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Groundwater Model for the Lower Bari Doab Canal, Punjab, Pakistan

Report No. 158

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Contents

List of Tables

List of Figures

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
ADB	Asian Development Bank
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Data
EA	Executing Agency
EC	Electrical conductivity (1 mS cm^{-1} = 1dS m^{-1} = 1000 µS cm^{-1})
FO	Farmers Organization
GDP	Gross Domestic Product
GOP	Government of Punjab
HSU	Hydrologically Similar Units
IA	Implementing Agency
IWMI	International Water Management Institute
LBDC	Lower Bari Doab Canal
LBDCIP	Lower Bari Doab Canal Improvement Project
LCC East	Lower Chenab Canal East
MAR	Managed Aquifer Recharge
NDC	National Development Consultants
NDVI	Normalized Difference Vegetation Index
NESPAK	National Engineering Services Pakistan
PID	Punjab Irrigation Department
PIDA	Punjab Irrigation and Drainage Authority
Ppm	Parts per million
R.C.P	Representative concentration pathway
RSC	Residual Sodium Carbonate
SAR	Sodium Adsorption Ratio
SCARP	Salinity Control and Reclamation Project
SEBAL	Surface Energy Balance Algorithm for Land
SRTM	Shuttle Radar Topography Mission
TMR	Telescopic Mesh Refinement
UAAR	Arid Agriculture University, Rawalpindi
UNDP	United Nations Development Programme
USGS	United States Geological Survey
WAPDA	Water and Power Development Authority
WASID	Water and Soil Investigation Division

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1 Executive Summary

Groundwater (GW) is considered as one of the most important but scarce natural resources in many arid and semi-arid regions of the world. GW contributes around 55% of the crop water requirements globally. Under changing climate, increased over extraction of GW for irrigation is considered as the main threat for coping with surface water scarcity. Many studies globally have reported that GW extraction is exceeding GW recharge for large areas, which over time causes persistent GW depletion. A comprehensive knowledge on inflows and outflows from the aquifer is prerequisite for sustainable GW management and policy.

The districts of Okara and Sahiwal in the Lower Bari Doab (LBDC) Canal command area, selected for this modelling study, are situated in the Punjab province of Pakistan. The LBDC is a major part of the larger Indus River Irrigation System in Pakistan, and provides an example of an area facing irrigation and drainage issues including reduced surface water supplies. Farmers there rely on groundwater as a safety net to meet crop water requirements, but its use also leads to declining groundwater levels, and deteriorating soil health from using poor quality groundwater. The model covers an area of 0.78 million ha of irrigated land. The present irrigation system in the Lower Bari Doab consists of 2,264 km of distributaries, 201 km of main canals and 95 km of link canals, and over 60,000 tubewells which are installed in the freshwater areas.

The hydrogeology of LBDC consists of a deep unconsolidated and unconfined aquifer. The major contribution to groundwater levels is due to seepage from rivers, canals, and farmers' fields with very low lateral flows. This shows that surface and groundwater levels are highly interconnected which is mainly due to the light texture of the soils.

To assess the implication of groundwater pumping on groundwater levels in LBDC command area under several biophysical and socio-economic scenarios, a regional groundwater flow model using MODFLOW was developed. This GW model captures the spatial and temporal variations of the factors affecting GW levels. We envisaged that this study will assist policy makers in the region to improve understanding of the sustainability of groundwater usage and provide guidance for future investments to achieve this goal. The custodian of this GW model is the Punjab Irrigation Department (PID). Our approach was to work closely with PID to develop the model and to build capacity of mid-career professionals within the PID in groundwater modelling.

The major components of the water balance are recharge from rainfall, river leakage, canal leakage and irrigation recharge which accounts for 90 percent of inputs to the system. Based on the calibration period from September 2009 to October 2015, we recommend pumping from the Lower Bari Doab should be managed around 4300±215 MCM/year depending on the need for pumping in response to drought and or lack of surface water supplies. When surface water supplies are plentiful pumping levels should be decreased so that the groundwater system gets recharged with freshwater. Additionally, PID may want to consider establishing managed aquifer recharge (MAR) schemes in specific suitable areas of Lower Bari Doab where GW levels are sufficiently deep and where soil conditions are favourable for establishing MAR schemes.

The water balance for case studies of 1-R in Okara and 11-L in Sahiwal districts was extracted from the regional Lower Bari Doab model to understand groundwater usage in our case study sites. The water balance for 1-R in Okara district shows pumping for 1-R is 7.53 MCM which consists of about 45% of inflows from recharge and canal seepage. By considering only the inflows one could allow for an increase in pumping from 1-R, however, the net balance for 1-R is -0.85 MCM, which is due to significant outflows of 22.38 MCM from 1-R to the surrounding areas of Okara.

The water balance for the top three layers for the Lower Bari Doab Canal model shows flows from layer 3 to the upper layer 2 is 786 MCM/year. This has the potential for salt transport upwards from the deeper aquifer which is known to have higher salinities. Thus there is a need to manage both pumping from shallow areas in both fresh water and saline groundwater areas as well as pumping from deeper parts of the aquifer as the latter has the potential for mobilizing salt transport. The water balance for layer 3 shows that the deepest layer is in balance with a net flow into the layer of 1.2 MCM/yr. In the Indus Basin salinity generally increases with depth, thus keeping the third layer in equilibrium and minimizing the risk of higher salinity groundwater flowing upwards from the deeper layers. However, continued increase in tubewell irrigation from the second layer will likely result in a reversal of gradients which will increase salinity of irrigation water ultimately impacting crop yields and soil structure.

Seven future groundwater scenarios were undertaken, as per recommendation of PID officials, from September 2015 to October 2035 to evaluate aquifer status in future, and to assess the availability of groundwater for irrigation (see Table 1 below). The results of Business as Usual (no change) scenario indicates that if conditions remained similar to the September 2015 to October 2035 period then pumping of 4316 MCM/yr will not result in significant drawdowns. However in Scenario 2 a 20% increase in pumping will result in reduction of net groundwater storage by 146 MCM/yr. The trend in incresed pumping has been due to increase in population, and increase in cropping intensity to meet food requirements, while surface water supply is constant.

Table 1: Results from the calibrated model and scenarios

<table>
<tr><th></th><th>Model</th><th>Okara</th><th>Sahiwal</th><th>1-R</th><th>11-L</th></tr>
<tr><td rowspan="2">C1: Calibrated model Oct 2009–Sep 2015</td><td>GWS=87.9 MCM/yr
SEL=4300±215 MCM</td><td>GWS = 80.9
SEL=740±37</td><td>GWS = 5.84
SEL=1830±92</td><td>GWS = -0.85</td><td>GWS = 7.14</td></tr>
<tr><td colspan="5">The Calibrated model indicates surplus groundwater storage for LBDC. However, some areas will require management as pumping is likely to keep increasing in the future.
For 1-R and 11-L Extended calibration period required to recommend SEL</td></tr>
<tr><td rowspan="2">S1: Business As Usual</td><td>GWS = 78.12</td><td>GWS= -5.45</td><td>GWS= 25.06</td><td>GWS= -0.88</td><td>GWS= 2.58</td></tr>
<tr><td colspan="5">For BAU scenario if conditions remained similar to the Oct 2009 to Sep 2015 up to 2035 then pumping of 4316 MCM/yr will not result in significant drawdowns. The BAU scenario shows surplus groundwater storage for LBDC. However, hotspots will likely develop in individual areas and will need to be managed as pumping is likely to keep increasing in the future.</td></tr>
<tr><td rowspan="2">S2: Pumping Increased 20%</td><td>GWS= -146.06</td><td>GWS= -40.17</td><td>GWS= -80.00</td><td>GWS=-2.91</td><td>GWS=-5.46</td></tr>
<tr><td colspan="5">Increasing pumping by 20% will result in water level declines which will likely induce lateral intrusion of saline groundwater and may also mobilse higher salinity groundwater from deeper layers of the aquifer.</td></tr>
<tr><td rowspan="2">S3: Pumping Increased 20% and canal supply decreased 5%</td><td>GWS=-143.86</td><td>GWS= -41.78</td><td>GWS= -84.48</td><td>GWS=--2.96</td><td>GWS=-5.11</td></tr>
<tr><td colspan="5">Increasing pumping by 20% coupled with 5% decrease in canal supplies will result in water level declines which will likely to induce lateral intrusion of saline groundwater and may also mobilse higher salinity groundwater from deeper layers of the aquifer. Decrease in canal supplies also results in falling water tables which reduces ET from -204.7 MCM for Scenario 2 (20% increase in pumping) to -154.76 MCM for Scenario 3 which results in slightly higher groundwater storage for Scenario 3.</td></tr>
<tr><td rowspan="2">S4: Pumping increased 10% and Canal supply increased 5%</td><td>GWS=44.43</td><td>GWS= -11.28</td><td>GWS= 7.29</td><td>GWS=-1.28</td><td>GWS= 0.94</td></tr>
<tr><td colspan="5">GWS is positive indicating that with increased pumping an increase in canal supplies will alos be required</td></tr>
<tr><td rowspan="2">S5: Pumping decreased 10%</td><td>GWS=162.97</td><td>GWS= 8.33</td><td>GWS= 68.54</td><td>GWS=0.0</td><td>GWS=6.34</td></tr>
<tr><td colspan="5">Additional net water available is due to reduced groundwater pumping equating to 116 mm rise in groundwater depth across the LBDC, however, individual areas will recover more depending on the spatial distribution of pumping.</td></tr>
<tr><td rowspan="2">S6: RCP 4.5</td><td>GWS=34.25</td><td>GWS= 8.85</td><td>GWS= 15.69</td><td>GWS=0.92</td><td>GWS=6.30</td></tr>
<tr><td colspan="5">Recharge has decreased by about 1% in comparison to the BAU scenario. This decrease is due to the variation of rainfall in the study region. Higher individual rainfall events have resulted in rising water tables which has decreased ET from the agriculture fields.</td></tr>
<tr><td rowspan="2">S6: RCP 8.5</td><td>GWS=179.20</td><td>GWS= 22.38</td><td>GWS= 81.47</td><td>GWS= 1.67</td><td>GWS= 26.65</td></tr>
<tr><td colspan="5">Recharge increased by 460.7 MCM in LBDC area Groundwater levels are likely to rise rapidly in response to higher rainfall in the upper aquifer (<30 m) in study area, and PID would need to manage waterlogging in some areas which had largely abated due to the increase in pumping in the Lower Bari Doab.</td></tr>
</table>

Note: GWS – Groundwater Storage MCM/yr; SEL – Sustainable Extraction Limit MCM/yr;

Results of Scenario 3 (with the increase in 20 percent groundwater usage the surface water supplies also reduced by 5 percent) shows that the net change in groundwater storage will be -144 MCM/yr over the whole LBDC area. It will result in average decline of 102 mm/yr in depth in LBDC. Whereas, in Scenario 4, a 10% increase in GW pumping with 10% increase in canal water will not result in significant drawdowns in groundwater levels. Furthermore, if PID manages to reduce pumping by 10% (Scenario 5) a saving of 163 MCM/yr of groundwater is possible. The water balance for climate scenarios R.C.P 4.5 shows that the gain of net groundwater storage is 34 MCM/yr, with no change in pumping. This shows that improved controls on pumping as mentioned in the National Water Policy (2018), will achieve greater water savings. Therefore, PID needs to focus on effort to enhance water efficiencies significantly to avoid the increase in groundwater pumping in the study area. Comparing scenario 7 (climate change scenario R.C.P 8.5, which predicts the extreme events of rainfall) with scenario 1 (Business as Usual) we find that if climate conditions remain as defined in R.C.P 8.5 data an estimated 179 MCM/yr of additional water will be stored in the underlying aquifers of LBDC.

The project outcomes will support PID in implementing more equitable, economically efficient and sustainable canal and groundwater management options for Lower Bari Doab and build capacity to utilize groundwater models for planning improved water management outcomes in the Lower Bari Doab. Finally the report makes specific recommendations for improved governance of groundwater and to assist PID in establishing a groundwater group which will be responsible for improved sustainability of groundwater in the four major doabs in Punjab.

2 Introduction

Pakistan, a farming nation, lies in an arid to semi-arid region where its agricultural production relies on access to a combination of surface and groundwater for irrigation (Archer et al., 2010; Qureshi et al., 2010a). The normal yearly precipitation changes from under 200 mm in most parts of southern Pakistan to more than 1500 mm in northern areas. (Archer et al., 2010; Archer and Fowler, 2004). In addition to the 5 Mha of barani or rain fed agriculture, there is 17 Mha of irrigated agriculture. Surface water for irrigation comes from the Indus River and its tributaries and is supplied via a vast network of irrigation canals and distributaries. The supply of river water varies seasonally and ranges from less than 123 billion cubic meters (BCM) during the dry period to more than 185 BCM during floods and in heavy rainfall seasons.

Globally, a huge amount of water is consumed for agricultural production. Agriculture consumes about 70% of the worldwide water withdrawals (Döll, 2009; Siebert et al., 2010). The area irrigated comprises about 20% of the worldwide cropland, however it contributes over 40% of the worldwide production of food (Döll and Siebert, 2002). Surface water is the main source of water for crops (58%), and groundwater (42%) is also a major contributor to irrigation. As of now, the contribution of groundwater is around 42% of the worldwide supplies of irrigation (Doell et al., 2012; Rodell et al., 2009; Siebert et al., 2010). The groundwater irrigated area is approximately 113 (Mha) and this represents around 38% of the irrigated area worldwide (Siebert et al., 2010). The incredible intensification in the use of groundwater in the past 50 years has resulted in widespread use of tubewells, not only in Pakistan but all over the world (Scanlon et al., 2012; Schwartz and Ibaraki, 2011).

The expanding reliance on groundwater is resulting in higher rates of extraction. As a consequence, groundwater resources are deteriorating in many parts of the world. Globally, the volume of groundwater that is extracted (1,500 km^3) is far lower than the volume of groundwater being recharged (12,600 km^3), however, in many areas, groundwater resources are in steady decline (Döll, 2009; Konikow, 2011; Scanlon et al., 2012; Wada et al., 2010). Aeschbach-Hertig and Gleeson (2012), studied groundwater extractions and remapped the world groundwater consumption rates and this demonstrated that the highest rates of groundwater extraction were in the USA, followed by China, India and Pakistan.

It is broadly perceived that Pakistan lies among the nations where increased extraction of groundwater is taking place (Khan et al., 2008a; Wada et al., 2010). Pakistan uses about 9% of the worldwide groundwater extractions, and is the third largest groundwater consumer (Giordano, 2009). About 5.2 million hectares of land is being irrigated in Pakistan by groundwater which constitutes about 4.6% among the worldwide groundwater-sustained cropland (Siebert et al., 2010). Current agricultural practices in Pakistan were developed during the ‘green revolution’ in the 1960s when high yield varieties of crops were introduced and adopted by farming communities. In addition to producing higher yields, these crops required significantly more water (Ahmad et al., 2004), and so endeavours to increase water supplies to the crops were made. Canal irrigation systems were developed, and accessibility of these system allowed landowners to control the quantity and timing of water application and provided protection against crop failures. However, the efficiency of irrigation systems in Pakistan is very low at around 35% and this is because of losses of water that occur from conveyance and application in the field (Hussain et al., 2011). Most of the land in Punjab that is being cultivated under canal command irrigation is flat and most of the fields are levelled and farmers grow row crops and irrigate them by using water intensive flood irrigation method (Ashraf et al., 2010).

Pakistan is becoming a water scarce country as per capita water availability is now about 1000 m^3, classifying the nation as water scarce (DAP, 2016). It is predicted that with the likely increase in demand for water from population growth and urbanisation, water accessibility will be further reduced to 915 m^3 per capita in 2020 (GOP, 2011). As such, the key factor in future farming and cropping development will be the efficient use of groundwater resources, which will require a different approach with respect to water use and water productivity needs to increase by 0.1 kg/m^3 (GOP, 2011).

At present the irrigation system diverts 129.7 BCM (106 MAF) of water and the irrigated area is about 17.2 Mha. The amount of cultivable land that isn't presently used for cultivation is about 9.2 Mha (Arshad et al., 2005). The canal irrigation system provides nearly 40% of the crop water requirements in the field and the remaining 60% of the water is provided by groundwater extraction in the area (Awan et al., 2013). Arshad et al. (2005) estimated that in Punjab Province, farmers are pumping 59 BCM of groundwater annually to supplement surface water supplies. This is resulting in an annual groundwater depletion in the Indus Basin of about of 1 BCM (Young et al., 2019). Reduced surface water supplies will reduce the groundwater recharge rates and can impact shallow ground water levels. Rising water shortage due to reduced availability of surface water supplies, losses in irrigation system, and increasing agricultural intensity for increasing population are the most important elements constraining farming in Pakistan. Use of groundwater now constitutes in excess of 50% of the aggregate water supplies of the system (Awan et al., 2013). Utilization of groundwater is considered an important factor for improvement in agriculture sector (Khan et al., 2008b; Qureshi et al., 2010b)

The capacity to estimate groundwater recharge is critical in hydrogeologic studies. Approaches for estimating groundwater recharge include using a water budgeting technique or taking the product of water level fluctuation in a well with the specific yield of the geologic formation. The widening gap between water demand and supply requires more efforts to find productive use of this resource. In Pakistan, several management strategies are being adopted that may help in directly or indirectly managing groundwater more sustainably. These include on-farm interventions such as laser land levelling, water course improvement, High Efficiency Irrigation Systems (HEIS), and the introduction of different crop varieties. Off-farm interventions such as lining of canals, construction of small dams and reservoirs are also being used. However, to-date, success has remained limited.

Punjab Province is Pakistan's most populous province and is also the largest agricultural producer in the country. As such, from a food security perspective, Punjab is a major contributor towards the country's economy and food production (Hussain, 1993). Recharge to groundwater and its extraction are the most important factors in this scenario (Cheema et al., 2014) . Researchers have successfully used the various forms of remotely sensed data to estimate the distributed recharge in various parts of the world (Huang et al., 2013; Szilagyi et al., 2011; Yin, 2011). To appraise actual evapotranspiration (ETa) in the watershed, time series of satellite product images will be taken, which are further analysed by means of modelling approach. Appropriate physically based hydrological models can estimate ETa yet require detailed field information which are often inaccessible in numerous river basins of the world. These remote sensing techniques give an effective approach to estimate ETa from the size of an individual pixel up to a whole raster picture. Different strategies have been utilized for evaluating groundwater recharge including use of lysimeter along with the point estimation strategy, applying the water balance approach to complete basin analysis (Liaqat et al., 2016; Maréchal, 2006; Mjemah et al., 2011). The above techniques did not consider the impact of various factors that vary spatially, having influence of groundwater recharge (Awan et al., 2013). In the present report, effect of spatial variability has been studied by selection of various sites taking influence of ET, rainfall and irrigation.

There is considerable potential to improve groundwater management practices to enhance crop production and improve farming livelihoods. The continuous decline of groundwater levels observed throughout the Punjab and in some places in the Indus Basin points to an imbalance between extraction and recharge (Ashraf and Ahmad, 2008). Innovative management strategies are needed to enhance groundwater supply and manage demand more effectively. Even a modest increase in groundwater productivity will have significant benefits given that over 50% of Pakistan's irrigation requirements come from groundwater (Qureshi et al., 2010b). Farmers with access to groundwater have been observed achieving 50-100% higher crop yields than those using surface water only (Qureshi et al., 2010b). On the other hand, losses result from inadequate land and water management, including the mismanagement of groundwater. Almost 27% of the Indus Basin is salt affected (WAPDA, 2006), 81% of Sindh area is waterlogged (WAPDA, 2005), and 56% of Sindh's irrigated lands are salt-affected (Bhutta and Smedema, 2007), all resulting in considerable losses in production.

Computer-based modelling has always remained a very good option as the most efficient and effective tool to improve understanding of the groundwater systems. Modelling also provides optimization and best management strategies running various scenarios before the implementation; eventually saving time, money, and cost. There are various groundwater and surface water models that simulate the performance of canals and tubewells along with crop yields. The United States Geological Survey (USGS) has developed MODFLOW and other updated versions of MODFLOW for study of groundwater and surface water.

In this research, MODFLOW is used to simulate different management options in the Lower Bari Doab Canal (LBDC) command area. The LBDC irrigation system falls in the centre of the Bari Doab, the area bounded by River Ravi and river Sutlej. LBDC was constructed from 1909 to 1912 with a total length of 201km covering an area of 740,674ha, off-taking from Balloki Headwork on the left bank of the River Ravi. The LBDC canal supplies water to a total of 65 distributaries, out of which 45 fall in the study area Figure 2.1.

Agriculture is mainly carried out with canal water supplies supplemented by groundwater use. The system was originally designed for a cropping intensity of 60% with a design discharge of 190 m^3/s (6,700 cfs) which has risen to 200% over the years with revised design discharge of 311 m^3/s (11,000 cfs) in 1984. After a hundred years, it has almost deteriorated and become inefficient in delivering optimal water supplies for agriculture. So, currently the maximum design discharge capacity of LBDC is 250 m^3/s (8,600 cfs). In the present scenario of insufficient surface water supplies groundwater extraction exceeds 50% for fulfilling crop needs. This is resulting in the groundwater table decreasing at the rate of 0.55 m/yr for the Lower Bari Doab (Basharat and Tariq, 2015).

2.1 Project objectives and outputs

This project was undertaken as part of a larger ACIAR-funded project, “Improving groundwater management to enhance agriculture and farming family livelihoods in Pakistan” (project LWR036). The aim of this larger project was to *build capacity* to improve groundwater management to enhance agriculture and farming livelihoods in Pakistan. The project used case study sites across three provinces, Punjab, Sindh and Balochistan. A key objective of this larger project was to collaboratively develop groundwater management tools and options that have the potential to enhance livelihoods of farming families. Under this objective, this project was designed to develop a groundwater model for the case study site in the Punjab Province, the Lower Bari Doab Canal (LBDC) command area (Figure 2.1). Groundwater models have also been developed for case study sites in Sindh and Balochistan Provinces. The groundwater models that have been developed collaboratively with the relevant Irrigation Departments from Sindh, Punjab and Baluchistan are the central focus for building capacity in-country to improve monitoring, modelling and management of groundwater.

The development of the groundwater model for the LBDC in Punjab includes the districts of Okara and Sahiwal where groundwater is used for irrigated agriculture. In these areas, the groundwater has accumulated due to seepage from the rivers as well as from the LBDC canal and its distributaries and major link canals. The development of a groundwater model enabled an in-depth analysis of the water balance in order to estimate sustainable yield from the freshwater lens. Moreover, the model allowed scenario analysis to be undertaken to improve understanding of the impact of growth in groundwater usage, reduction in canal supplies, and the impact of an uncertain climate future. This sub-regional model also allows for interrogation of zonal water balances to better understand groundwater dynamics at the case study sites for 1-R in Okara district and 11-L in Sahiwal district.

The main issues facing the development of models in Punjab is the lack of long-term groundwater monitoring data. The Department of Land Reclamation (DL) has made a concerted effort to establish several hundred monitoring bores which are monitored during pre- and post-monsoon seasons since about 2008, although there are some records from 2005. Although the Punjab Irrigation Department (PID) has been monitoring bores particularly in the Eastern doabs, there is an urgent need to improve data quality, archiving and accessibility of data. It is imperative that the

PID take the lead on establishing a groundwater monitoring strategy for regular and strategic monitoring of groundwater resources in Punjab. Spatial and temporal groundwater information are key elements for improving understanding of groundwater resources and for governments to make informed decisions.

This project has established two monitoring sites on the 1-R (Okara) and 11-L (Sahiwal) irrigation divisions and these monitor depth to water and electrical conductivity (EC) on a six hourly interval. Establishing several monitoring sites is constrained by the lack of suitable monitoring wells in the study areas. In this case monitoring bores were drilled specifically to install loggers. The aim here is to demonstrate the importance of groundwater monitoring and also to demonstrate the value of understanding both short- and longer-term trends in water level and salinity. Additionally, monitoring data can be used visually to demonstrate to farming communities how groundwater is responding to continued use of groundwater both in terms of quantity and quality.

The model will also play an important role in addressing aspects of the third objective of the larger ACIAR project: *to enhance capacity and institutional arrangements for post project adoption of tools and options developed by stakeholders*. Thus, capacity development of stakeholders to improve monitoring, modelling and management of groundwater resources is central to improving sustainable use of groundwater resources, and to allow stakeholders which includes the farming community to make informed decisions that will improve livelihood outcomes.

The major output from this report is a groundwater model of the LBDC covering the districts of Okara and Sahiwal. The model has been used to simulate future scenarios to guide the development of sustainable groundwater management practices in LBDC command area. The tools and options are expected to optimise the use of scarce groundwater resources by providing improved understanding of the aquifer system, by enhancing recharge to aquifers and by better managing groundwater demand. This will reduce adverse salinity and sodicity impacts, achieve more profitable and sustainable agricultural practices, and thus benefit farming families

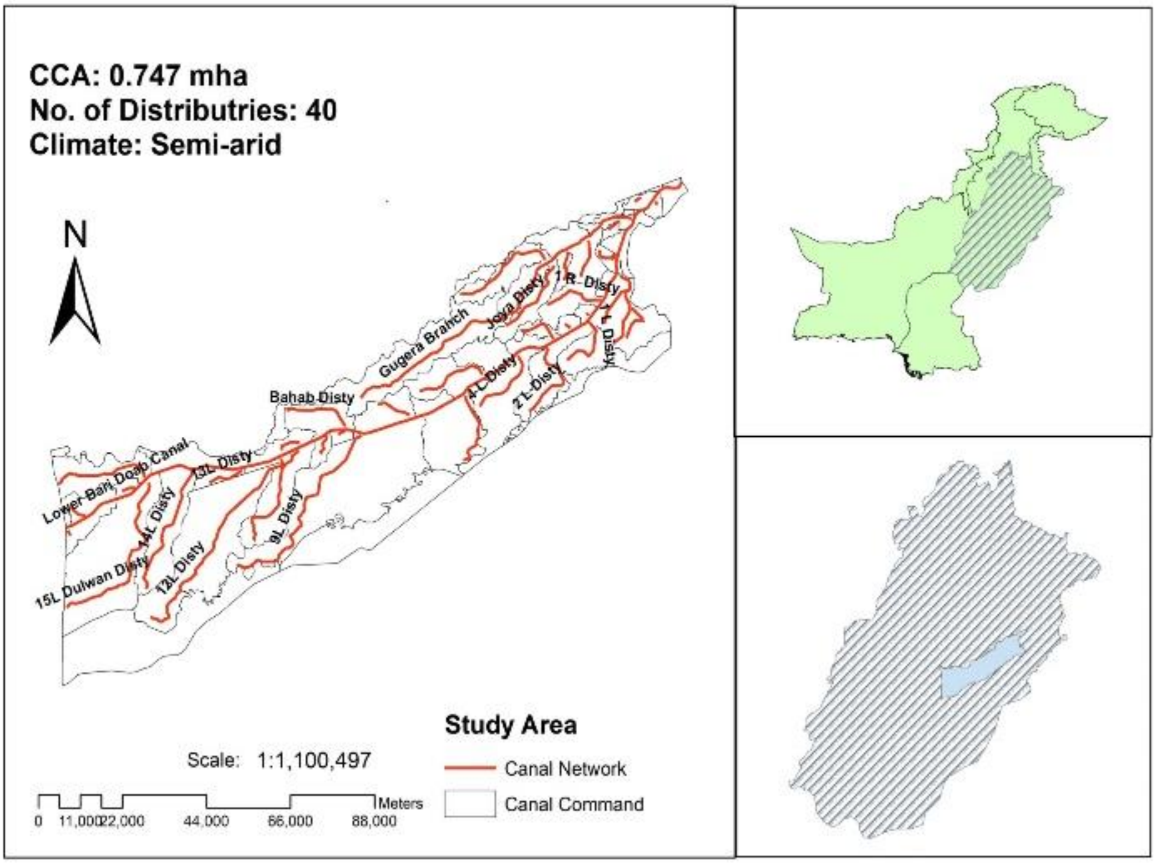


Figure 2.1: Location of Lower Bari Doab Canal command area in the Punjab province of Pakistan

3 A Review of Groundwater Models in the Indus Basin

This chapter reviews the previous modelling studies that have been undertaken in the Indus Basin. A number of groundwater models have been developed in the Indus basin over the years but there are very few modelling studies that cover the entire basin. The studies documented in this review are either at the doab scale, or at the canal command level, or focus on specific issues on a much smaller scale. Of these the most recent work covers the Rechna Doab model developed by CSIRO and IWMI (Khan et al., 2008b), the Upper Chaj Doab model (Ashraf and Ahmad, 2008), Lower Bari Doab (Basharat, 2012), Lower Bari Doab (ADB 2013), and the revised Rechna Doab model developed in conjunction with UAAR and PID with Australian financing (Punthakey et al., 2015).

3.1 Groundwater Models in Punjab

3.1.1 Chaj Doab Model

A 3-D finite element model (FEFLOW) has been used for regional groundwater flow modelling of Upper Chaj Doab in Indus Basin, Pakistan. The groundwater flow model was used to analyse the regional groundwater flow of Upper Chaj Doab area in the Indus basin and to estimate the groundwater budget of the aquifer. Modelling results show a gradual decline in water table from year 1999 onward. The persistent dry condition and high withdrawal rates have resulted in lowering groundwater levels (Ashraf and Ahmad 2008). Different scenarios were developed to study the impact of extreme climatic conditions (drought/flood) and variable groundwater extraction on the regional groundwater system.

3.1.2 Rechna Doab Models and Studies

Water balance model for Rechna Doab: An early study was the development of a water balance model for Rechna Doab by Hassan and Bhutta (1996). A regional lumped water balance model and the specific yield method was applied to estimate recharge for Rechna Doab on a seasonal basis for a period of 31 years (1960 1990). Both methods were in close agreement. The average value of net groundwater recharge during Kharif (April September) season was estimated at 60 mm, whilst for Rabi (October March) there was no recharge, rather there was depletion of the groundwater reservoir during the winter months. Long term average annual depletion of the groundwater reservoir was found to be greater than corresponding value of annual recharge. Their study concluded that regional groundwater levels in Rechna Doab had declined by 2.3 m over a 31 year period from 1960 to 1990, an average decline of 74 mm per year.

CSIRO IWMI Rechna Doab model: The Rechna Doab CSIRO IWMI model (Khan et al., 2008b) was developed to address problems of sustainable groundwater and surface water use, groundwater quantity and quality response to changes in recharge and groundwater pumping rates. The study aimed at identifying a combination of institutional and technical strategies to manage surface and groundwater at the regional scale to promote environmental sustainability and maximize agriculture water productivity (‘crop per drop’). This was to be achieved by development and calibration of a flow and solute transport model to describe the surface water–groundwater interactions in the Rechna Doab, and the spatial and temporal impact of future surface water and groundwater use scenarios. An internal review was undertaken of this model by CSIRO and a number of areas for modifying the modelling approach were identified.

ACIAR Rechna Doab groundwater and solute transport model: The Rechna doab model was redeveloped using PID’s extensive data set on water levels and salinity which have been monitored since 2008. Additionally, the monitoring of salinity from several hundred tubewells undertaken by PID staff in Rechna Doab provided a valuable data set for calibration of the salinity transport model. The Rechna Doab model was redeveloped with ACIAR funding to develop a tool which was suitable for use by PID (Punthakey et al., 2015). The main areas where the latest Rechna Doab model differs from the previous model is shown in Table 3.1.

Table 3.1: Enhancements in model approach for Rechna Doab (Punthakey et al., 2015)

1. Monthly stress periods versus seasonal stress periods significant enhancement.
2. Four layers first 3 layers 30 m each, lower layer variable depth to bedrock. Previous model had adopted 7, 21, 30 m, and variable depth to bedrock
3. River and canal locations corrected, restated grid origin for model
4. Recharge only to top layer previous model had recharge going directly to very deep layers.
5. River and Canal Conductance constant does not change (previous model had one set of numbers for Kharif and 10% conductance in Rabi).
6. River and canal stage variable and simulated for each grid cell along reach for each month. Previous model had 2 heads that were varied cyclically depending on Kharif and Rabi.
7. Utilised PID monitoring wells not SCARP wells and aligned to the monitoring being undertaken by Punjab Irrigation Department.
8. PID data from 2008 to 2013 is used, which has extended coverage of the doab for both piezometer heads and salinity monitoring bores.
9. Spatial and temporal distribution of rainfall and ETa is used for each month using remote sensing (NDVI) in the previous model a traditional approach is used using rainfall stations.
10. Pumping is calculated spatially as a difference between actual evapotranspiration and recharge from rainfall and irrigation, before entering it in the model. This is certainly not the best approach but with almost two hundred thousand wells which are not monitored, there are limited options.
11. Calibration is undertaken for top two layers where most of the data is available.

In this model doab bounding rivers formed no flow boundaries in the sense of a groundwater divide assuming that horizontal flow across these boundaries is negligible and vertical fluxes are dominant. Additionally, the deeper aquifer layers also require boundary conditions to simulate flows occurring across doab boundaries.

The Rechna Doab model development by Punthakey et al., (2015) is a regional flow and solute transport model which was developed to assess availability of groundwater resources and interaction of surface and groundwater in the Rechna Doab. Spatial and temporal assessment of groundwater use, availability of surface water supplies, and climatic variability were modelled to assess the quantity and quality of groundwater resources. This study found the major components of the water balance are recharge from rainfall, river leakage, canal leakage and irrigation recharge which accounts for 93% of inputs to the system. The model was used to assess the sustainable yields from the system. The reduction in pumping during years when surface water supplies are plentiful is important for replenishing the aquifer and minimising salinity increase due to groundwater pumping which enhances lateral inflows and upconing of saline groundwater from deeper layers.

The findings from scenario analysis show that improved controls on pumping will achieve greater water savings. Thus PID will need to focus effort on significantly enhancing the level of groundwater management. The study has allowed improved understanding of the sustainability of groundwater usage in Rechna Doab and to improve the management of surface and groundwater in the doab. The main finding recommended an estimated sustainable yield from Rechna Doab of 10 BCM and recommended an upper limit of 1 BCM to allow for adaptive management during drought periods when pumping is expected to increase as the demand for irrigation increases. Moreover, the trend in Rechna Doab has been an increasing trend in groundwater pumping with over 200,000 tubewells currently using groundwater. This brings into question the resilience of the system, given that PID at present does not have the institutional structure or the regulatory framework in place to enforce the recommended sustainable yield. It is therefore prudent to understand the limitations of the current system as pumping rates increase in response to increasing tube-well installation by farmers.

3.1.3 The Lower Chenab Canal Command Sub Model

A sub-model comprising the Lower Chenab Canal (LCC) East region was extracted from the regional Rechna Doab model using a detailed grid structure compared to the coarse grid used for the regional Rechna Doab model (Punthakey et al., 2015). The TMR sub model for LCC East required additional calibration as the distribution and coverage of the river and canal network had changed. Thus the spread of river cells in the LCC East sub model are much less than in the regional Rechna Doab model. The preferred course of action for future enhancements of the LCC East sub model would be to incorporate the distributaries and important minors which would also allow a more realistic spread of canal losses in the model and allow improved assessment of canal losses and groundwater quantity and quality.

It is recommended that future work with the LCC sub model re-evaluate the pumping which would also entail reworking the spatial estimates of Et0 and Eta at a fine spatial scale of 500x500 m. Moreover, our assessment is that the approach used in this study to estimate pumping works best where groundwater availability is not constrained by salinity. Where salinity of the groundwater is high farmers may only use groundwater when forced to due to the lack of surface water supplies, thus there is a high probability that in areas with poor quality groundwater the estimation of pumping by this method is likely to be overestimated.

3.1.4 Conjunctive use Model for QB Link Upper Chenab subarea

A FEFLOW model covering an area of 38,100 ha between the Qadirabad Bulloki Link canal and Upper Chenab canal in the Rechna Doab was developed by Sarwar and Eggers (2006) to evaluate alternative management options for surface and groundwater resources. The study site is shown in Figure 3.1.

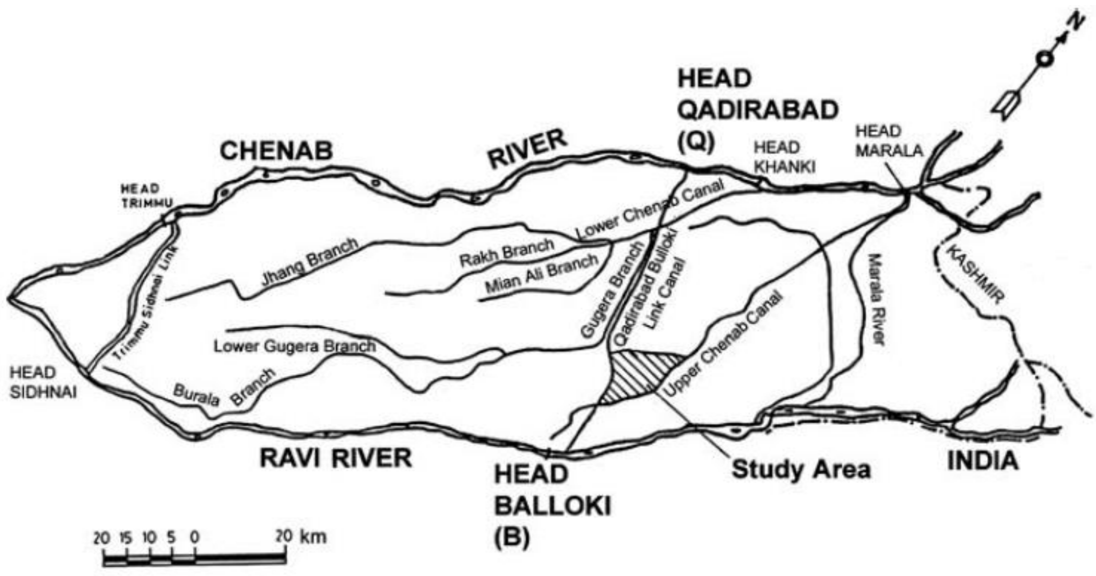


Figure 3.1: Study area (hatched) for the Qadirabad Baloki Link Upper Chenab subarea model (after Sarwar and Eggers, 2006)

A simple water balance approach was used to estimate net recharge to the aquifer. A groundwater model using FEFLOW was used and the net recharge from the water balance model was used as an input for the water balance calculation and to simulate groundwater flow. The calibration of the model used water level data from 1982 to 1990 and data from 1991 to 1995 was then used to verify the model. The model was applied to predict groundwater levels up to 2010 in response to the possible need for intervention in irrigation and/or agricultural practices. The study found that pumping for a cropping intensity of 130% would result in water table falling by 4.17m, whilst an increase in pumping for a cropping intensity of 150% would result in declining groundwater levels up to 6.57 m. The authors proposed lining of watercourses and adjustment in cropping pattern could be adopted as alternatives for better management of surface and groundwater resources, as this would result in additional surface water supplies available for irrigation.

