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Spatial Climate Variability and Its Impact on Irrigated Hydrology in a Canal Command

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Abstract Depth to watertable continuously increases from head to tail in most of the canal commands in Punjab, Pakistan, in spite of equitable canal water supplies. In the wake of increased groundwater use with passage of time, the tail end farming community and irrigation management institutions are to confront this emerging issue very prudently. To comprehend this dilemma, canal water availability, crop water requirement and groundwater recharge across the Lower Bari Doab Canal command were analyzed. Annual rainfall decreases towards tail (212 mm) as compared to head (472 mm), in contrary, annual gross and net crop water requirement at tail end are 10.2 and 32.5 % higher, respectively, as compared to head end. As a result, groundwater mining is taking place in tail end at 0.34 m/year, whereas in head end areas, the situation is stable. Actually, in tail end areas, groundwater recharge rates are considerably low as compared to the head end. Spatial climate variability across the command is the main cause for these inequities. Reallocation of canal water and/or enhancing recharge to groundwater in these relatively more water stressed areas during wet years needs to be sought, otherwise any groundwater management activity in this regard will not have any technical and social viability. Ignoring climatic variability within the canal command is one of the serious issues in irrigation system design that prevents achieving the optimal level of conjunctive water use and as a result, the highest potential agricultural output cannot be achieved.

Keywords Equity · Groundwater recharge · Reallocation · Climatic variability · Water requirement · Irrigated hydrology

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الخلاصـة

إن العمق إلى watertable يزداد باستمرار من الرأس إلى الذيل في معظم أوامر القناة في ولاية البنجاب- باكستان على الرغم من إمدادات المياه العادل في القناة. وفي أعقاب زيادة استخدام المياه الجوفية مع مرور الوقت، فإن مجمع نهاية الذيل ومؤسسات إدارة الري عليها مواجهة هذه القضية الناشئة بحكمة شديدة. ولفهم هذه المعضلة تم تحليل توافر مياه القناة والاحتياجات المائية للمحاصيل وتغذية المياه الجوفية عبر الممرات السفلى لقناة باري Doab. ينخفض معدل هطول الأمطار السنوي نحو الذيل (212 ملم) مقارنة مع الرأس (472 ملم)، وبالعكس فإن الإجمالي السنوي وصافي الاحتياجات المائية للمحاصيل في نهاية الذيل هي 10.2 و 32.5٪ على التوالي مقارنة بنهاية الرأس. ونتيجة لذلك فإن تعدين المياه الجوفية يجري في نهاية الذيل عند ذيل 0.34 متر / عام، في حين أن الوضع غير مستقر في مناطق نهاية الرأس. ويُشار هنا إلى أن معدلات تغذية المياه الجوفية - في مناطق نهاية الذيل- فإن تكون منخفضة بشكل كبير مقارنة بنهاية الرأس.

إن تقلبات المناخ المكاني عبر الأمر هو السبب الرئيسي لهذه الفوارق. والمطلوب هو إعادة توزيع مياه القناة و / أو تعزيز التغذية للمياه الجوفية في هذه المياه في المناطق المرهقة نسبيا أكثر خلال السنوات الرطبة، وإلا فإن أي نشاط لإدارة المياه الجوفية بهذا الصدد ليس له أي جدوى تقنية واجتماعية. إن تجاهل التقلبات المناخية داخل قيادة القناة هي واحدة من القضايا الخطيرة في تصميم نظام الري الذي يمنع تحقيق المستوى الأمثل من استخدام المياه المتواصل . ولايمكن - نتيجة لذلك - أن يتحقق مستوى أعلى من الإنتاج الزراعي الذي يمكن حدوثه.

1 Introduction

In more than 70 % of canal irrigated areas of Pakistan, groundwater is providing on demand irrigation water source and is the single most factor in sustaining the increased cropping intensities over the decades. But this assured supply of irrigation water to the tune of above 50 % is at stake due to over use mostly in tail end areas of the canal commands. In general, groundwater potential for irrigation use diminishes over the alluvial aquifers of Indus Basin Irrigation System (IBIS) in downstream direction. The reasons are twofold, i.e., either the groundwater is highly mineralized for use or the depth to groundwater increases in this direction and the demand for supplemental irrigation supplies increases towards south in downstream direction of canal systems in IBIS. This is due to the fact that climate becomes more arid in this direction. Although temperature, solar radiation, and wind, all affect evapotranspiration demand, rainfall is often the single most important determinant of net irrigation demand. The normal annual rainfall decreases from 1,000 mm in north to 100 mm in south of the Punjab Province. But irrigation duties in upper Indus Basin (Punjab Province) are based, in general, on equitable canal water distribution, particularly within a canal command, in spite of the above-mentioned anomalies regarding irrigation water requirement. For canal supplies, irrigation water duty in Punjab is adopted as about 0.245 l/s/ha (3.5 cusecs per 1,000 acre).

1.1 Increasing Importance of Groundwater in Irrigation

More than a century old irrigation system design had ignored the difference in crop water requirement and annual rainfall while allocating canal water across and within canal commands. At that time, canal supplies were adequate due to low cropping intensities and groundwater needs were negligible in irrigated areas. With passage of time, cropping intensities have increased by about three times, i.e., 60–75 % at design stage to about 160 % at present. Now, the groundwater usage has successively increased in meeting crop water demands and has been reported to be at par with canal water supply [1–3]. This is more prevalent in areas where canal water is insufficient. Therefore, the increasing use of groundwater has become a major factor underlying raising agricultural production in the past three decades. IWMI [4], based on the work in Pakistan and India, has concluded that groundwater irrigation has surpassed surface irrigation as the primary source of food production and income generation in many rural areas. Thus, the variation in depth and quality of groundwater across most of the canal commands has created anomaly in the total water availability to the farmers and farmers' income [5]. The areas with deeper groundwater levels are located generally in tail reaches of the canal systems [6]. IWMI [7] has concluded that water managers could improve the equity, sustainability and productivity of irrigated systems by considering groundwater availability and quality when allocating surface water.

1.2 Irrigation System Design Features in Pakistan

The IBIS was designed for an annual cropping intensity of about 60–75 % with the intention to spread the irrigation water over as large an area as possible to expand the settlement opportunities [8]. The mainly stressed objective of the irrigation managers till now has been to assure maximum possible equity of canal water distribution with minimum O&M costs. 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 [9]. The system's inherent rigidity towards meeting potential crop water requirements was incorporated 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. Within any canal command, the equity of canal water distribution among outlets whether at head or tail reaches has been achieved by accounting for seepage losses in the design capacity in addition to withdrawal requirements of downstream feeding channels and outlets.

1.3 Inequity and Its Established Impacts on the System

In Pakistan, the inequity of water distribution among water users located at head, middle and tail reaches, particularly at secondary (distributaries and minors) and tertiary (watercourse) level irrigation channels, has been reported by many researchers [9–15]. Nowadays, irrigation water equity is being studied with respect to both canal and ground water because of increasing importance of the latter in meeting crop water demand, both in terms of share and on demand availability. In this regard, Ahmad et al. [16] has concluded through remote sensing analysis of actual evapotranspiration (ET_a) in Rechna Doab Irrigation System in Punjab that the adequacy and reliability of combined surface water and groundwater deliveries decline towards the tails of the canal commands and towards the central and downstream parts of the Rechna Doab. It was also noted that the areas close to the main canals or river have higher ET_a due to better access to canal and groundwater for agriculture.

