	98.6	98.8	99	98.7
December	55.7	58.0	60.2	61.7	64.4	67.0	70.0	67.7
Total:	1671.8	1679.1	1693.2	1710.7	1743.8	1775.2	1810.7	1782.5

(ii) Groundwater depletion rate of 0.34m/year in the tail reach areas as compared to 0.09- 0.04m/year in head reach reveals doubts about sustainability of groundwater irrigation in tail reach of LBDC command.

(iii) Tail reach areas of LBDC receive only about 45% of the rainfall at head reach.

(iv) Higher groundwater depletion rates of 0.94m/year in Okara division (head reach) during drought period (1999-2002) as compared to corresponding 0.53m in middle and tail reaches (Sahiwal and Khanewal) reveals considerably higher contribution of rainfall towards crop consumptive use and groundwater recharge in head reach as compared to tail reach of LBDC command.

(v) The crop delta increases from head to tail, with minimum difference of 13mm and maximum of 147mm for oilseeds and sugarcane crops respectively.

(vi) Crop water requirement for wheat/cotton rotation in tail reach areas is about 33% higher for the same crops grown in head reach of LBDC command.

The results show that the difference in crop delta is more profound for kharif crops as compared to Rabi. The farmers falling on the tail ends of LBDC command are facing a constant inequity from years to years in the form of less annual rainfall and higher crop water requirement due to higher ET_o. But equitable allocation of canal water irrespective of decreasing rainfall and increasing ETo towards tail ends of the irrigated commands is causing much higher depletion of groundwater in tail reach areas of many of the canals commands.

At present no attention is being paid by the irrigation agencies towards conjunctive management of the two separately treated and managed but complementary resources. The current trend in aquifer management requires determining the maximum and minimum water levels, in order to regulate under ground storage capacity

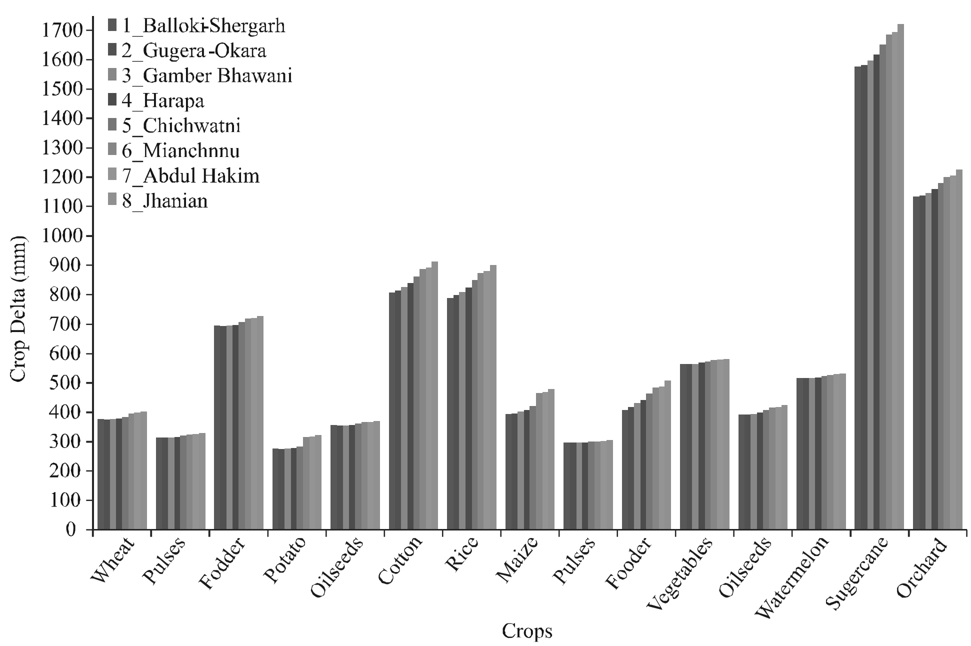

FIG. 6. COMPARISON OF FIELD DELTA OF CROPS IN HSUS OF LBDC COMMAND

within each canal command. As a matter of fact, uncontrolled overexploitation of groundwater causing progressive drawdown below the minimum permissible piezometric levels, is leading to increased pumping costs at tail areas. Groundwater resources under the command solely depend upon canal water deliveries and rainfall recharge (decreasing downstream), so this poor and sole management of canal water ignoring the groundwater resource is non optimal and unsustainable. If this continues without giving due consideration to the conjunctive management of both the resources at government level, the agriculture in the area will come under increasing stress due to falling groundwater levels in the tail reach areas.

4. CONCLUSIONS

(i) Climatic variability across the command of LBDC has pernicious impact on inequitable usage of irrigation water from head to tail in the form of increasing depth to water towards tail end.

(ii) The irrigation system performance in the country needs to be assessed from strategic point of view and corrective measures are needed accordingly for sustainability of the irrigated agriculture.

(iii) Presently practiced surface water management and irrigation system design (one century old) has ignored the variation of rainfall and crop water requirement across the canal command areas.

(iv) The prevailing fragmented approach where groundwater and surface water are managed separately has contributed to high vulnerability and low agricultural productivity for farmers in the tail ends of canals.

(v) Excessive lowering of watertable has made groundwater pumping expensive in tail reach areas as compared to areas in the head reach. The unprecedented decline of watertable due to intensive pumping in these areas has made the groundwater irrigation out of the reach of poor farmers.

(vi) By considering difference in rainfall, ET_o, groundwater availability and quality when allocating surface water, the governments can improve the situation of millions of poor farmers with inadequate access to both surface and groundwater, thereby ensuring long term sustainability of agriculture productivity of the irrigation systems.

(vii) Cutting short of canal supplies to fresh and shallow groundwater areas in order to divert this canal water to depleted groundwater areas seems to be optimal solution. This is possible through augmentation of groundwater into channeled canal water supplies in these groundwater rich areas.

(viii) Higher depletion rates during possible drought periods to come is emerging as a new challenge for water managers for which there exists awareness in general among the professional community but no critical management plan is considered necessary by the concerned authorities.

ACKNOWLEDGEMENTS

The Authors are thankful to Punjab Irrigation Department, SCARPs Monitoring Organization of Pakistan, Water and Power Development Authority, and Pakistan Meteorological Department, for providing their valuable datasets used in the study. Satellite images used for developing irrigation network map of the command area were the purchased property of WAPDA. The field data collection over one year period was made possible by providing funds for Ph.D. study by the Director, Centre of Excellence in Water Resources Engineering, University of Engineering & Technology, Lahore, Pakistan.

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