3.1.5 Simulating Seepage from the Upper Gogera Branch Canal

A MODFLOW model was developed by Arshad et al., (2009) to estimate seepage from the Upper Gogera Branch Canal in the Rechna Doab. Model simulations were undertaken to assess the time dependent seepage to groundwater. The contribution of seepage to groundwater is based on the water balance components including recharge flow, applied irrigation, rainfall, lateral flow and evapotranspiration from the existing cropping system. The monthly average seepage rate from the canal was estimated as 12.10 m^3s^{-1}million m^{-2}, for a monthly average flow rate of 106 m^3s^{-1}. Seepage contribution to groundwater ranged from a low of 1425 $m^3d^{-1}100m^{-1}$ of canal length during February 2003 to a high of 1942 $m^3d^{-1}100m^{-1}$ of canal length during July 2003. An empirical relationship between seepage (S) and the canal flow rate (Q) was developed ($S = 0.006\ Q^{1.44}$) to quantify the seepage to groundwater from the canal for any flow rate.

3.1.6 Lower Bari Doab Canal Command Model

Basharat (2012) and Basharat and Tariq (2013) developed a flow model for the Lower Bari Doab canal command to evaluate long term irrigation cost inequities due to increasing groundwater depletion towards the tail end of canals. They used a uniform grid of 500 m to model the LBDC command covering an area of 7874 km^2. A total depth of 200 m was modelled with five layers. The model was calibrated over a period of eight years from Kharif 2001 to 2009 with two stress periods per year.

The mass balance for the entire domain from 2001 to 2009 showed total recharge (including groundwater returns) for 8.5 years is 23.45 MAF and tube-well extraction is 27.02 MAF. Values per year for these two parameters are 2.759 MAF (3.403 BCM) and 3.178 MAF (3.92 BCM), respectively, showing that groundwater extraction is higher than the recharge to the aquifer. The groundwater budget component due to evaporation is relatively less due to water table being deep in most of the command areas (Basharat and Tariq, 2013).

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 irrigation system. With the prevailing canal supplies and increasing climate severity in the downstream direction, groundwater recharge from canal supplies and rainfall reduces from 430 mm at head end to 285 mm at tail end. Thus, decreasing rainfall and increasing crop water requirement towards the tail end, is resulting in greater groundwater depletion downstream from canals particularly at the tail end. The temporal trends of average depth to water for each Hydrologically Similar Unit (HSU) are shown in Figure 3.2.

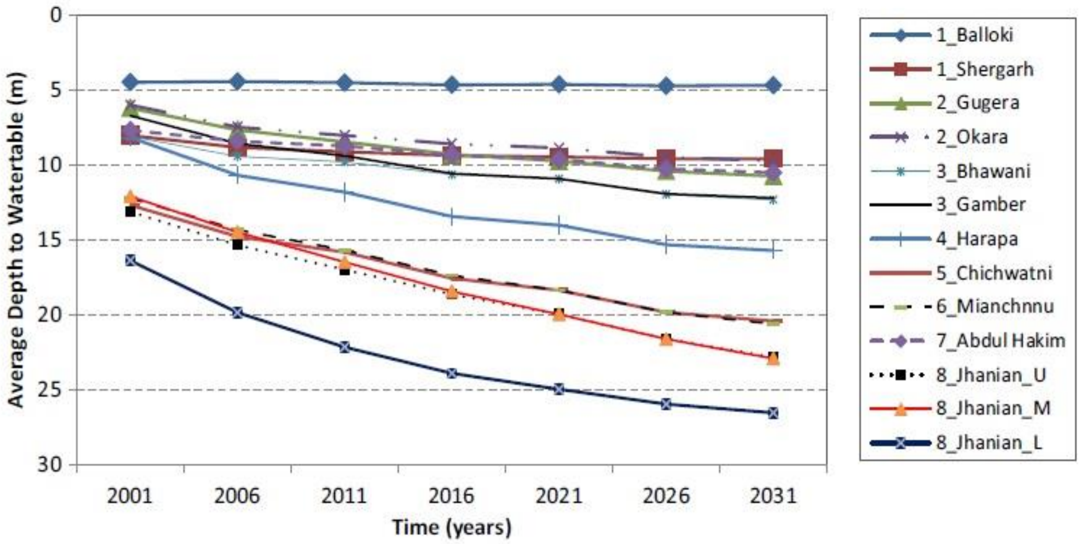


Figure 3.2: Temporal trends (~ 3 decades) of average depth to water for Hydrological sub-units (HSU) in Lower Bari Doab (after Basharat and Tariq, 2013)

The deeper water tables at the tail ends incur additional costs for farmers as indicated by Basharat and Tariq (2015). Cost per cubic metre of pumped groundwater increases about 3.5 times as the depth to water table drops from 6 to 21 m from head to tail in LBDC command. Due to excessive groundwater depletion, a tail end farmer currently incurs 2.19 times higher irrigation costs as compared to the head end counterpart. An additional depletion of 8–11 m (about 0.3 to 0.4 m per year) is expected in the lower half of the command by 2031. They concluded that with the existing canal water distribution, the comparative cost of groundwater pumping and the combined cost of canal and groundwater use are expected to further increase from 2.37 to 2.53 and 2.19 to 2.36 times, respectively, from 2011 to 2031, resulting in greater inequity between head end farmers and tail end farmers.

3.1.7 Lower Bari Doab Canal Improvement Project (LBDCIP)

A model of the Lower Bari Doab (LBDC) was developed by Lahmeyer International and NDC consultants with funding from ADB as part of the Lower Bari Doab canal improvement project, Lahmeyer (2013). The LBDC model was designed to understand the groundwater conditions in the LBDC command and to model the spatial and temporal behaviour of recharge and discharge dynamics of the LBDC aquifer and salinity transport across the seasons. From 1995 to 2012 the area with fresh groundwater resources reduced from 71% in 1995 to 32% in 2012. The area with marginal groundwater quality increased from 22% in 1995 to 49% in 2012. The area under hazardous water quality has been increased from 7% in 1995 to 19% in 2012. The trend over the last 17 years is that groundwater quality in LBDC command is generally deteriorating. In some area near the Ravi River and along the main canal, the EC of groundwater declined, whereas in some areas away from the Ravi River and towards the centre of the doab the EC of the groundwater increased. This finding is consistent with our current understanding of salinity dynamics in the other doabs.

The LBDC model was used to determine the impact of different scenarios of canal water availability and groundwater extraction to show the impact of surface and groundwater resources in LBDC. The main finding from the scenario runs showed that reducing tube-well pumping and increasing canal water supplies seems to be the only effective way of arresting the current pace of groundwater drawdowns in large areas of LBDC.

3.2 Lessons Learned from Previous Models

There is urgent need for integrated surface water and groundwater models for doabs in Punjab and in southern Punjab where groundwater use is increasing. Also needed in conjunction with flow models are solute transport models in areas experiencing salinization, given the:

- rapid increase in tubewells in Punjab and in the freshwater zones in Sindh,
- need for improved understanding of how groundwater is used at the farm scale,
- lack of regulatory and policy frameworks for managing groundwater,
- opportunities for enhancing recharge where conditions are favourable,
- need for farming community participation in improving understanding of groundwater use and impacts on crop production and livelihoods.

The literature review shows that there are a number of models in the eastern doabs of Punjab, but there are glaring deficiencies in model coverage in southern and western Punjab, and virtually no models covering upper, middle and lower Sindh.

4 Physical Setting

4.1 Topography and Drainage

The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) for over 80% of the globe. This data is currently distributed free of charge by USGS and is available for download from the National Map Seamless Data Distribution System, or the USGS ftp site. The LBDC digital elevation model (DEM) is based on the SRTM 30m Digital Elevation Data. The elevation of the locations of piezometers within the LBDC has been calculated from the 30m DEM.

The LBDC digital elevation model (DEM) based on the SRTM 30m Digital Elevation Data for study area was extracted using ArcGIS. The surface elevation ranges from 128m to 208m. The north-west side of model area has the highest value of elevation of 208m above mean sea level with reddish brown colour represent the highest value (Figure 4.1). The south-east side of model area has the lowest value of elevation 128 m above mean sea level with bluish colour. The elevation in model area is higher near the Ravi River and gradually decreases towards Pakpattan canal, and similarly elevation decreases gradually from east to west in the model area. The study area was divided into two sections high elevation value and lowest elevation value. There are two profiles of the model area longitudinal profile AA' and longitudinal profile BB'. The coordinates of starting and ending elevations is given in Table 4.1. The section length of AA′ is 205.49 km, the elevation varies from 194 m to 136 m along the line AA'. It showed that elevation varies along North-East area of model boundary to the South-West area. The difference in Elevation is 58 m. The section length of BB′ is 37.8 km and the elevation varies from 168 m to 159 m. It showed that elevation varies along North-East area of model boundary to the south-west area. The difference in Elevation is 9 m.

Table 4.1: Topographic features of command area

Description	Section AA′	Section BB′
Start Position	31° 13' 10" N, 73° 51' 44" E	30° 44' 24" N, 72° 56' 13" E
Elevation at Start	194 m	168 m
End Position	30° 3' 1.0" N, 72° 11' 57" E	30° 26' 38" N, 73° 8' 0.6" E
Elevation at End	136 m	159 m
Distance of Line	205.49 km	37.8 km
Difference in Elevation	58 m	9 m

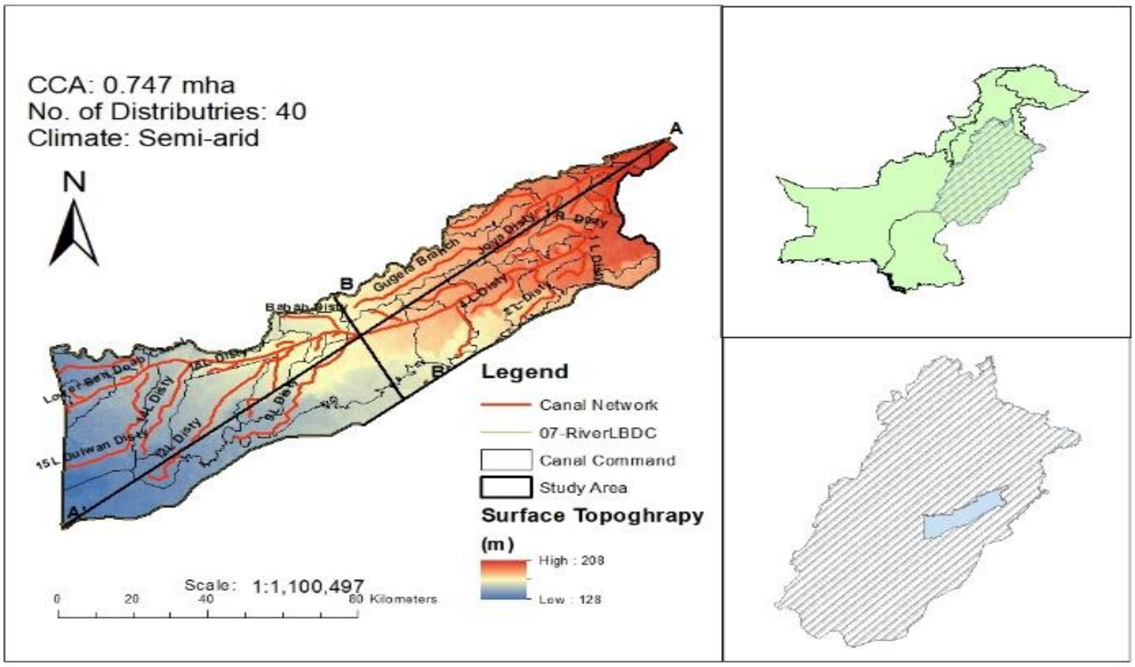


Figure 4.1: Surface topography (m) from mean sea level in different distributary command areas of the Lower Bari Doab Canal

4.2 Groundwater Monitoring Points:

Prior to 2003, all groundwater monitoring was carried out by WAPDA (Water and Power Development Authority) SMO (SCARP Monitoring Organisation). Since then the Directorate of Land Reclamation (DLR) has started monitoring groundwater and drilled a number of new boreholes.

The DLR manages about 3,175 piezometers spread over seven irrigation zones in Punjab however, a significant number of these are not functional. LBDC command falls inside the Multan Irrigation zone. There are total 171 piezometers in our study area out of which only 45 piezometers are functional for the given time period. The field teams measure the water level before and after the monsoon season. The pre-monsoon measurement is recorded in June-July and the post-monsoon measurement in October-November. The groundwater monitoring points include the location of piezometers and depth to water table (Figure 4.2). Additionally, water quality is also monitored from tubewells. The groundwater quality parameters include Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) data.

For this ACIAR project, data loggers have been installed on head and tail of 1-R and 11-L distributaries of LBDC. The loggers monitor depth to water table, temperature and conductivity of groundwater at an interval of twelve hours.

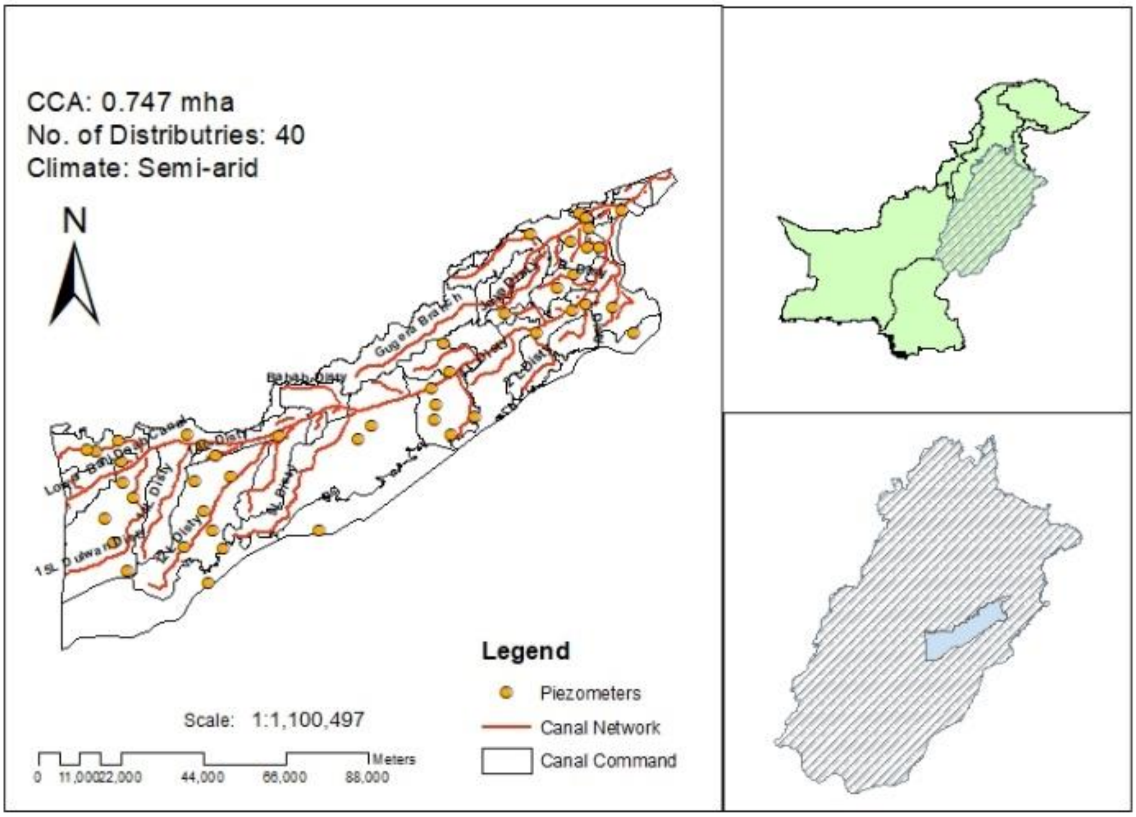


Figure 4.2: Spatial variation of piezometers in Lower Bari Doab Canal command area

4.3 Groundwater Quality and Saline Intrusion

The PID is regularly monitoring groundwater quality. The groundwater quality was characterized for irrigation water quality into three categories: useable, marginal and hazardous as given below.

Table 4.2: Irrigation Water Quality Criteria

Category	EC (mmoh/cm)	SAR	RSC (meq/L)
Useable	<1.5	<10	<2.5
Marginal	1.5-3.0	10-15	2.5-5.0
Hazardous	>3.0	>15	>5.0

Groundwater quality data for the LBDC command was analyzed for the period 1995 to 2012. Areas under useable, marginal and hazardous irrigation water quality are shown in Table 4.2. Over 17 years, the area with useable quality groundwater has reduced from 71% in 1995 to 32% in 2012. The area with marginal groundwater quality has increased from 22% in 1995 to 49% in 2012. The area under hazardous water quality has increased from 7% in 1995 to 19% in 2012. The trend in Table 4.3 shows that groundwater quality in LBDC command is deteriorating over time.

Table 4.3: Groundwater Quality in LBDC Command

Survey Period	Year	LBDC Command Area (%)		
		Usable	Marginal	Hazardous
LBDC Feasibility Study	1995	71	22	7
WAPDA Survey	1991-01	51	26	24
WAPDA Survey	2002-03	44	34	22
DLR Survey	2005	44.4	31.7	23.9
GMMM-LBDCIP	2012	32	49	19

The present suitability of the LBDC groundwater for use in irrigation is shown in Figure 4.4. Areas with hazardous groundwater are generally located towards the centre of the doab and towards the southwest of the LBDC command where the depth to the water table is also deeper. Farmers in these areas face the dual problem of deteriorating water quality and declining water tables, both of which will increase their production costs significantly.

Groundwater quality data (EC, SAR, RSC) for the period 2003 to 2012 were analysed to determine the change in the different groundwater quality parameters over time and the results are shown in Figure 4.3. Over the ten-year period, the EC of six tubewells reduced, while the EC of 117 tubewells (35% of total tubewells) remained unchanged and the EC of 215 tubewells (64%) increased. Over the same period, the SAR of 8 tubewells decreased while the SAR for 182 tubewells (54%) remained unchanged and the SAR for 148 tubewells (44%) increased. The RSC for 30 tubewells reduced while the RSC in 202 tubewells (60%) remained unchanged and the RSC in 106 tubewells (34%) increased. Increasing EC, SAR and RSC values clearly indicate the gradual deterioration of groundwater quality in LBDC command.

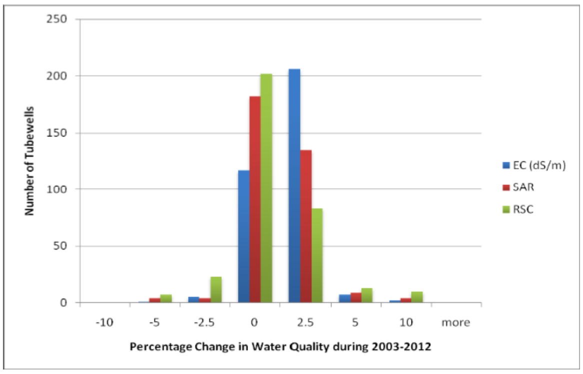


Figure 4.3: Percentage change in groundwater quality from 2003-2012 in Lower Bari Doab Canal command area. EC = Electrical Conductivity, SAR = Sodium adsorption ratio, RSC = residual sodium carbonate

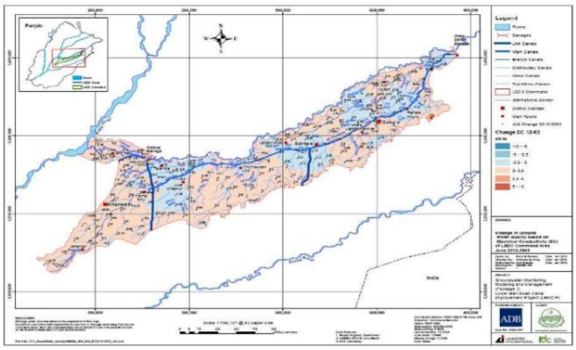


Figure 4.4: Change in groundwater quality (Electrical Conductivity (dsm^{-1}) from 2003 to 2012 in Lower Bari Doab Canal command area

The change of EC of the groundwater during the period 2003-2012 is shown in Figure 4.4. In some areas near the Ravi River and along the main canal, the EC of the groundwater declined (that is the quality improved) whereas away from Ravi River and towards the centre of the doab, the EC of the groundwater increased (that is the quality became worse).

4.4 Irrigation Canals and Administrative Units

There are 65 distributaries in LBDC command area. 45 distributaries falls under the project study area. To avoid the doubling of distributaries in one grid of model, we merge five distributaries with closet one. There are three administrative divisions in our study area, Okara, Sahiwal and Khanewal with two rainfall stations, one in Sahiwal and other in Okara (Figure 4.5). The command area of each distributary is managed by a community group called farmers organization (FO). The primary source for irrigation is canal water but ground water is also used for irrigation. A vast network of distributaries, minors and sub-minors in the LBDC command area is shown in Figure 4.6.

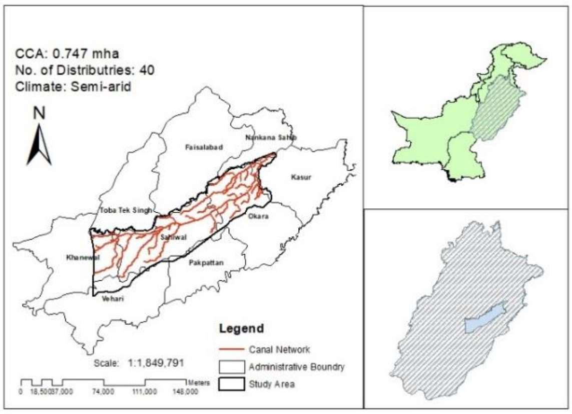


Figure 4.5: Irrigation administrative boundaries of Okara, Sahiwal and Khanewal in Lower Bari Doab Canal command area

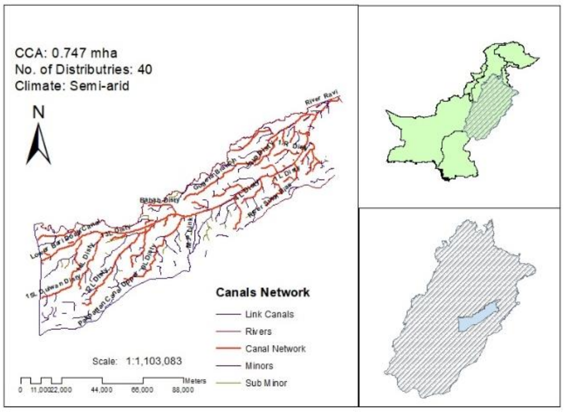


Figure 4.6: Network of main and branch canals, distributaries, minors and sub-minors for Lower Bari Doab Canal command area

4.5 Rainfall and Temperature

The rainfall data for the period of 2005 to 2015 is shown in Figure 4.7. The maximum rainfall of 296 mm occurred in 2010 in the Lower Bari Doab Canal Command. The monthly effective rainfall values were calculated from the rainfall data of three rain gauging stations located in the vicinity of the LBDC command using the Theissen Polygon Method (Equation 1).

$$Effective\ Rainfall\ (Pe) = 0.8\ P - 0.001\ P^2 \qquad \text{(Eq. 1}$$

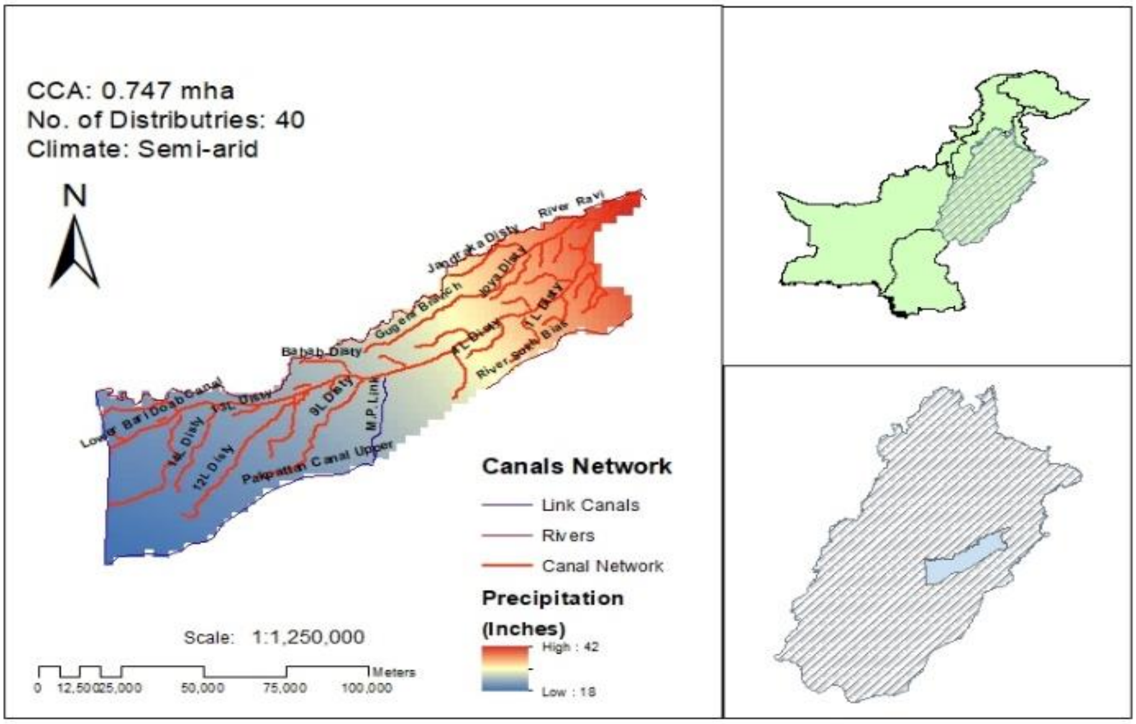


Figure 4.7: Distribution of precipitation (average for the last 10 years) in Lower Bari Doab Canal command area

4.6 Geology

The study area comprises of two physiographic landform units i.e. the upper half of the command bar upland (high elevation area) and towards the tail end the abandoned flood plain (between Ravi and Sukh Beas Rivers). The tail end is mostly separated by sharp river cut escarpment known as "Dhaya". In the bar upland, soils are of brighter colours (mostly silty) having the definite developed profile (horizons). These contain secondary lime in form of nodules (kankars) of different size, generally in sub-soil substratum. In abandoned flood plain soils have greyish colours with little or weak profile development in sub soils and layering of different textures in the substratum. In LBDC command there are no “deep” drainage systems present and no SCARP (Salinity Control and Reclamation Project) measures. The topography of the basin divides it in two natural drainage areas (the boundary traversed by the LBDC canal), draining to the River Ravi to the North, and to the bed of the old Sukh Beas River to the south. With sudden increase of number of tubewells since early 2000, waterlogging is no more a significant issue in the study area.

The parent material consists of diverse calcareous alluvium comprise sand and fine gravels which are intercalated with silt and clay derived from a various types of rocks. The ground slope of LBDC command area is generally mild at tail end (south-west direction) with the average ground slope fluctuating from 1 in 4,000 to 1 in 10,000. The elevation of agricultural land is ranging from 394 - 640 ft (120 to 195 m) above the mean sea level.

The alluvial sediments that make up the aquifer show obvious heterogeneity in both the horizontal and vertical directions. Nevertheless, it is generally believed that the aquifer behaves as a single continuous, unrestricted aquifer. Research on lithology, logging data of boreholes (depth 180 to 300 m) and test wells (depth 30 to 110 m) shows that Bari Doab is composed of unconsolidated sand, silt and silty clay soils and f kanker. The sand is mainly grey or grey-brown, fine to medium-grain, and secondary angle to secondary round. Very fine sand is common, and fine-grained sediments usually include sandy silt, silt and silty clay, as well as a considerable amount of kanker and other consolidation materials.

NESPAK (1995) divided the LBDC Area into three zones i.e., Upper (Balloki), Middle (Sahiwal) and Lower (Khanewal) Zones on the basis of lithological variations (Table 4.4).

Table 4.4: Lithological zones in LBDC command area (NESPAK, 1995)

Upper Zone (Balloki)	Predominantly underlain by sand of different grades, with thin near surface layer of silty clay
Middle Zone (Sahiwal)	Intercalations of sand silt and clay
Lower Zone (Khanewal)	Coarse sediments (sands and gravels) to NW; intercalations of sand and clay to SW

When reassessing the original data, it is recommended that there is a moderately persistent "layer" of finer materials (clay, silt) with a thickness of about 15-30 m (50-100ft) at a depth of 75-140m (250-450ft). In the Balloki-Okara area, these finer materials are more common at the top of the irrigation system. The near-surface layer of clay silt is still obvious with a thickness of 6-15 m (20-50 feet). In the central region, as represented by the cross-section near Sahiwal (Halcrow, 2006), the silt clay layer tends to be thin and unevenly distributed both in the vertical and horizontal directions. More importantly, this section shows that the characteristics of the aquifer in Harappa are often very sandy (Halcrow, 2006).

A detailed study of the lithology, logging data of the borehole on the left side of the LBDC, revealed that there is no obvious clay layer in the sandy aquifer. The lower area, as represented by the cross-section near Mianchannu (Chichawatni to Khanewal), is dominated by sand and rare clay/silty materials. Except for some local lenses, there are few feet of hard rock and dense clay in the area. During the test exercises in 1954-62, the LBDC command failed to reach the bedrock. No hard gravel is found in the alluvial layer and rough or very coarse sand is rare.

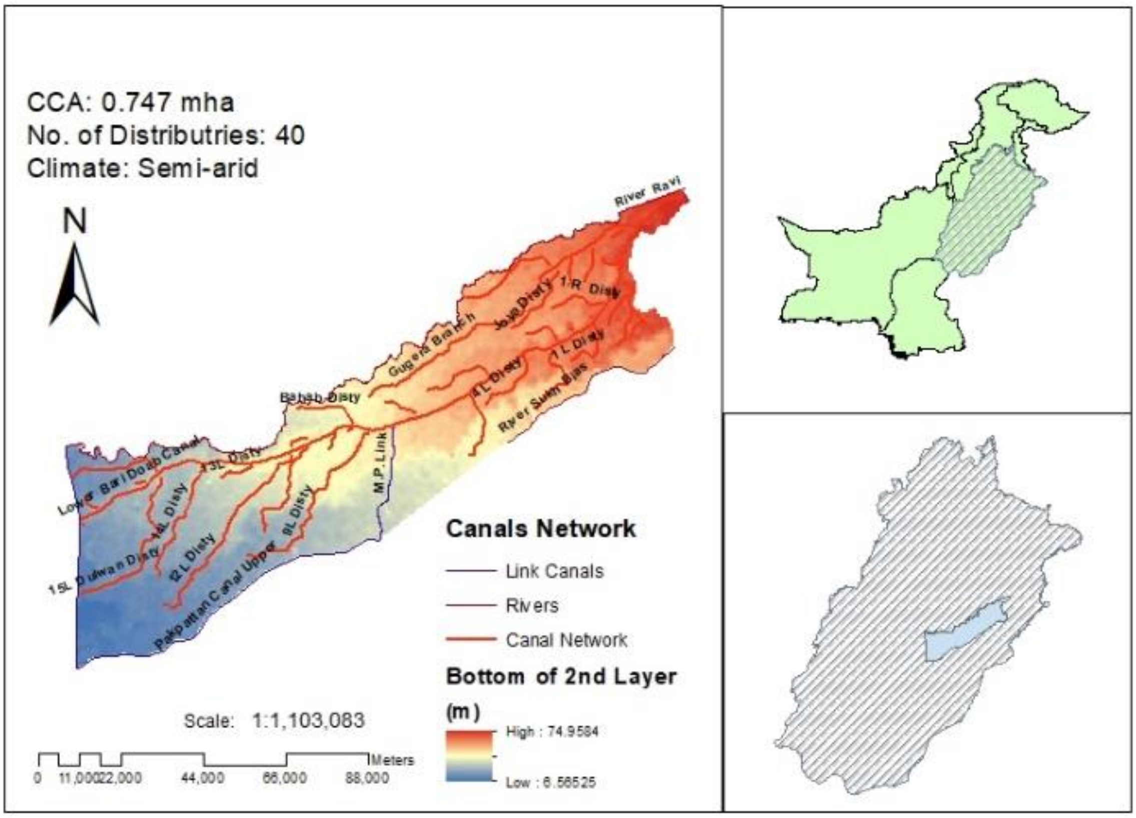


Figure 4.8: Basement structure for LBDC Study site (m AMSL)

4.7 Hydrogeology

The foundation of the study area is a thick alluvial layer with a depth of 300 m. These riverbed sediments were deposited in sinking troughs by the ancestors of the Indus River system and current tributary channels. This was confirmed by previous water and soil research in the 1960s by WAPDA's Investigation Department (WASID). In this program, exploratory work was carried out in 149 locations in order to define the underground lithology. The locations of these test wells are shown in Figure 4.9.

Direct turn method was used to drill test holes within a depth range of 180 to 305 m (600 feet to over 1000 feet). The drill cuttings from a depth of 3 m (10 feet) were macroscopically inspected at the drilling site and analysed in the laboratory to study the particle size distribution. Generally, electrical records are made on test holes to correlate with underground lithology and water quality. Accordingly, the contact between the fine material and the coarse material was performed in the lithology logging. Differential sampling of groundwater is also done by pumping water from different depths of each test hole.

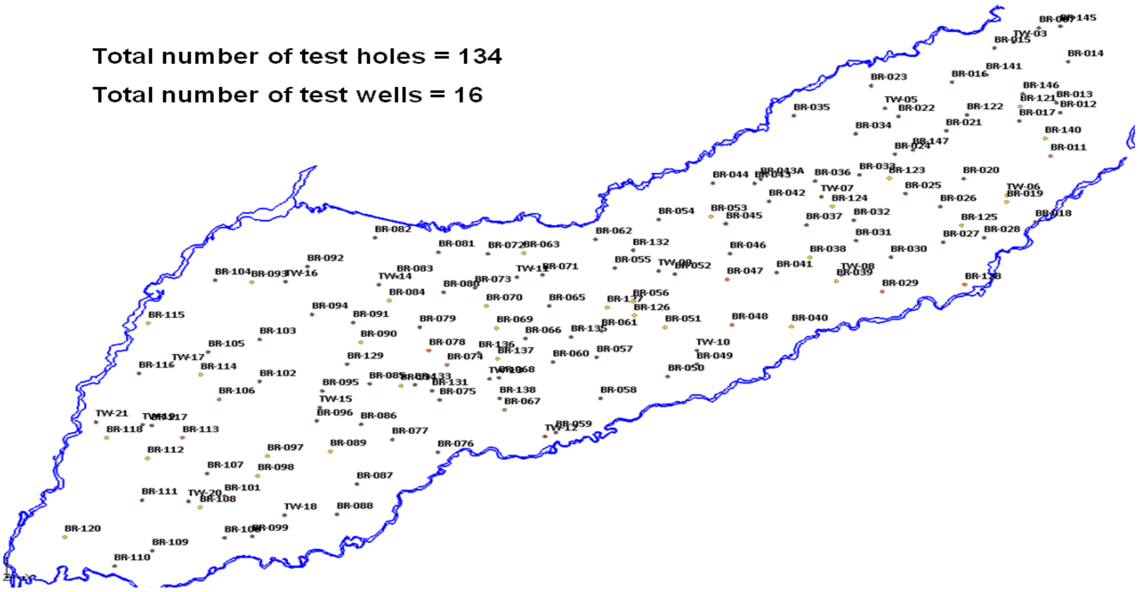


Figure 4.9: Location of test holes and test wells in the Lower Bari Doab Canal command area

Using the same data set, the United States Geological Survey (USGS) released a report on Groundwater Hydrology in Punjab during 1967. Furthermore, in 1980, WAPDA released the report "Hydrogeological Data of Bari Doab, Volume 1, Basic Data Release. Nr. 1" which includes the geological records of all test holes and test boreholes in Bari Doab. These data are used in this study to analyze and determine the lithology of the aquifer (Figure 4.10, Figure 4.11, Figure 4.12, Figure 4.13, and Figure 4.14).

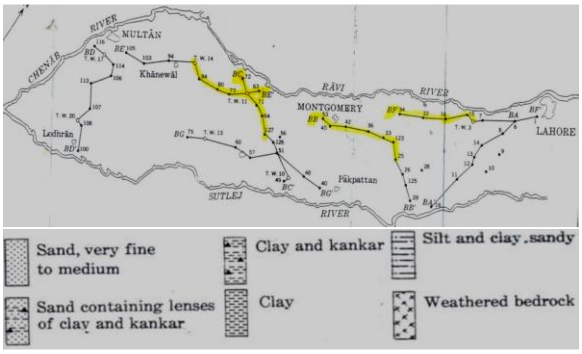


Figure 4.10: *Locations of borelog alongwith soil types in the Lower Bari Doab Canal command area*

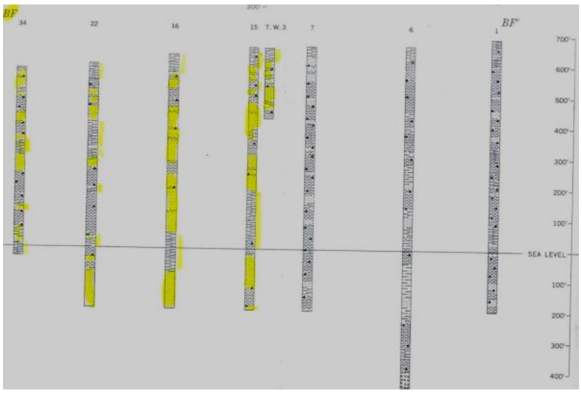


Figure 4.11: Geologic x-sections (BF) of Bari Doab falling in Lower Bari Doab Canal command area (continued in next figures)

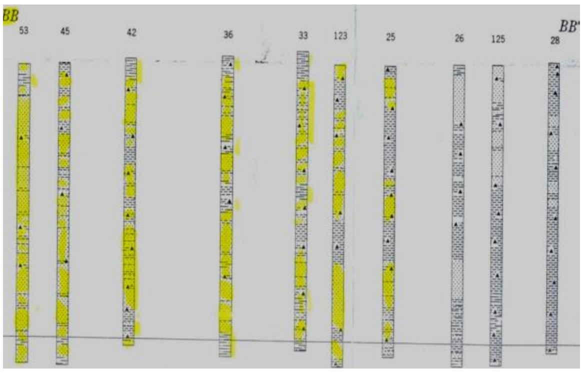


Figure 4.12: Geologic x-sections (BB) of Bari Doab falling in Lower Bari Doab Canal command area (continued in next figures)

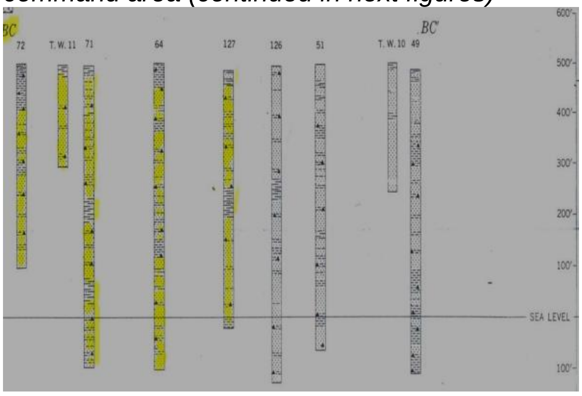


Figure 4.13: Geologic x-sections (BC) of Bari Doab falling in Lower Bari Doab Canal command area (continued in next figures)

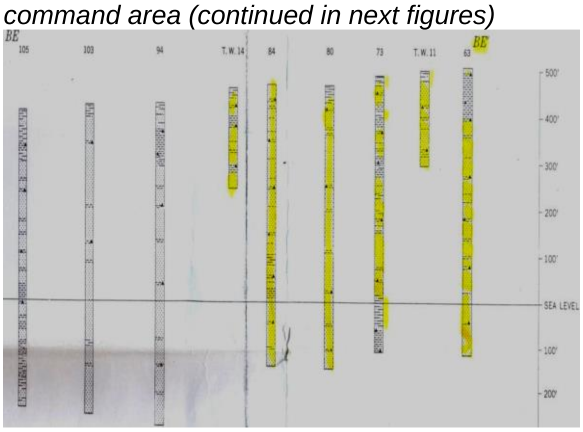


Figure 4.14: Geologic x-sections (BE) of Bari Doab falling in Lower Bari Doab Canal command area

Source: WASID (WAPDA), 1961, United States Department of the Interior Geological Survey Water Supply Paper 1608-H Plate 6

4.8 Depth to Groundwater

The data for depth to groundwater shows the fluctuation in groundwater levels. Groundwater levels data has been plotted and interpolated to check the uniformity of the level. As the groundwater levels for different periods has been interpolated by using krigging in Geographic Information System environment. The data for the level is shown below in Figure 4.15, Figure 4.16 and Figure 4.17. The observations are taken twice a year i.e. before and after the monsoon rains. It is understandable that most of the deficiency in canal water supplies compared with irrigation water requirements is met by groundwater extractions, largely by private tubewells which can have a significant impact on the sustainability of the groundwater resources. The data indicate that groundwater tables are declining in Sahiwal, and Khanewal districts of the LBDC command area while it shows an upward trend in Okara district. The data further revealed that groundwater tables lowered at an average rate of 0.3 to 0.4 m per year mainly in the Sahiwal and Khanewal Divisions of the LBDC command area.