According to studies in central Punjab, Pakistan, farmers located at upper reaches of the irrigation canals get higher income and it progressively decreases downstream along all main, secondary and tertiary irrigation canals [5,17]. The difference in income was attributed to larger use of groundwater towards the tail reaches of the irrigation channels incurring higher costs to the farmers. The results also revealed that salts in groundwater increase progressively from head to lower reaches of almost all the tertiary canals. The difference has been attributed only to lower recharge to groundwater from 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 from head to tail at main canal command level has been overlooked. Basharat et al. [18] have highlighted that the already committed water allocations in the canal commands in the IBIS have not taken into account the rainfall patterns and the underlying groundwater resources of the respective canals. This, being the major weakness of irrigation system design in Pakistan has created detrimental and strategic impacts on the life and earnings of tail end farmers of most of the canal commands. This aspect is in line with that the equity in developing countries is decreasing due to other competing uses for scarce water resources [19]. Tail end farmers, often the poorest, suffer a twin disadvantage—less water and more uncertainty. Poverty among tail end farmers as compared to head end farmers has been pointed the highest as being 11 and 6 % for India and Pakistan [20]. Bagher and Rasoul [21] have highlighted the increase in groundwater salinity with declining groundwater levels in Iran and pointed out that saline intrusion due to declining groundwater is a major factor in increasing the salinity.

The greater part of the water consumed by cultivated plants is transpired into the atmosphere. This means that the water consumption of a crop is decisively governed by the evaporating capacity of the atmosphere, which can be termed as the suction force or, in everyday language, the atmosphere's thirst for water. Potential crop demand, being an important irrigation design parameter, is spatially variable in north south direction in Pakistan as pointed out by Ullah et al. [22]. The upper and northeastern part of the Indus Basin has lower reference evapotranspiration (1,200–1,300 mm) because of mild climate, whereas the lower part of the basin, i.e., Southern Punjab and Sind has much higher ETo values (1,700–2,100 mm). The study reports spatial variation in potential evapotranspiration of different crops to be from 14 to 50 % across the Indus Basin [22]. In Pakistan, the water allowance within any canal command is based on achieving equity in conveying canal water, but difference in crop water requirement along with groundwater availability and rainfall variation has not been considered in irrigation system design. Furthermore, the recharge to groundwater varies across any canal command due to proximity difference to line sources of recharge such as main canals and the rivers. The main objective of this paper is to evaluate climatic variability and its impact on irrigated hydrology within a canal command. This can further support and help in implementation of conjunctive water use and integrated water resources management (IWRM) at canal command level within the same province but its interprovincial implementation may still be doubtful due to legal bindings for water distribution such as Water Apportionment Accord of 1991 as pointed out by Biswas [23] for Canada, India and Pakistan.

2 Methodology and Data Analysis

2.1 Study Area

The Lower Bari Doab Canal (LBDC) command area lying in Bari Doab and covering gross command area (GCA) of 0.80 million hectares (Mha) was selected for this study. The main canal with a design discharge of 278 m^3/s off-takes from the left bank of the Ravi River at Balloki Barrage and flows for 201 km supplying water to its 65 nos. off-taking channels (Fig. 1). These consist of 53.5 km branch canals and 2,261 km of distributaries, minors and sub-minors. The canal irrigation is managed through four irrigation administrative divisions, i.e., Balloki, Okara, Sahiwal and Khanewal as shown in Fig. 1. Agriculture in the area is sustained through surface water supplies in the LBDC and pumped ground water 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 (2001–2009) deliveries of about 4,847 million cubic meters (MCM) at canal head. 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 %. However, the sustainability of this increased food security is most importantly linked to the sustainability of groundwater reservoir.

2.1.1 Soils and Physiographic Features

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., the Ravi and the Sutlej rivers. The parent material comprises mixed calcareous alluvium derived from a variety of rocks. The general slope of the area is mild towards the southwesterly direction (tail end) with average ranging from 1 in 4,000 to 1 in 10,000. The predominantly agricultural land is at an elevation of 120–195 m (394–640 ft) above mean sea level. The 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 colors (mostly silty), deeply developed and show definite profile development (horizons). They contain secondary lime precipitated in the form of nodules (kankars) of variable size, mostly in the sub-soil, substratum. The soils of the abandoned flood plain are characterized by greyish colors, with weak or little profile development in the sub-soil and layering of different textures in the substratum.

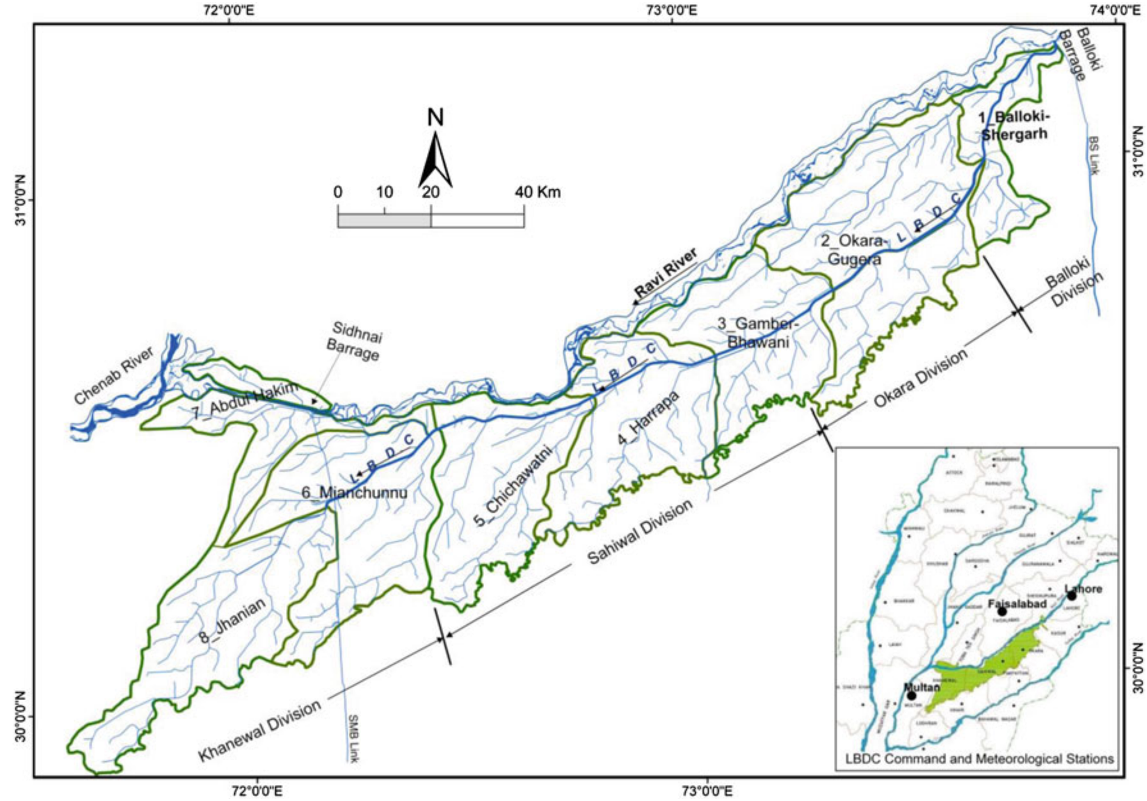


Fig. 1 LBDC command, irrigation divisions further divided into hydrologically similar units and location of meteorological stations

2.1.2 Groundwater Geology

The alluvial sediments that comprise the aquifer exhibit considerable heterogeneity both laterally and vertically. Despite, it is broadly viewed that the aquifer behaves as a single contiguous, unconfined aquifer. Study of the lithologic logs of test holes (180–300 m depth) and test tubewells (30–110 m depth) indicates that Bari Doab consists of consolidated sand, silt and silty clay, with variable amounts of kankers. The sands are principally grey or greyish-brown, fine-to-medium grained and subangular to sub-rounded. Very fine sand is common, finer grained deposits generally include sandy silt, silt and silty clay with appreciable amounts of kanker and other concretionary material. Re-evaluation of the original data [24] and geological sections [25] 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, 6–15 m 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 characteristics tend to be very much sandy towards Harrapa town. Also, detailed study of lithologic logs of bore holes on the 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.