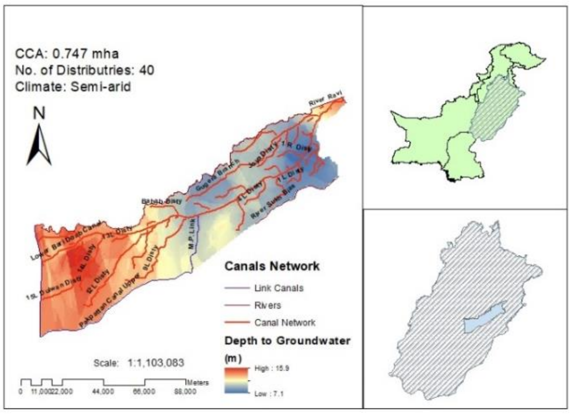


Figure 4.15: Spatial variation of groundwater levels (m) in layer 1 (7.1-15.9 m) during June, 2006 in Lower Bari Doab Canal command area

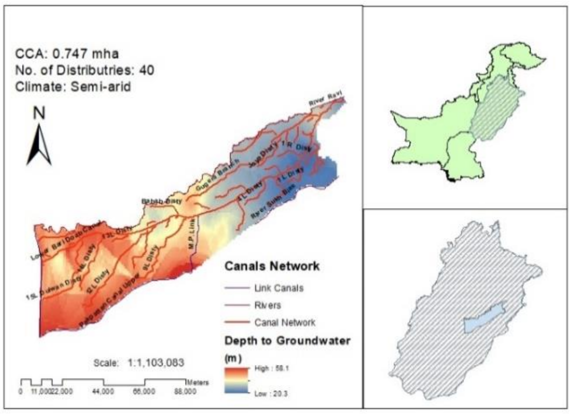


Figure 4.16: Spatial variation of groundwater levels (m) in layer 1 (20.3-58.1 m) during June, 2010 in Lower Bari Doab Canal command area

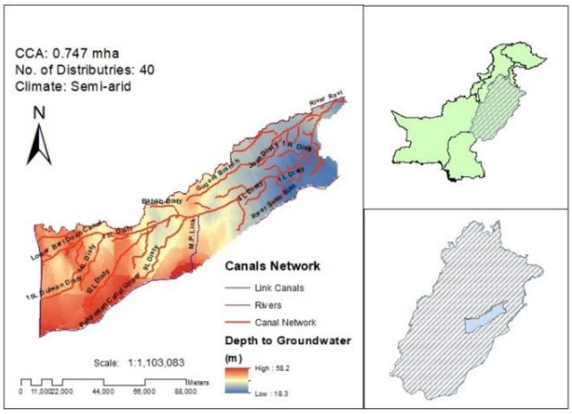


Figure 4.17: Spatial variation of groundwater levels (m) in layer 1 (18.3-58.2 m) during October, 2010 in Lower Bari Doab Canal command area

5 Model Development

The use of groundwater models to support water management has increased dramatically during the past three decades. Modelling helps to understand and predict the future scenarios with existing groundwater conditions. Aquifer characteristics are needed to develop a flow model. Model calibration is carried out with the observed data of a specific time period. After successful calibration, the next step is to validate the model. Following calibration and validation, and the model can then be utilised to simulate future scenarios and development of different management options.

5.1 Conceptual Model for LBDC

The conceptual model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding systems. In the groundwater flow model, boundary conditions will describe the exchange of flow between the model and the external system (Figure 5.1).

The following boundary conditions were used to develop the LBDC groundwater flow model:

1. River
2. Recharge
3. Evapotranspiration
4. Pumping Well

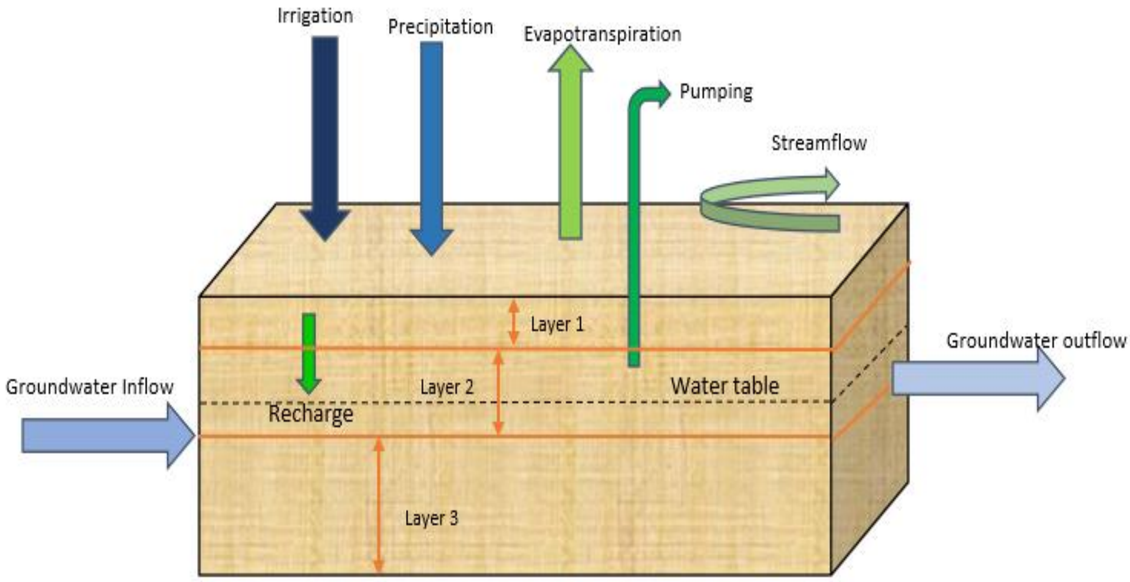


Figure 5.1: Conceptual hydrogeological cross-section of the Lower Bari Doab Canal command area

5.2 Model Grid and Model Boundaries

The proposed model area lies between two rivers i.e. Ravi at one side and Sutlej at the other side. Boundary conditions that are applied to the top, bottom or intermediate layers can be defined by using a Polygon or Polyline. Figure 5.2 shows the Ravi is specified along the northern boundary. Along the western side the model study is bounded by S.M.B link canal. The southern model boundary is defined by bed of the Sukh Beas and the Pakpattan canal.

The model grid was formed using 129 rows and 167 columns with a grid size of 1000m by 1000m. Each row and each column in the data input grid represents a required attribute for the selected boundary conditions. Model grid was formed using GIS software 10.4. After grid formation, Shapefiles are imported for defining boundary condition attributes for river stage, river bottom, riverbed thickness, river width and riverbed conductance and starting head and ending head etc. (Figure 5.3).

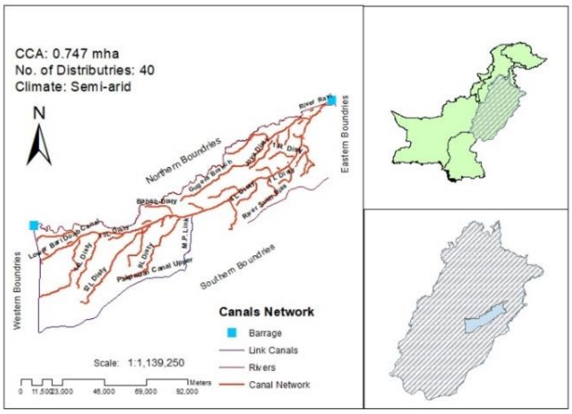


Figure 5.2: Eastern, Western, Northern and Southern boundaries used for the groundwater vistas model in the Lower Bari Doab Canal command area

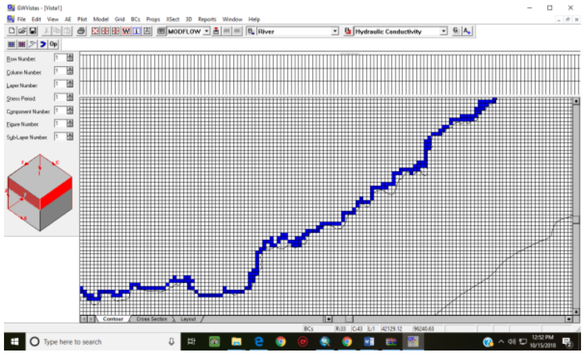


Figure 5.3: A demonstration of grids showing river cells in groundwater Vistas model in the Lower Bari Doab Canal command area

5.3 Aquifer Geometry

The groundwater flow model provides an excellent way to describe different elements of groundwater flow and proved useful in prediction of changes taking place in the flow of ground water in response to stresses imposed on the system. The major components of groundwater flow system are horizontal and vertical movement of water. The description of these components can be explained better by considering the different layers in the hydrogeological formation. Each of the layers has its own specific hydraulic characteristics. To study these characteristics, a grid is overlaid on the layers, to provide a means of assigning differing values for these characteristics to different parts of each layer, and to facilitate the simulation of the vertical component of flow. This kind of approach is known as quasi three dimensional approach for depicting the fully three dimensional groundwater system.

In this study, a three-layered model is developed after considering the different hydrogeological conditions at the site. The thickness of the layers is 30m (unconfined), 95m (unconfined) and 180m (confined) for the first, second and third layer respectively with model grid size of 1000m by 1000m. Top of first layer is considered as surface topography (DEM with 30m resolution SRTM NASA). With this configuration, top of second layer is 30m and top of third layer is 125m (30+95m) from the natural surface level. The depth of each layer is decided on the basis of hydrogeology of that study site. The first layer (30m) will capture the bed of rivers, canals, distributaries as well as seepage losses from these channels. Also represents recharge from irrigation, ET and stream flows. The second layer (95m) shows the tubewells bore depth falls in this layer and bottom surface of the third layer represents bedrock as shown in conceptual model diagram (Figure 5.4).

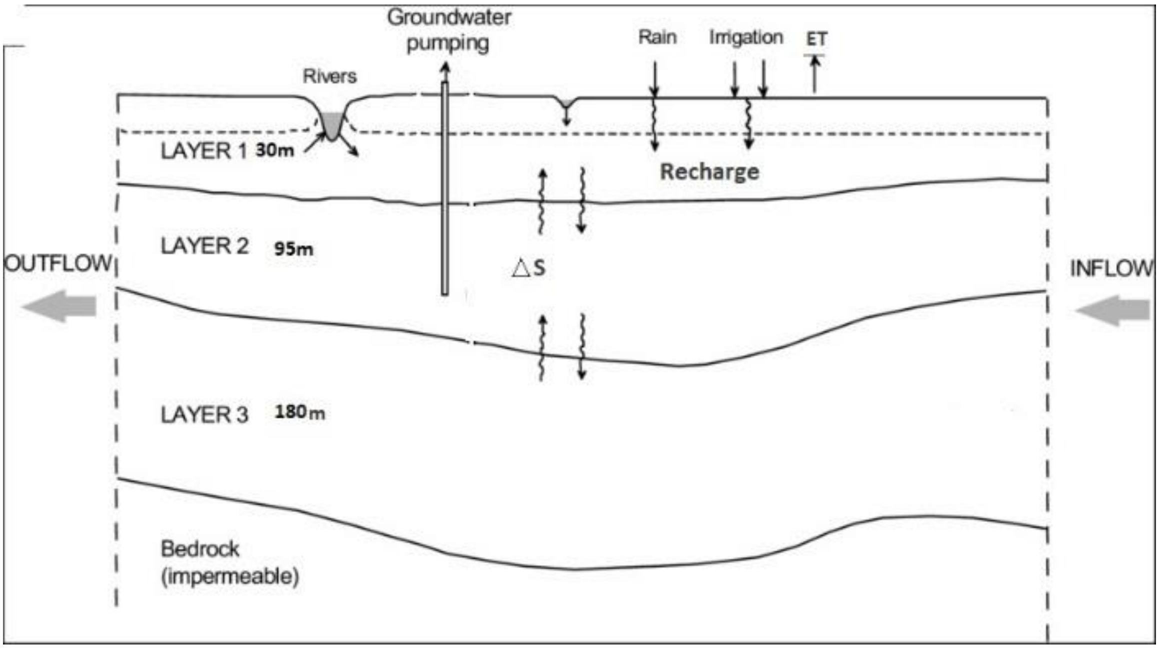


Figure 5.4: Aquifer geometry for the Lower Bari Doab Canal command area

5.4 Aquifer Parameters

The alluvial sediments that make up the aquifer show clear heterogeneity in both the horizontal and vertical directions. Nevertheless, the aquifer is widely believed to exist as a single continuous, unrestricted aquifer. There is little information available with respect to the key aquifer hydraulic parameters of permeability (K), transmissivity (T) and storativity (S).

According to Bennett's (1967) pump test results, the lateral permeability of LBDC and surrounding areas ranged from 28.96 to 255.45 m/day with average of 84.09 m/day. The specific yield values reported for these four tests alone were 0.06 (Renala Khurd), 0.24 (Pakpattan), 0.04 (Harrapa) and 0.31 (Arifwala), and the vertical permeability was 1.04, 3.95, 11.06 and 21.06 m/day, respectively. Bennett (1967) mentions that the average anisotropy ratio based on the whole Punjab state is of 25 to 1.

The 1995 Feasibility Study (NESPAK 1995) reports the permeability (K) values as between 2.9 to 256 m/day, transmissivity (T) values from 1200 to 9725 m^2/day and specific yield (S) from 0.04 to 0.31 (Table 5.2).

Areas fall in the study area to which different transmissivity values were allocated is as follow:

• Balloki- Sahiwal 3000 m^2/day

• Cichawatni 1600 m^2/day

These values were then used for calculations of groundwater inflow and outflow.

Indeed the only available data within LBDC is that from 5 test wells installed by WASID in the project area in the early 1960’s. These data are reproduced in Table 5.1.

Table 5.1: Aquifer data from WASID (1960)

Well no.	Screen length (m)	Tube-well Depth (m)	Depth to water (m)	Test Discharge (Q) m^3/day	Maximum drawdown (s) (m)	Specific Capacity (Q/s) m^3/day/ m	Permeability (K) m/day	Specific yield (storativity)	Transmissivity m^2/day – WASID analysis	Transmissivity m^2/day – Logan Estimation (Modified Logan estimation)
B-5	36.5	68.6	3.1	4281	4.82	888	39.6	0.06	3168	1083 (1172)
B-7	38.1	79.2	6.46	7339	8.81	833	255		2040	1016 (1100)
B-9	36.5	96.0	10.67	6679	14	477	36.9	0.04	2952	582 (629)
B-11	36.5	62.4	8.23	6116	3.19	1917	63.1		5048	2339 (2531)
B-14	36.5	76.2	9.27	7339	3.44	2133	65.8		5264	2603 (2816)

Source:

Note: Transmissivity values based on assumption that aquifer is 80m thick. Permeability/transmissivity values determined by the WASID analysis appear at odds with well specific capacity. They were therefore re-evaluated using the Logan estimation approximation method (where T= 1.22Q/s) and by the modified Logan method determined by Hunting Technical Services and Mott McDonald for Indus Valley aquifers (where T = 1.32Q/s). These values are given in the table for comparison purposes.

Table 5.2: Lateral Permeability, Specific Yields and General Test Information

Test B-1	Site	Pr cfs per ft^2	Sy decimal fraction	L (ft)	D (ft)	DTW (ft)	r (^{0}F)	Q_w (cfs)	Drn (hr)	Max s_w (ft)
6	B.S .Link	0.0025		120	205	11.1	82	2	96	27.7
7	Chak 27 Near Ghamber RI ST	0.0097		125	260	21.2	82	3	96	28.9
8	Pakpattan L.R	0.0012	0.24	152	235	19.7	74	3	384	20.5
9	Near Harrapa	0.0014	0.04	120	315	35	76	2.73	240	46.1
10	Arif wala	0.0011	0.31	135	228	21.9		2.5	244	22.14
11	Iqbal Nagar	0.0024		120	205	27	78	2.5	144	10.45
12	Luddan	0.0077		120	355	17.3	82	2.5	87	25.6
13	Near Sheranwala R.H	0.0096		135	355	33.6	76	2	96	21.5
14	Porowala Jungle	0.0025		120	250	30.4	79	3	144	11.3
15	Toba Sultanpur	0.0018		140	215	23	82	2.44	187	12.08
16	MS 621/4 Lahore-Multan Road	0.0015		120	228	23.4	80	2.75	144	17.1
17	Munirabad	0.0019		120	230	26	82	2.48	144	12.55
18	Korar Pacca	0.0018		120	205	27.3	84	2	96	24.45
19	Village Khalla wala	0.0011		135	220	24.1	80	3.81	68	22.55
20	Near Chak pattanwala	0.0013		135	215	25.4	82	2.5	144	13.6
21	shujabad	0.0012		140	220	30	82	2.73	72	18

Abbreviation: Pr, average lateral permeability of screened interval; Sy, Specific Yield of material at water table depth expressed as a dimensionless fraction; L, Length of test well screen; D, Depth of test well; DTW, depth to water at test site; $^{\gamma}$ temperature of pumped water; Q_w, discharge of test well; Drn, duration of test; Max s_w, maximum drawdown observed in pumping well.

5.4.1 Estimation of Aquifer Parameters

MODFLOW computes the conductance components of the finite difference equation which determines flow between adjacent cells. It also computes the terms that determine the rate of movement of water to and from storage. The aquifer geometry, leakage between layers, and the properties of the aquifer system need to be specified. The aquifer parameters that need to be specified are hydraulic conductivity (kh) and specific yield (Sy) for layer 1, and kh and specific storage (Ss) for layers 2 and 3. This section describes how these properties were estimated.

A database of 59 bores with borelogs was compiled from sources provided by PID from previous reports (WAPDA report from 1980) and from various previous field studies. These logs were digitised, geo referenced and compiled in a lithology database. The digitised logs along with locations and reference elevations were included in the database. The aim was to include information from as many bores as possible in order to have adequate spatial coverage of the Lower Bari Doab model which covers the districts of Okara and Sahiwal as shown in Figure 5.5. Although the spatial coverage shown in Figure 5.5 is a reasonably good coverage of these two districts, there are large patches in central southern Sahiwal which do not have bores. A total of 59 boreholes were used for parameter estimation for layers 1 and 2 of the model and 53 for layer 3 as some bores did not penetrate layer 3. The coverage is reasonable, however, the LBDC area has been studied extensively over the years so it would be reasonable to assume there may be additional bores with IWASRI or undertaken in other studies, however, these reports were not available in hardcopy or digital form.

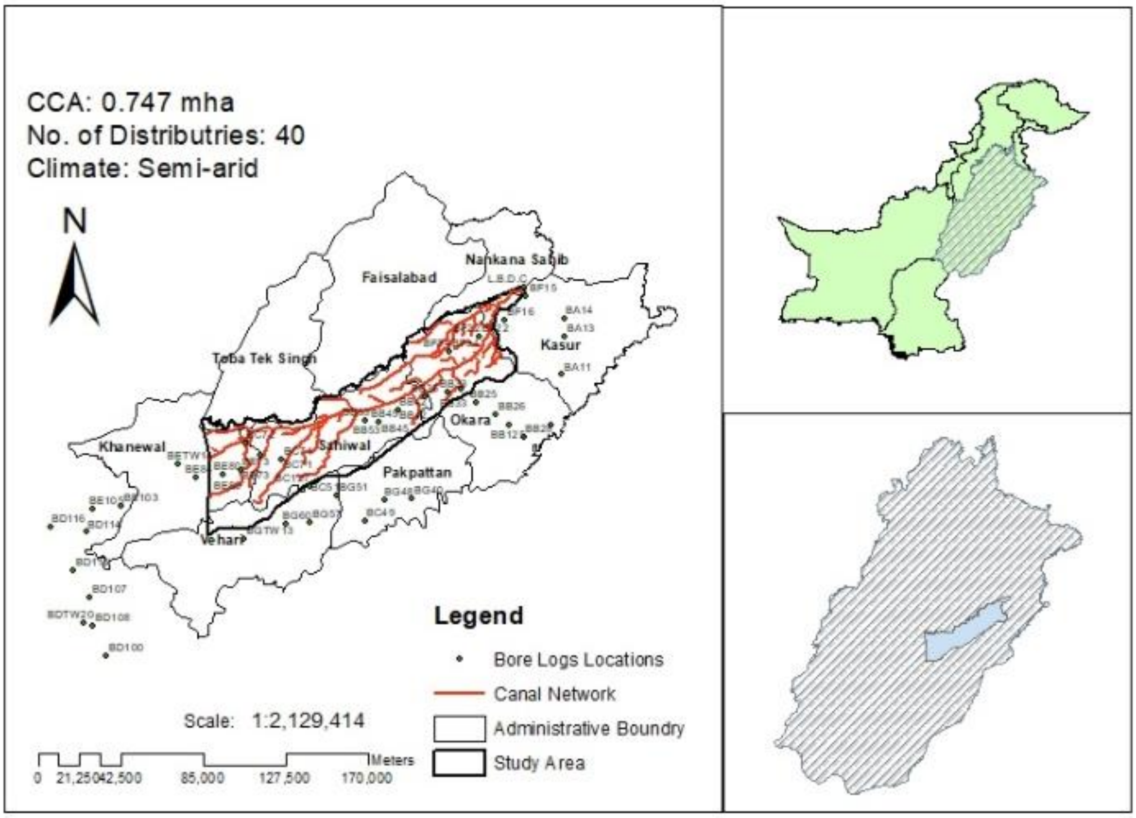


Figure 5.5: Locations of borelogs in the Lower Bari Doab Canal command area (Okara and Sahiwal districts)

The borelogs for these 59 bores have been plotted using Strater a borehole and well logging software. Examples of typical borelogs are shown for selected bores for Okara district are shown in Figure 5.6, and for Sahiwal district in Figure 5.7. A complete list of all borelogs is provided in Appendix 1 (Punthakey et al., 2017). The bores are drilled to different depths and do not necessarily penetrate the full thickness of the alluvium, therefore interpretations of the basement surface needs to account for either a less permeable horizon such as a clay sequence or clay and kankar sequence if one is present at deepest depth, or where in some cases the bore is deep enough to have reached the basement rock typified by granite or other hard rock. The file containing the estimated depth to basement is filtered by eliminating bores that have been drilled to shallow depths. Using these criteria about 71 bores were used for defining the bottom surface of layer 3 which is discussed earlier in Section 4.3.

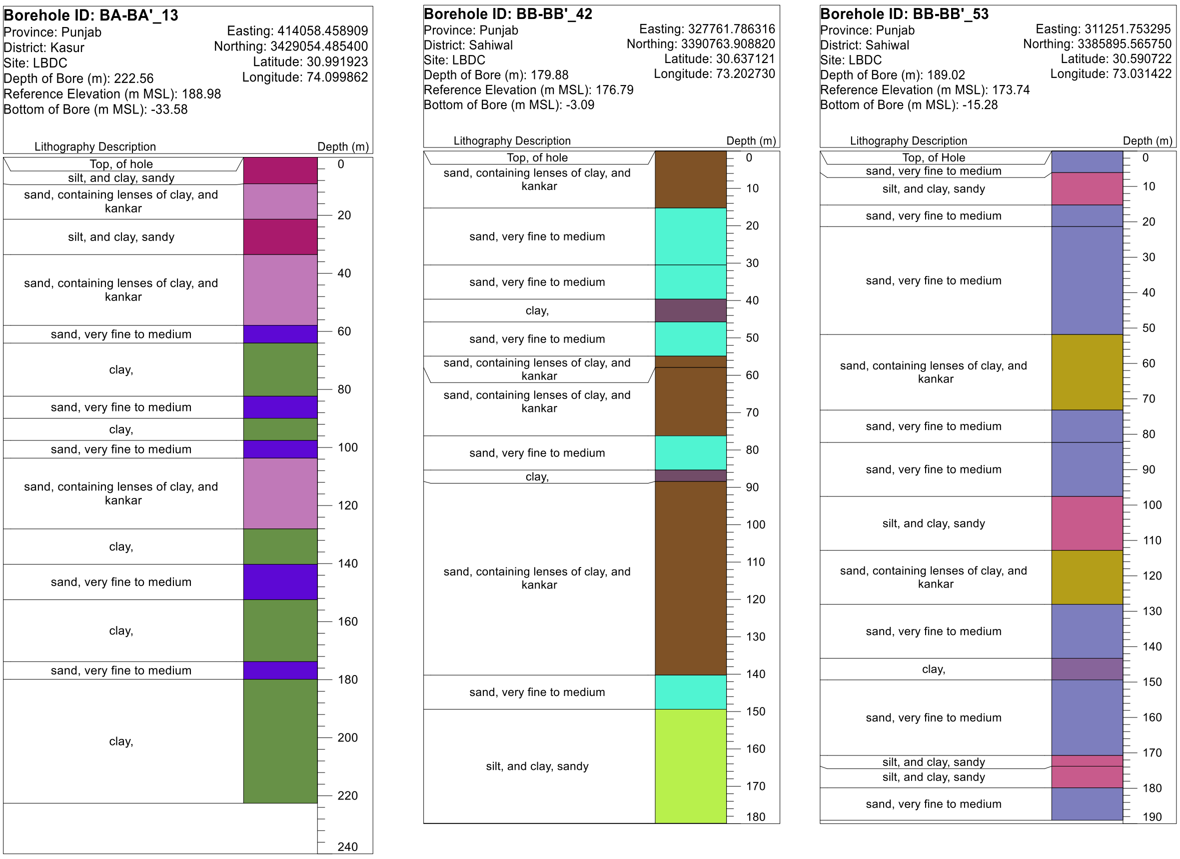


Figure 5.6: Description of lithography for borelogs in Lower Bari Doab Canal command area (Okara district)

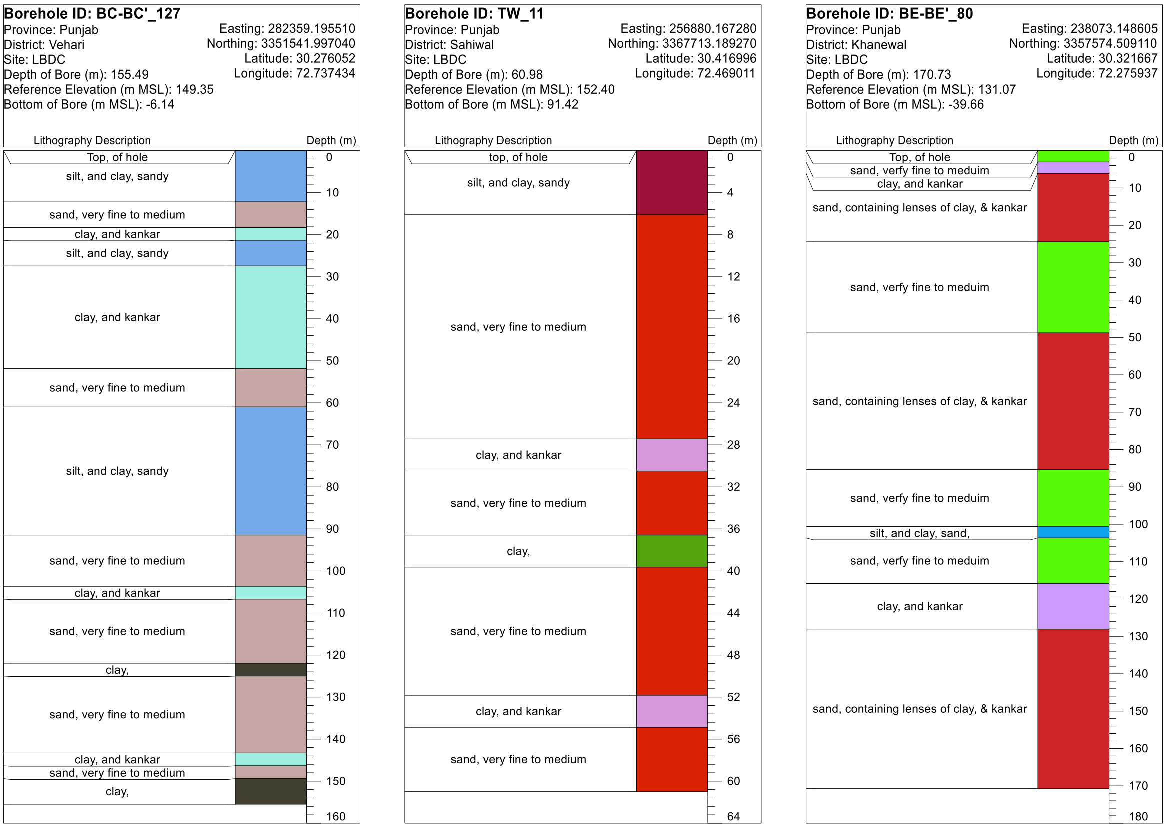


Figure 5.7: Description of lithography for borelogs in Lower Bari Doab Canal command area (Sahiwal district)

Each of the 59 bore logs were used to estimate hydraulic conductivity, specific yield, specific storage and porosity. The approach used involves interpreting the drilled logs using average values for various lithologic components. The interpretation of the logs is not intended to give a perfectly calibrated value; rather it provides the initial estimates of aquifer properties for the model domain which will subsequently be refined during calibration.

Once the layer structure was finalised, the next step was to estimate a composite value of aquifer properties for each layer. The purpose of this approach is to provide a reasonable estimate of aquifer properties which can be used in the model to start calibration once the model set up has been completed. The estimated hydraulic conductivities (k_h) are shown in Figure 5.8, Figure 5.9, and Figure 5.10 for layers 1, 2 and 3 respectively. The k_h values for the first 25 m (layer 1) have a range from 0.48 to 84.3 m/d with grid average values ranging from 24 to 51 m/d as shown in Figure 5.8. Taking a median value of 37 m/d the average transmissivity of the layer is 925 m^2/d where the layer thickness is 30 m. The distribution of k_h values range from lows around 24 m/d in the northeast of the model domain as shown by the orange and red regions in Figure 5.8 to progressively higher k_h values downgradient towards Sahiwal. There are also areas of low k_h in the north near the Sukh Bias river in Okara district.

The k_h values for the next 95 m (layer 2) have a range from 0.48 to 74.2 m/d and grid average values from 24.8 to 47.3 shown in Figure 5.9. Taking a median value of 36 m/d the average transmissivity of the layer is 3420 m^2/d for a thickness of 95 m which also coincides with the layer in which high yielding tubewells are located. The distribution of k_h values is similar to layer 1 with lower values in the north and grading towards higher values to the south of the model domain in Sahiwal district. There is also a low k_h zone in the north around Sukh Bias as shown by the orange and red zones in Figure 5.9.

The k_h values for layer 3 (approx. 240 m to base) have a range from 0.48 to 77.5 m/d with gridded values ranging from 21 to 56.8 m d^{-1} shown in Figure 5.10. Taking the median value for the deepest layer is 33 m/d, the average transmissivity of the layer is variable due to the variable thickness of layer 3. In some areas the gridded transmissivity can be in excess of 8,000 m^2/d. The distribution of k_h values follows a similar gradation from lows of 21 m/d in the north to gradually increasing values towards the south of 51 m/d. The Sukh Bias region in the north also has a similar zone of low k_h shown by the orange and red regions in Figure 5.10. In contrast to the upper layers the distribution of k_h for layer 3 has a much larger region of lower k_h values.

The spatial distributions for specific storage (Ss) for layers 1, 2 and 3 are shown in Figure 5.11, Figure 5.12 and Figure 5.13. The median Ss for layer 2 is 5.65E-5 (1/m) which gives an average storage coefficient of 0.00537. The range of Ss for layer two is from 8.32E-6 to 4.12E-4. The distribution of specific storage for layer 2 is variable with high Ss in the northern zones of Okara and in the central part of the model domain which covers southern Okara and northern Sahiwal. In addition, the lowest Ss zone is found in a belt along the middle portion of Okara district. The median Ss for layer 3 is 1.224E-4 (1/m) and the range is from 3.81E-6 to 4.92E-4 (1/m). Regions of higher Ss in layer 3 are in Okara district and generally lower specific storage is in Sahiwal district.

The spatial distribution of specific yield (Sy) for layer 1, 2 & 3 is shown in Figure 5.14, Figure 5.15 and Figure 5.16 with an median value of 0.109. The Sy is relatively lower in the north in the upper part of Okara. The gradation of Sy is gradually higher from North of Okara to south of Sahiwal districts. Overlaying the distribution of salinity for this layer will provide improved insights into availability of freshwater from areas with higher storage potential.

These initial estimates of K_h, Sy and Ss are imported in the MODFLOW model and will be subsequently refined during model calibration.

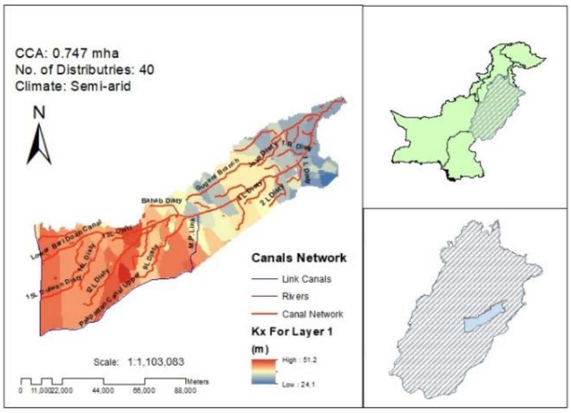


Figure 5.8: Spatial variation of hydraulic conductivity (kx, m d^{-1}) for layer 1 (24.1-51.2 m) in Lower Bari Doab Canal command area

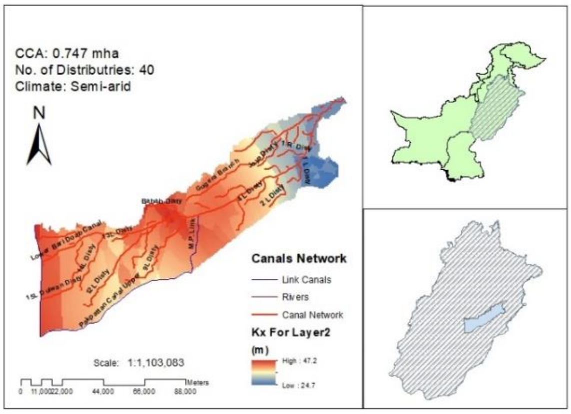


Figure 5.9: Spatial variation of hydraulic conductivity (kx, m d^{-1})) for layer 2 (24.7-47.2 m) in Lower Bari Doab Canal command area

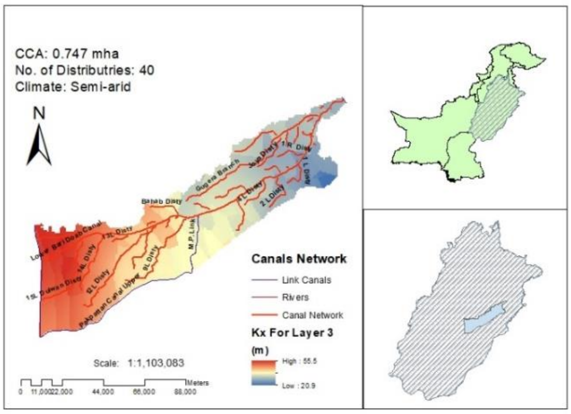


Figure 5.10: Spatial variation of hydraulic conductivity (kx, m d^{-1}) for layer 3 (20.9-55.5 m) in Lower Bari Doab Canal command area

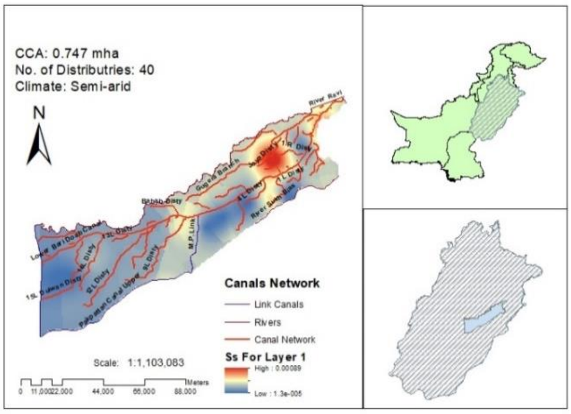


Figure 5.11: Spatial variation of Specific Storage (Ss) for layer 1 ($1.3e^{-005}$-0.00089 L^{-1}) in Lower Bari Doab Canal command area

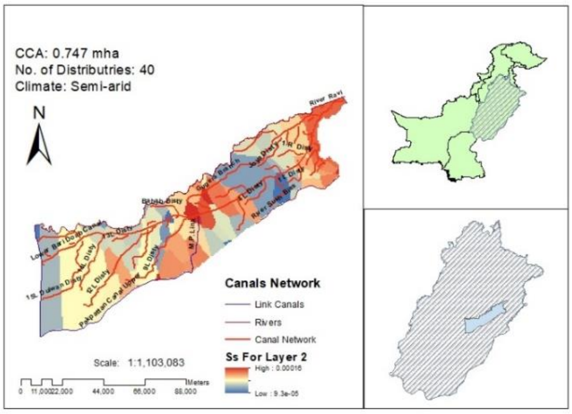


Figure 5.12: Spatial variation of Specific Storage (Ss) for layer 2 (9.3^{e-005}-0.00016 L^{-1}) in Lower Bari Doab Canal command area

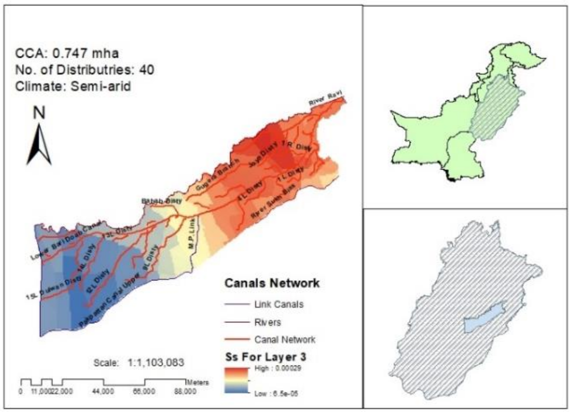


Figure 5.13: Spatial variation of Specific Storage (Ss) for layer 3 ($6.5e^{-005}$-0.00029 L^{-1}) in Lower Bari Doab Canal command area

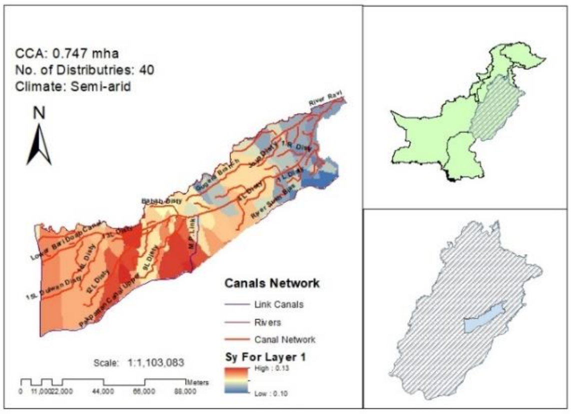


Figure 5.14: Spatial variation of specific yield (Sy) for layer 1 (0.10-0.13) in Lower Bari Doab Canal command area

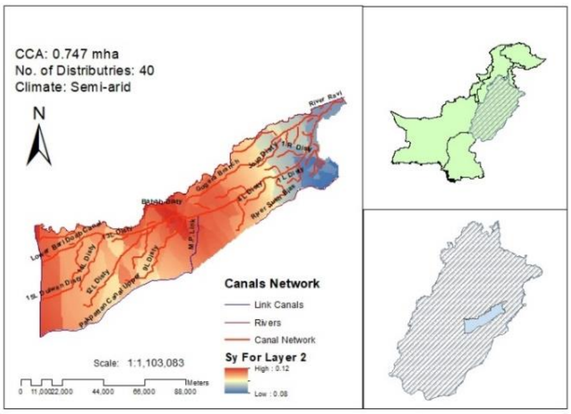


Figure 5.15: Spatial variation of specific yield (Sy) for layer 2 (0.08-0.12) in Lower Bari Doab Canal command area

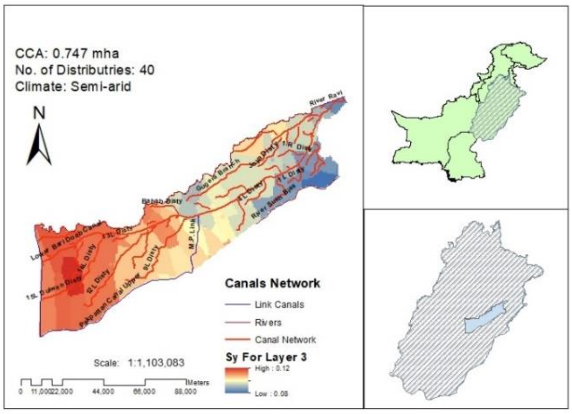


Figure 5.16: Variation of specific yield (Sy) for layer 3 (0.08-0.12) in Lower Bari Doab Canal command area

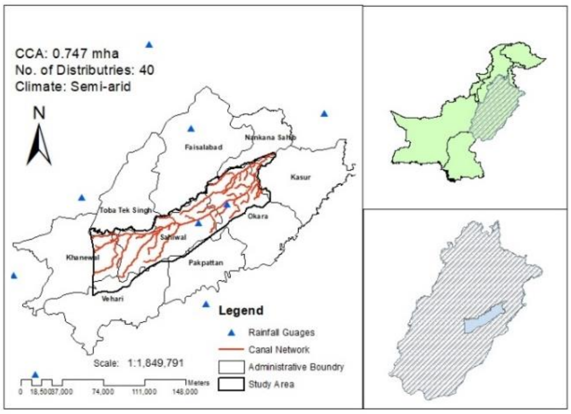


Figure 5.17: Location of rainfall gauges in Lower Bari Doab Canal command area

5.5 Recharge[1]

To estimate the groundwater recharge at field scale a water balance model was adopted which was set to local conditions. Groundwater recharge is defined as change between amount of irrigation water which is entering into root zone and leaving root zone after fulfilling the crop water needs. Generally in humid climates the crop water needs are fulfilled by precipitation (Basharat and Basharat, 2019). However, in arid climates, in addition to precipitation, sustainable agriculture depends on surface water supplies by canals. The average annual precipitation in LBDC command area is 327 mm. In the study region surface water supplies is provided by the intensive irrigation network to supplement crop water demands, which is also the major source of groundwater recharge to the aquifers. For this study groundwater recharge (GWR) estimated is determined by Equation 2.

$$GWR = [(Gross\ Irrigation + effective\ rainfall) - Net\ Irrigation] \times K \qquad \text{(Eq. 2}$$

where, GWR is the groundwater recharge in mm and K is fraction (0.9) of change in gross and net irrigation which recharges the groundwater aquifer (Awan et al., 2013). This fraction is included to account for evaporation and operational losses which does not contribute to groundwater recharge or percolation.