2.2 Main Canal Water Distribution Equity

While highlighting the impact of spatial climatic variability over the canal command, it is necessary to look into, if there is any inequity regarding canal water delivery on main canal level. For the purpose, daily discharge data of distributaries off-taking from the main canal from 2006 to 2009 was analyzed and compared for evaluating equity along the length of the main canal. The delivery performance ratio (DPR) defined as the ratio of actual flow of water to intended flow of water has been widely used in the literature for equity evaluation. The DPR enables to determine the extent to which

Table 1 Thirty-year normal (1971–2000) values of temperature, rainfall and ET_o for Lahore, Faisalabad and Multan

Month	Mean daily temperature (°C)			Rainfall (mm)			ET_o (mm)		
	Lahore	Faisalabad	Multan	Lahore	Faisalabad	Multan	Lahore	Faisalabad	Multan
January	12.8	11.8	12.7	22.1	11	8.2	65.1	62	65.1
February	15.4	14.5	15.4	33.1	19.1	11.1	75.6	72.8	75.6
March	20.5	19.5	21	37.8	22	16.6	124	120.9	130.2
April	26.8	26.8	27.5	23.9	21.5	14.6	165	162	168
May	31.2	30.6	32.4	20.8	13.8	11.5	210.8	207.7	217
June	33.9	33.7	35.5	47.7	35	15.1	231	231	237
July	31.5	32.1	33.9	217.9	117	60.3	145.7	189.1	226.3
August	30.7	31.3	33	197.6	84.7	36.4	136.4	164.3	210.8
September	29.7	29.7	31.0	75.1	37.6	24.9	171	171	177
October	25.6	25.0	26.4	18.5	4.4	5.2	164.3	139.5	148.8
November	19.5	18.7	19.7	6.6	2.5	2.3	114	93	99
December	14.2	13.2	14.1	11.5	5.9	2.7	46.5	62	71.3
Total	–	–	–	712.6	374.5	208.9	1,649.4	1,675.3	1,826.1

water is actually delivered as intended during a selected period and at any location in the system. The spatial variation of the indicator [26] has been used to access the degree of uniformity or equity of canal water distribution among the channels off-taking from the main LBDC canal. In addition, total water diverted to channels at their heads was also determined from March 2006 to December 2007 and compared accordingly.

2.3 Variation of Climatic Conditions Across LBDC Command

The climate of the LBDC command is characterized as hot summers and moderate and pleasant winters. Meteorological stations with long-term records are operated by Pakistan Meteorological Department (PMD) at Lahore, Faisalabad and Multan, located to the northeast, north and southwest of the command area, respectively (Fig. 1). Each of these stations is about 50 km outside the canal command boundary. The maximum reported temperature for Lahore is 48 °C and Multan is 49 °C during the month of June. While, minimum reported temperature for Lahore, Faisalabad and Multan is −2.0, −4.0 and −3.9 °C, respectively, during the month of January. These figures show that climate becomes more severe towards the tail of the LBDC command both during summer as well as winter. Monthly normal values (based on 30-year data) of temperature, rainfall and ET_o are given in Table 1. The 30-year normal (1971–2000) values of rainfall and ET_o (computed by PMD using Blanney–Criddle method) of these stations were used to study the impact of climatic variation on irrigated hydrology across spatial domain of the LBDC command. The average annual rainfall varies from 713 mm for Lahore in the northeast to 209 mm sfor Multan in the southwest and the ETo difference is 177 mm between the two stations (Fig. 2). This indicates that aridity of the climate increases in head to tail direction across the command. In view of the substantial variability of the climatic parameters and the elongated shape of LBDC command (261 km long) in this direction, the command area is divided into eight hydrologically similar units (HSUs) (Fig. 1), assuming similar hydrological conditions within each unit. These HSUs were marked in GIS in consideration of distributary command boundaries. Rainfall and ET_o were interpolated for each HSU by inverse distance weighting (IDW) interpolation as below:

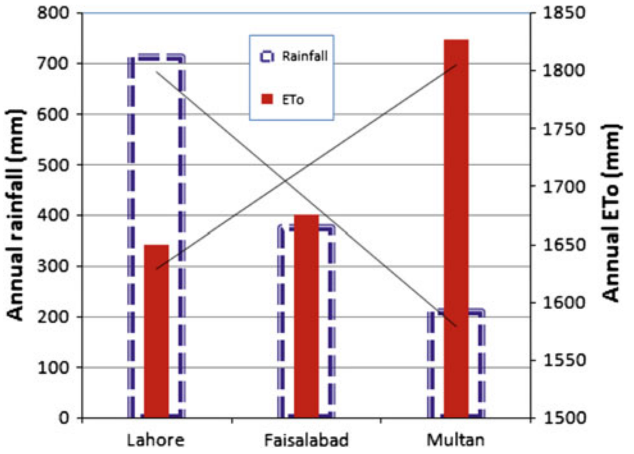


Fig. 2 Increasing aridity shown by met stations across the command

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

where Z_p is the interpolated value at the desired location, Z_i the parameter value at the known point, W_i the weight assigned to the known location, and n is the no. of sample points. The weighting function W_i is based on distance (d) between center of HSU under consideration and the meteorological stations as:

$$W_i = \frac{1}{d_i^2}. \quad (2)$$

2.4 Net Crop Water Requirement

Based on 10-year cropping data (1993–2003), on an average, 159.7 % of the command area of 1.73 million acres is normally cropped during each year. This includes 83.6 % during Kharif (April–September) and 77.8 % during Rabi (October–March) season. The cropping intensities in Sahiwal Division are the highest at 172 % followed by Okara Division 163 %. This is due to the short duration crops such as spring maize, autumn potatoes and vegetables popularly grown in these divisions. In Kharif, cotton at 46 % and in Rabi wheat at 50 % are dominant crops in Khanewal Division. In Sahiwal and Okara, fodders are also grown at quite high percentage, 20–22 % of CCA for consumption of the prosperous dairy industry in these Divisions. On the whole, cotton, Kharif fodder and maize are grown at 27, 16 and 16 % of LBDC command area during Kharif. During Rabi, 48 % of the cultivated farmland is occupied by wheat followed by Rabi fodder at 12 %, followed, in turn, by vegetables and oilseeds occupying about 7 % each. Intensity of Rice crop is highest towards head (17.3 %) as compared to 3.1 % towards tail and cotton is highest towards tail (47 %) and lowest in head end (3.7 %). This shows that the farmers have already adopted suitable cropping patterns according to the climatic conditions in the respective areas.