5.5.1 Canal Water Supplies

The main source of surface water supplies in LBDC command area is the water supplied from the main canal (LBDC). However, the irrigation system in LBDC command area was designed for only 67% cropping intensity (Basharat 2016). Water in LBDC (main canal) is diverted by regulating structure to distributaries and minors. Nawaz et al., (2021) reported the whole picture for discharge measurement in LBDC command area. Discharge at the head of each distributary was collected from the Programme Monitoring and Implementation Unit (PMIU) who is responsible for updating an online database. The daily values were aggregated into monthly values.

[1] *Awan U. K., Nawaz R. A., et al., (submitted). Potential for artificial recharge in Indus basis irrigation system of Pakistan under changing climate. Initial submission in Journal of Agricultural Water Management.*

5.5.2 Net Canal Water Irrigation

Net canal water irrigation is the irrigation water which is available to plants at the root-zone. The irrigation efficiency concept is used to assess the net canal water irrigation i.e., irrigation efficiency (irrigation network and field application efficiency) multiplied by total water available at the head of each distributary. For study region results, in a study done by Hussain et al., (2011) was used to incorporate the field and irrigation network losses which is 75% and 48% respectively. Therefore the resultant irrigation efficiency is 36% for study area.

5.5.3 Crop-specific Evapotranspiration (ET_c) and Effective Precipitation

The FAO-56 methodology was used to estimate the crop-specific evapotranspiration (ET_c) (Allen et al., 1998). Effective precipitation (Nawaz et al., 2021), relative humidity, solar radiation, air temperature and wind speed data were collected from Punjab Meteorological Department. Traditionally, wind speed is measured at 10 m to12 m height and then converted to 2-m values as required in FAO-56 methodology. ET_c values was calculated for all the distributaries of LBDC command area, with wheat-rice rotation and vegetables and maize rotation. The values of physical parameters like root depth, crop height and crop coefficients was taken from the literature. Rice, maize and wheat are the dominant crops in the study region (Ali Imran et al.,2018), Rice is cultivated and harvested in April and September respectively, whereas winter wheat is cultivated in October and harvested in March. In general, the root depth of wheat crop is approximately 90 cm.

CROPWAT was used to estimate the irrigation requirements and crop water requirements. The detailed methodology presented by Allen et al., (1998). Crop water demands is product of crop coefficient and reference evapotranspiration (ET_o), according to a study conducted by Allen et al., (1998). To estimate the reference evapotranspiration weather data i.e., solar radiation relative humidity, wind speed, maximum and minimum air temperature was collated from the Punjab meteorological department. ET_c was estimated by converting ET_o using the crop-physiological parameters (rooting depths, crop coefficients and development stages) which was collected from literature.

Figure 5.19 shows spatial distribution of crop evapotranspiration (ET_c) in LBDC command area. The significant variation of ET_c can be observed from the Figure 5.19, at head and tail end reaches of LBDC. The maximum ET_c is (1523 mm) at the head of LBDC and minimum values are at the end of LBDC. This may be due to less water supplies available to plants. On the other hand, ET_c values are minimum for the months of Rabi season. Results shows that the minimum value of ET_c during the month of January is due to closure of canals at the beginning of the month and due to low delta crops cultivated in Rabi season. The peak values of ET_c is in Kharif season with the maximum values during May (189 mm) and June (226 mm) months as shown in Figure 5.18. Results of this study reveals that annual average ET_c (1523 mm) is 60% more than annual average surface water supplies, i.e., average surface water supply (615 mm).

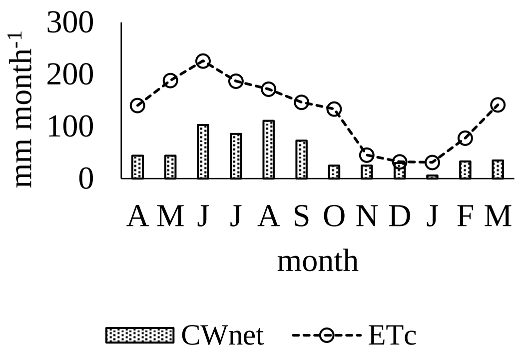


Figure 5.18: Monthly average crop evapotranspiration (mm) during study period in Lower Bari Doab Canal command area

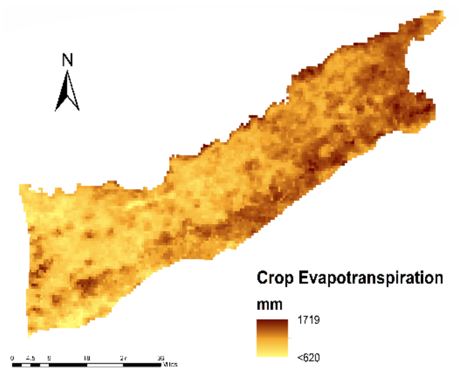


Figure 5.19: Spatial variation in annual average crop evapotranspiration in Lower Bari Doab Canal command area

5.5.4 Canal vs Crop Evapotranspiration (ET_c)

The results are shown in Figure 5.20. Under current Irrigation efficiency (36%) the average surface water supplies are 615 mm annually. However the crop evapotranspiration is 1523 mm annually. This reveals the limited availability of supply water supplies from irrigation system or with a given volume of water, supplies will be limited in order to irrigate more fields. The seasonal trends of surface irrigation supplies and ET_c for study period, shows that more than 60% irrigation supplies are available to farmers in Kharif season. Thus farmers should judiciously utilize surface water supplies in Rabi season.

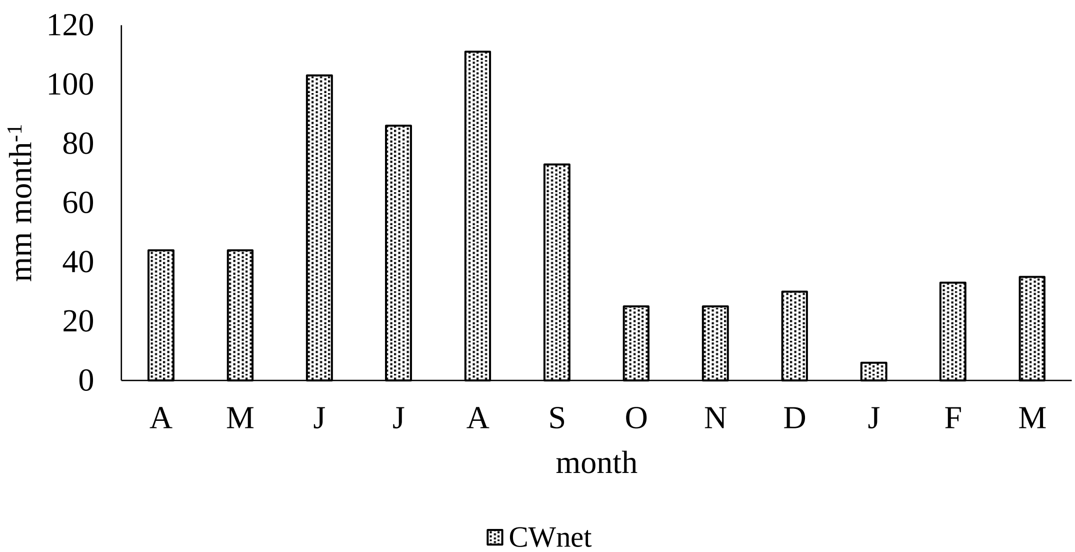


Figure 5.20: Variation of crop specific evapotranspiration (ETc) during different months (2010-15)in Lower Bari Doab Canal command area

5.5.5 Net Canal Water and Recharge Variation

For the study region average annual groundwater recharge was 694 mm, calculated by using Equation 2. The peak values (≥60 mm) for monthly groundwater recharge occur in months of April to August. Reason for these high recharge values is the increase of surface water supplies in these months, whereas it decreases (<60 mm) in the other months (Figure 5.21). The seasonal averages of groundwater recharge during Kharif and Rabi season was 431 mm and 263 mm respectively. These seasonal values reveals that groundwater recharge is 62% and 38% of total annual values during Kharif and Rabi seasons, respectively. It is worth noting that even during high intensity rainfalls which occurs in study region, during monsoon period, the moderately elevated slope and elevated field boundaries (bunds) in region helps to prevent the runoff and increase groundwater recharge (Ahmad et al., 2005).

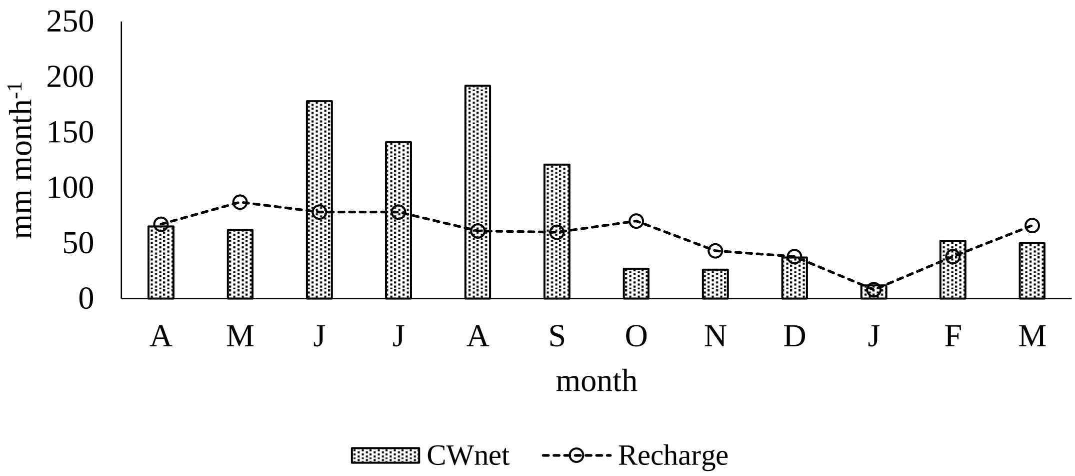


Figure 5.21: Variation of net canal water (CWnet) and recharge during different months (2015) in Lower Bari Doab Canal command area

5.5.6 Irrigation Efficiency Scenarios

The conventional surface irrigation systems, is inherently inefficient in Pakistan, with unlined canals considered as one of the main reasons of poor performance. Different scenarios were developed to study the impact of irrigation efficiencies on canal water supplies and potential of canal water supplies in the LBDC command area. According to Hussain et al., (2011) the average irrigation application efficiency for Punjab is 75% and conveyance efficiency of current irrigation system is 48%, so overall irrigation efficiency is 36%. According to the Bos and Nugteren, 1990 the current irrigation system poor. Table 5.3 is show the current and potential efficiencies of irrigation system of Pakistan (Bos and Nugteren, 1990).

Table 5.3: Recharge scenario in Lower Bari Doab Canal command area

Scenarios	Application Efficiency	Conveyance Efficiency	Irrigation Efficiency
Scenario A	0.75	0.48	0.36
Scenario B	0.9	0.48	0.43
Scenario C	0.75	0.80	0.60
Scenario D	0.90	0.80	0.72

Scenario A: BAU (Business As Usual).

Scenario B: Target application efficiency up to 90% and conveyance efficiency is BAU.

Scenario C: Application efficiency is BAU and target conveyance efficiency up to 80%.

Scenario D: Target both application efficiency up to 90% and conveyance efficiency up to 80%.

Figure 5.22 shows the results of groundwater recharge under different irrigation efficiencies for different scenarios. The trend shows that for all crops when irrigation efficiency for surface supplies increases from 36% to 72% recharge decreases from 694 mm year^{-1} to 337 mm year^{-1} and surface water supplies available for plants increases from 18% to 33%. This is attributed to increase in the crop evapotranspiration rate and decrease in the infiltration rates as well. The existing irrigation efficiencies on farm under actual field conditions are poor. Majority of irrigation events are over-irrigated. The excess irrigation applications were lost as deep drainage because all the fields in Pakistan is not equipped with tail drainage system.

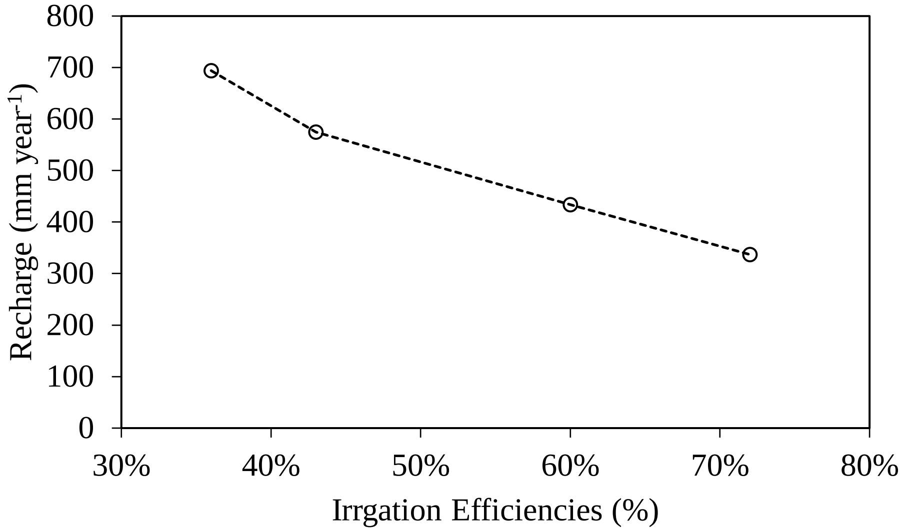


Figure 5.22: Efficiency vs recharge curve for Lower Bari Doab Canal command area

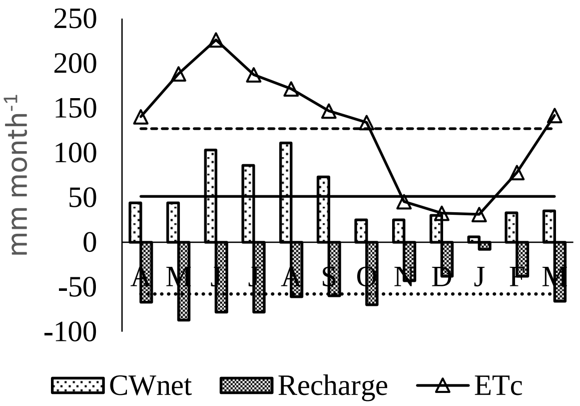


Figure 5.23: Variation of net canal water (CWnet), recharge and crop specific evapotranspiration (ET_c) during different months (2015) for scenario A in Lower Bari Doab Canal command area

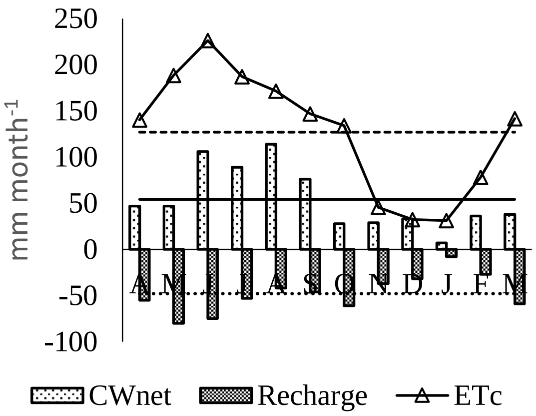


Figure 5.24: Variation of net canal water (CWnet), recharge and crop specific evapotranspiration (ET_c) during different months (2015) for scenario B in Lower Bari Doab Canal command area

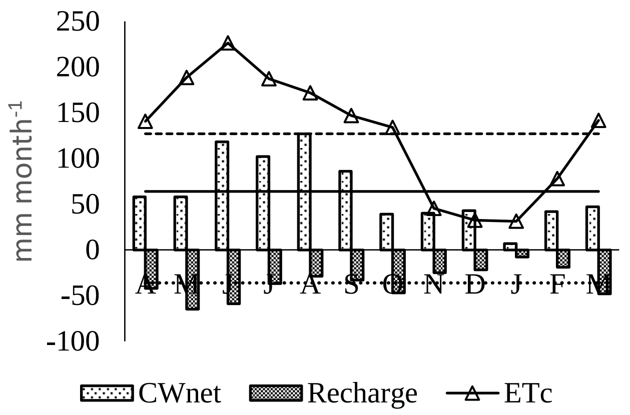


Figure 5.25: Variation of net canal water (CWnet), recharge and crop specific evapotranspiration (ET_c) during different months (2015) for scenarion C in Lower Bari Doab Canal command area

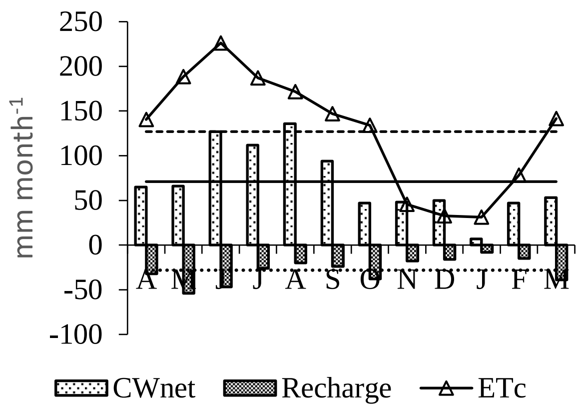


Figure 5.26: Variation of net canal water (CWnet), recharge and crop specific evapotranspiration (ET_c) during different months (2015) for scenario D in Lower Bari Doab Canal command area

5.6 Pumping and Groundwater Use[2]

A methodological framework was established to calibrate and validate the groundwater (GW) extraction by geo-informatics technique (Figure 5.27). The key components of the framework were canal water (gross and net), actual evapotranspiration (ET_a) and the effective rainfall. However, there are several complexities and uncertainties involved in estimating these components. Therefore, the results were calibrated and validated with ground truthing using in-situ measurements.

[2] *Nawaz, R. A., Awan, U. K., Anjum, L., & Liaqat, U. W. (2021). A novel approach to analyze uncertainties and complexities while mapping groundwater extractions in large irrigation schemes. Journal of Hydrology, 126131. https://doi.org/10.1016/j.jhydrol.2021.126131*

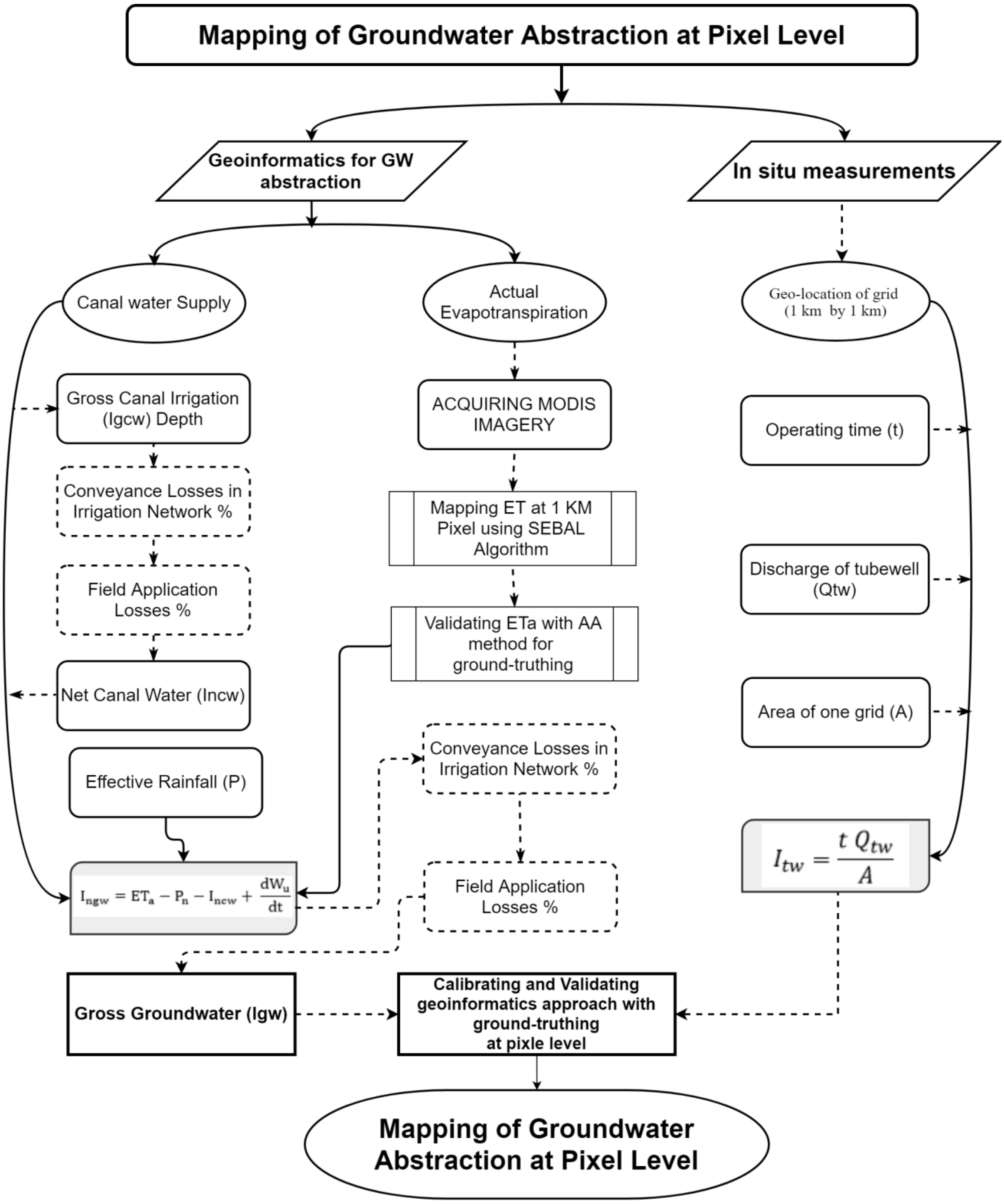


Figure 5.27: A schematic diagram explained mapping of GW extraction at pixel level in Lower Bari Doab Canal command area

5.6.1 Geo-information Technique

A geo-informatics technique was used to estimate GW extraction on monthly and annual basis. Ahmad et al., (2005); Awan et al., (2016b); Campos et al., (2013); Liaqat et al., (2016) found that geo-informatics provide more reliable results than direct and indirect methods. To estimate the net GW extraction by geo-informatics, the root-zone water balance was established at a 1 km grid size. According to this approach, net GW irrigation (I_{ngw}) is a residual product derived from water balance in the unsaturated zone for the given period (dt) as given below (Equation 3):

$$I_{ngw} = ET_a - P_n - I_{ncw} + \frac{dW_u}{dt} \qquad \text{(Eq. 3}$$

where I_{ncw} = net canal water irrigation; ET_a = actual evapotranspiration; P_n = effective rainfall; dW_u = change in the soil moisture storage over time; and I_{ngw} = net GW irrigation. The dW_u values are given in Nawaz et al., (2021).

As net GW extraction is not the total amount of water abstracted from aquifer, the conveyance and application losses were introduced to determine total GW extraction. Hussain et al., (2011) showed that irrigation and field application efficiency in the Indus basin for GW use are 90% and 75%, respectively. Thus an overall irrigation efficiency for the LBDC is taken as 68% to determine the gross GW extraction. Equation (3) describes net values for both surface and GW use by the plants. To achieve net irrigation (I_{ngw} = net GW irrigation) required for Equation (3), the efficiency concept is used which incorporates the deep percolation losses that are contributing to the GW aquifer. The application efficiency at field level is 75% and according to Awan et al., (2016a) around 90% of the field losses are percolated to recharge the GW aquifer.

The canal water supply data is collated from Punjab Irrigation Department (PID) for all distributaries in the LBDC command area. The ET_a used in Equation (3) was estimated by forcing the Surface Energy Balance Algorithm for Land (SEBAL).

5.6.2 Actual Evapotranspiration

The SEBAL is a well-known remote sensing-based algorithm to map ET_a at high temporal and spatial resolution. Detailed methodology for the SEBAL algorithm is published by Bastiaanssen et al., (1998). When SEBAL algorithm was validated under different agro-climatic conditions, it yielded around 95% accuracy (Bastiaanssen et al., 1998). The recently published literature showed that SEBAL algorithm was used in several water balance studies which has been conducted across the globe (e.g. Awan et al., 2011; Conrad et al., 2007; Hafeez et al., 2008; Hellegers et al., 2009; Karatas et al., 2009). The fundamental basis of the algorithm is surface energy budget where ET_a is residual product of energy balance (Equation. 4):

$$\mathrm{Rn} = \mathrm{G}_o + \mathrm{H} + \lambda\mathrm{E} \qquad \text{(Eq. 4}$$

where R_n = net radiation (W m^{-2}), G_0 = soil heat flux (W m^{-2}), H = sensible heat flux (W m^{-2}), λE = latent heat flux (W m^{-2}).

Bastiaanssen et al., (2002) introduced the evaporative fraction concept according to which Equation. (4) can be expressed as a latent heat flux by considering evaporative fraction and net available energy (R_n-G_o):

$$\lambda\mathrm{E} = \Delta(\mathrm{R}_n - \mathrm{G}_o) \qquad \text{(Eq. 5}$$

where Δ is evaporative fraction and can be described as:

$$\Delta = \frac{\lambda\mathrm{E}}{(\mathrm{R}_n - \mathrm{G}_o)} = \frac{\lambda\mathrm{E}}{\lambda\mathrm{E+H}} \qquad \text{(Eq. 6}$$

The net available energy (R_n – G_o) can be estimated from instantaneous timescale to daily or to monthly timescale. For timescales of 1 day, soil heat flux can be ignored, and net available energy reduces to net radiation (R_n) by which ET_a on daily basis can be calculated as:

$$\mathrm{ET}_{24} = \frac{86400\times10^3}{(\mathrm{Rn}-\mathrm{G0})} = \frac{\lambda\mathrm{E}}{\lambda\mathrm{E+H}} \qquad \text{(Eq. 7}$$

where R_{n24} = 24 h averaged net radiation; k = latent heat of vaporization; and qw = density of water. In the current study, MODIS (Moderate Resolution Imaging Spectroradiometer) used to map ET_a for LBDC command area (Table 5.4). MODIS standard products utilized in this study are collected free of cost from the website (https://earthexplorer.usgs.gov/). For this study, climatic data was collated form Pakistan Metrological Department.

Table 5.4: MODIS data used for SEBAL algorithm

Product	Name	Dataset Spatial resolution (m)	Sensor
MOD09Q1	Land surface reflectance (band 1 and band 2)	250	TERRA

MOD11A2	Land surface temperature and emissivity	1000	TERRA
MOD13A2	NDVI	1000	TERRA

5.6.3 Canal Water Use

Different distributaries which diverts water from the main LBDC by flow regulating infrastructure are the major source of irrigation water distribution in the command area. The PID is mainly responsible for the measurement and control of water release in the distributaries as well as maintaining the online discharge dataset. Water depth in the distributaries is measured by stream-gauges which then use rating curves to estimate the flow in distributaries. The concept of irrigation efficiency (conveyance and field efficiency) was applied to estimate the net canal water (amount of water accessible by plant). Hussain et al., (2011) reported that field application and conveyance efficiency in the LBDC command area is approximately around 75% and 48%, respectively. This results in an overall irrigation efficiency of around 36% which was used for the current study.

5.6.4 In-situ measurements of GW extraction

There is unplanned and rapid development of private tubewells for mitigating surface water scarcity. However, there is no mechanism established to estimate the GW extraction in the entire Indus basin. In current study, we determined the GW extraction by physically calculating GW extraction at 1 km by 1 km grid size. The canal discharge and operation time was determined from each tube-well. Equation (8) was then used to compute the GW extraction (I_{tw}) of the given tube-well (N_{tw}):

$$I_{tw} = \frac{t\,Q_{tw}}{A} \qquad \text{(Eq. 8}$$

where t is operating time of the tube-well in hours for the given time period, Q_{tw} is discharge of tube-well ($m^3\ day^{-1}$) and A (m^2) is area of grid (1 km by 1 km).

5.6.5 Calibration and Validation of Groundwater Extraction

There are complexities and uncertainties in geo-informatics techniques which may result in an inaccuracy. However, to mitigate these complexities and uncertainties there is need to calibrate and validate the GW extraction estimated by geo-informatics technique with in-situ measurements. Survey was conducted in thirty grids (each grid is 1 km^2 of size) for tubewells data (Figure 5.28). For calibration purposes, fifteen grids were selected at head (5 grids), middle (5 grids) and tail (5 grids) end reaches of LBDC. For validation purposes, fifteen more grids were selected at head (5 grids), middle (5 grids) and tail (5 grids) end reaches of LBDC. The GW extraction in these grids were estimated by in-situ measurements.

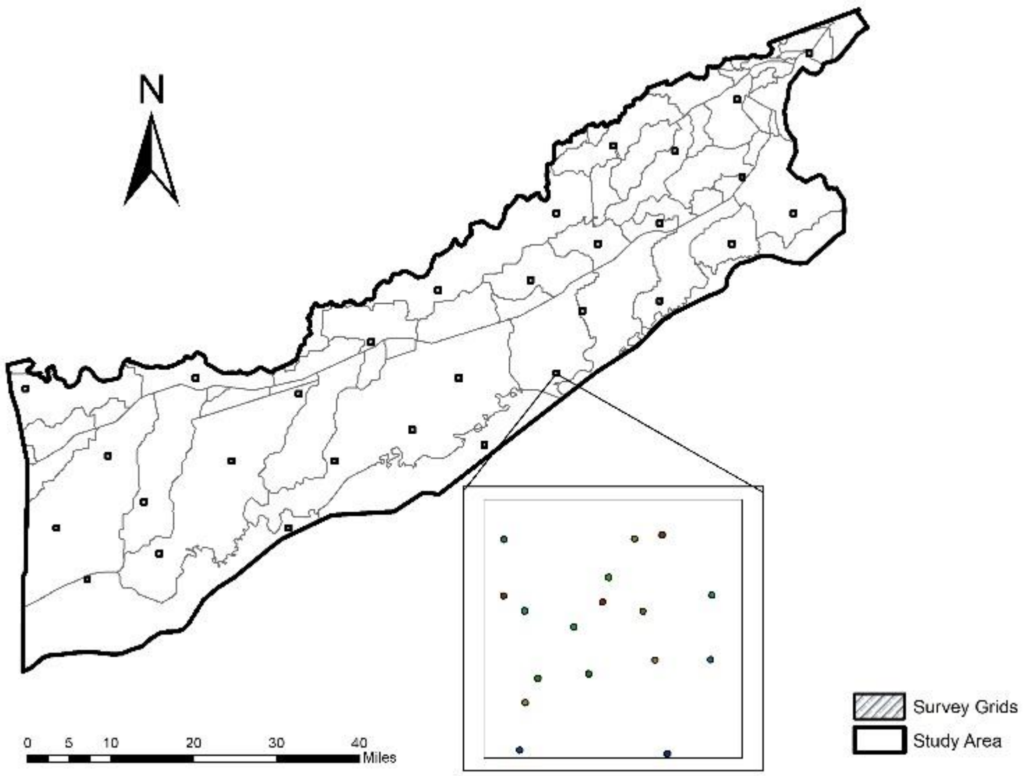


Figure 5.28: Location of grids for estimating groundwater extraction in Lower Bari Doab Canal command area

The factors which can influence the GW extraction includes canal water supplies, rainfall data and ET_a. As GW extraction by geo-informatics is estimated at 1 km^2 pixel size, these factors vary significantly within the pixel. The ET_a estimated from SEBAL is validated with AA method and thus can least influence the GW extraction. The rainfall data is also observed at Pakistan Metrological Department stations with high accuracy. However, canal water supplies data measured at head of distributary cannot be assumed constant for the entire distributary with on average 2000 ha size. Awan et al., (2016a) reported inequity at head, middle and tail reaches. Therefore, we used the canal water consumption at head, middle and tail reaches for the calibration of GW extraction. After calibration of the GW extraction at 1 km pixel size, the geo-informatics approach was validated for other 15 pixels. The coefficient of determination (R^2) for evaluating the predictive performance of geo-informatics results was used (Awan et al., 2014) and calculated using Equation (9):

$$R^2 = \frac{\Sigma(R-R_m)(E-E_m)}{\{\Sigma(R-R_m)^2\}^{0.5}\{\Sigma(E-E_m)^2\}^{0.5}} \quad \text{(Eq. 9}$$

where E is estimated data and E_m is the mean of the estimated data whereas R_m is the mean of the reported data and R is the reported data.

5.6.6 Intra-grid Variation of Groundwater Extraction in Lower Bari Doab Canal Command Area (LBDC)

Table 5.5 is shows the statistical analysis of groundwater (GW) extraction in 9 grids selected as a sample out of 30 for head, middle and tail end reaches of the Lower Bari Doab Canal (LBDC). Results reveal that there are around 22 (±2), 20 (±3) and 18 (±3) tubewells in one grid (1 km) at head, middle and tail end reaches of the LBDC, respectively. The variation of GW extraction within all the grids is significantly high ranging from 105 mm year^{-1} to 244 mm year^{-1} at all spatial scales. This variation typically depends on type and size of tube-well, cropping patterns and cropping intensities, surface water supplies, and agro-climatic conditions. Basharat and Tariq (2014) reported that there is no governance regime in Indus basin to regulate over exploitation for judicious use of the GW resources. Maximum GW extraction was 854 mm (±105) in grid-5 whereas minimum GW extraction was 649 mm (±244) in grid-26. The wide ranges of GW extraction for LBDC can be attributed to diverse cropping patterns. Interviews with farmers in Okara, Khanewal and Sahiwal Divisions revealed that due to cotton-wheat cropping rotation in Khanewal and Sahiwal Division, the GW extraction is low in these Divisions as compared to Okara Division. More water consumption in Okara division is due to more crop water requirements for the predominant rice-wheat and sugarcane crops. Results of the survey further show that sugarcane and rice crops use three times more water when compared to cotton and wheat crops. The overall GW extraction in all 30 grids was 747 (±145) mm year^{-1}.

Table 5.5: Distribution of GW extraction in survey grids

	Head			Middle			Tail			LBDC
Grid Number	1	5	8	12	15	19	23	26	29	
SD	159.8	104.8	178.7	219.6	137.9	173.9	180.6	244.1	175.6	175
Mean (mm)	785	854	813	742	761	717	680	649	718	747
CV	20.4	12.3	22.0	29.6	18.1	24.2	26.6	37.6	24.4	23.9
Variance	25525	10991	31948	48230	19008	30225	32598	59583	30838	32105

SD is standard deviation; CV is coefficient of variation

5.6.7 Inter-grid Variation of Groundwater Extraction at Different Locations in LBDC

Figure 5.29 is showing the GW extraction from all tubewells (524) in all 30 grids. The GW extraction was decreasing from head to tail. The average GW extraction in head distributaries was 814 mm year^{-1} whereas average GW extraction in tail end distributaries was 688 mm year^{-1}. This analysis reveals that farmers at head grids are using 16% more GW as compared to farmers at tail end grids. Majority of the tubewells (approximately 60%) are installed around 40 m below the soil surface at head and middle reaches of LBDC due to shallower GW levels. Tubewells at the tail end reaches are installed at a depth of 60 m or more. Different studies show that GW extraction from deeper aquifer raises the cost of installing tubewells and also causes a risk of accumulation of salts in the soil profile.

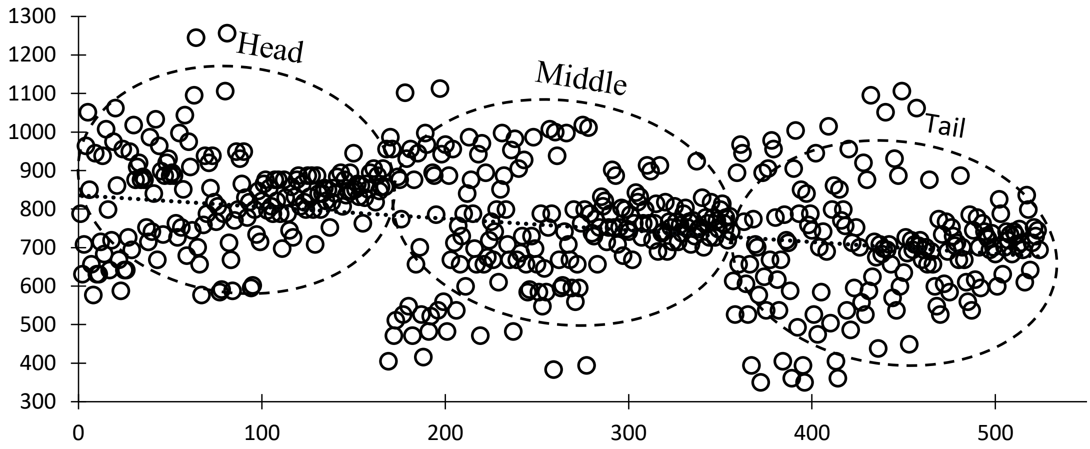


Figure 5.29: Groundwater extraction for different tube-well in at head, middle and tail end reaches of Lower Bari Doab Canal command area

A statistical analysis of GW extraction between the head, middle and tail end reaches depict relatively large differences (Table 5.6). The analysis of variance shows that GW use significantly differs at head, middle and tail end reaches at confidence interval of 95%.

Table 5.6: Statistical analysis of GW extraction between the grids

	Head	Middle	Tail
SD	52	44	56
Mean	814*	769*	688*
CV	6.6	6.1	8.4
Variance	2681	1909	3150

*Correlation is significant at 0.05 level; SD is standard deviation; CV is coefficient of variation

5.6.8 Calibration and Validation of Groundwater Extraction

Results show that the trend of GW extractions by geo-informatics and in-situ measurements does not vary significantly. The GW extraction is higher at head end grids and reduces at tail end grids (Figure 5.30). However, the R^2 value after first results is less than 0.6. The reason for that is huge discrepancies of GW extraction between the middle and tail end reaches (Figure 5.30). This could also be related with the simplified assumptions of constant canal water use at all spatial scales during estimation of GW extraction which result in uncertainties. However, researchers have shown that the canal water availability differ at head, middle and tail end reaches approximately by 40%, 34% and 26%, respectively (Anwar and Haq 2013; Awan et al., 2016a). Therefore, the differences in GW extraction by geo-informatics was greater (±68 mm) at tail end reaches.

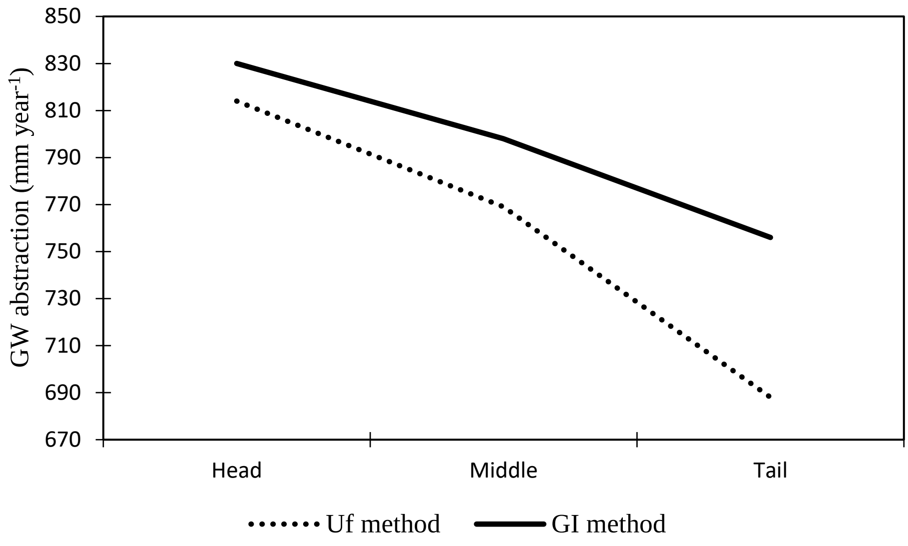


Figure 5.30: A comparison of groundwater extraction at head, middle and tail end reaches of Lower Bari Doab Canal command area

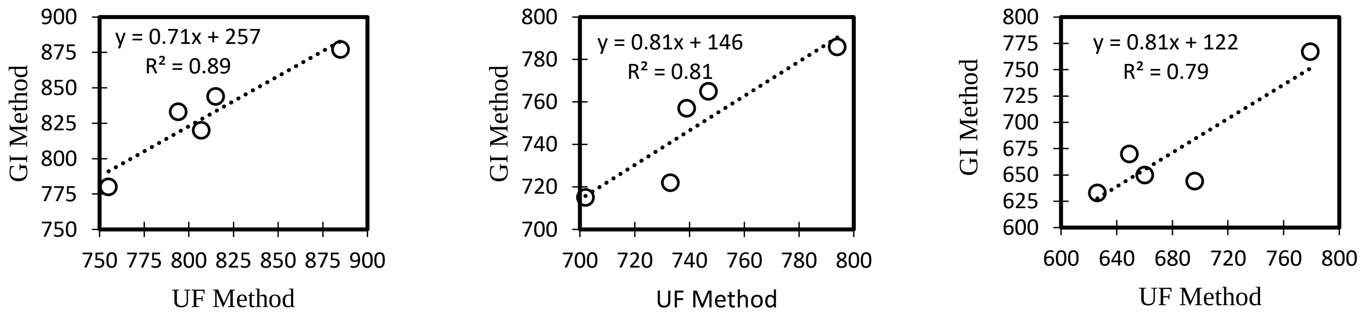
After multitudinous run, calibration was done by rectifying the canal water supplies and the scatter plot comparison which reveal good agreement between the two methods at head, middle and tail grids. The R^2 at head, middle and tail was 0.89, 0.81 and 0.79, respectively. The equations were developed after calibration at head (Equation 10), middle (Equation 11) and tail (Equation 12) which are shown in Figure 5.31.

$$GW_{GI} = 0.71U_f + 257 \quad \text{(Eq. 10}$$

$$GW_{GI} = 0.81U_f + 146 \quad \text{(Eq. 11}$$

$$GW_{GI} = 0.81U_f + 122 \quad \text{(Eq. 12}$$

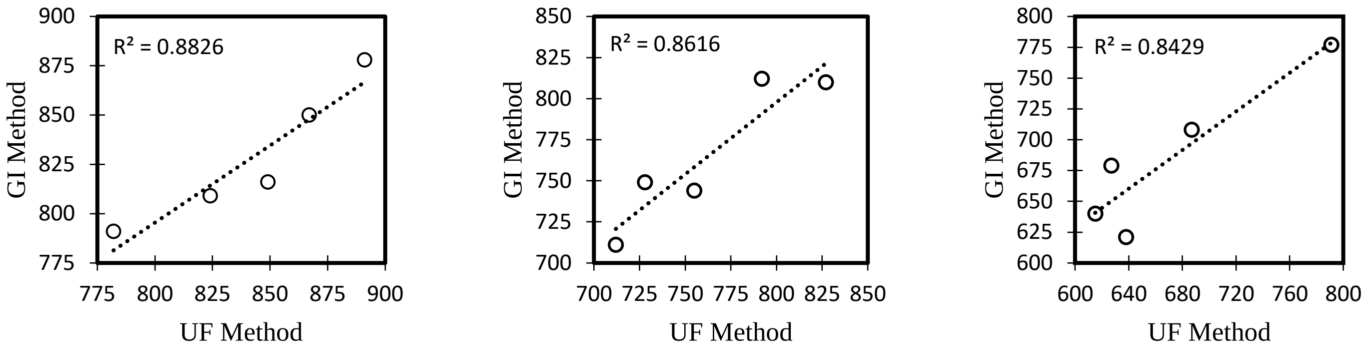
where GW_{GI} = GW extraction using GI method and U_f = GW extraction using U_F method



a) Head **b)** Middle **c)** Tail

Figure 5.31: Comparison of Uf method and geo-informatics results after calibration at head, middle and tail

Figure 5.32 shows the validation results using Eq. (10), Eq. (11) and Eq. (12). Such a level of similarity in annual GW extraction can give confidence to use geo-informatics for other regions after calibration. The R^2 value between estimated and calculated GW extraction at head, middle and tail end reaches is 0.88, 0.86 and 0.84, respectively.



a) Head **b)** Middle **c)** Tail

Figure 5.32: Validation of Uf method and geo-informatics results after calibration at head, middle and tail

Figure 5.33 shows the annual GW extraction in different distributaries of LBDC command area. The GW extraction map shows that there is a variation in GW use at head and tail end reaches of the LBDC. The GW extraction is quite high from where the LBDC originates (north-east side) and low at tail of the LBDC (south-west side).

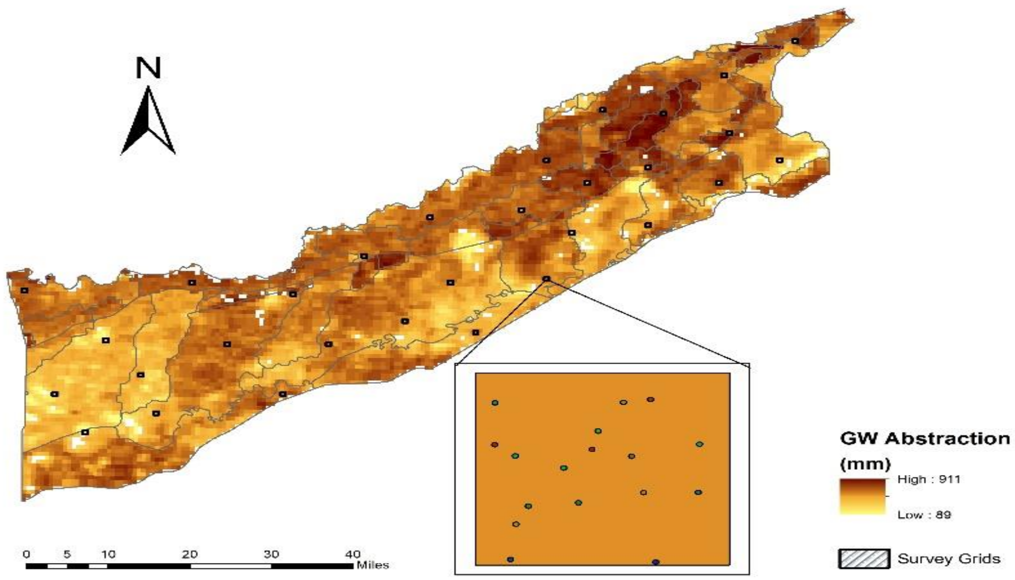


Figure 5.33: Spatial distribution of GW extraction in LBDC command area

5.6.9 Interrelations of Groundwater with canal water at Different Spatial and Temporal Scale

Among different distributaries, maximum canal water irrigation was 823 mm whereas the minimum canal water irrigation was 579 mm for the entire cropping year. In the entire LBDC, the average annual canal water supply was 2.02 mm day^{-1}. The canal water supply was 21% more during Kharif season when compared to Rabi season. Since December and January are the months when accumulated silt is removed, there is no canal water supply during these months (Ahmad et al., 2005). Results further show that around 2.4 mm day^{-1} of water is supplied during the Kharif season whereas 1.6 mm day^{-1} is supplied during the Rabi season to the entire LBDC command area (Figure 5.34).

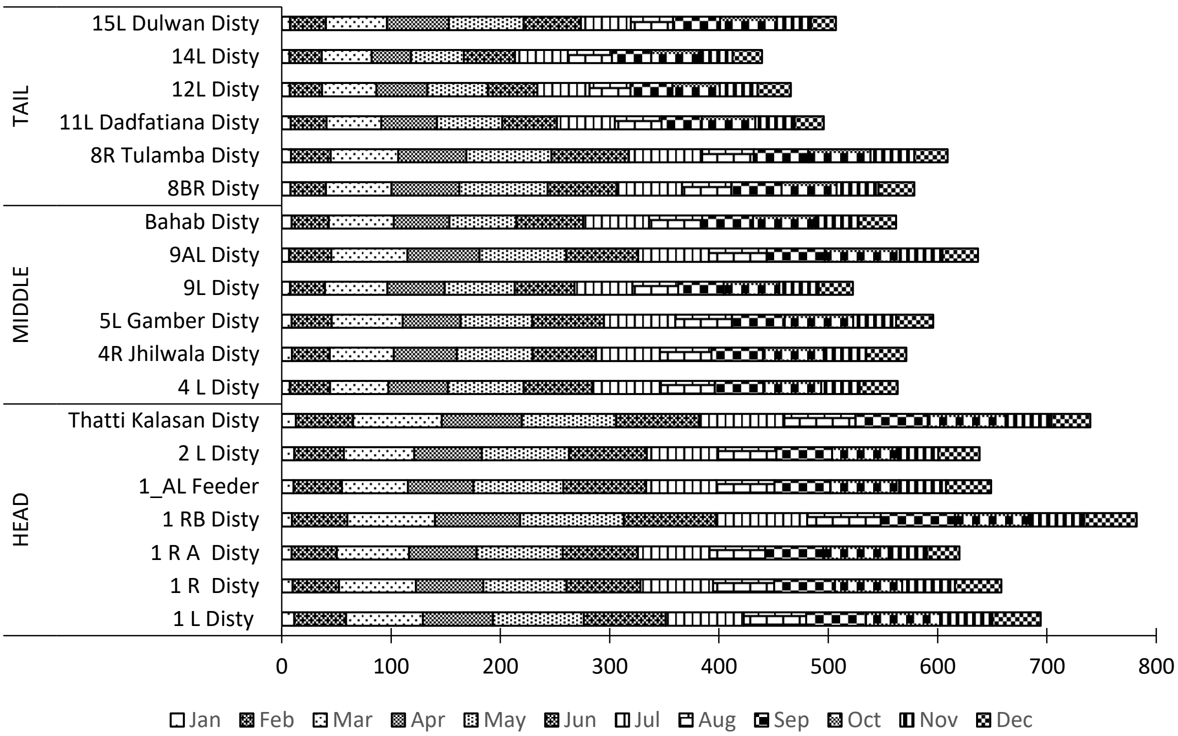


Figure 5.34: Gross canal water on monthly and annual basis in different distributaries of LBDC command area

As the sum of net canal water and rainfall was only 518 mm (44% of ET_a), farmers generally rely on the GW extraction to mitigate the water scarcity (Awan et al., 2017). The annual GW extraction from aquifer varied from 576 mm to 846 mm, with an average of 730 mm (Figure 5.35), out of which 64% is extracted during Kharif season and rest is extracted during Rabi season. In various months, the GW fluctuated between 0 mm to 183 mm which is mainly controlled by crop water requirement and rainfall pattern. In study area, GW extraction is minimum during January (13 mm) and November (4 mm), due to low crop water demand and high rainfall, respectively (Basharat 2012). The maximum GW extraction occurred in month of May which could be due to the insufficient canal water supplies and low rainfall as well as cultivation of rice crop.

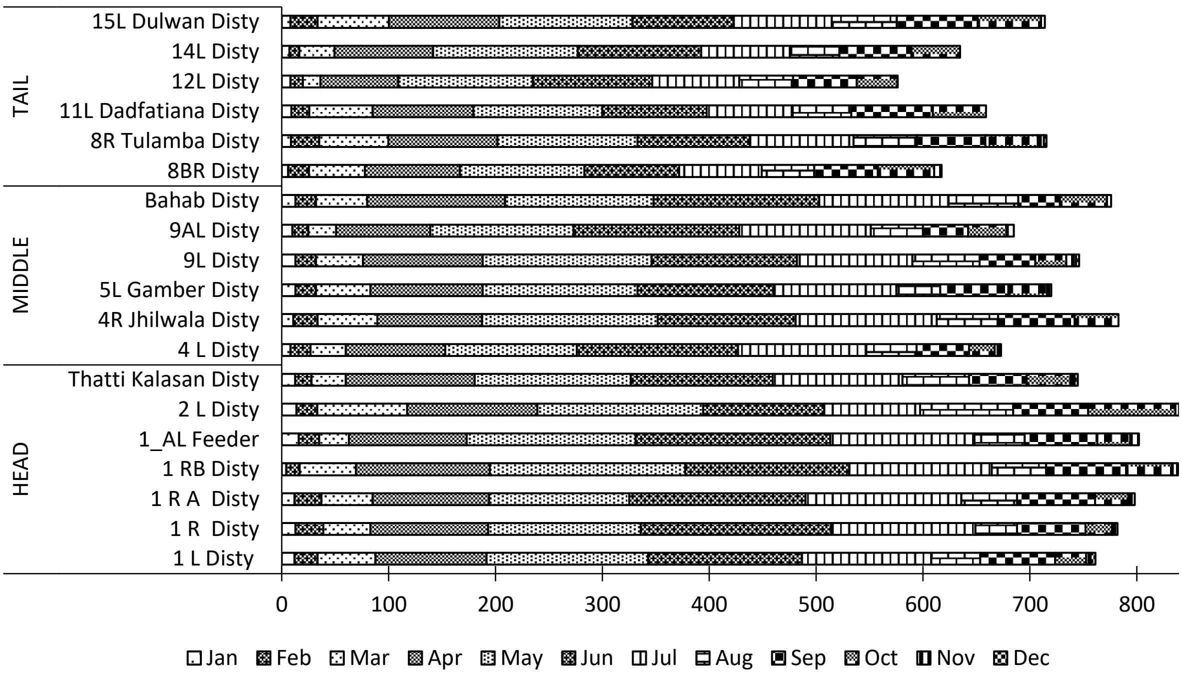


Figure 5.35: Gross ground water on monthly and annual basis in different distributaries of LBDC command area

A comparison of spatial distribution of groundwater irrigation at head, middle and tail end reaches is presented in Figure 5.36a.

The results show that of the total GW extracted in LBDC command area, 37% is extracted by farmers situated at head end reaches, while the fields in the middle and tail end reaches use 33% and 30% of the total GW abstracted respectively (Figure 5.36a). These results are in line with the findings of Awan et al., (2016a) who reported comparable results for Hakra canal command area of Punjab province, Pakistan. According to that study, farmers situated at head, middle and tail end reaches use 42%, 35% and 23% GW of total GW abstracted, respectively.

Figure 5.36b shows that farmers situated at head end reaches of the LBDC receive only 39% of the total surface water supply whereas only 32% and 29% surface water supply is received by farmers situated at the middle and tail end reaches, respectively. Awan et al., (2016a) reported that in Hakra canal command area, the surface water supplies at the head, middle and tail end reaches is only 40%, 34% and 26%, respectively. The results of both studies show similar trends of canal water and GW use. Results show that 36% of the total rainfall occurs at head end reaches which reduces to 34% and 30% for middle and tail end reaches (Figure 5.36c). The variation between rainfall at head and middle reaches is only 2%. However, at tail end reaches rainfall reduce by 6% as compare to the head end reaches.

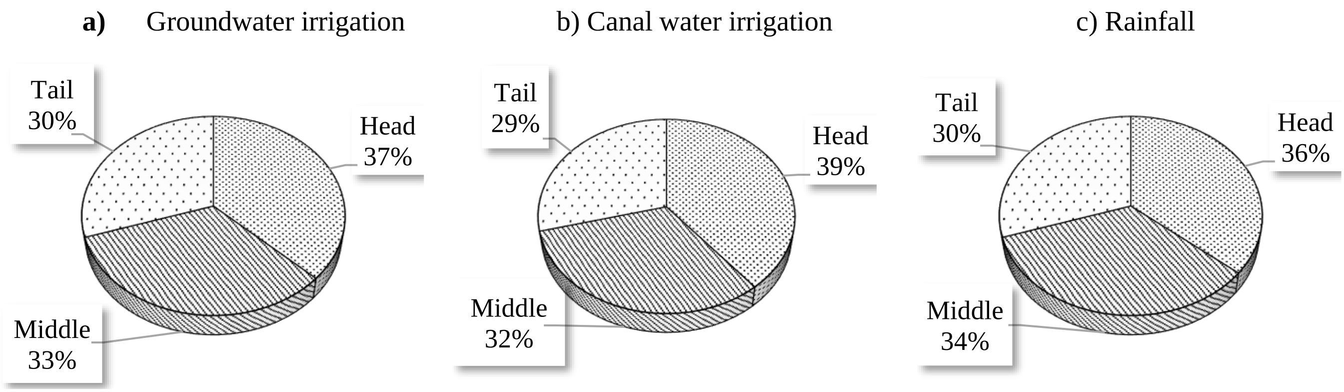
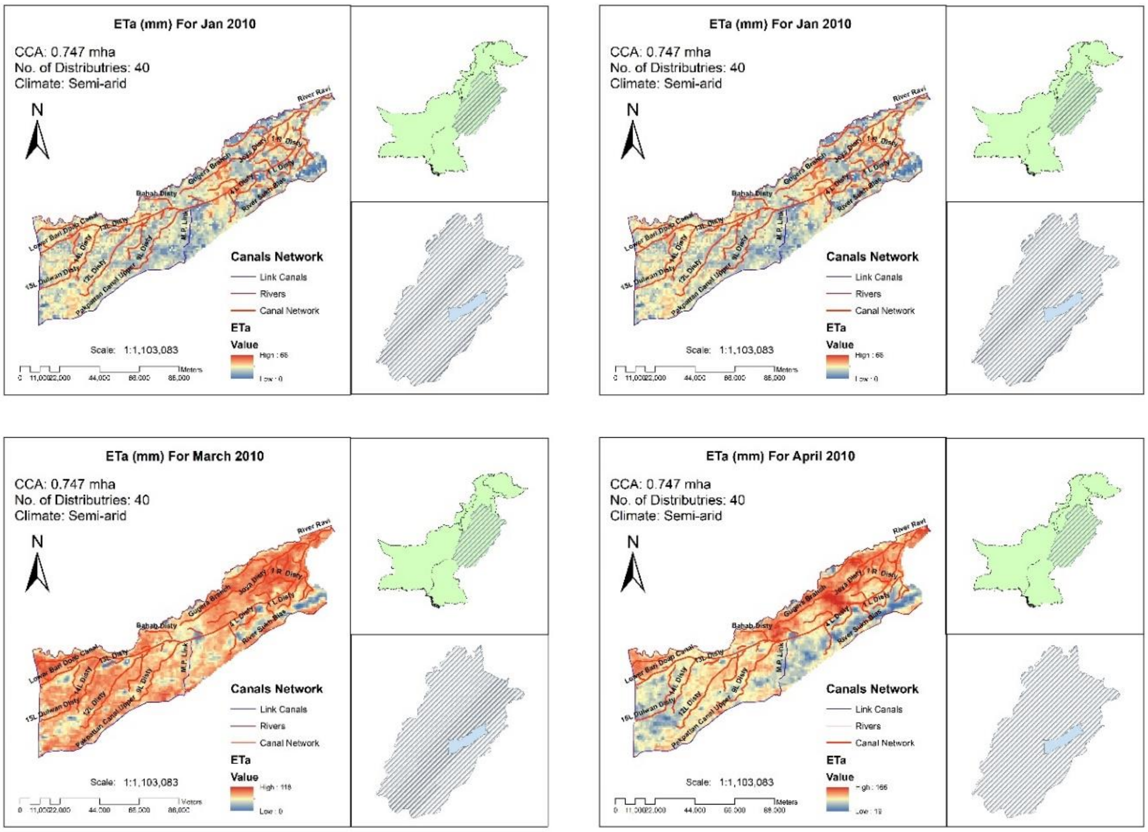


Figure 5.36: Variation of (a) groundwater irrigation, (b) canal water irrigation, and (c) rainfall on annual basis at head, middle and tail end reaches of Lower Bari Doab Canal command area



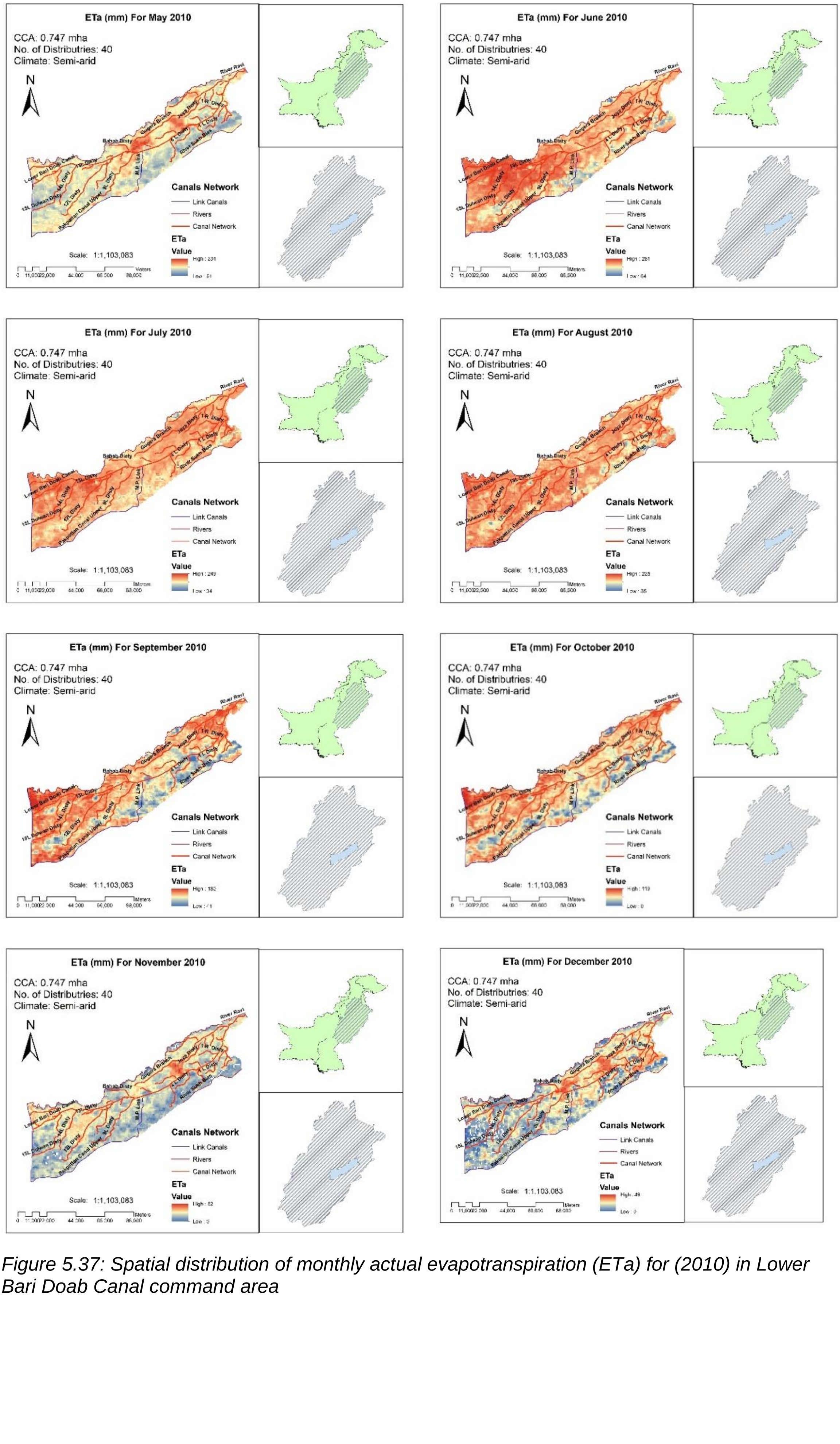


Figure 5.37: Spatial distribution of monthly actual evapotranspiration (ETa) for (2010) in Lower Bari Doab Canal command area

5.7 Estimation of Different Water Uses by Water Accounting[3]

5.7.1 Water Accounting Framework for Lower Bari Doab Canal Command Area in Context of National Water Policy of Pakistan

A framework is developed to account for water supply and demand for LBDC in context of the National Water Policy (NWP) 2018 (Figure 5.38). NWP 2018 prioritize the uses of water as sanitation and drinking, irrigation purposes including the land reclamation, livestock, wildlife and fisheries, hydropower, industry and mining, environmental use, aquatic life and wetlands, forestry, sport and recreation, and navigation. There are three water resources in LBDC command area to fulfill the overall demand of the LBDC including surface water, GW and rainfall. Water supply from canals are naturally uncontrolled as water is coming through glaciers and rainfall (in watersheds). However, GW is controlled as it is extracted from aquifer on demand basis. Tools and performance indicators have been developed to assess the water supplies and demands of agriculture, domestic, industrial and environment use.

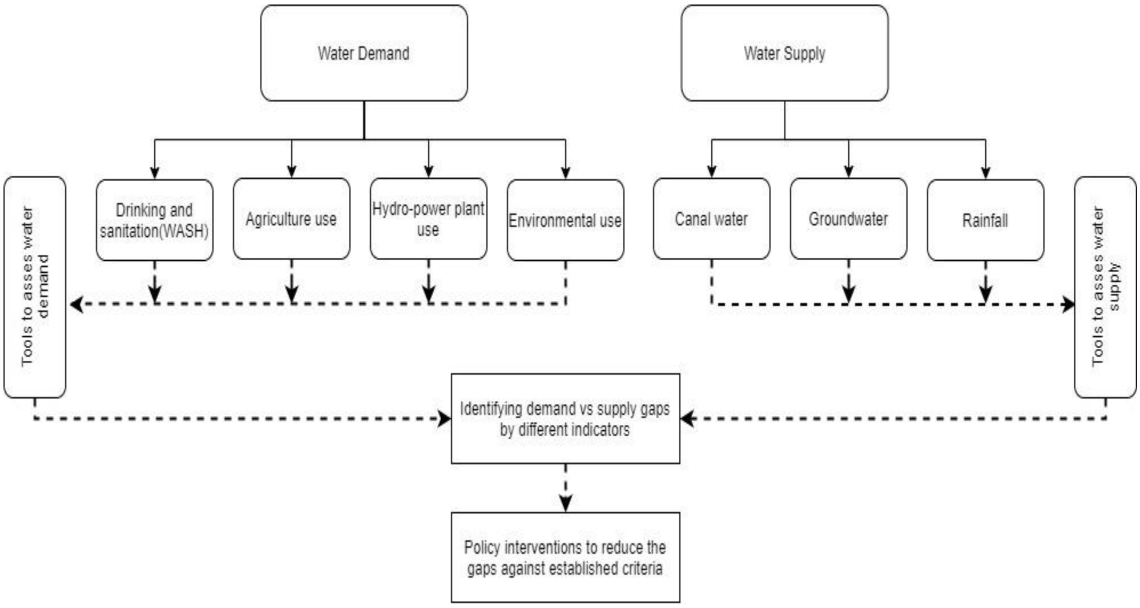


Figure 5.38: Water accounting framework for Lower Bari Doab Canal command area

5.7.2 Water supply to Lower Bari Doab Canal area

For the key management of water assets in LBDC command area, three water supplies components are identified. These include gross canal water use, gross GW use, and rainfall. Canal water supplies data were collected from the Programme Monitoring and Implementation Unit (PMIU) who is accountable for quantifying discharges and then maintain and update an online database of surface water supplies in the study area as well. By using actual evapotranspiration (ET_a) within the geo-informatics approach, the net GW use is quantified.

[3] *Awan U. K., Nawaz R. A., et al., (submitted). Water accounting in decision-making processes of surface and groundwater resources management: Benefits, limitations and implications. Initial submission in Journal of Agricultural Water Management.*

Ahmad et al., (2005) reported that such geo-informatics approach has more advantages over the direct and indirect methods as such approach require minimal field data with high computational efficiency and accuracy. Furthermore in many regions around the globe this approach has been successfully implemented (Ahmad et al., 2005; Campos et al., 2013; Castaño et al., 2010; Liaqat et al., 2016). In this approach, the consumptive water use by means of ET_a was estimated by Surface energy balance algorithm for land (SEBAL) model. Whereas, the losses at the farm level and network level was used to calculate gross GW extraction. The rainfall data utilized in forcing the geo-informatics approach was collected from Okara and Sahiwal meteorological stations which are being operated and maintained by Pakistan Meteorological Department (PMD).

Canal water supplies LBDC is the main source of surface water supply, which offtakes from Balloki headworks. By regulating structures, water from LBDC is diverted into the distributaries. PID is responsible for regulation and measurement of discharge. To determine the discharge in distributaries PID use the depth (stage) of water.

At head of each distributary, staff-gauges are installed to measure the water depth. Normally, PID measure discharge twice a day. Irrigation water which is available to plants in the root-zone is known as net canal water. The irrigation efficiency concept is used to estimate the net canal water irrigation, e.g., irrigation efficiency (irrigation network and field efficiency) multiplied by total water available at distributary's head. Results from Hussain et al., (2011) were used, in order to incorporate field application and irrigation network losses. They reported that the field application and irrigation network efficiency are widely varied in the study area which accounts as a 75% and 48%, respectively, which cumulatively results 36% of irrigation efficiency.

Groundwater supplies Geographic information technology is used to evaluate the net amount of GW used in the LBDC. According to such an approach, net GW irrigation (I_{ngw}) is a residual product derived from water budget in unsaturated zone for given period (dt) as depicted below (Equation 13):

$$I_{ngw} = ET_a - P_n - I_{ncw} + \frac{dW_u}{dt} \qquad \text{Eq. 13}$$

where I_{ncw} = net canal water irrigation; ET_a = actual evapotranspiration; P_n = effective rainfall; dW_u = change in the soil moisture storage over time; and I_{ngw} = net GW irrigation. The dW_u values are taken form study published by Ahmad (2002) for the LBDC area and is described in Table 5.7. To estimate gross GW extraction, losses at the farm level and network level were used. Hussain et al., (2011) showed that irrigation and field application efficiency in the Indus basin for GW use are 90% and 75%, respectively. Thus an overall irrigation efficiency for the LBDC is taken as 68% to determine the gross GW extraction.

5.7.3 Water Demand for Lower Bari Doab Canal Command Area

SEBAL is a well-known algorithm which is used as a tool to estimate ET_a. Bastiaanssen et al., (1998) provided the detailed methodology for this approach and validated it under the different agro-climatic conditions as well. The SEBAL model has consistently been used in several water balance studies (e.g., Awan et al., 2011; Conrad et al., 2007; Hafeez et al., 2007; Hellegers et al., 2009; Karatas et al., 2009) conducted in recent years around the globe. Most of these studies reported 90-95% accuracy of SEBAL model indicating the algorithm utility for deriving the consumptive water use by using satellite remote sensing data.

A survey was conducted in LBDC command area to estimate the water used by industrial and commercial sectors in different process i.e. cooling, at given time. For agriculture use, LBDC is the main source of water supply, however, a small portion of water is also used by industrial sector such as 29 cusec of water is used by thermal coal project in Sahiwal coal power project. Despite this almost all of the industrial sector fulfil their water requirement from GW withdrawals. Further, Lahmeyer (2013) reported that the domestic and industrial sector is extracting 32 MCM $year^{-1}$ of water from the aquifer in this study area.

5.7.4 Supply vs Demand Analysis Using Water Resources Performance Indicators

The performance indicators are usually identified as process and depleted fractions to avoid misconceptions by the use of the efficiency term (Jensen 1993; Willardson et al., 1994). They intend to depict a system, rather than being an assertion of the performance of the system.

Depleted Fraction (DF) is that inflow fraction which spend by both the non-process and process uses. The process depletion includes domestic and industrial use and evapotranspiration as well, and the non process depletion is the water evaporated from non-crop vegetation and return flows to GW. DF can be defined with reference to available, gross and net water.

$$\mathrm{DF_{net}} = \frac{\mathrm{Depletion}}{\mathrm{Net\ inflow}}$$ (Eq. 14

$$\mathrm{DF_{gross}} = \frac{\mathrm{Depletion}}{\mathrm{Gross\ inflow}}$$ (Eq. 15

$$\mathrm{DF_{available}} = \frac{\mathrm{Depletion}}{\mathrm{Available\ water}}$$ (Eq. 16

The total volume of water coming in the region from surface water supplies, rainfall and GW sources is known as *Gross inflow*. However summation of gross inflow and change in storage is equivalent to *Net inflow*.

Process Fraction (PF) is the process depletion from the amount of water available or total depletion.

$$\mathrm{PF_{depleted}} = \frac{\mathrm{Process\ depletion}}{\mathrm{Total\ depletion}}$$ (Eq. 17

$$\mathrm{PF_{available}} = \frac{\mathrm{Process\ depletion}}{\mathrm{Available\ water}}$$ (Eq. 18

The removal or use of water either in non-process or process depletion is included in water depletion. It is the key to discriminate water depletion from water that delivered to service or a use as not all the water which is delivered for a use is depleted. Whereas in addition to the process and non-process depletion, uncommitted water is also include in available water.

The process fraction for the depleted water ($PF_{depleted}$) is similar to the effective efficiency idea presented by Keller and Keller (1995). Moreover when the basin is fully committed, particularly $PF_{depleted}$ is useful in identifying water savings opportunities. $PF_{depleted}$ and the $PF_{available}$ both are equal when there is no uncommitted water. *Uncommitted outflow* is water within a basin which is not committed or depleted and thus is available for service or a use however flows out due to lack of operational measures or storage. Alternatively, c*ommitted water* is the share of outflow which is devoted to environmental and downstream users. These all are important indicators and parameters which are estimated in this study to accounts the demand and supplies for different sectors.

5.7.5 Policy Advice and Value of Performance Indicator

Figure 5.39 shows the (measured or collected) data through a (dimensionless) performance indicator, which includes the ratio of an intended (or critical) value and an actual value of data on the considered key parameter. Bos et al., 2005 reported that based on the 'service agreement', indicator should have a target level. An allowable range around the target level, within which without triggering a management action indicator can fluctuate. However, in case the indicator differs from this range, corrective action must be planned based on the analysis of problem.