The crop consumptive use requirement ($\mathrm{ET_c}$) was calculated by multiplying crop coefficient, K_c [27] of the particular crop with the respective $\mathrm{ET_o}$ during the month based on 10 daily cropping calendar as:

$$\mathrm{ET_c} = K_c \times \mathrm{ET_o}. \quad (3)$$

The canal irrigation system in Pakistan has been intentionally designed as deficit irrigation, assuming 60–75 % cropping intensity [8]. Now, the increasing demand for food to cope with the ever increasing population has caused the annual cropping intensities to rise to 150–180 % in different canal commands. This has become possible only with increasing use of groundwater, along with the part of rainfall called effective rainfall (R_e) which directly contributes towards crop water requirement. Therefore, the farmer tries to prudently fulfill the difference in $\mathrm{ET_c}$ and R_e, using groundwater in conjunction with canal water. It means, during planning or management of an irrigation system, R_e can be the most important parameter for utilization of scarce irrigation water in conjunction with groundwater. In a study about estimating effective rainfall in Pakistan for Rabi and Kharif seasons, Adnan and Khan [28] used four different methods with data from 58 meteorological stations covering irrigated plains of Pakistan. It was observed that effective rainfall as percentage of actual rainfall for Rabi and Kharif seasons calculated by potential evapotranspiration/precipitation ratio method vary widely (17.57–99.92 %) throughout Pakistan, depending upon the climatic patterns. The R_e percentage values calculated therein for Lahore (65 %) and Multan (90 %) were linearly interpolated for finding corresponding values for the HSUs within LBDC command. The R_e for each crop was calculated by multiplying the corresponding percentage in each HSU with the interpolated rainfall for the crop period. The net crop water requirement ($\mathrm{ET_n}$) for each crop is determined as:

$$\mathrm{ET_n} = \mathrm{ET_c} - R_e. \quad (4)$$

Table 2 Adopted recharge rates for LBDC irrigation system to groundwater (PPSGDP, 1998)

Discharge (cusecs)	<100	100–500	500–1,000	>1,000
Seepage coefficient (cfs/msf)	2.0	4.0	6.0	8.0

2.5 Groundwater Recharge Analysis

The recharge to groundwater in the area is occurring from canal network seepage, watercourse and field application losses and rainfall. The recharge rates were assessed on HSU basis as follows.

2.5.1 Canal Network Seepage

Punjab Private Sector Groundwater Development Project (PPSGDP) [29] made an extensive analysis of seepage rates from a wide ranged capacity of canals in Pakistan. Seepage rates adopted therein for different channel capacities were used for this study (Table 2). The data about hydraulic parameters, i.e., design discharge, full supply level, flow depth and bed level of all the LBDC system available in GIS format was used. The database file was imported in Excel and seepage losses were computed for each channel reach based on its wetted perimeter and corresponding seepage rates, i.e., cusecs per million sq. feet (cfs/msf). The computed results were imported into the GIS database shape file and the total seepage rate (cusecs) from the channel network within each HSU was determined using quarry and analysis techniques in GIS. To account for partial flows and canal closure in the LBDC system, the daily flow volumes of LBDC canal for the period 2006–2008 were compared to maximum possible flow volumes, assuming LBDC drawing its maximum discharge without any closure. The ratio of actual volume of water diverted to that of assumed full capacity without closure was determined and found to be 0.7176. Calculated seepage rates for each HSU were corrected by multiplying with this ratio.

2.5.2 Watercourse and Field Application Losses

Seepage rate from LBDC channel network only was at $44.53\,\mathrm{m^3/s}$ (1,572.6 cfs), which is 18.72 % of current maximum discharge of LBDC. Annual average diversions to LBDC (2001–2008) were reduced by 18.72 % for calculating water availability at watercourse head. For the water diverted to watercourse head, 25 % were adopted as seepage losses within the watercourse (before entering farm gate) and 80 % of this assumed as recharge to groundwater [30]. The irrigation application efficiency at the farm level was considered to be 80 %, and 75 % of this was taken as recharge to the groundwater [31]. The total recharge to groundwater from watercourse and field application is 31.25 % (20 + 11.25) of that diverted to watercourse head. The irrigation system efficiencies adopted for groundwater recharge are summarized in Table 3.

2.5.3 Rainfall Recharge

Rainfall recharge to groundwater in LBDC command is also variable due to decreasing rainfall towards tail. Ahmad and Chaudhry [32] reported the rainfall recharge to groundwater as calculated in Revised Action Program (RAP) using Massland's approach for the year 1977–1978 for all the canal commands in Punjab province. In this method, the condition of land such as fallow, recently irrigated area, within the middle of irrigation interval and that just before the next irrigation are identified as factors affecting the recharge. The groundwater recharge reported therein for irrigated areas in Punjab was calculated as a percent recharge (R_r) of total annual rainfall (R) in inches and found to be varying from 10.3 to 23.8 % of the annual rainfall and a linear relationship was worked out as:

$$R_\mathrm{r} = 0.286 \times R + 13.9. \tag{5}$$

2.6 Groundwater Development and Use

As a result of increasing cropping intensities caused by increasing population, farmers have resorted to groundwater development for supplementing the short canal supplies under conjunctive water use system at farm level. The number of tubewells in the command area has been rising from about 20,000 in 1994 to about 48,000 in 2005 [33]. The tubewell density varies considerably from head to tail, and is highest in Okara division, the head reach (1 tubewell per 25 acres) and lowest in Khanewal division, the tail reach (1 tubewell per 49 acres). Low cost centrifugal pumps primed by diesel engine and high cost turbine pumps by electricity at head and tail ends, respectively, are used for groundwater extraction. Due to larger watertable depth and continued mining of groundwater at tail end of the command, the centrifugal pumps are becoming less practicable and now farmers are forced to further deepen their pump sumps or totally change to turbine pumps. While deepening of the sumps, 1–3 deaths per year, 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. The total groundwater pumping for agriculture purposes over the LBDC command, based on average tubewell discharge and operation hour figures for 2005, has been estimated as 3,394 MCM as given in Table 4.

2.7 Canal and Ground Water Use-Field Survey

A fresh field data collection was carried out during the water year 2008–2009 to investigate about the equity and water usage from canal and groundwater across the LBDC command. Four water courses were selected at random in the command, well spread from head to tail. The actual discharge being drawn by each outlet was measured at watercourse head; during the time that respective parent channel was flowing at its full capacity. Data of canal water supplies and groundwater pumping on individual basis for each farmer was recorded for the period. The results with respect to water use at farm level on seasonal basis, i.e., Kharif and Rabi, were calculated.

2.8 Groundwater Level Change Analysis

Depth to watertable data from 1987 to 2008 were analyzed by dividing the period in three intervals, i.e., 1987–1996 (pre-drought), 1998–2002 (drought period) and 2005–2008. Temporal change in groundwater level has been calculated on the basis of Canal Divisions in the head to tail direction. Depth to watertable map for the command area was also prepared for June 2008.

Table 3 Irrigation efficiencies adopted for calculation of recharge to groundwater

Component	Efficiency (%)	Remarks
Conveyance system	81.28	LBDC head to minor canals
Watercourse	75	80 % of this recharge to groundwater
Field application	80	75 % of this recharge to Groundwater
Overall	48.75	Available to crop consumptive use

Table 4 Groundwater pumping (MCM) based on field survey data (2005)

Division	CCA (ha)	Groundwater pumping (MCM)			Depth (cm) over CCA
		Kharif	Rabi	Annual	
Balloki	35,674	79	54	133	37.2
Okara	140,096	501	254	755	53.9
Sahiwal	267,306	817	527	1,344	50.3
Khanewal	260,934	727	436	1,162	44.5