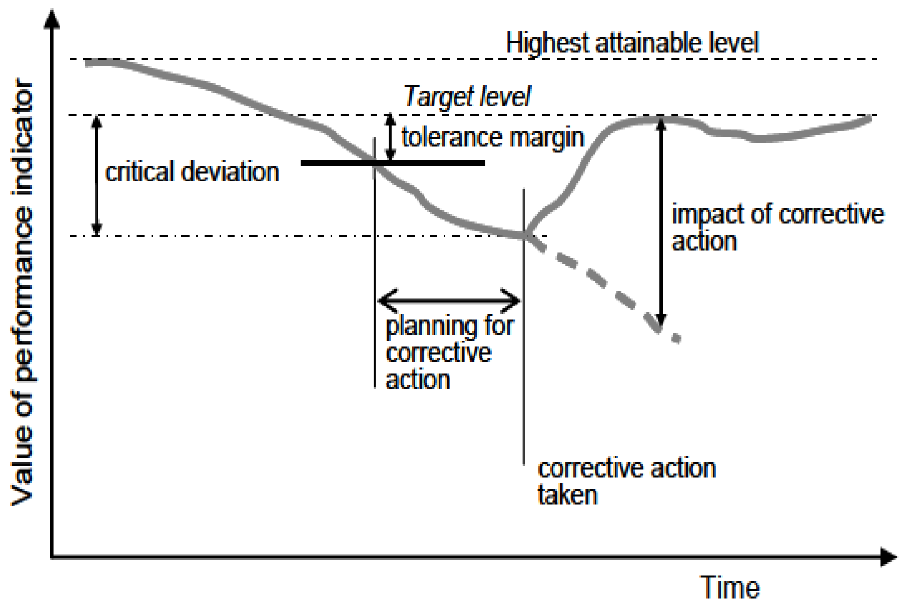


Figure 5.39: Terminology on the use of performance indicators
Source: Bos et al., (2005)

5.7.6 Water Inflows From Lower Bari Doab Canal and Rainfall

The results of surface water supplies are presented in Figure 5.40 under current Irrigation system. The maximum canal water supplies (>170 mm month^{-1}) are in May to July to fulfill the water requirement of high delta crops grown in the region (i.e., rice and sugarcane). The minimum or no canal water supplies are in months of December and January, due to closure of canal to remove silt form canal. The average canal water supplies for LBDC are 737 mm annually which only fulfill 23% of crop water requirement. This is attributed to limited availability of supply from the system or reduced water to their fields in order to irrigate more fields with a given volume of water. Basharat et al., (2012) reported that only 33% of crop water requirement is fulfilled by canal irrigation supplies the rest is fulfilled by rainfall and GW extraction. The seasonal trends of irrigation supplies for a given irrigation method shows that farmers have more than 60% irrigation supplies in Kharif season. It reflects that farmers have limited surface water supplies (40%) in Rabi season and they usually fulfill rest of their crop water demands from GW withdrawals and rainfall.

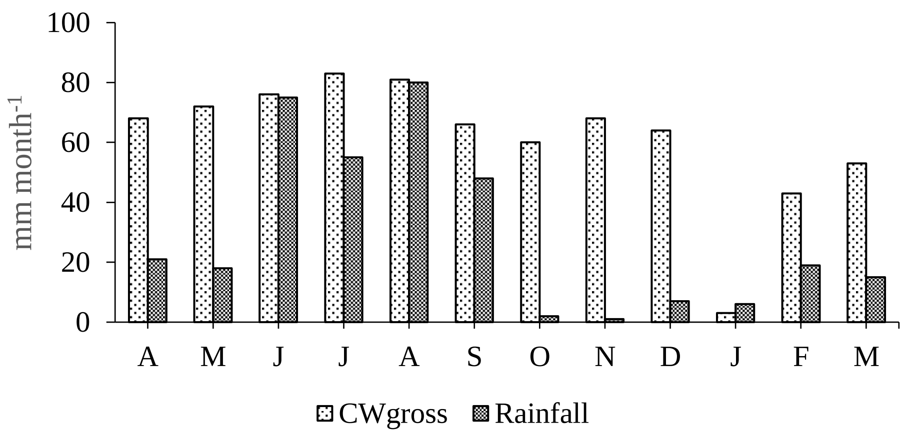


Figure 5.40: Canal water supplies and rainfall for Lower Bari Doab Canal command area

5.7.7 Rainfall

Results shows that for the LBDC command area, average annual rainfall is 347 mm. A maximum value of 80 mm $month^{-1}$ rainfall occurs in August. About 65% (±5) of the total annual rainfall takes place in three months of monsoon season (Figure 5.40). There is almost no rainfall in months of October and November. During these months farmers have to rely on canal water supplies and GW extraction to fulfil the crop water requirement. During the high intensity rainfall, during the monsoon season, the moderately elevated slope and elevated field boundaries (bunds) in the region help to prevent runoff (Ahmad et al., 2005) which also increases the groundwater percolation in the study region.

5.7.8 Water Inflows from Groundwater

Figure 5.41 shows the spatial variation of annual GW extraction in distributaries of LBDC command area. There is significant discrepancy of GW extraction particularly between head end reaches and tail end reaches of LBDC. The GW extraction is high at head end reaches (north-east side) from where LBDC takes water from Balloki headworks and low at tail end reaches (south-west side) end of LBDC.

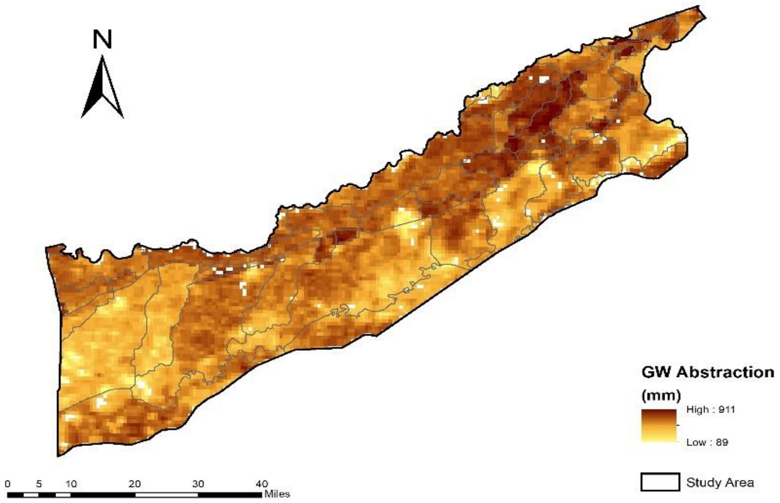


Figure 5.41: Annual spatial distribution of GW extraction in LOWER BARI DOAB CANAL command area

The total annual average GW extraction estimated was 911 mm. Figure 5.42 shows that maximum monthly GW extraction (>115 mm) occurred from May to June as surface water supplies also increases in these months, while in other months, it reduces (<115 mm). Seasonal averages of GW extraction throughout Kharif and Rabi were 585 mm and 326 mm, which mirrored 64% and 36% of the annual GW extraction, correspondingly. The reason for this discrepancy is high actual evapotranspiration during Kharif season (April to September), due to which farmers needs to abstract more GW for their crop water needs.

Figure 5.42: Monthly average groundwater extraction in Lower Bari Doab Canal command area

5.7.9 Actual Evapotranspiration from SEBAL

The maximum monthly ET_a in Kharif season is in months of May, June and July with the >140 mm as visualized in Figure 5.43 is due to cultivation of high delta crops. Whereas the minimum value of ET_a is 25 mm (December) and 24 mm (January) due to lowest crop water requirement and closure of canals.

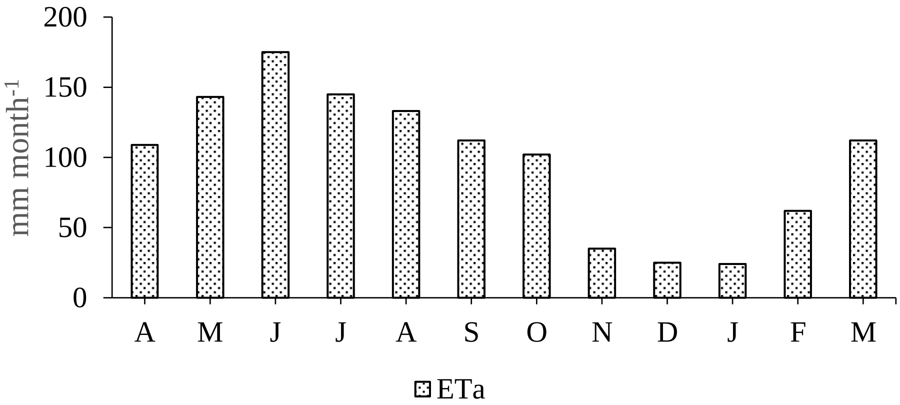


Figure 5.43: Monthly average actual evapotranspiration in Lower Bari Doab Canal command area

The significant variation of ET_a in different distributaries of LBDC command is shown in Figure 5.44. There is a significant variation at head and tail end reaches as shown in ET_a map. ET_a is maximum in the northwest along the Ravi River, and minimum in the southeast of LBDC.

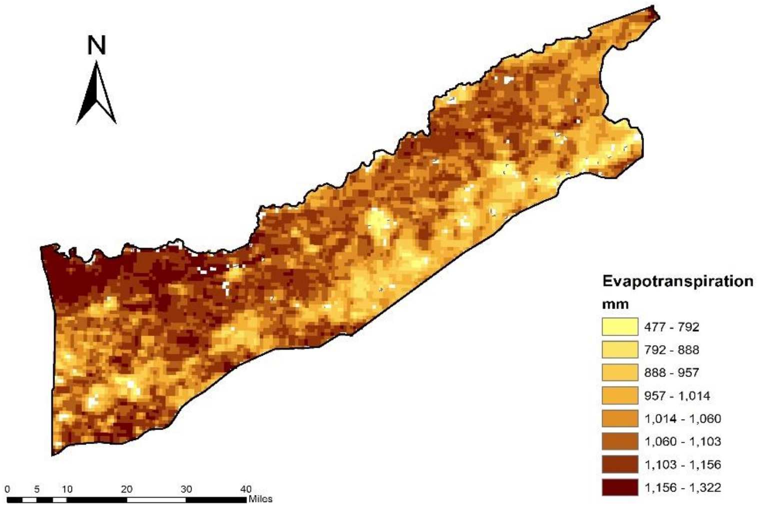


Figure 5.44: Spatial distribution of annual actual evapotranspiration in Lower Bari Doab Canal command area

5.7.10 Domestic and industrial use

The results of survey conducted in LBDC command area for estimation of industrial water demand revealed that almost all industrial sector fulfil their water requirements from GW withdrawals. However, the Sahiwal Thermal Coal Power Project uses 0.82 cumec (29 cusec) of water from LBDC, for cooling purposes. Literature revealed that the total annual GW extraction from the aquifer for domestic and industrial use is 32 MCM (Lahmeyer 2013).

5.7.11 Environmental use

Environmental flow is essential for a sustainable ecosystem within the study area. Sahiwal district has 28,956 acres (117 km^2) of forested land. A distributary named Forest, supplies water to this forested land. It is estimated that 0.3 km^3 (300 MCM) water is supplied through the Forest distributary, is s committed for restoring and maintaining environmental health in the National Water Policy (NWP) 2018.

5.7.12 Water Use in Different Sectors

Water accounts for LBDC command area is shown in Figure 5.45. Figures used in this study are based on water balance studies. Gross inflow into the command area of LBDC is 15.2 km^3, consisting of 5.2 km^3 of releases from the LBDC, 6.5 km^3 from GW extraction plus 3.5 km^3 of rainfall. It was estimated that 3.0 km^3 from canal seepage go to aquifer storage, 1.9 km^3 from GW irrigation and 1.0 km^3 from rainfall recharges the aquifer. Adding these into 3.0 km^3 of storage from canal water yields a total storage of 5.9 km^3. In the study area, sources of surface water supplies are limited. Whereas water demands includes consumptive crop water use by means of ET_a, domestic and industrial water use and environmental water use is high. Major process uses of water in LBDC command area are agricultural, domestic and industrial. The total water depleted by ET_a is assessed at 8.2 km^3, whereas process consumption by domestic and industrial uses is assessed as 0.2 km^3. On the other hand, water consumption by means of ET_a rates are high as LBDC is one the dense agriculture canal command areas of Punjab province, Pakistan. Other non-process depletion occurs as water store in soil and does not reach the GW aquifer. It is estimated that 0.3 km^3 water for LBDC is supplied to the forest as it is committed to ensure environmental sustainability.

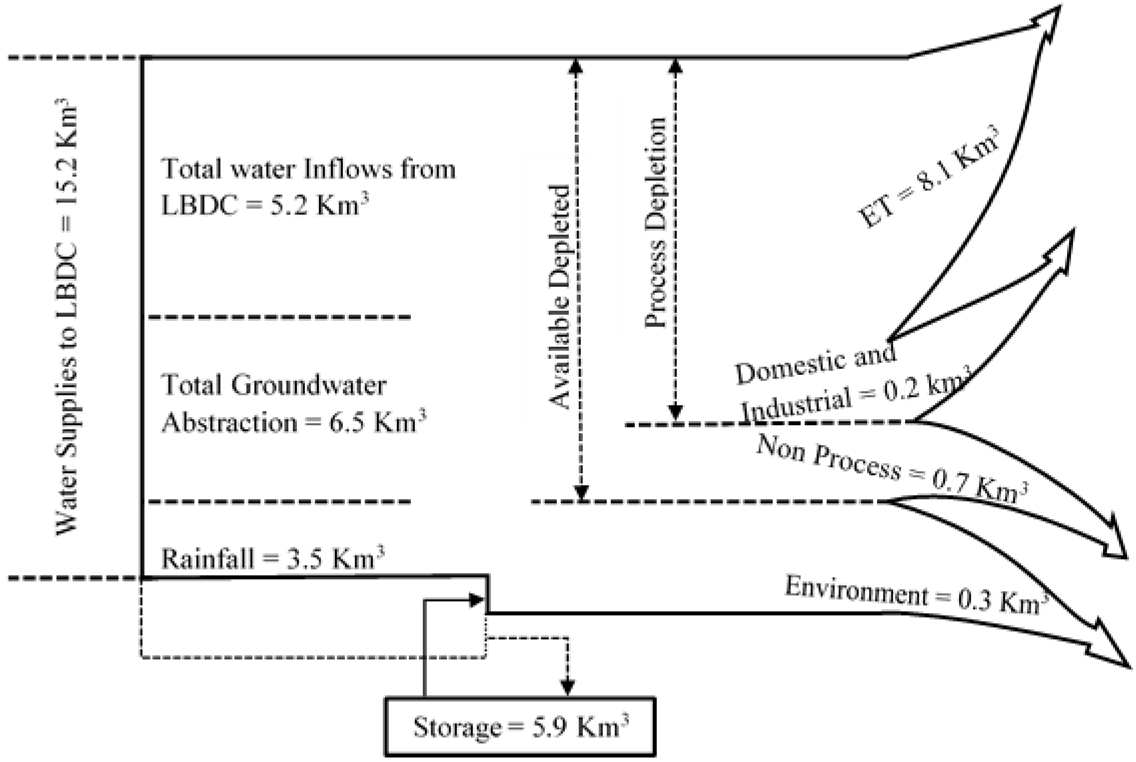


Figure 5.45: Water accounting for Lower Bari Doab Canal command area

5.7.13 Water Use Productivity

Sources from outside the irrigation system includes the inflow sources for irrigation. Table 5.7 shows the accounts for all inflow sources of LBDC command area. These are based on statistical simulations which is calibrated to local conditions. The gross inflows in LBDC command area including surface diversions, sub-surface sources and rainfall are 2152 mm (Table 5.7). The estimated change of storage term was only 4% of gross inflow, which was added to GW storage annually. However, over this area it is estimated that GW is declining with an average rate of 0.18 m annually, in Sahiwal (Basharat and Tariq 2015) which is on the tail side of the study area. For long term sustainable use of GW, there is need to deal with a declining water table situation in the study domain. In general, a large negative or positive change of storage, over time periods of several years, represents issues of sustainability corresponding to the mining from GW or a rise in water table.

Process depletion also includes crop evapotranspiration. On productivity and non-process, there was no information available. Boels et al., 1996 assumed that all the outflow could be considered as committed water, as it was required by downstream users. Table 5.7 shows that process depletion including evapotranspiration, domestic and industrial use is 1175 mm. Further the non-process depletion includes flow to GW and evapotranspiration from non-crop vegetation is 776 mm. There is no outflow as well as uncommitted water for the LBDC command area, so available water is equal to net inflow excluding the volume of water reserve for environment flow (44 mm).

Table 5.7: Water accounting components at head middle tail and CCA of Lower Bari Doab Canal.

Components	CCA of LBDC (mm)
Land and water resources database	
Gross Inflow	2152
Water resources availability	
Surface diversions	737
Sub-surface sources	920
Rainfall	495
Storage change	
Surface	57
Subsurface	26
Net Inflow	2068
Water demand	
Process depletion	
Evapotranspiration	1150
Domestic and Industrial use	25
Non process depletion	
Flow to Groundwater (Recharge)	754
ET from non-crop vegetation	22
Total depletion	1951
Outflow	
Total utilizable outflow	n.a.
Surface outflow	n.a.
Subsurface outflow	n.a.
Committed water	
Environmental use	44
Downstream uses	n.a.
Uncommitted water	0
Available water	2024
Performance	
Depletion fraction net	0.94
Depletion fraction gross	0.91
Depletion fraction available	0.96
Process fraction depletion	0.60
Process fraction available	0.58

Table 5.7 shows that for LBDC there is relatively high depleted fraction of available water, 0.96 (96% of available water is depleted), this is due to the deficit irrigation practice. Similarly, depletion fraction of gross and net water is 0.91 and 0.94, respectively. The process fraction from the above described depleted fraction is only 0.6 that means 60% of total water depleted is used by crop ET, domestic and industrial use, while remaining 40% is possibly wasted to evaporation from non-crop

vegetation or free water surface and the GW aquifer, however plenty of this may be considered beneficial.

5.8 Interaction of Different Water Balance Components[4]

5.8.1 Crop Evapotranspiration

The crop evapotranspiration results shows large variation on a seasonal basis however the small differences were observed between years (Table 5.8). High crop evapotranspiration is due to high reference evapotranspiration during Kharif, ultimately high crop water needs. Annual average of crop evapotranspiration is 1563 mm (around 391 mm more than average actual evapotranspiration), whereas during May to August crop evapotranspiration was high (>150 mm) and lowest (<50 mm) from December to January. Due to reduced availability of irrigation water supplies (including from all sources) for crops, relative to their actual water requirements, there is a large difference between crop and actual evapotranspiration. The Indus Basin Irrigation System (IBIS) was designed initially for only 70% cropping intensities. However, after the green revolution of 1960s the cropping intensities eventually doubled (Awan et al., 2016a; Ahmad et al., 2014). Whereas canal water supplies remains constant, that caused a large supply and demand gap, which results in water shortage in the study area.

To observe the gap between crop and actual evapotranspiration, the groundwater use is restricted to reduce the pumping cost and unreliability of surface water. Based on Lower Bari Doab Canal command, the overall estimated crop water requirement was around 4.2 mm day^{-1}, with distribution of 6.1 mm day^{-1} during Kharif and 2.5 mm day^{-1} during Rabi season approximately.

Table 5.8: Distribution of Recharge (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rab i						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	117	154	232	206	192	143	139	48	35	46	64	137	1512
2011	156	217	254	218	185	161	127	42	33	25	84	137	1638
2012	148	189	221	188	170	148	148	57	34	30	59	127	1519
2013	147	193	224	190	186	134	119	50	18	29	95	150	1534
2014	144	213	243	197	177	151	139	49	38	27	83	156	1617
2015	149	178	239	211	189	139	131	46	33	27	88	168	1599
Annual Average	142	193	235	200	182	147	134	49	32	31	77	141	1563
Seasonal Average	1099 (70.3%)						464 (29.7%)						

5.8.2 Actual Evapotranspiration

Table 5.9 shows that during the Kharif season actual evapotranspiration (ET_a) was 44% higher than in the Rabi season, whereas values on annual basis indicated relatively insignificant change. During Kharif season, due to higher crop water requirements coupled with the larger availability of

[4] *Nawaz R. A., Awan U. K., et al., (submitted). Understanding interrelationships of different agriculture water management components in Indus basin of Pakistan. Initial submission in Journal of Hydrology.*

water in the irrigation system results in High ET_a. Over the six year study period (2009–2015) the monthly ET_a varies between 24 mm (January) to 174 mm (June), with a yearly average value of 1177 mm. During the months of May to August, ET_a rates were at peak, corresponded to rice crop areas. During January and December the lowest ET_a occurred, due to little or no water supplies in the irrigation scheme coupled with decreased crop water requirements (Ahmad et al., 2005).

Table 5.9: Distribution of Actual Evapotranspiration (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rabi						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	89	116	172	148	139	110	106	34	28	35	50	105	1132
2011	118	163	188	157	134	124	97	30	26	19	66	105	1227
2012	112	142	164	135	123	114	113	41	27	23	46	98	1138
2013	111	145	166	137	135	103	91	36	14	22	74	115	1149
2014	109	160	180	142	128	116	106	35	30	21	65	120	1212
2015	113	134	177	152	137	107	100	33	26	21	69	129	1198
Annual Average	109	143	175	145	133	112	102	35	25	24	62	112	1177
Seasonal Average	817 (69.4 %)						360 (30.6 %)						

5.8.3 Canal Water Supplies

For the Lower Bari Doab command area the annual average of gross canal water irrigation (IC_{gross}), in terms of depth, is of 2.0 mm day^{-1}, maximum IC_{gross} was 789 mm during the 2011, whereas the minimum was 631 mm during the 2015 (Table 5.10). During Kharif season water supply was 21% more than in Rabi season, as the irrigation department closes the canals during the months of December and January for removal of accumulated silt deposition. (Ahmad et al., 2005). Overall, during the Kharif season around 2.5 mm day^{-1} water was available for crops, and during the Rabi season only 1.6 mm day^{-1} was available. According to IC_{gross} depths, net canal water use (IC_{net}) results were varied (Table 5.11). For the entire season, against IC_{gross} of 2.0 mm day^{-1}, during Rabi, Kharif and on annual basis the average IC_{net} was only 0.58 mm day^{-1}, 0.91 mm day^{-1} and 0.73 mm day^{-1}, respectively (Table 5.11).

Table 5.10: Distribution of canal water use (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rabi						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	61	57	64	67	64	68	36	68	62	7	49	35	638
2011	72	85	87	86	90	54	61	76	71	6	48	53	789
2012	70	56	61	89	88	58	56	63	58	1	62	56	718
2013	70	81	84	89	76	82	68	67	60	0	35	57	769
2014	68	79	83	83	86	68	79	66	68	0	22	62	764
2015	32	79	59	41	81	55	36	55	39	33	65	56	631
Annual Average	62	73	73	76	81	64	56	66	60	8	47	53	719
Seasonal Average	429 (59.7%)						290 (40.3%)						

Table 5.11: Distribution of Net canal water use (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rabi						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	14	21	28	30	28	30	22	22	21	0	12	16	244
2011	26	31	31	31	32	20	22	27	26	2	17	19	284
2012	25	20	22	32	32	21	20	23	21	0	22	20	258
2013	25	29	30	32	27	30	24	24	22	0	13	21	277
2014	25	28	30	30	31	25	29	24	25	0	8	22	277
2015	11	28	21	15	29	20	13	20	14	12	23	20	226
Annual Average	21	26	27	28	30	24	22	23	22	2	16	20	261
Seasonal Average	156 (59.8%)						105 (40.2%)						

Table 5.12 shows the monthly variation of Rainfall over the study period. During 2009-2015, the annual average precipitation of 350 mm $year^{-1}$, which varied between 286 mm $year^{-1}$ and 424 mm $year^{-1}$. Table 5.12 shows that the sum of IC_{net} and rainfall was insufficient to meet the crop water needs i.e., ET_a. During the monsoon season (June to September) the occurrence of rainfall is more than 45 mm $month^{-1}$. However, monthly average rainfall varied between 1 mm and 97 mm, with seasonal averages of 85.6% (Kharif) and 14.4% (Rabi) of the total rainfall amount.

Table 5.12: Distribution of Rainfall (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rabi						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	21	18	75	55	81	53	2	1	7	6	19	15	353
2011	25	22	90	66	97	64	2	1	8	7	23	18	424
2012	18	20	81	53	78	49	6	2	14	7	15	22	365
2013	11	12	68	44	71	43	2	2	9	7	9	8	286
2014	12	13	75	48	78	47	3	2	10	8	10	9	315
2015	13	15	82	53	86	52	3	2	11	8	11	10	347
Annual Average	17	17	79	53	82	51	3	2	10	7	15	14	350
Seasonal Average	299 (85.6%)						51 (14.4%)						

5.8.4 Groundwater Recharge

Using Equation (2) the estimated total annual average groundwater recharge was 694 mm, with variation of 40 mm approximately, over the study period (Table 5.13). During the months from April to October maximum monthly groundwater recharge (>60 mm) occurred, whereas it decreases in other months (<50 mm). During Kharif and Rabi season groundwater recharge were 263 mm and 426 mm, indicating 38.2% and 61.8% of the total annual groundwater recharge, respectively. It is noteworthy that during high intensity rains which occurs in the monsoon period, the moderately elevated slope and elevated field boundaries (bunds) in the region help to avoid runoff (Ahmad et al., 2005).

Table 5.13: Distribution of Recharge (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rabi						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	49	69	79	76	60	64	69	41	36	12	30	60	645
2011	75	100	88	86	65	59	65	46	42	8	43	64	741
2012	71	80	65	74	61	56	70	43	35	7	42	62	666
2013	72	91	77	77	60	61	66	43	35	6	42	70	700
2014	70	97	83	76	60	61	78	44	42	6	32	74	723
2015	57	84	72	64	61	51	56	37	26	21	53	76	658
Annual Average	66	87	77	76	61	59	67	42	36	10	40	68	689
Seasonal Average	426 (61.8%)						263 (38.2%)						

The results of net groundwater recharge for the study period in Table 5.14 shows the groundwater extraction exceeds groundwater recharge. During the six years the annual average net groundwater recharge is 204 mm year^{-1}. During both Rabi and Kharif season negative and positive values were observed. The negative value shows that subsurface fluxes are less than water fluxes at the surface or above, which cause the decline in groundwater tables. Although the average value is 204 mm year^{-1}, some months have high groundwater recharge values (e.g., August, November and December) while all others months have high discharge values. Positive groundwater recharge during these months was likely caused by either high rainfall amount observed during the study period (See Table 5.12) or due to the initial sowing period of wheat crop, which has reduced water requirements in winter months (November and December).

Table 5.14: Distribution of Net Recharge (mm) in LBDC from 2010 to 2015

Seasonal	Kharif						Rabi						
Annual	A	M	J	J	A	S	O	N	D	J	F	M	Total
2010	-52	-60	-83	44	42	-6	-49	23	24	-35	-4	-55	-211
2011	-28	-79	-31	15	44	28	-46	34	32	-13	21	-51	-74
2012	1	-90	-109	13	31	33	-50	19	31	-12	20	-44	-157
2013	-22	-74	-20	10	41	-25	-29	31	31	-14	19	-53	-105
2014	-39	-88	-46	-27	17	-18	-39	24	29	-16	-36	-61	-300
2015	-77	-55	-61	-77	8	-16	-66	19	14	14	-3	-74	-374
Annual Average	-36	-74	-58	-4	31	-1	-47	25	27	-13	3	-56	-204
Seasonal Average	-142.5 (70%)						-61 (30%)						

5.8.5 Establishing a Correlation Among Identified WRM Components

Table 5.15 and Table 5.16 present the Pearson correlation (R) results, between the different water resource management (WRM) components, at two different significance levels (pvalue of 0.01 and 0.05) during both the Kharif and Rabi seasons. Except net groundwater recharge, ET_a was positively correlated with all WRM components. During Rabi and Kharif seasons, at a significance level of $p < 0.01$, it revealed a good correlation of 0.99 and 1.00 with ET_c, respectively. It is worth noting that the relationship between ET_a and ET_c for this region reflects the high diurnal cycle of solar energy, which is required for the estimation of both variables. In general, there is a very weak relationship, shown by correlation ($R \leq 0.16$) between ET_a and irrigation water components, e.g., rainfall, canal (IC_{gross} and IC_{net}) and groundwater (IGW_{gross} and IGW_{net}). However the correlaton is slightly better during Kharif season (Table 5.15) ($R \geq 0.32$) as compared to the Rabi season (Table 5.16). It is noteworthy that, the correlations of ET_c with other WRM components were slightly better in Kharif season than in Rabi season. For this difference, a possible explanation is that ET_a is estimated pixel by pixel and changes even for the same crops, whereas ET_c calculations are at a point level and are mostly kept uniform for the entire region. The correlation results indicate seasonal differences could be related to fluctuating variations in solar radiation, changes in groundwater extraction, unreliable surface water supplies and rainfall patterns between seasons. Groundwater fulfills the crop water requirements as shown in the results presented in section 5.7.8, whereas at a significance level of $p < 0.05$ the moderate positive correlation ($R \geq 0.49$) between groundwater use and ET_c, reveal that the relationship between crop water requirement and demand based water supply in the system are happening at the same time and place.

During Kharif and Rabi seasons, groundwater use has negative ($R \leq -0.24$) or a very weak ($R \leq 0.16$) correlation with canal water use, respectively. This inconsistency was expected, as without information on actual crop water need, surface water supply from the canals are provided at a constant rate (supply based irrigation system), whereas depending upon crop use, farmers extract the groundwater (demand base groundwater supply). The use of groundwater decreased with an increase in rainfall amount, as their relationship showed significant negative correlation ($R \leq -0.63$) during the Kharif season, while on canal water supply, the impact of rainfall was less or non-significant, which is supplied to fields at a constant rate, as stated above. The several WRM components behave differently in their contribution to groundwater recharge. Maximum groundwater recharge was contributed from pumped groundwater, during the Kharif season ($R \geq 0.88$; Table 5.15) followed by canal water supplies ($R \geq 0.23$). This is due to the ponding of water for rice paddies, which is usually fulfilled by all irrigation resources, including groundwater extraction. On the other hand, during the Rabi season both pumped groundwater and canal water losses are mainly contributing to groundwater recharge, as observed from their strong and significant correlation ($R \geq 0.73$; Table 5.16). Since net groundwater recharge was estimated as the difference between groundwater discharge and recharge, the results show that net groundwater recharge values were positively and negatively affected with net rainfall amount or canal water supplies and groundwater pumping, respectively. This was due to the fact that losses from groundwater use were less, as compared to combined field application and canal network losses. Overall, the recognized major source for net groundwater recharge were canal irrigation and rainfall, with correlations of 0.39, 0.48 (Table 5.15) during Kharif season. However, during Rabi season the correlation for net recharge with canal irrigation and rainfall were 0.25, -0.13 (Table 5.16) which is due to the less amount of rainfall and little or no canal water supplies for the study region.

Table 5.15: Correlation matrix of water resources management components through Pearson correlation during Kharif season.

	ET_a	ET_c	IC_{gross}	IC_{net}	IGW_{gross}	IGW_{net}	Rainfall	Recharge	Net Recharge
ET_a	1								
ET_c	0.99	1							
IC_{gross}	0.55	0.64	1						
IC_{net}	0.56	0.64	0.95	1					
IGW_{gross}	0.37	0.31	-0.23	-0.32	1				
IGW_{net}	0.38	0.31	-0.23	-0.32	1.00	1			
Rainfall	0.46	0.50	0.58	0.69	-0.64	-0.64	1		
Recharge	0.67	0.64	0.23	0.16	0.89	0.88	-0.33	1	
Net Recharge	-0.43	-0.34	0.39	0.45	-0.92	-0.93	0.48	-0.74	1

Table 5.16: Correlation matrix of water resources management components through Pearson correlation during Rabi season.

	ET_a	ET_c	IC_{gross}	IC_{net}	IGW_{gross}	IGW_{net}	Rainfall	Recharge	Net Recharge
ET_a	1								
ET_c	1.00	1							
IC_{gross}	0.29	0.30	1						
IC_{net}	0.36	0.37	0.99	1					
IGW_{gross}	0.99	0.98	0.14	0.21	1				
IGW_{net}	0.99	0.98	0.14	0.21	1.00	1			
Rainfall	0.19	0.16	-0.17	-0.19	0.19	0.19	1		
Recharge	0.86	0.87	0.73	0.78	0.78	0.78	-0.02	1	
Net Recharge	-0.82	-0.82	0.25	0.16	-0.90	-0.90	-0.13	-0.48	1

6 Sensitivity Analysis

The groundwater model was developed to forecast different future scenarios. The purpose of the sensitivity analyses is to understand the significance of each individual model parameter during the simulations. The uncertainties was quantified by multiple runs of sensitivity analysis in the model which was due to uncertainty in assessing the different aquifer parameters. Multiple sensitivity runs were undertaken for different parameters including recharge, specific yield, hydraulic conductivity and storage coefficients from the top layer of the model. GV provides an automated way of performing sensitivity analysis that allows selecting a parameter type, the number of simulations, and a parameter multiplier for each simulation.

Multiple sensitivity runs were undertaken for different selected parameters including recharge, specific yield, hydraulic conductivity, and storage coefficients. The Multipliers values used was 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 for different simulations, respectively. Results of sensitivity analysis showed that the groundwater model is more sensitive to hydraulic conductivity as compared to other parameters. Model calibration was largely based on the values of hydraulic conductivity used for PEST analysis. Based on a review of the literature a detailed database with minimum and maximum values for the hydraulic conductivity was assigned for each soil type. This approach provided us with greater confidence on the hydraulic conductivity values we used in the model.

7 Model Calibration

The calibration of groundwater models is a process of comparing the actual field measurements with hydraulic heads simulated by the model. The purpose of calibration is to reduce the residuals by adjusting the parameters to ensure modelled and observed heads are within an acceptable range. The effectiveness of model calibration is defined by residual statistical parameters including sum of squares of the residuals, residual mean error, and absolute mean.

Mean Error (ME) is the average variation between observed (h_o) and simulated heads (h_s) as shown in Equation 19.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_o - h_s) \qquad \text{(Eq. 19}$$

Mean Absolute Error (MAE) is average of absolute values of difference in observed heads (h_o) and simulated head (h_s) as shown in the Equation 20.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|h_o - h_s| \qquad \text{(Eq. 20}$$

Root Mean Squared Error (RMSE) is mean of squared differences in observed heads (h_o) and simulated head (h_s) as shown in the Equation 21.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_o - h_s)_i^2} \qquad \text{(Eq. 21}$$

The modeling efficiency (MEF) was calculated using the Equation after Ashraf

et al., (2008) as shown in Equation 22.

$$MEF = 1 - \frac{\sum_{i=1}^{n}(h_o - h_s)^2}{\sum_{i=1}^{n}(h_o - \bar{h})^2} \qquad \text{(Eq. 22}$$

Calibration is a contrary modelling technique in which model input parameters were valued by minimizing the objective function in terms of hydraulic head. This analysis was done manually without using the GV calibration module because the hydraulic conductivity and recharge value were assigned to each unit by considering the heterogeneity of the aquifer. The adjusted parameters include hydraulic conductivity, recharge and canal bed hydraulic conductivity.

Model calibration involves changing the values of the model input parameters to try to fit the field conditions within acceptable standards. Model calibration is an iterative process that conforms to model results (such as water head) with historical field measurements by adjusting aquifer parameters, boundary conditions and stresses within a reasonable range. This process includes the possibility of achieve non-unique model solutions and the number of variables that can be used to calibrate the target.

DLR of PID and SMO of WAPDA observe a total of 57 observation points in the LBDC command area. The aquifer being unconfined and the purpose to monitor the depth to water table is basically observation for any waterlogging condition in command area. Furthermore it is an indicator of the decline in groundwater levels in response to pumping. It is also use to monitor the changes in water level in response to rainfall and recharge etc. Some SMO wells have been levelled; the NSL of the remaining observation wells is derived from the SRTM value. To obtain calibration parameters in acceptable ranges, inverse simulations and trial and error method were used. These parameters includes hydraulic conductivity and recharge. For calibration, comparison was made based on water levels of 57 observation points and simulated heads obtained by the model. Statistical parameters including residual standard deviation, minimum residual, maximum residual, root mean square (RMS) error, sum of squared deviations, absolute mean error and absolute residual mean used to represent calibration performance. Volumetric budget and groundwater levels were interpreted for simulation results.

Conventionally model calibration was undertaken by defining different zones for the model area for adjusting aquifer parameters until results of field observations and model outcomes are as close as possible. Extra zones are added if the goodness of fit obtained by these zones was not acceptable (Rumbaugh and Rumbaugh, 2010). This process continued until the best fit of field observations and model outcomes was acceptable, which is a slow and laborious procedure. To overcome the above problems, distribution of the calibrating parameters (hydraulic conductivity) was modelled by the set of pilot points in the model domain. PEST determines the parameter values for these pilot points and groundwater vista interpolated these pilot point values to assign the parameters to the whole of the model domain. This technique gives better estimation of the parameters in the sense that there is a gradual variation in the parameters. Singular Value Decomposition or SVD-Assist which is incorporated in GV is one of the most powerful tools of PEST. When pilot points were used, it reduced the number of runs significantly. This feature (SVD-Assist) can handle various parameters with different sensitivities. The drawdown of SVD-Assist is that the procedure is more complex to follow. Using PEST, the model was automatically calibrated by executing the following five steps.

- Create Sensitivity Run
- Launch Sensitivity Run
- Launch SVDAPREP
- Launch SVD PEST Run
- Create Final PEST Run

In this study, semi-automatic calibration process was used, i.e., canal seepage was adjusted manually by changing the hydraulic conductivity of the canal bed and hydraulic conductivity of the aquifer and recharge was calibrated using SVD Assist ability of PEST. Since the start of of pumping from the well field, the water table in some parts of the study area is declining so the transient state groundwater model was calibrated for this study area. The model was calibrated for the period of October 2009 to September 2015.

7.1 Calibration Statistics

Table 7.1 shows the calibration statistics of the model. Residuals at targets are ranging from -3.87 to +2.83 m, with a mean of -0.11 and with absolute residual mean of 0.86 m. Model simulated hydrographs of head versus observed water levels are plotted in Figure 7.1 which represent the model's prediction ability. Figure 7.3 represent 55 targets contributing 50% of the cumulative sum of squares, which shows that the model was calibrated reasonably well. Figure 7.2 and Figure 7.4 indicates the model outputs which show the observed value vs residual and residual vs cumulative probability, respectively (Figure 7.4).