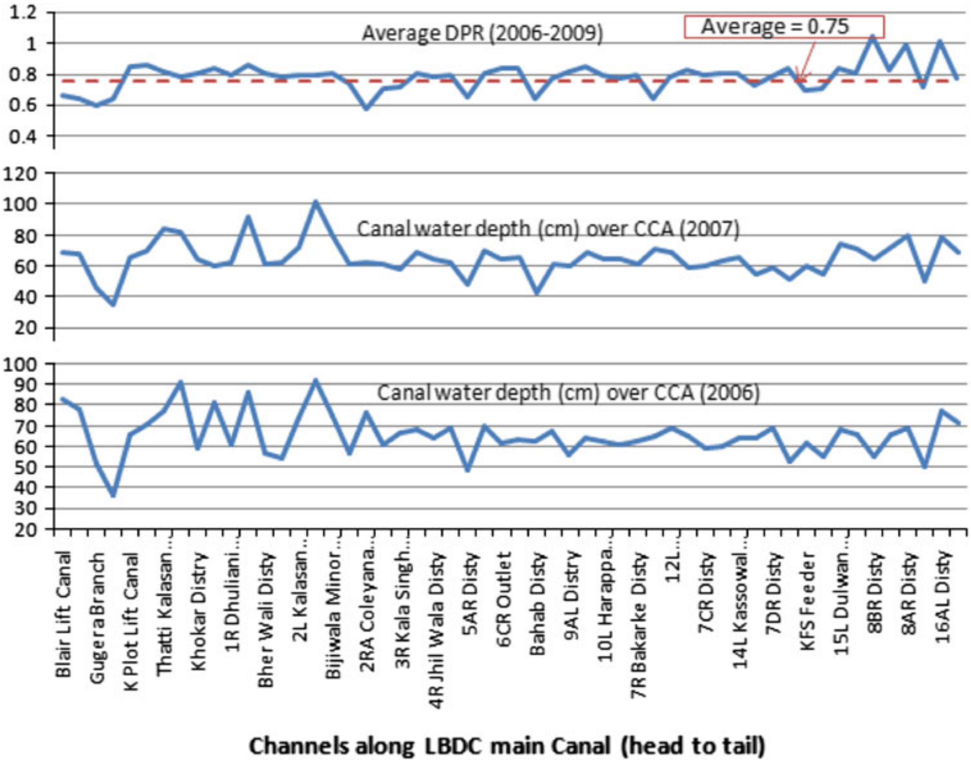


Fig. 3 Equity of canal diversions to off-taking channels from LBDC main canal

3 Results and Discussions

3.1 Canal Command Level Surface Water Equity

Daily DPR values calculated for the off-taking distribution channels from the main LBDC canal varied from zero to about one. Average DPR for the period (2006–2009) is shown in Fig. 3 for these channels. The resulting statistics indicate an average DPR of 0.75, coefficient of variation as 0.11, minimum and maximum DPR of 0.53 and 0.96, respectively. The channel with the minimum DPR is Gugera Branch, lying at the head reach, its capacity has reduced due to deferred maintenance. The channels with maximum DPR are those with small design discharges falling mostly towards tail of LBDC canal. As shown in Fig. 3, most of the channels have DPR values close to the average of 0.75 and variability is found to be random, without any trend towards tail.

Resulting water withdrawals for 2006 and 2007 in the form of water depth distributed over the respective CCA of distribution channels are also shown in Fig. 3. It is seen that the inequity in surface water diversion from head to tail of the main canal is present but, it does not have any trend with respect to head–tail end perspective. The mean canal water diversions are 65.7 and 65.1 cm and the corresponding standard deviation is 10.3 and 11.3 cm, respectively, for 2006 and 2007. The corresponding coefficients of variation were found to be 0.16 and 0.17. So, the data analysis shows that there is no perceptible increasing/decreasing trend in canal diversions in head to tail direction along the main canal. However, other factors such as poor maintenance due to long-term shortage of funds may cause tails of some of the secondary channels to be permanently dry or receiving less share as quoted by Halcrow [15] for tails of Jandraka and 15L distributaries.

Table 5 Interpolated monthly rainfall (mm) for the HSUs

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

Table 6 Interpolated monthly ET$_o$ (mm) for the HSUs

Month	Hydrologically similar units (HSU)							
	1	2	3	4	5	6	7	8
January	63.5	63.2	63.1	63.4	63.9	64.4	64.4	64.9
February	74.2	73.9	73.8	74.0	74.5	74.9	75	75.4
March	122.7	122.5	123.0	123.9	125.7	127.5	127.8	129.4
April	163.6	163.4	163.5	164.1	165.3	166.3	166.5	167.5
May	209.5	209.3	209.8	210.7	212.5	214.3	214.6	216.2
June	231.3	231.5	231.9	232.6	233.9	235.1	235.3	236.4
July	172.1	178.9	185.9	191.3	201.1	210.7	213.1	221.5
August	154.5	159.5	165.7	171.7	182.8	193.4	196.0	205.5
September	171.3	171.5	171.9	172.6	173.9	175.1	175.3	176.4
October	150.8	147.7	146.1	146.3	147.2	147.9	147.9	148.6
November	102.5	99.8	98.3	98.3	98.6	98.8	98.7	99
December	55.7	58.0	60.2	61.7	64.4	67.0	67.7	70.0
Annual	1,671.8	1,679.1	1,693.2	1,710.7	1,743.8	1,775.2	1,782.5	1,810.7

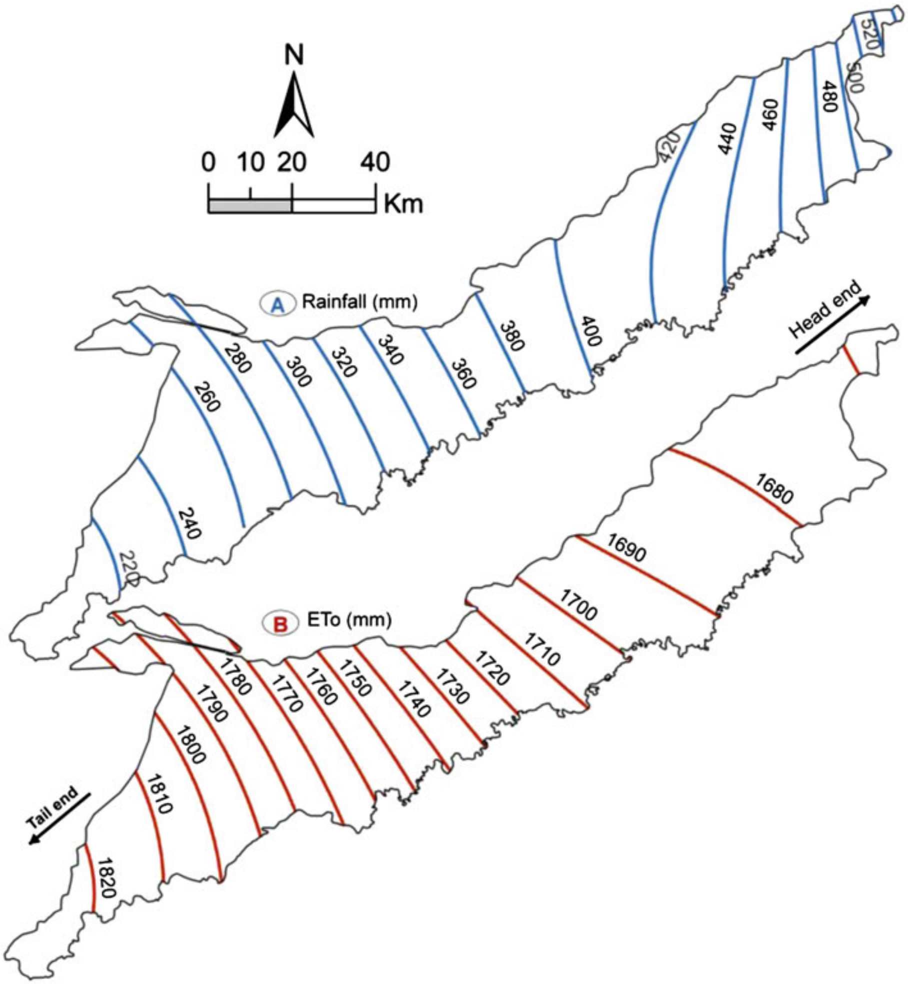
3.2 Rainfall and ET$_o$ Variation

Interpolated monthly rainfall and ET$_o$ for the HSUs are given in Tables 5 and 6, respectively. Annual rainfall decreases from head to tail; the maximum difference between the HSUs is 261 mm. In contrary, reference crop evapotranspiration (ET$_o$) increases from head to tail of the command, the maximum annual difference between HSUs is 139 mm. Spatial variability of these parameters over the LBDC command is shown in Fig. 4 in the form of contours.