Table 7.1: Statistical parameter estimate for evaluating model (Calibration phase)

Parameter	Calibration Phase (October 2009 to September 2015)
Residual Mean	-0.11
Abs. Res. Mean	0.86
Res. Std. Dev.	1.12
Sum of Squares	762
RMS Error	1.13
Min. Residual	-3.87
Max. Residual	2.83
Number of Observations	598
Range in Observations	63.45

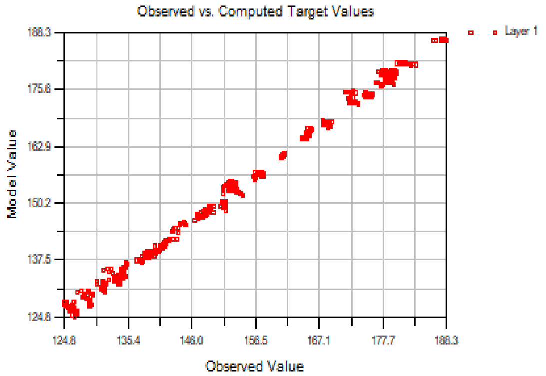


Figure 7.1: Computed versus observed head (m) (Calibration Phase)

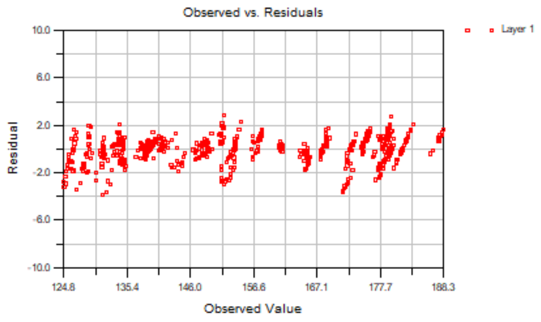


Figure 7.2: Model output of observed value versus residual (Calibration Phase)

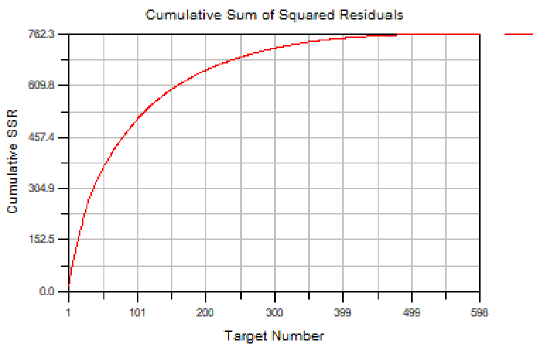


Figure 7.3: Model output showing the contribution of observation points to Cumulative SSR (Calibration Phase)

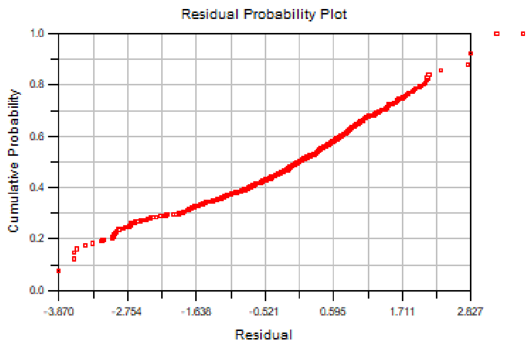
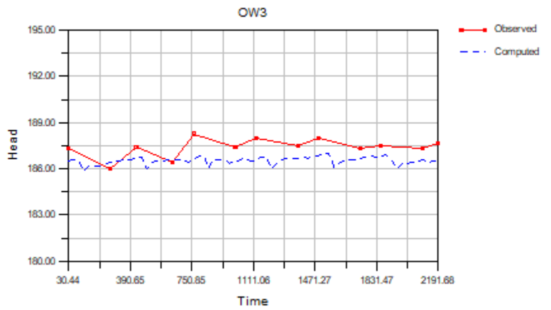


Figure 7.4: Model output of cumulative probability versus residual (Calibration Phase)

7.2 Hydrograph Response

The second part of calibration involves evaluation of model results with key hydrographs of simulated and observed water heads. Temporal calibration allows the user to identify within the model domain how much confidence can be placed in the selected locations. The observation well calibrations compromises comparison of field measured heads and simulated heads in the model domain. Some limitations in this calibration approach are that field measured heads are point measurements. However these are the best indications of the heads in proximity to the bore. In the Lower Bari Doab Canal, groundwater model stresses are averaged for each grid cell which is 1000 m x 1000 m. Moreover, modelled heads are spatially and temporally averaged values.

The deficiencies in groundwater usage data for the Lower Bari Doab Canal groundwater model which were discussed previously pose an additional limitation to the bore calibration process. Observation bores in the vicinity of pumping bores are greatly influenced and so the lack of usage data directly impacts the level of correlation between simulated and observed heads. Despite these limitations, bore calibrations are an important aspect of model calibration. The selection of key bores was based on a reasonable spread over the area as most of the Lower Bari Doab Canal groundwater is under irrigated agriculture. Some of the key bores were also selected due to their proximity to canals to evaluate model behaviour. Comparisons of observed and simulated heads for bores are shown in *Figure 7.5*. A selection of 20 bores show reasonably good temporal calibration. Some of the bores show good reproduction of trends such as bore OW23 and OW41 whilst the water level response in some bores such as OW22 and OW30 could be improved if accurate pumping information is available. Similar results suggesting that the recharge and adjustment in hydraulic conductivity may improve simulated results.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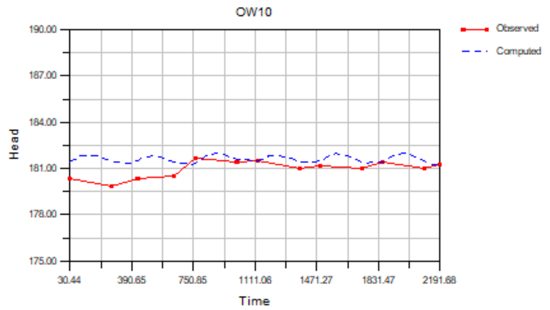
192.00
189.00
186.00
183.00
180.00
Head
30.44
390.65
750.85
1111.06
1471.27
1831.47
2191.68
Time
Observed
Computed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Head
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1111.06
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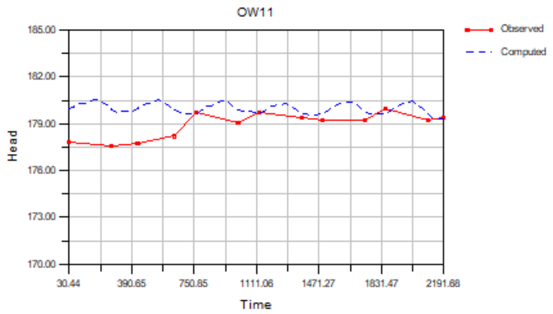
1831.47
2191.68
Time
Observed
Computed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182.00
179.00
176.00
173.00
170.00
Head
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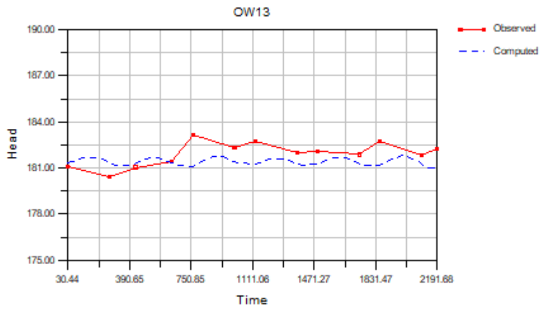
750.85
1111.06
1471.27
1831.47
2191.68
Time
Observed
Computed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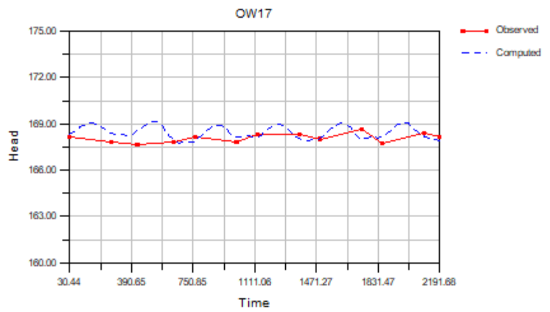
1831.47
2191.68
Time
Observed
Computed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163.00
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1111.06
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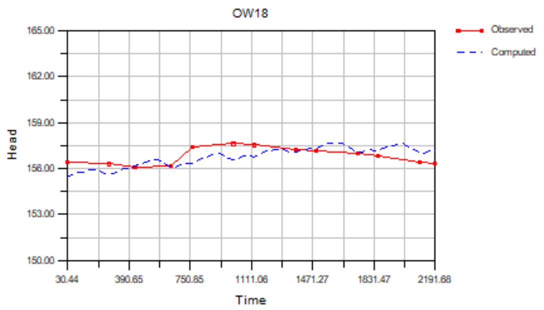
2191.68
Time
Observed
Computed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159.00
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Head
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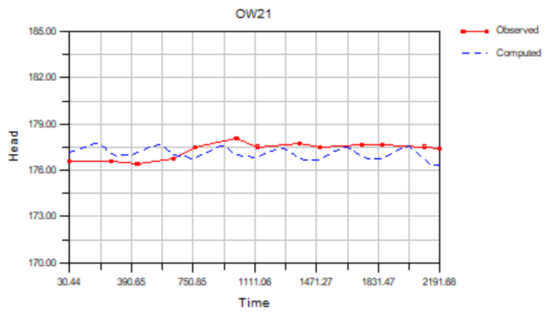
1831.47
2191.68
Time
Observed
Computed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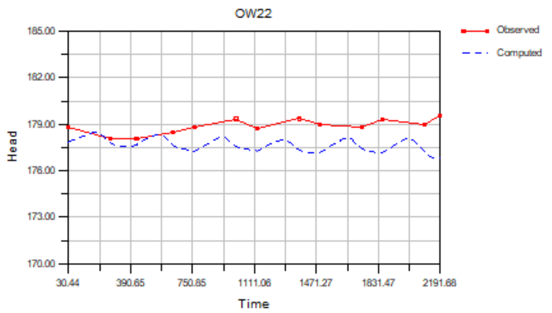
2191.68
Time
Observed
Computed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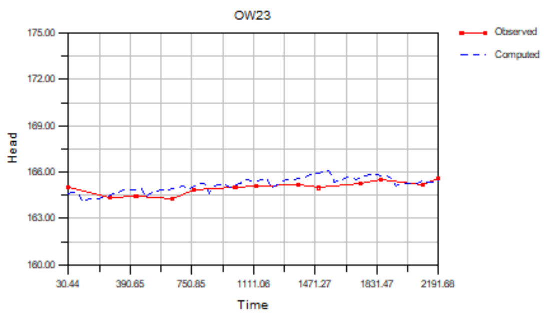
2191.68
Time
Observed
Computed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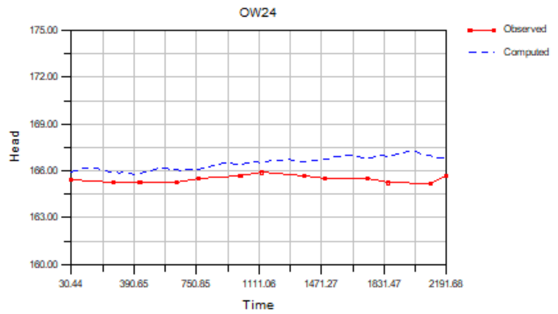
2191.68
Time
Observed
Computed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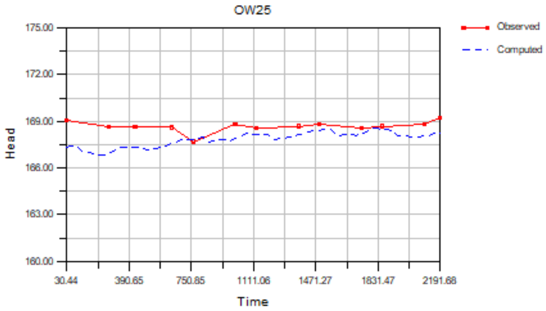
1831.47
2191.68
Time
Observed
Computed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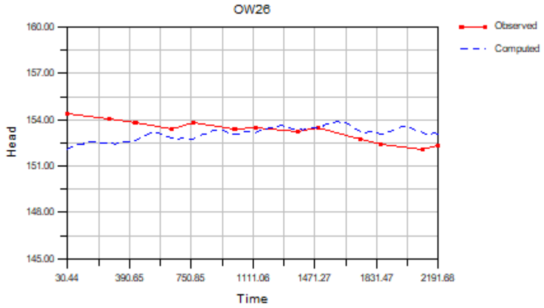
Time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Observed
Computed
Head
160.00
157.00
154.00
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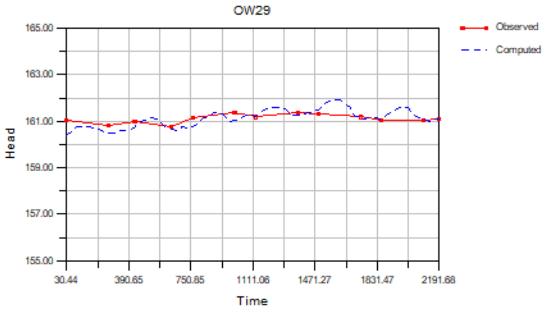
Time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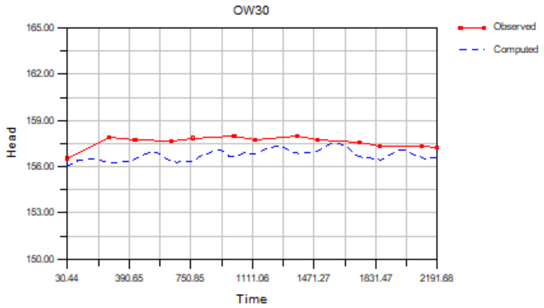
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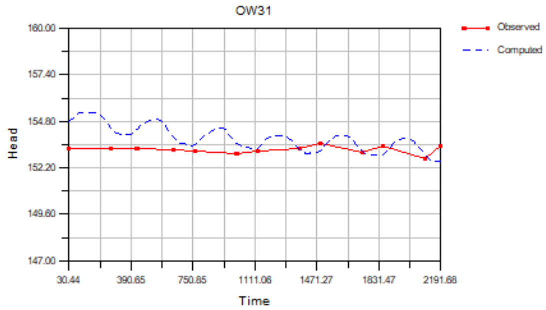
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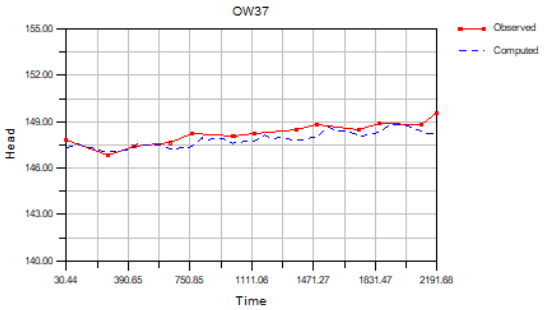
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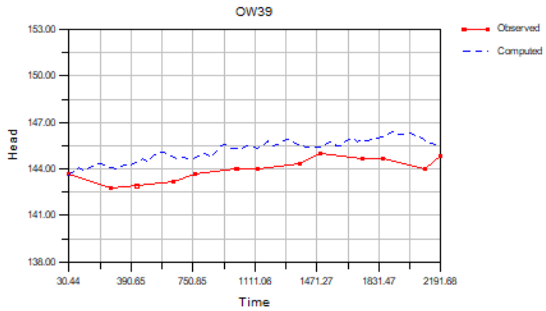
Time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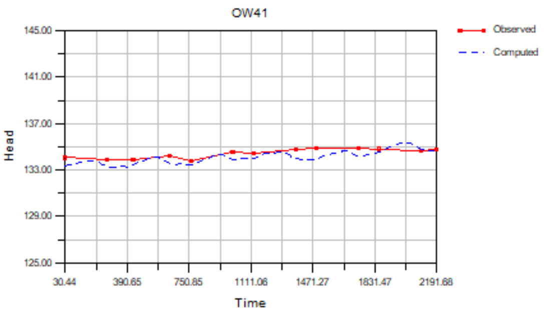
Time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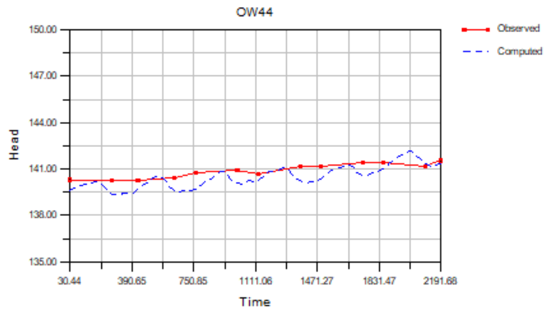
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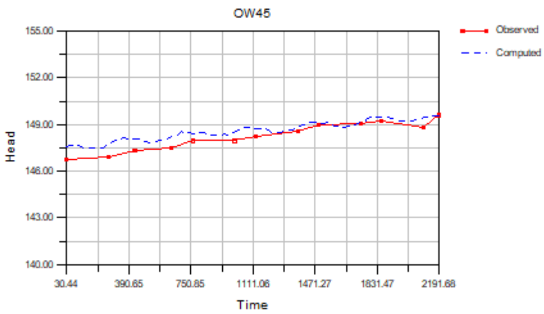
Time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Time

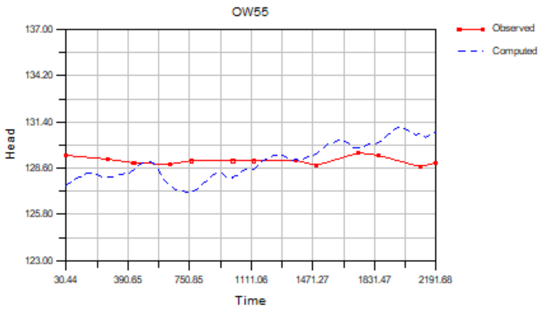


Figure 7.5: Observed and simulated head (m MSL) for piezometers within model boundary

8 Water Balance for Lower Bari Doab

Evaluating the water balance for Lower Bari Doab will provide better information on improving the sustainability of the aquifer. The water balance will also provide an understanding of sustainable extraction levels for Lower Bari Doab. The approach we have taken in this study is to focus efforts in the top two model layers. The top layer incorporates the rivers and canal leakage, rainfall recharge, evapotranspiration and pumping, making it the most important layer from a management perspective. Layer 2 is also used substantially for groundwater extraction thus estimation of sustainable yield must also take layer 2 into consideration.

8.1 Water Balance for Lower Bari Doab

Groundwater Vistas generated mass balance for the LBDC command area from October 2009 to September 2015 is given in *Table 8.1*. Annual average seepage losses from the rivers and canal system are 1556 MCM/yr, total recharge (including groundwater returns) is 3164 MCM/yr and tube-well extraction from the LBDC command area is 4316 MCM/yr. Results show that groundwater extraction is higher than the recharge to the aquifer. The groundwater budget component due to evaporation is relatively small due to the water table being deep in most of the command except the areas towards the head end of the irrigation system. This is due to low canal supplies during the modelled period. Annual average seepage losses from the rivers and canal system are 1556 MCM year^{-1}. The net gain in storage in the study area over the simulation period is 87.9 MCM year^{-1}. The simulated results show that there is very little potential for increasing groundwater extraction but it would not be advisable as farmers have to increase groundwater extractions during the drought period.

Table 8.1: Water balance for Lower Bari Doab Canal command area October 2009 to September 2015

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
River	1556.2	-19	1537.3
Recharge	3164.3	0	3164.3
Well	0.0	-4316	-4315.7
ET	0.0	-298	-298.0
Total	**4720.5**	**-4632.5**	**87.9**

The irrigation losses from fields and seepage from the canal systems are the two main water balance components especially for layer 1 (*Table 8.2*). The net gain in storage over the simulation period is 80.9 MCM year^{-1}. The water balance also indicates that river discharge or flows from the aquifer to the river system are negligible.

Table 8.2: Water balance for model layer 1 October 2009 to September 2015

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Bottom flow	249.6	-4153	-3903.1
River	1556.2	-19	1537.3
Recharge	3163.3	0	3163.3
Well	0.0	-419	-418.6
ET	0.0	-298	-298.0
Total	**4969.1**	**-4888.2**	**80.9**

The major inflow component in layer 2 is inflows from layer 1 whereas the major outflow component is groundwater extraction which is 3897 MCM/year (*Table 8.3*). It indicates that most of the groundwater extraction is from the layer 2 except near the main canals and distributaries as the water table is not very deep and groundwater quality is also good. Water balance for layer 2 indicates there is nearly a balance between inflows and outflowsoutflows and the net gain in storage over the simulation period is 5.84 MCM/year. However it is not advisable to increase the groundwater extraction as it will lead to poor quality groundwater, decreased crop productivity, salinization and sodicity.

Table 8.3: Water balance for model layer 2 October 2009 to September 2015

Layer 2	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Top flow	4153	-250	3903
Bottom Flow	786	-788	-1
Recharge	1	0	1
Well	0	-3897	-3897
Total	**4940.01**	**-4934.17**	**5.84**

The water balance for layer 3 (Table 8.4) shows that the deepest layer is in balance with a net flow into the layer of 1.2 MCM/yr. In the Indus Basin salinity generally increases with depth, thus keeping the third layer in equilibrium will minimise the risk of higher salinity groundwater flowing upwards from the deeper layers. Continued increase in tubewell irrigation from the second layer will likely result in a reversal of gradients which will increase salinity of irrigation water ultimately impacting crop yields and soil structure.

Table 8.4: Water balance for model layer 3 October 2009 to September 2015

Layer 3	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Top flow	787.5	-786.3	1.2
Total	**785.5**	**-786.3**	**1.2**

The current average annual pumping from LBDC (Okara and Sahiwal) is 419 MCM from layer 1 and 3897 MCM from layer 2; totalling 4316 MCM. The surplus for layer 1 is 87 MCM. The sustainable yield for LBDC is estimated at 4300±215 MCM to allow for adaptive management during times of drought. We recommend that an allowance of 5% (215 MCM) will allow farmers to increase extraction during drought years and which will allow replenishment when rainfall and surface water flows increase. We further recommend that as improved monitoring data is collected the model calibration period needs to be extended to account for increased number of tubewells and to ensure the robustness of calibration. In Australia each groundwater area of significance has an agreed long term sustainable yield. This sustainable yield is revisited after 5 or 10 years depending on the agreement with groundwater users, the level of development in the groundwater management area and the incidence of drought. Given the severe drought experienced in Australia between 2017 and 2019 it is likely that the long term average annual extraction limits will need to be revised for most groundwater management areas. Incorporating this process of revising and improving groundwater models will offer PID as the Resource Manager improved understanding of risks to the groundwater from overexploitation and salinity intrusion. It will also allow PID to support the objectives of the National Water Policy and Punjab Water Policy.

8.2 Water Balance for Okara and Sahiwal Districts

The hydrostratigraphic units (HSU) in *Figure 8.1* shows Okara is designated as unit 2, Sahiwal as unit 3 and the areas outside these two zones are designated as HSU unit 1.

The water balance for Okara District (*Table 8.5*) shows the major inflows are recharge and canal inflows followed by lateral flows from zone 1 which is the area surrounding Okara and Sahiwal. There is an inflow of 27.6 MCM/yr into Okara district across the boundary along Sahiwal. The major outflow is pumping from Okara, followed by outflows to HSU 1, and a very small outflow of 9

MCM/yr from Okara to Sahiwal district. The water balance shows a net surplus of 4.6 MCM/yr which represents less than 1% of current pumping from Okara. Thus any increase in pumping has to come from increased inflows from canals and irrigation, or increased lateral inflows from HSU 1. If the inflows are not sufficient then groundwater users in Okara will experience declining water levels.

Table 8.5: Water balance for Okara District, Lower Bari Doab Canal command area October 2009 to September 2015

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
River	184.6	-1.0	183.5
Recharge	473.1	0.0	473.1
Well	0.0	-739.6	-739.6
ET	0.0	-10.0	-10.0
HSU-1	180.0	-101.1	78.9
HSU-3 (Sahiwal)	27.6	-9.0	18.6
Total	**865.2**	**-860.6**	**4.6**

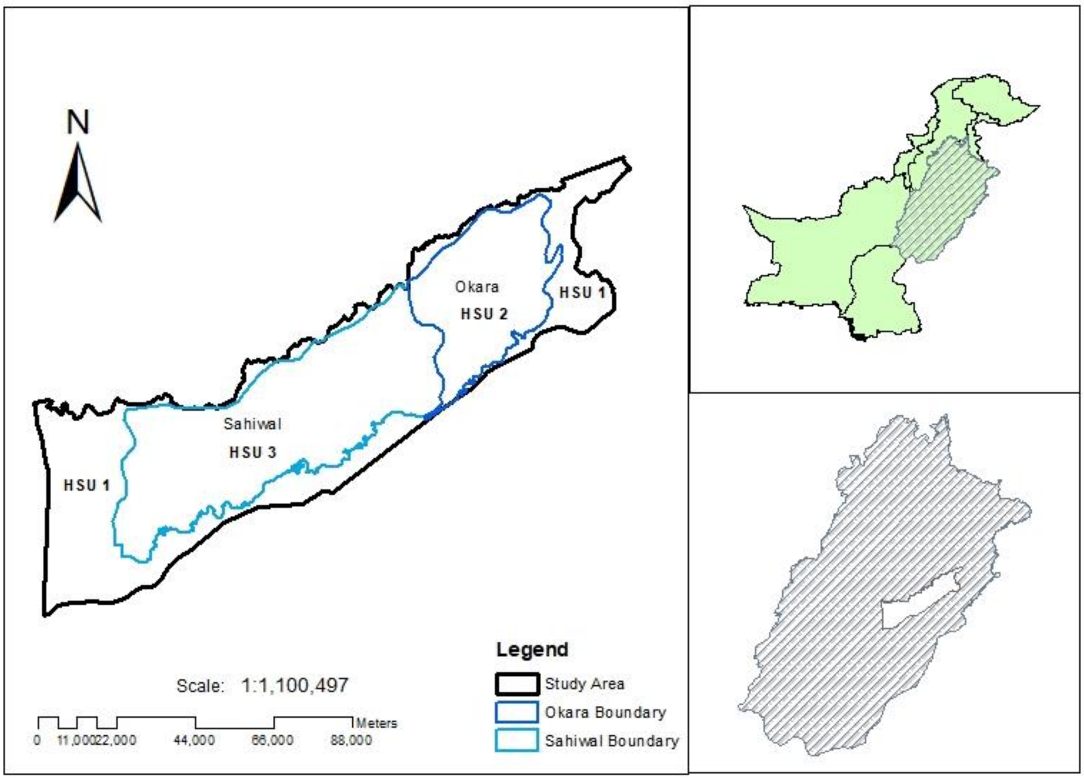


Figure 8.1: Location of Okara (HSU 2) and Sahiwal (HSU 3) boundary area in the Lower Bari Doab Canal Command (study area)

The water balance for Sahiwal District (*Table 8.6*) shows the major inflows are recharge and canal inflows followed by lateral flows from zone 1 which is the area surrounding Okara and Sahiwal. There is an inflow of 14.1 MCM/yr into Sahiwal district across the boundary along Sahiwal. The major outflow is pumping from Sahiwal (1825 MCM/yr), followed by outflows to HSU 1 (259 MCM/yr), and a small outflow of 33 MCM/yr from Sahiwal to Okara district. The water balance shows a net surplus of 64.3 MCM/yr which represents about 3.5% of current pumping from Sahiwal. Thus any increase in pumping has to come from increased inflows from canals and irrigation, or increased lateral inflows from HSU 1. If the inflows are not sufficient then groundwater users in Sahiwal will experience declining water levels.

Table 8.6: Water balance for Sahiwal District, Lower Bari Doab Canal command area October 2009 to September 2015

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
River	808.3	-1.6	806.7
Recharge	1203.7	0.0	1203.7
Well	0.0	-1824.7	-1824.7
ET	0.0	-34.9	-34.9
HSU-1	191.0	-258.8	-67.8
HSU-2 (Okara)	14.1	-32.7	-18.7
Total	**2217.1**	**-2152.7**	**64.3**

We recommend that PID invest in the future to extend and test the model calibration from an extended monitoring program. The LBDC districts of Okara and Sahiwal are almost in balance and it is probable that a decrease in rainfall and surface water supplies in response to drought will cause the net balance for the aquifer to become negative which will further put pressure on water levels. It is on this basis that we have suggested a conservative sustainable yield of 4300±215 MCM for the model domain. If the PID designates Okara and Sahiwal as separate groundwater management areas then the recommended sustainable yield is 740±37 MCM/yr for Okara and 1830±9 MCM/yr for Sahiwal. These estimates can be further refined once the scenarios have been simulated.

8.3 Water Balance for case studies 1-R and 11-L

The hydrostratigraphic units (HSU) in *Figure 8.2* shows the canal command for 1-R in Okara designated as unit 4, and the canal command for 11-L in Sahiwal as unit 5 and the areas outside these two zones are designated as HSU unit 1 (for areas outside Okara and Sahiwal), unit 2 (for the rest of Okara), and unit 3 (for the rest of Sahiwal).

The water balance for 1-R in Okara district (*Table 8.7*) shows the major inflows are from recharge and inflows from Okara which surround CCA 1-R. The major outflows are flows out of 1-R to surrounding area of Okara. Pumping for 1-R is 7.53 MCM which is about 45% of inflows from recharge and canal seepage. By considering only the inflows one could allow for an increase in pumping from 1-R, however, the net balance for 1-R is -0.85 MCM, which is due to significant outflow of 22.38 MCM from 1-R to the surrounding areas of Okara. The impact of pumping outside the area of 1-R is resulting in a net lateral flow out of 1-R of 9.32 MCM. From this we can surmise that due to the large number of pumping wells in Okara (37,254 tTubewells based on Punjab Government estimates), are contributing to the lateral flows across the 1-R boundary into Okara.

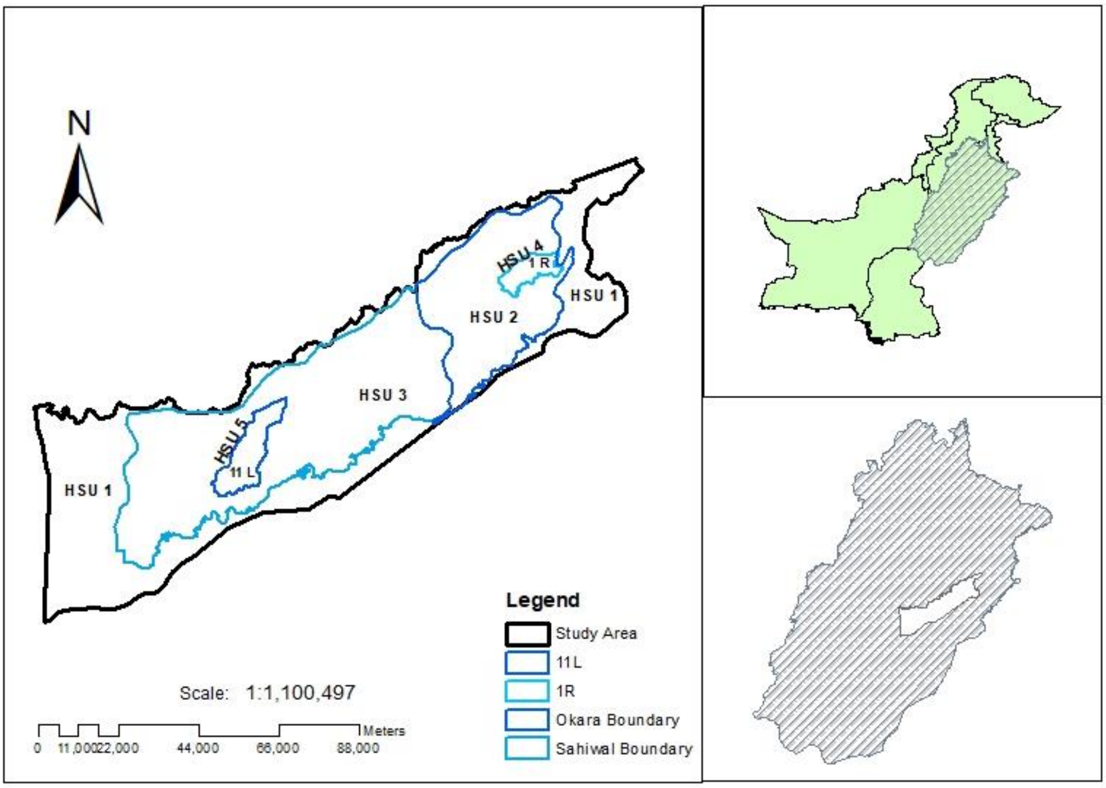


Figure 8.2: Location of 1 R (HSU 4) and 11 L (HSU 5) canal command area in the Lower Bari Doab Canal Command (study area)

Table 8.7: Water balance for 1-R canal command in Okara District, Lower Bari Doab Canal command area October 2009 to September 2015

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
River	4.36	-0.03	4.33
Recharge	12.24	0.00	12.24
Well	0.00	-7.53	-7.53
ET	0.00	-1.18	-1.18
HSU-1	1.15	-0.54	0.61
HSU-2 (Okara)	13.06	-22.38	-9.32
Total	**30.80**	**-31.65**	**-0.85**

The water balance for 11-L in Sahiwal district (*Table 8.8*) shows the major inflows are from canal seepage and recharge and inflows from Sahiwal which surround CCA 11-L. The major outflows are flows out of 11-L to surrounding area of Sahiwal. Pumping for 11-L is 18.85 MCM which is about 25% of inflows from recharge and canal seepage. By considering only the inflows one could allow for an increase in pumping from 11-L, as the net balance for 11-L is 7.14 MCM. With careful monitoring of the water levels particularly during pre-monsoon a small increase in pumping may be possible particularly when the demand for groundwater is higher to meet crop water requirements which has been catered for in the recommended sustainable yield. We also note that there is a significant outflow of 86.26 MCM from 11-L to the surrounding areas of Sahiwal. The impact of pumping outside the area of 11-L is resulting in a net lateral flow out of 11-L of 48.03 MCM.

Table 8.8: Water balance for canal command 11-L in Sahiwal District, Lower Bari Doab Canal command area October 2009 to September 2015

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
River	58.66	-0.00	58.66
Recharge	15.37	0.00	15.37
Well	0.00	-18.85	-18.85
ET	0.00	-0.00	-0.00
HSU-3 (Sahiwal)	38.23	-86.26	-48.03
Total	**112.25**	**-105.11**	**7.14**

We recommend Okara and Sahiwal be designated as groundwater management areas that can be managed to ensure that groundwater depletion is managed within acceptable limits. The overall guidance for recommended sustainable yields is given in the previous sections for Okara and Sahiwal. We further recommend that the model calibration be tested by extending the model from 2016 to 2021 and to update the model and to undertake improvements in model calibration where required. Extension of the model will also allow review of the sustainable yields recommended in this report.

9 Scenario Modelling

The following scenarios are proposed by PID to meet their operational guidance and management of groundwater, and a series of climate change scenarios for managing groundwater subjected to the impacts of climate change. These scenarios were developed in consultation with PID and the socio-economist team from UAF. The scenarios were run from October 2015 to September 2035 by replicating data of groundwater, rainfall, canals and rivers from October 2009 to September 2015. The seven proposed groundwater scenarios are listed in *Table 9.1*.

Table 9.1: List of proposed groundwater scenarios

1	Scenario 1: Business as usual - No changes	Surface water supplies and groundwater usage remain the same.
2	Scenario 2: 20% increase in GW - no change in canal water	Population is growing due to which cropping intensity is increasing to meet food requirement while surface water supply is constant.
3	Scenario 3: 20% increase in GW - 10% reduction in canal water	Population is growing due to which cropping intensity is increasing to meet food requirement while surface water supply is decreasing due to silting of dams or due to low rain etc.
4	Scenario 4: 10% increase in GW - 10% increase in canal water	Population is growing due to which cropping intensity is increasing to meet food requirement. If surface water supply is also increased due to canal and water course lining or development of new water storage dams.
5	Scenario 5: 10% reduction in GW - no change in canal water	Projected increase in water use efficiency.
6	Scenario 6: Climate change scenarios- RCP 4.5	Representative concentration Pathway RCP 4.5
7	Scenario 7: Climate change scenarios- RCP 8.5	Representative concentration Pathway RCP 8.5 scenarios

9.1 Business as Usual - No changes

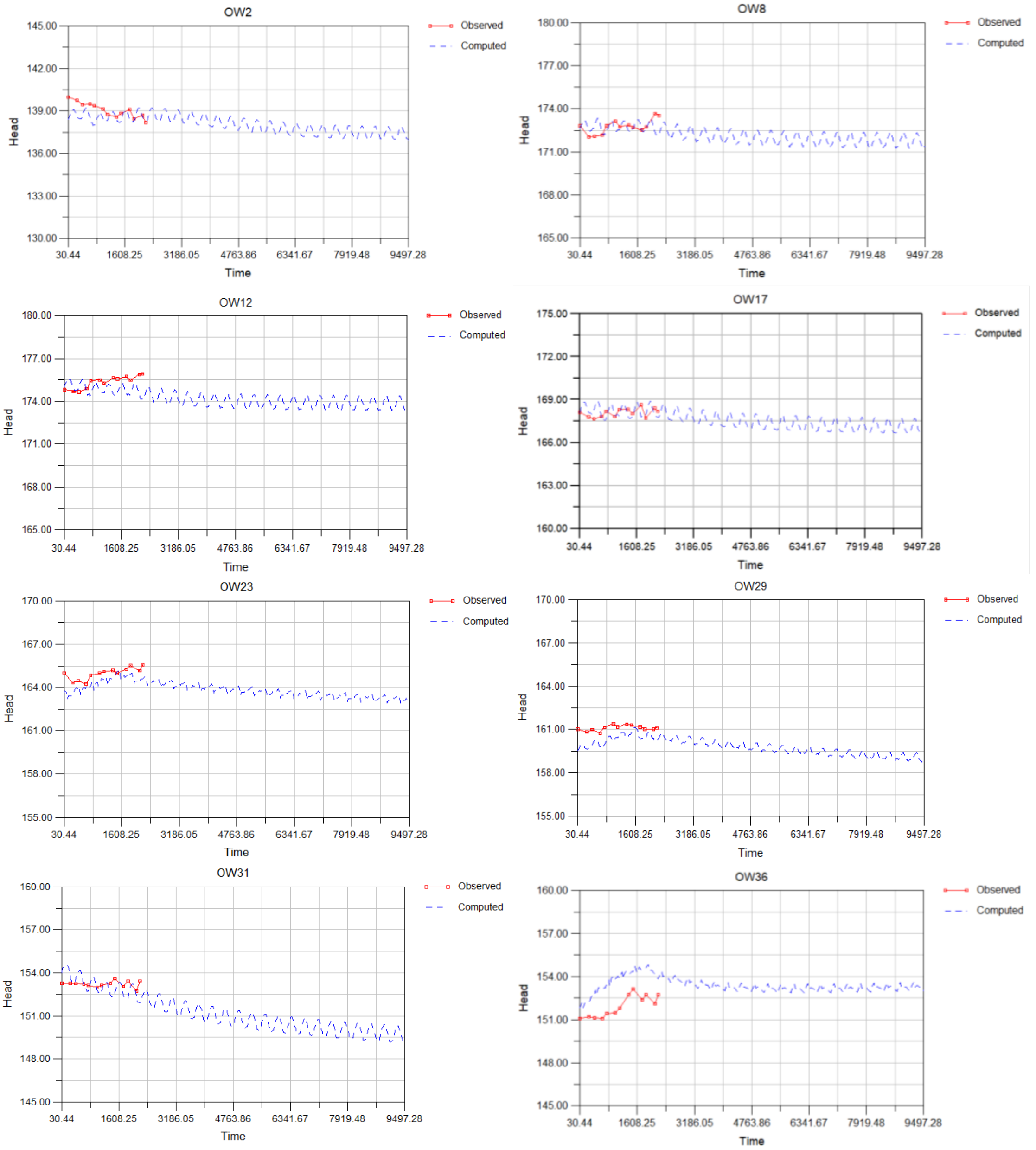
The water balance for the Business as Usual (BAU) scenario for the period from October 2009 to September 2035, is presented in *Table 9.2*.