3.3 Variation of Net Crop Water Requirement

The variation of ET$_n$ from head to tail across the command is shown in Fig. 5, on HSU basis for wheat, Rabi fodder, cotton, rice, maize, Kharif fodder, Kharif oil seeds, sugarcane and orchard. The tail–head end difference in ET$_n$ determined as $\Delta ET_n = ET_n$ for tail HSU $- ET_n$ for head HSU for each crop is also labeled in the figure. The ET$_n$ increases from head to tail across the command for all the crops. The difference is maximum for the crops cultivated during months in which either the difference (head to tail) is maximum for rainfall or ET$_o$. The months with significant difference in mean monthly rainfall (mm) are January (8.4), February (12.5), March (11.6), June (16.7), and those with striking difference are July (81.3), August (79.0) and September (28.5). Similarly, the months with striking difference in ET$_o$ (mm) are July (49.4), August (51.0) and December (14.3). For wheat/cotton crop rotation with corresponding intensities of 48 and 28 %, respectively, on LBDC basis, the increase in ET$_n$ from head to tail for the two crops is 283 mm (46 + 237) which is 32.5 % of the ET$_n$ at head reach. Assuming same cropping pattern and intensities (158.6 %) across head to tail of LBDC command, annual ET$_c$ requirement at tail HSU is 10.2 % higher than for head HSU. Whereas, ET$_n$ calculated after subtracting effective rainfall for each crop is 33.5 % higher for the tail HSU as compared to head HSU.

Fig. 4 Contours of normal values over LBDC command: **a** rainfall (mm), **b** ET_o (mm)



3.4 Variation of Groundwater Recharge Across the Command

The total groundwater recharge, along with its components, i.e., canal network seepage, watercourse and field application losses and rainfall recharge are shown in Fig. 6. It is seen that the irrigation network (main and secondary canals) seepage decreases from head to tail of the LBDC command. This is due to the decreasing density of the channels (main canal, branches and distributaries) and their discharges towards the tail of the canal system. The watercourse and field application losses joining to groundwater remains equitable with respect to head–tail end perspective. However, there is a possibility of minor variations in this recharge component but that too, within the HSU, mostly due to local inequity at secondary level channels. This minor level local inequity is not considered to be adding towards anomaly in groundwater recharge in head–tail perspective of the canal command. The third component, i.e., rainfall recharge decreases most significantly towards tail end of the command.

Thus, there is a significant reduction in recharge to groundwater, both, from rainfall and canal network seepage. As a result, total recharge to groundwater from all the three components decreases significantly in the downstream direction of the command.

3.5 Water Requirement and Availability

Canal water supplies to LBDC command were analyzed from 2001 to 2009. On an average, 4,847 MCM canal water is diverted to the command, out of this 1,648 and 3,199 MCM are supplied during Rabi and Kharif seasons, respectively, which corresponds to 23.31 and 45.24 cm, respectively, over the CCA. Monthly crop consumptive use requirement and diversions to LBDC, along with canal water availability at field level (after conveyance losses and deep percolation at farmer's field) for LBDC command is shown in Fig. 7. Of the total canal supplies, 48.75 % are available for crop consumptive use and about 44.12 % adds to groundwater during

Fig. 5 Comparison of ET_n for main crops on HSUs basis (head to tail) of LBDC command

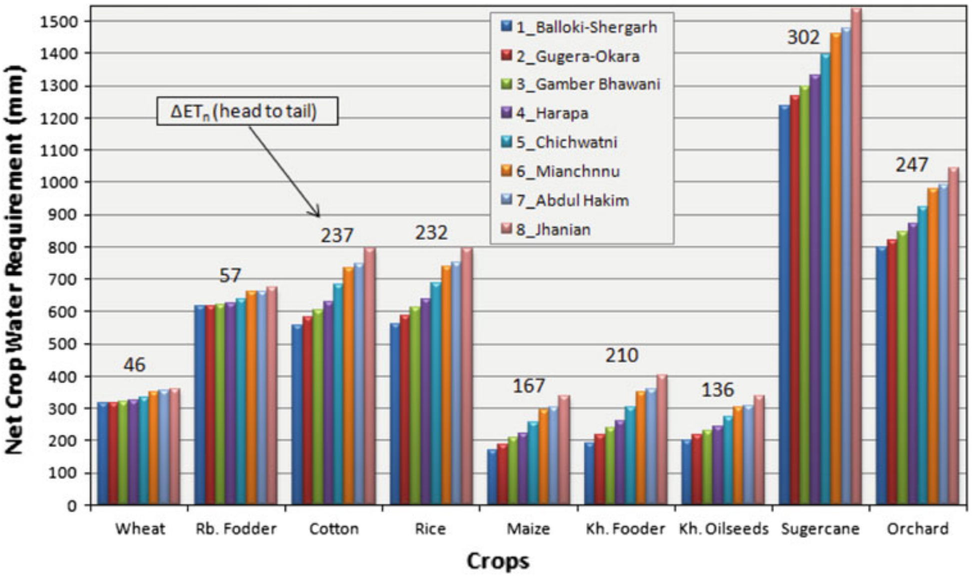
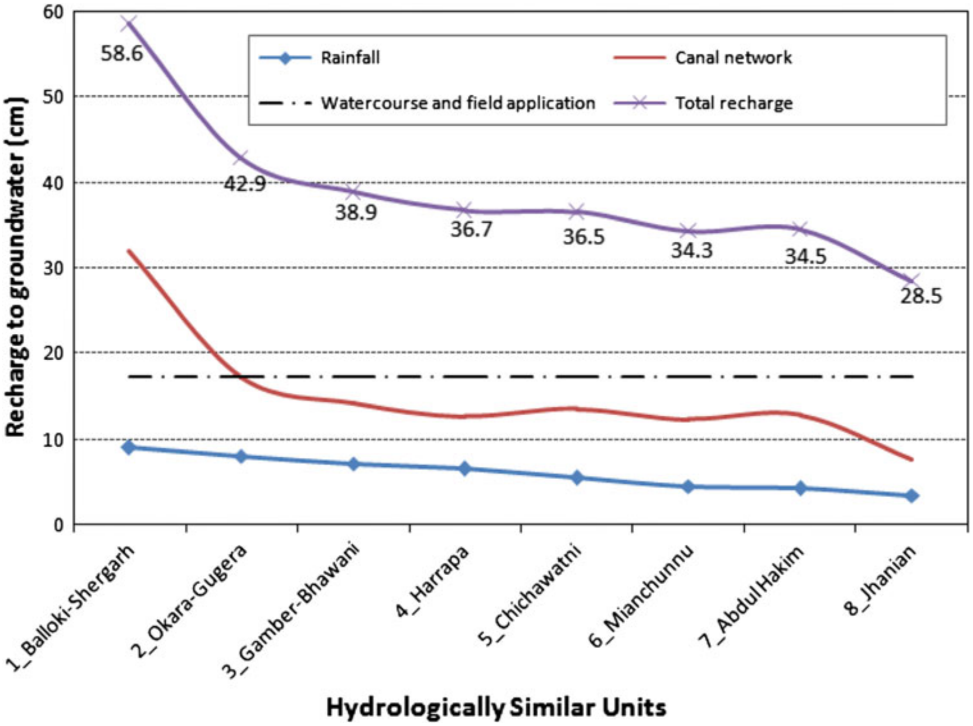


Fig. 6 Variation of groundwater recharge from head to tail of the LBDC command



conveyance through canals and watercourses and field application losses. The rest (7.11 %) is considered to be evaporating to the atmosphere (non-beneficial losses) within the conveyance or after seepage losses from the channels. On an average, the net canal supply available to the crops equals to about 33.8 % of crop consumptive use requirements. And the remaining shortfall between the requirement and net canal supply is partly met from groundwater reservoir.

3.6 Combined Equity of Canal and Groundwater Usage Across LBDC Command

The watercourse discharge measurements (Table 7) show that watercourse nos. 1 and 3 are drawing their design share, while no. 2 is drawing significantly in excess and the no. 4 slightly higher than the design discharge. These anomalies in watercourse discharge are wide spread but are accepted

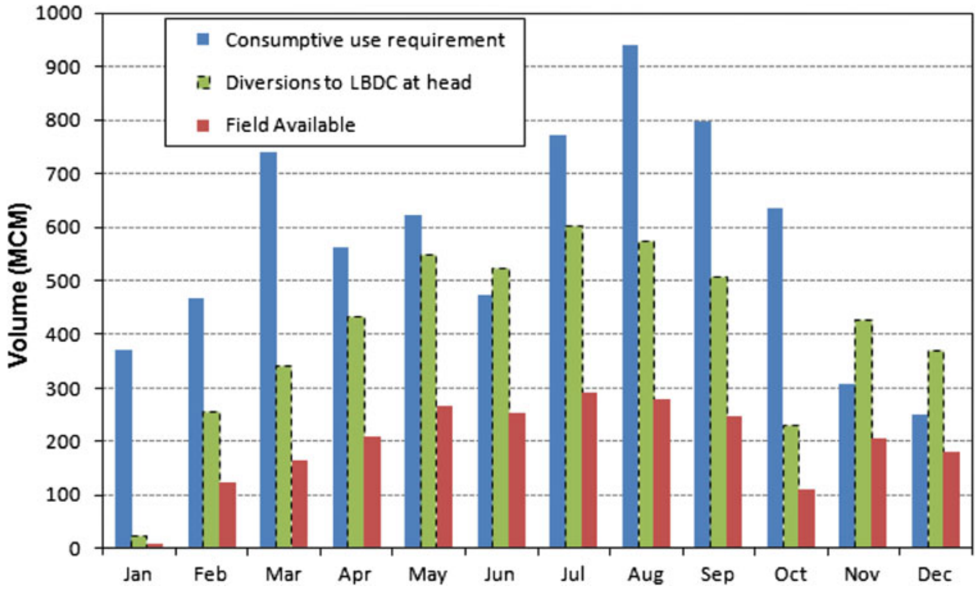


Fig. 7 Crop consumptive use requirement and availability at field level for LBDC command

Table 7 Salient features of selected watercourses (head to tail of LBDC command)

S. no.	Watercourse number	Distance from LBDC head (km)	Canal division	Parent channel		Watercourse		
				Name	Discharge (m^3/s)	Designed (m^3/s)	Measured (m^3/s)	CCA (ha)
1	26030R/1R	48.39	Okara	1R	2.311	0.0413	0.0405	177.3
2	31200L/5L	94.96	Sahiwal	1R/5L	1.047	0.0487	0.0731	209.3
3	60750R/1R-12L	161.98	Sahiwal	1R/12L	4.842	0.0526	0.0479	204.0
4	60630R/2L-10R	237.24	Khanewal	2L/10R	3.087	0.0531	0.0625	227.8

Table 8 Field measured water usage (cm) at watercourse level

Watercourse no.	Kharif			Rabi			Annual		
	Canal	T/W	Total	Canal	T/W	Total	Canal	T/W	Total
26030R/1R	33.2	60.4	93.3	19.8	12.5	32.3	53.0	72.8	125.9
31200L/5L	55.2	15.5	70.4	32.0	21.6	53.6	86.9	37.2	124.1
60750R/1R-12L	34.1	32.0	66.4	24.4	22.9	47.5	58.8	55.2	113.7
60630R/2L-10R	39.3	32.2	72.8	–	–	–	–	–	–

T/W tubewell

as norm in Pakistan's irrigation system due to socio-political interference in canal water management. Table 8 shows that annual water usage (canal plus ground water) remains quasi-equitable with slight decrease from head to tail of the LBDC command. Based on this field data of watercourses and canal water diverted to channels off taking from the main canal (Fig. 3), it is viewed that there is not any decreasing trend in canal water distribution in the downstream direction of LBDC canal command. Also that canal water distribution is equitable, in general, up to the head of the tertiary channels called watercourses. However, other factors such as poor maintenance due to long-term shortage of funds may cause some tails of a very few secondary/minor channels to be permanently dry or receiving less share [15]. But this type of poor maintenance has only local scale impact on groundwater conditions in the command area of the channel concerned.

With regard to groundwater use, Fig. 8 shows that tubewell water usage is highest for Kharif season for the upper reaches due to the watertable being shallow and the low pumping cost. This is also supported by high density of tubewells and relatively more rice cultivation in Okara Division as reported by NESPAK [33]. Based on groundwater pumping data of Table 4 and water usage on watercourses level (Table 8), it is concluded that groundwater usage decreases slightly towards tail of the command. But, the additional stress on groundwater in tail areas is due to higher net crop water requirements (Fig. 5) and low recharge rates (Fig. 6). This is also supported by low cropping intensities towards tail as compared to head reach, i.e., for Khanewal Division, cropping intensity has

Fig. 8 Water usage at watercourse level in four selected watercourses in LBDC (2008–2009)

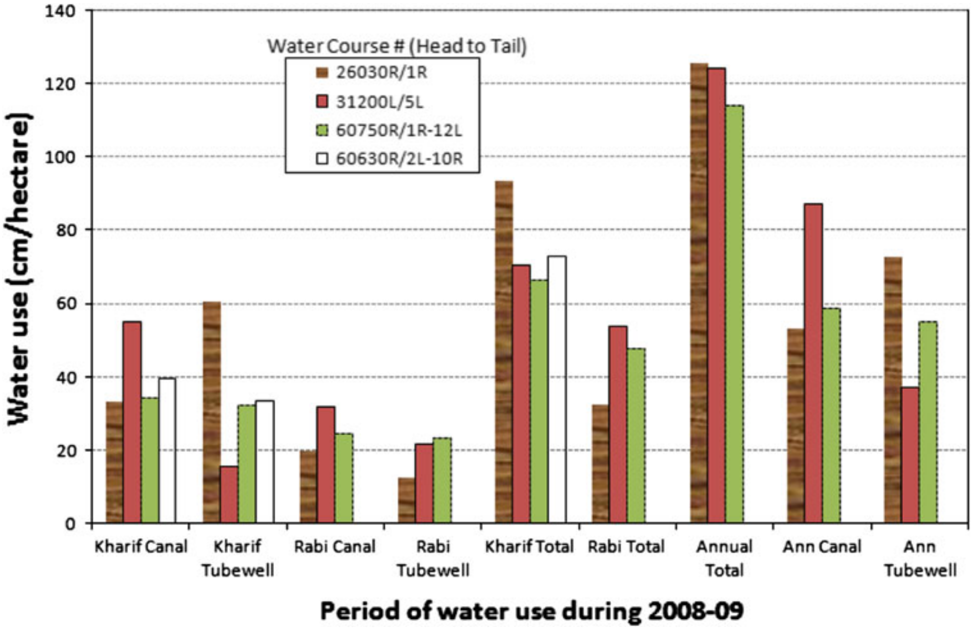
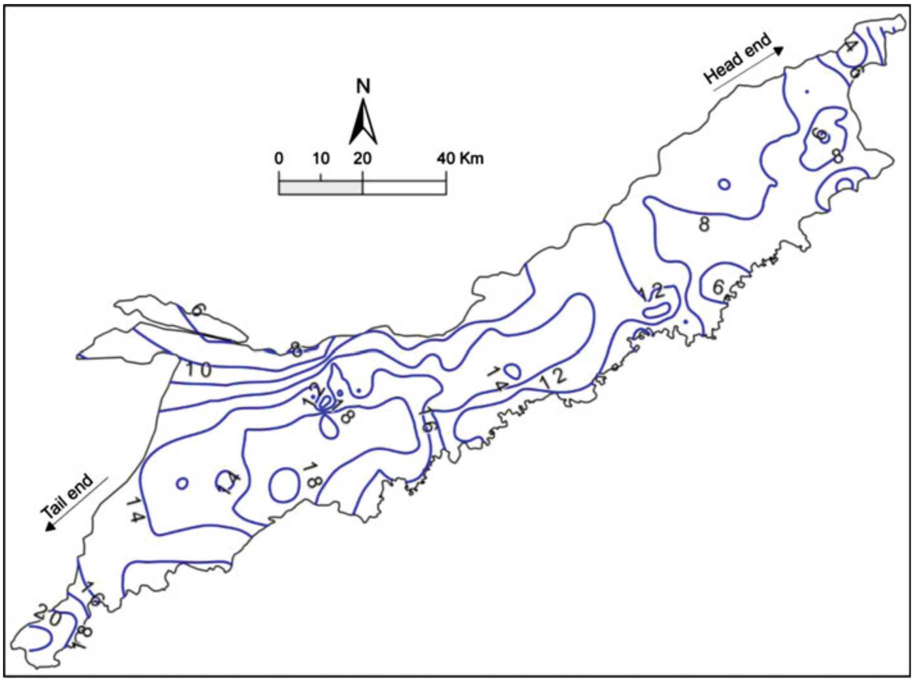


Fig. 9 Increasing depth to watertable (m) from head to tail in LBDC command (June 2008)



been reported as 148 % in comparison to 160.1 % on LBDC command basis [33].

3.7 Inequity of Depth to Groundwater and Depletion Rates

The depth to groundwater varies from 4–8 m in head reach as compared to 12–20 m in tail reach as depicted by the depth to watertable map for June 2008 (Fig. 9). Deepest depth to groundwater has been observed as 21.46 m (October 2009) in the observation well near tail end of the LBDC command in Khanewal Division. The depth to groundwater hydrographs for selected observation wells in the command are shown in Fig. 10 and the calculated groundwater depletion rates for different periods between 1987 and 2008 are given in Table 9. Currently (2005–2008), the groundwater table depletion rate is highest (0.34 m/year) in Khanewal Division, the tail reach of LBDC command, followed by Sahiwal Division (0.18 m/year), whereas the groundwater levels in Balloki and Okara Divisions (upper reaches) are stable. On the contrary, higher groundwater depletion rates of 0.94 m/year in

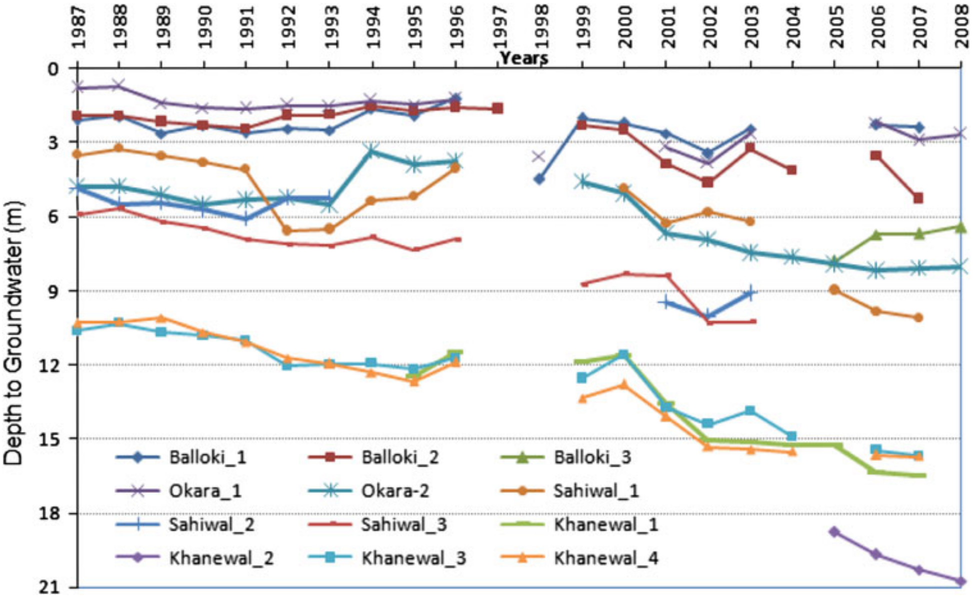


Fig. 10 Depth to groundwater hydrographs for selected wells in four divisions of LBDC (gaps show data not available)

Table 9 Change in depth to watertable (per year) over different periods in LBDC command

LBDC division	1987–1996		1998–2002 (drought)		2005–2008	
	No. of wells	Change (m)	No. of wells	Change (m)	No. of 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

−, rising watertable

Okara division (head reach) during drought period (1999–2002) as compared to corresponding 0.53 m 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. The results have shown that groundwater depletion is highest in tail end of the command and the situation is stable in head end areas, the reasons are threefold, i.e.:

- Decreasing rainfall towards the tail end,
- Increasing crop water demand towards tail end, and
- Higher channel network seepage in the head end side.

4 Conclusions

On an average, the net canal supply available to the crops in LBDC command equals to about 33.8 % of crop consumptive use requirements. The difference between the crop water requirements and surface water supplies has forced farmers to pump groundwater for supplementing the deficit in supply and demand at farm level though to varying degrees depending upon canal supply, crops cultivated and rainfall. In fact, much of the groundwater that is pumped by the farmers is actually a by product of canal irrigation systems at various levels and annual rainfall. Spatial climate variability within the irrigation system in Indus Basin has created differential variations in rainfall and as a result, in irrigation water demand.

The paper has clearly demonstrated that there is momentous increase in crop water demand towards tail within the LBDC command, particularly during Kharif season, but the irrigation system design has ignored this anomaly by equitably allocating canal water. In addition, rainfall and groundwater recharge, both from rainfall and irrigation conveyance system, decrease towards tail end. Ignoring spatial climate variability within the canal command is one of the serious issues in the design of irrigation system that prevents achieving the optimal level of conjunctive water use and as a result, the highest potential agricultural output cannot be achieved. These head–tail end anomalies in irrigated hydrology at canal command level are causing groundwater mining towards tail areas, particularly in upper and central Punjab, where climate becomes rapidly arid in the downstream direction. In the current scenario of increased groundwater use, the business as usual will be adding further miseries to the tail end farming community. As suggested by Qureshi et al. [34], the demand side management, e.g., improved irrigation and agronomic practices might partially improve the situation, but supply side management in the form of waste water and saline drainage effluent may not be viable because these highly depleted groundwater areas are mostly away from such sources. So, the only promising option is to ponder on fixing extra water allowance and/or diverting flood flows during wet years for compensation of low recharge in these ever depleting tail end areas of the canal commands. This reallocation means revisiting the water allowances on the basis of crop water requirement, rainfall and groundwater use potential for irrigation. In this way, over use of groundwater as pointed out by Qureshi [34] as a major problem in Pakistan, mostly in head end areas, can also be avoided and fruitfully utilized in the highly depleted groundwater areas that mostly lie in tail reaches of the canal commands. This reallocation of water will help to further increase cropping intensities at tail ends of the commands which are low as compared to head ends, thus ensuring maximum economic return from canal water.

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