The two major components of the water balance are recharge and river/canal leakage which account for 98% of inputs to the groundwater system. The main outflow is pumping from agricultural and municipal wells accounts for 82% of all outflows. The net gain in storage over the simulation period is 78 MCM/yr as compared to the net gain during the calibration period which was 87.9 MCM/yr.

Table 9.2: Water balance for all model layers for the Business as Usual scenario from October 2009 to September 2035

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	3150.06	0	3150.06
River	1533.57	-11.91	1521.65
Well	0	-4316.11	-4316.11
ET	0	-277.49	-277.49
	4683.63	**-4605.51**	**78.12**

This scenario indicates that if conditions remained similar to October 2009 to September 2015 period then pumping of 4316 MCM/yr will not result in significant depletion. This is borne out by a selection of hydrographs for selected piezometers which is shown in Figure 9.1. Observation wells named OW2 and OW31, shows a decline of water levels, however, OW37, OW39, OW41 and OW44 shows a slight rise in water level, the remaining observation wells are steady.



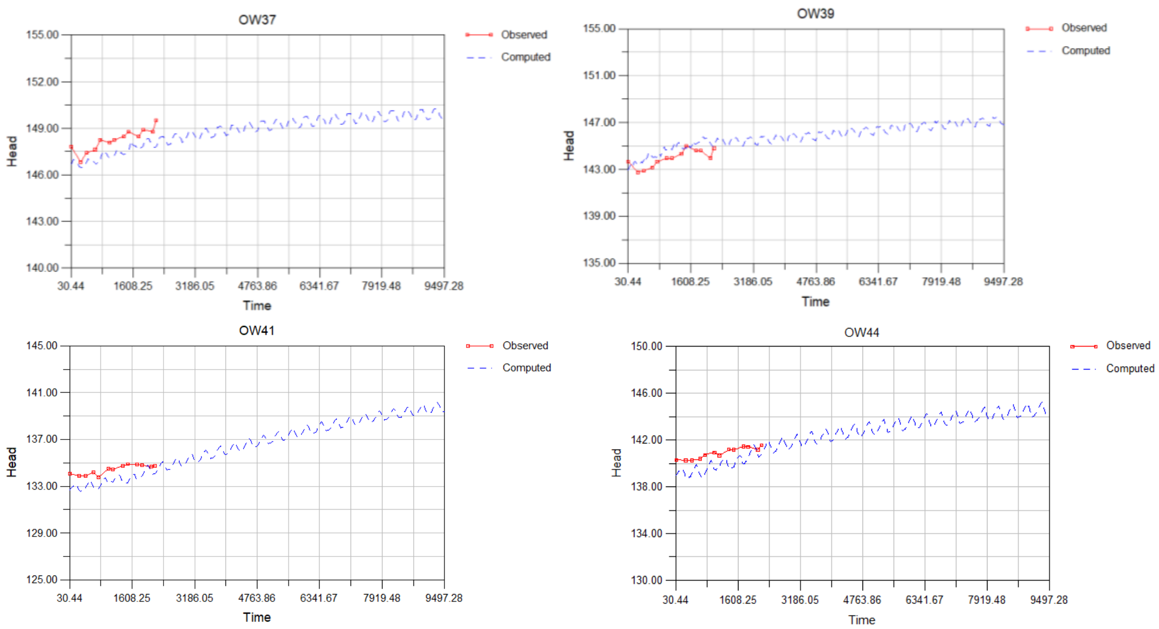


Figure 9.1: Simulated heads (mMSL) for piezometers for Scenario 1

9.1.1 Scenario 1: Water Balance for case studies 1-R and 11-L

An analysis of the water balance for the Case study of 1-R and 11-L distributaries was undertaken for scenario 1. The 1-R distributary command is shown in Figure 9.1. The analysis of the water budget for 1-R is presented in Table 9.3.

Water balance for 1-R shows that recharge in the distributary command area is only 13.26 MCM/yr. whereas the seepage from 1-R distributary is 4.44 MCM/yr only. However, there is significant pumping of -53 MCM/yr, which is 67% more than inflows from both recharge and canals. The inflows from East and south is 29.8 MCM/yr and 19.26 MCM/yr, this high inflow is due to the LBDC main canal passing from the east south side of the distributary command. The net change in storage is -0.88 MCM/yr, which shows the decline in water levels in 1-R distributary command area.

Table 9.3: Water balance for 1-R case study for the Business as Usual scenario from October 2009 to September 2035

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	0.01	-17.79	-17.78
East-flow	29.80	0.00	29.80
North-flow	8.84	-5.07	3.77
South-flow	19.27	-0.01	19.26
Recharge	13.26	0.00	13.26
River	4.44	0.00	4.44
Well	0	-53.03	-53.03
ET	0	-0.60	-0.60
	75.62	**-76.49**	**-0.88**

Table 9.4 shows the water balance for 11-L distributary in which main inflows includes recharge, river and boundary inflows from the north boundary and major outflows include pumping and outflows from the southern boundary. The values for recharge and canals inflows are 15.63 MCM/yr and 55.17 MCM/yr respectively. Results shows that farmers are pumping groundwater of 119.9 MCM/yr, which should be verified by survey in 11-L command area. The net change in storage is 2.58 MCM/yr, which indicates that pumping should not exceed 120 MCM/yr as further increases will result in groundwater levels declining.

Table 9.4: Water balance for 11-L case study for the Business as Usual scenario from October 2009 to September 2035

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	25.43	-18.27	7.16
East-flow	11.47	-20.21	-8.74
North-flow	122.77	0.00	122.77
South-flow	0.00	-69.47	-69.47
Recharge	15.63	0.00	15.63
River	55.17	0.00	55.17
Well	0	-119.90	-119.90
ET	0	-0.02	-0.02
	230.46	**-227.88**	**2.58**

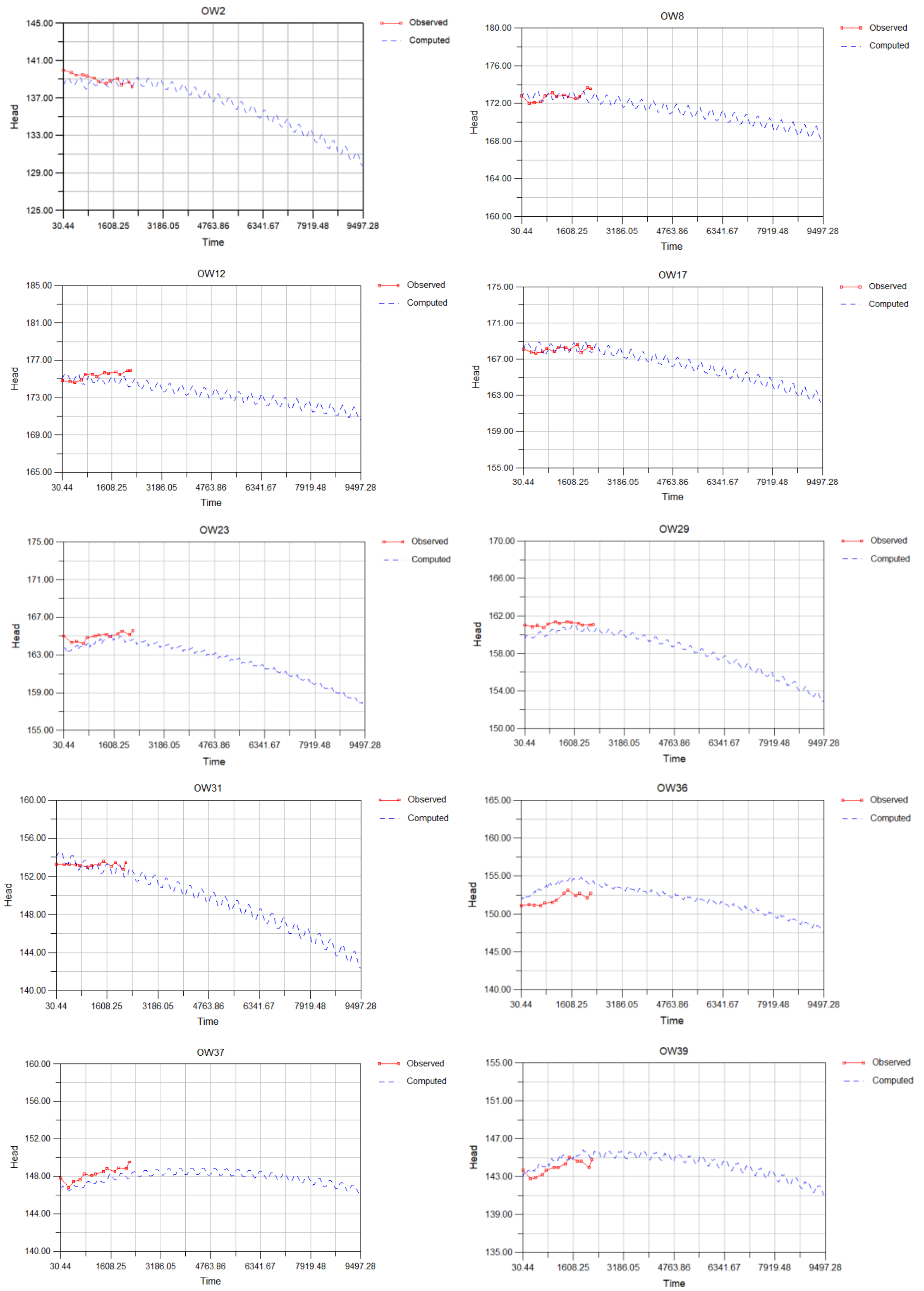
9.2 Scenario 2: 20% increase in GW pumping- no change in canal water

The water balance for scenario 2 from October 2015 to September 2035 with 20% increase in groundwater, is presented in Table 9.5. All values are in MCM/yr and are averaged over the 20 years of simulation.

Table 9.5: Water balance for all model layers for scenario 2 from October 2009 to September 2035

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	3150.06	0	3150.06
River	1584.11	-9.38	1574.74
Well	0	-4666.16	-4666.16
ET	0	-204.70	-204.70
	4734.18	**-4880.24**	**-146.06**

This scenario was undertaken to predict that if groundwater usage increased by 20 percent to 4666 MCM/yr, the net storage will decrease to -146 MCM/yr, as compared to 78 MCM/yr for the business as usual scenario, this will result in decline in groundwater levels. The net storage reduced due to increase in groundwater pumping translates to an average of -100 mm of depth across the Lower Bari Doab. Figure 9.2 shows the response of selected hydrographs. Trends in all hydrographs shows decline in water heads, which is due to increase in groundwater pumping. In the hydrograph of well OW2 there is a decline of about 10 m over the simulated period. These hydrographs shows the predicted groundwater levels from October 2009 to September 2035. These declines are likely due to induced lateral intrusion of saline groundwater and may also mobilse higher salinity groundwater from deeper layers of the aquifer.


OW2
Observed
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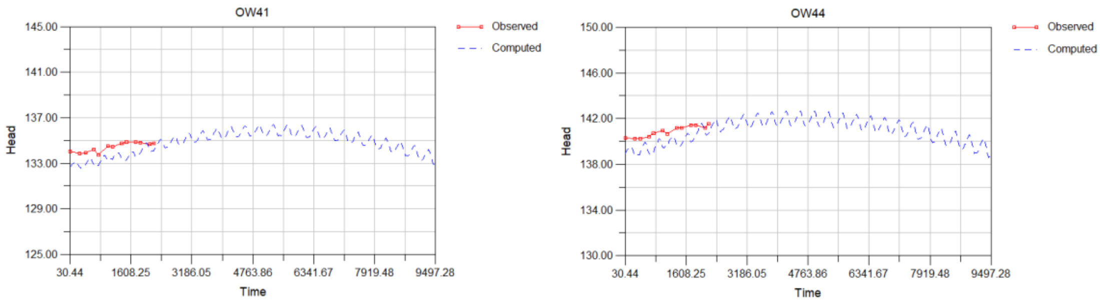


Figure 9.2: Simulated heads (mMSL) for piezometers for Scenario 2

9.2.1 Scenario 2: Water Balance for case studies 1-R and 11-L

A water balance analysis for the Case study of 1-R and 11-L distributaries was undertaken for the scenario 2. The analysis of the water budget for 1-R is presented in Table 9.6. All values are in MCM/yr.

Water balance for 1-R shows that recharge in the distributary command area is only 13.26 MCM/yr. whereas the seepage from 1-R distributary is 4.85 MCM/yr only. However, there is significant pumping of -57.39 MCM/yr, which is 68% more than inflows from both recharge and canals. The inflows from East and south is 32.13 MCM/yr and 21.98 MCM/yr, this high inflow due to seepage from LBDC main canal, passing from the east and south side of the distributary command. The net change in storage is -2.91 MCM/yr, which shows the decline in water levels is 140 mm/yr, in 1-R distributary command area.

Table 9.6: Water balance for 1-R case study for the scenario 2

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	0.01	-19.82	-19.81
East-flow	32.13	0.00	32.13
North-flow	8.31	-5.85	2.46
South-flow	21.99	-0.01	21.98
Recharge	13.26	0.00	13.26
River	4.85	0.00	4.85
Well	0	-57.39	-57.39
ET	0	-0.38	-0.38
	80.54	**-83.45**	**-2.91**

Water balance results for the 11-L distributary command area is presented in Table 9.7. Results shows that recharge and rivers inflow are 15.63 MCM/yr and 55.17 MCM/yr, respectively. However, the groundwater pumping for this case study is 45% more than total recharge and river inflow. The total inflows are 236.32 MCM/yr as compared to 241.78 MCM/yr of total outflows. It shows a reduction of -5.46 MCM/yr of net storage which reflects 129 mm/yr decline in water levels according to scenario 2 condition (20% increase in pumping).

Table 9.7: Water balance for 11-L case study for the scenario 2

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	27.27	-18.05	9.22
East-flow	11.23	-22.73	-11.50
North-flow	127.03	0.00	127.03
South-flow	0.00	-71.41	-71.41
Recharge	15.63	0.00	15.63
River	55.17	0.00	55.17
Well	0	-129.59	-129.59
ET	0	0.00	0.00
	236.32	**-241.78**	**-5.46**

9.3 Scenario 3: 20% increase in GW pumping- 5% reduction in canal water

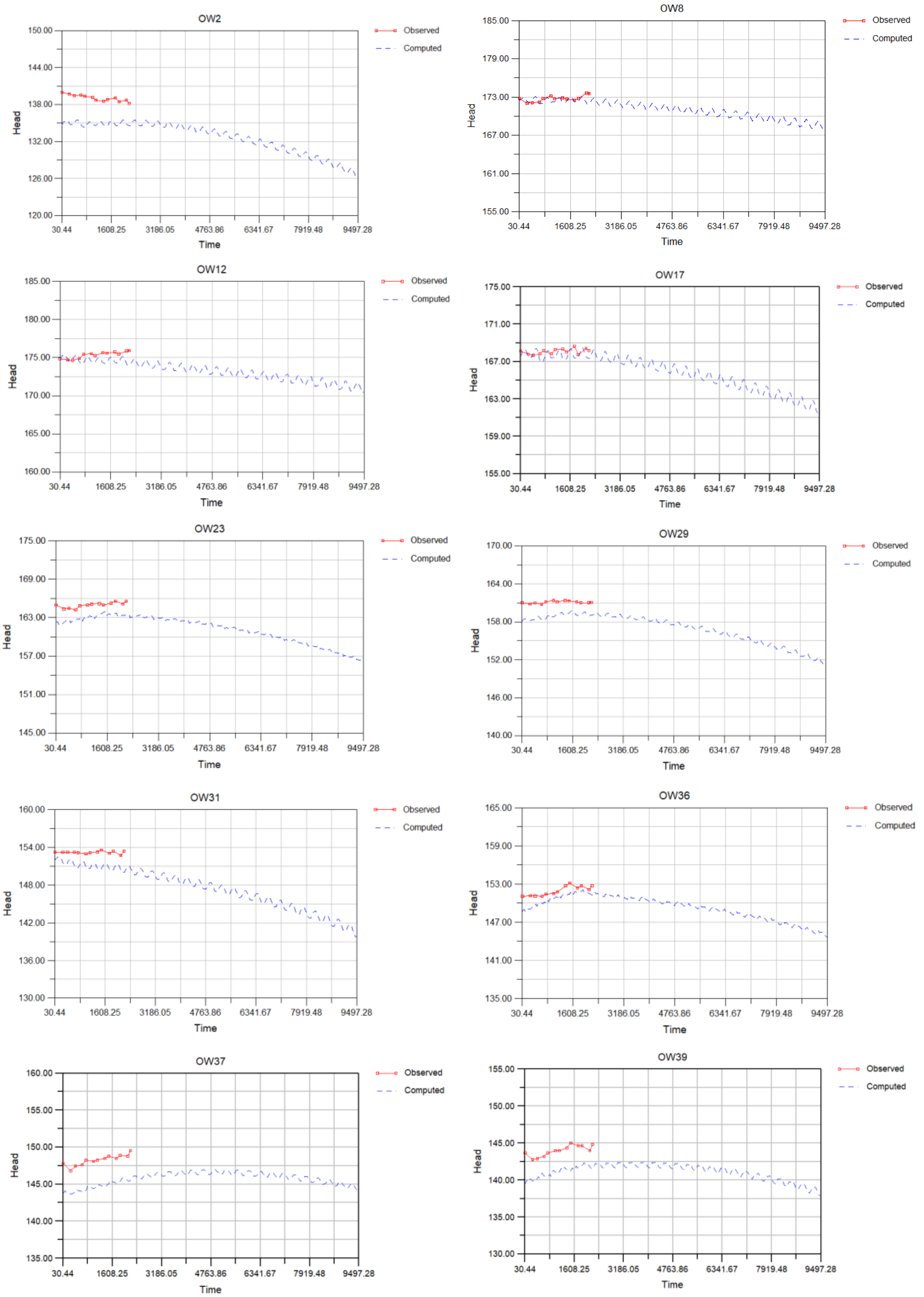
This scenario is depicting the situation if in future water supplies decrease by 5 percent, due to which farmers are compelled to increase groundwater pumping up to 20 percent in next 20 years. The water balance is presented in Table 9.8 for scenario 3. All values are in MCM/yr and are averaged over the 26 years of simulation.

Table 9.8: Water balance for all model layers for the scenario 3 from October 2009 to September 2035

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	3150.06	0	3150.06
River	1535.01	-8.52	1526.50
Well	0	-4666.16	-4666.16
ET	0	-154.26	-154.26
	4685.08	**-4828.94**	**-143.86**

In the water budget for scenario 3, groundwater pumping is 4666 MCM/yr, as compared to 4316 MCM/yr in the Business as Usual scenario. Reducing canal supplies by 5% resulted in a substantial area east of the case study site 11-L in Sahiwal with dry cells indicating the top layer had dried out. These areas to the east have been affected the most by curtailment of flows in the 3 eastern rivers and the very high density of tubewells in Indian Punjab. The decline in water levels have also resulted in reduction of evapotranspiration from 277 MCM/yr for the BAU scenario to 154 MCM/yr for this scenario.

Overall this scenario indicates that if canal water supplies decreases and groundwater pumping increase by 20 percent, the net change in groundwater storage will be -144 MCM/yr, as compared to 78 MCM/yr in Business as Usual scenario. This reflects an average decline of 102 mm/yr in groundwater levels. Hydrographs for the selected observation wells are shown in Figure 9.3. All the hydrographs shows the decline in water table from 2.5m in OW 41, to 11m in OW 2, which is in the middle of LBDC command area.


OW2
OW8
OW12
OW17
OW23
OW29
OW31
OW36
OW37
OW39
Observed
Computed
Head
Time
30.44
1608.25
3186.05
4763.86
6341.67
7919.48
9497.28

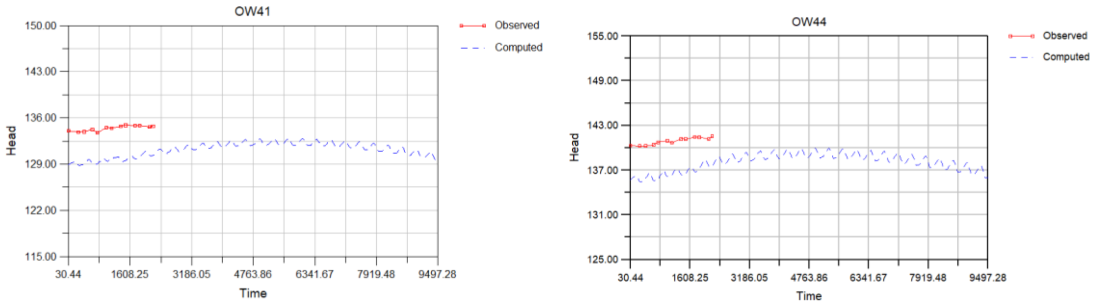


Figure 9.3: Simulated heads (mMSL) for piezometers for Scenario 3

9.3.1 Scenario 3: Water Balance for case studies 1-R and 11-L

A water balance analysis for the case study of 1-R and 11-L distributaries was undertaken for the scenario 3 (20% increase in pumping and 10% decrease in water supplies). The analysis of the water budget for 1-R is presented in Table 9.9. All values are in MCM/yr.

For scenario 3, water balance results shows that total inflows in the case study area is 81.55 MCM/yr. In this scenario inflow from canals has increased by 0.32 MCM/yr, in comparison to the BAU scenario, due to decline in groundwater levels which increases gradients between canal and groundwater system. Overall the inflows have increased in this scenario by 5.93 MCM/yr compared to the BAU scenario. This increase is due to lateral inflows from surrounding areas of Okara. The total outflows are -84.51 MCM/yr, which results in decrease in groundwater storage of -2.96 MCM/yr. This will result in the decline in watertable of 142 mm/yr.

Table 9.9: Water balance for 1-R case study for the scenario 3

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	0.01	-20.84	-20.83
East-flow	32.79	0.00	32.79
North-flow	8.16	-5.97	2.19
South-flow	22.56	0.00	22.56
Recharge	13.26	0.00	13.26
River	4.77	0.00	4.77
Well	0	-57.39	-57.39
ET	0	-0.30	-0.30
	81.55	**-84.51**	**-2.96**

Water balance for 11-L distributary command area is shown in Table 9.10. The total inflows and outflows in this case study area are 242.39 MCM/yr which have increased 11.93 MCM/yr compared to the BAU scenario. Much of the increase in inflows is from the north of Sahiwal. It shows that if water supplies reduces by 5% and farmers are compelled to increase pumping by 20%, then in this case net groundwater storage will reduce by -5.11 MCM/yr (negative sign shows the water fluxes are coming out of the groundwater aquifers is more than water fluxes going into the groundwater aquifers). It will results in decline in 120 mm/yr, in 11-L distributary command area.

Table 9.10: Water balance for 11-L case study for the scenario 3

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	28.07	-18.71	9.35
East-flow	11.22	-23.86	-12.63
North-flow	135.07	0.00	135.07
South-flow	0.00	-75.35	-75.35
Recharge	15.63	0.00	15.63
River	52.41	0.00	52.41

Well	0	-129.59	-129.59
ET	0	0.00	0.00
	242.39	**-247.50**	**-5.11**

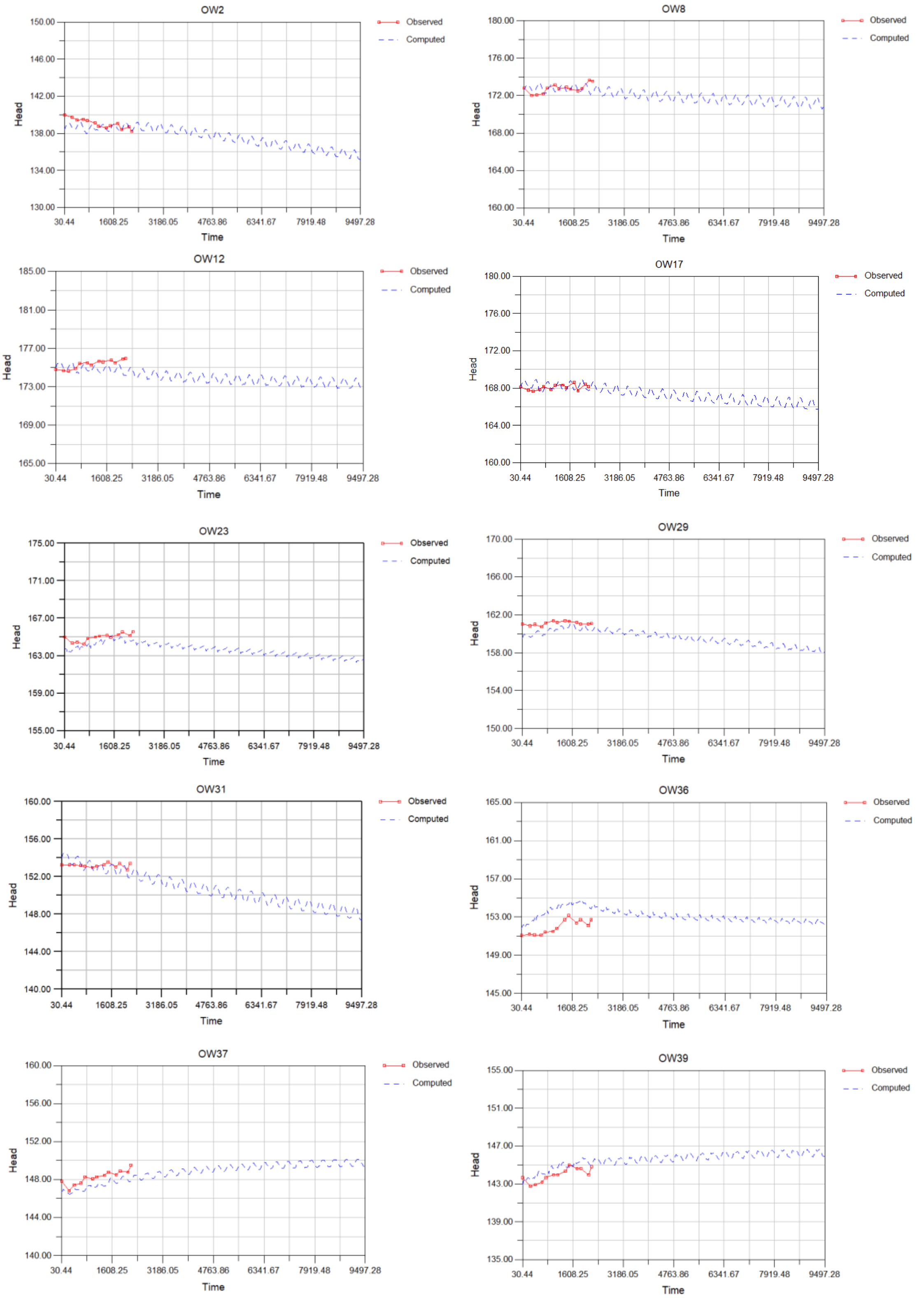
9.4 Scenario 4: 10% increase in GW pumping- 10% increase in canal water

This scenario is on the basis that population is increasing due to which cropping intensity is increasing to meet the food requirement. This scenario indicates the situation of groundwater in LBDC command area, if both groundwater pumping and water supplies increase by 10 percent in future, which can happen due to lining of water courses as well as construction of new dams. Table 9.11 present the water balance for this scenario. All the values are in MCM/yr.

Table 9.11: Water balance for all model layers for the scenario 4 from October 2009 to September 2035

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	3278.34	0	3278.34
River	1538.44	-11.99	1526.45
Well	0	-4491.15	-4491.15
ET	0	-269.22	-269.22
	4816.78	**-4772.35**	**44.43**

The water balance in Table 9.11 shows that recharge is slightly increased in the LBDC area, as water supplies at farm gate and groundwater pumping both are increasing, which results in increase of recharge from the agriculture fields. Groundwater pumping also increased by -178 MCM/yr. Th negative sign shows that water fluxes are coming out of the groundwater aquifer. Similarly recharge is also increased by 128 MCM/yr (recharge for the BAU scenario is 3150). Figure 9.4 shows the hydrographs for water levels in different observation wells in the LBDC command area. Some of the hydrographs shows a small decline in water table e.g. OW2, OW29, and OW31. However hydrographs for OW37, OW39, OW41 and OW 44 shows the rise in groundwater levels. This could be due to increase in recharge to groundwater from the field.


OW2
Observed
Computed
Head
150.00
146.00
142.00
138.00
134.00
130.00
30.44
1608.25
3186.05
4763.86
6341.67
7919.48
9497.28
Time
OW8
180.00
176.00
172.00
168.00
164.00
160.00
OW12
185.00
181.00
177.00
173.00
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OW17
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OW31
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143.00
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135.00

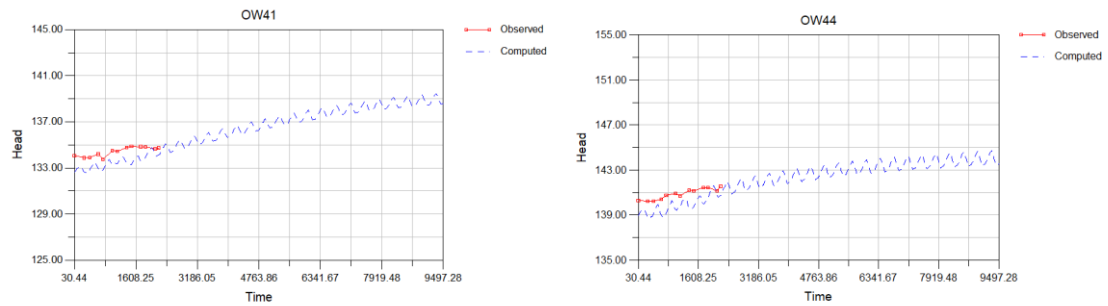


Figure 9.4: Simulated heads (mMSL) for piezometers for Scenario 4

9.4.1 Scenario 4: Water Balance for case studies 1-R and 11-L

A water balance analysis for the Case study of 1-R and 11-L distributaries command areas was undertaken for the scenario 4 (10% increase in both groundwater pumping and canal water supplies). The analysis of the water budget for 1-R is presented in Table 9.12. All values are in MCM/yr.

Table 9.12 shows the water balance results for the case study 1-R distributary command area. The total inflows and outflows in this case study area are 77.89 MCM/yr and -79.17 MCM/yr, respectively. Population is growing due to which cropping intensity is increasing to meet food requirement. If water supplies increase by 10%, due to canal and water course lining or development of new water storage dams and groundwater pumping increase only by 10%, then in this case net groundwater storage will reduce at a rate of -1.28 MCM/yr (negative sign shows the water fluxes coming out of the groundwater aquifers are more than water fluxes going into the groundwater aquifers).

Table 9.12: Water balance for 1-R case study for the scenario 4

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	0.01	-18.18	-18.17
East-flow	30.62	0.00	30.62
North-flow	8.97	-5.25	3.71
South-flow	20.02	-0.01	20.02
Recharge	13.80	0.00	13.80
River	4.47	0.00	4.47
Well	0	-55.21	-55.21
ET	0	-0.51	-0.51
	77.89	**-79.17**	**-1.28**

Water balance results for the 11-L distributary command area is presented in Table 9.13. Results show that recharge and rivers inflow are 16.25 MCM/yr and 55.17 MCM/yr, respectively. However, the groundwater pumping for this case study is -124.74 MCM/yr, which is 43% more than total recharge and rivers inflow. The total inflows and outflows are 234.70 MCM/yr and 233.76 MCM/yr respectively. It shows the net groundwater storage increased at the rate of 0.94 MCM/yr which indicates water levels will rise at a rate of 22 mm/yr in the 11-L case study area.

Table 9.13: Water balance for 11-L case study for the scenario 4

	Inflow MCM/yr	**Outflow MCM/yr**	**Net MCM/yr**
West-flow	26.95	-17.27	9.68
East-flow	11.31	-21.67	-10.36
North-flow	125.02	0.00	125.02
South-flow	0.00	-70.07	-70.07
Recharge	16.25	0.00	16.25
River	55.17	0.00	55.17
Well	0	-124.74	-124.74
ET	0	0.00	0.00
	234.70	**-233.76**	**0.94**

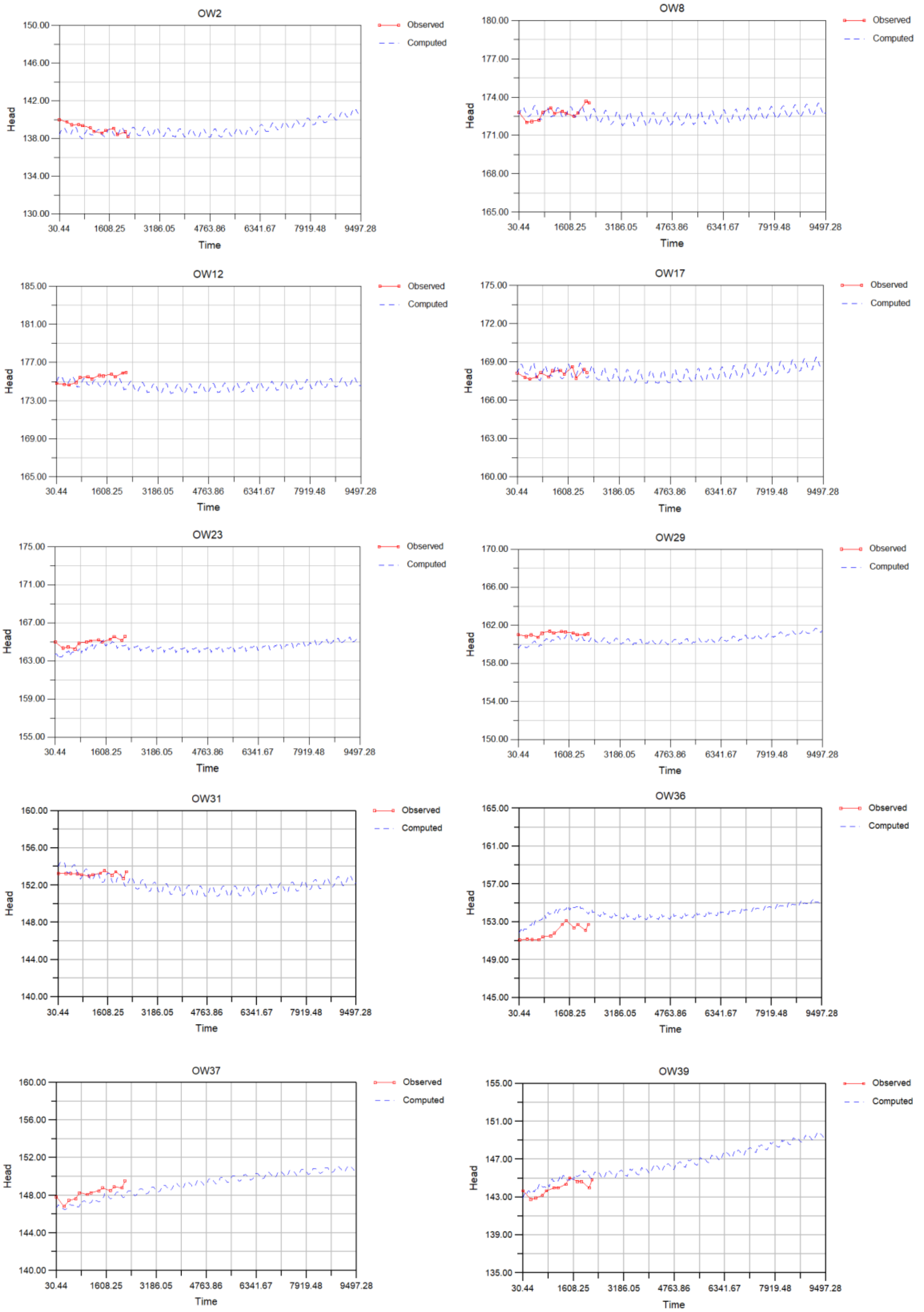
9.5 Scenario 5: 10% reduction in GW - no change in canal water

This scenario indicates the situation of groundwater in LBDC command area, if groundwater pumping decreases by 10 percent in future, as a result of increase in water use efficiency. Table 9.14 presents the water balance for this scenario. All the values are in MCM/yr.

Table 9.14: Water balance for all model layers for the scenario 5 from October 2009 to September 2035

	Inflow MCM/yr	**Outflow MCM/yr**	**Net MCM/yr**
Recharge	3150.06	0	3150.06
River	1500.83	-14.41	1486.42
Well	0	-4139.93	-4139.93
ET	0	-333.59	-333.59
	4650.90	**-4487.93**	**162.97**

In comparison with Business-as-Usual scenario, if groundwater pumping is decrease by 10 percent to 4139 MCM/yr, the change in groundwater storage term increases to 163 MCM/yr which is 85 MCM/yr higher than for Business as Usual scenario as indicated in *Table 9.2*. This additional net water available is due to reduced groundwater pumping which translates to an average of 116 mm of groundwater depth across the LBDC, however, individual areas will recover more depending on the pumping occurring in that grid cell. Figure 9.5 shows the similar trends to the Business as Usual scenario. In all hydrographs the water levels are increasing or remain constant, which is due to decrease in groundwater pumping. PID should take steps to manage groundwater pumping to ensure long term sustainability of the aquifer.


OW2
OW8
OW12
OW17
OW23
OW29
OW31
OW36
OW37
OW39
Observed
Computed
Head
Time
30.44
1608.25
3186.05
4763.86
6341.67
7919.48
9497.28

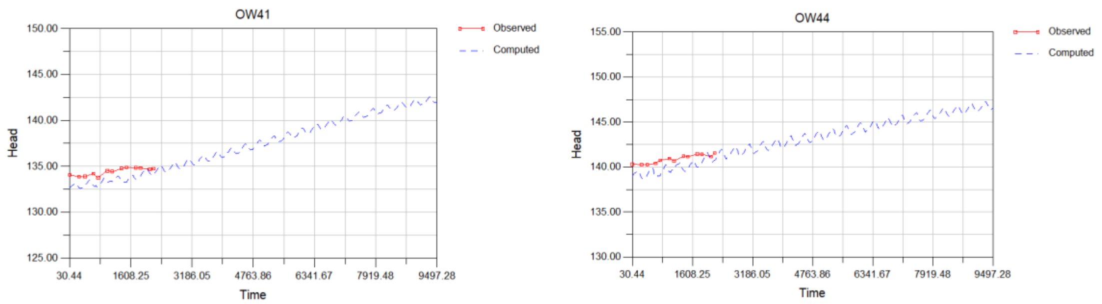


Figure 9.5: Simulated heads (mMSL) for piezometers for Scenario 5

9.5.1 Scenario 5: Water Balance for case studies 1-R and 11-L

A water balance analysis for the Case study of 1-R and 11-L distributaries was undertaken for the scenario 5 (10% decrease in pumping). The analysis of the water budget for 1-R is presented in Table 9.15. All values are in MCM/yr.

Results revealed that 10% decrease in groundwater pumping creates an equilibrium condition in 1-R. it means that water fluxes going and coming out from the aquifer will become equal. However any increase in groundwater pumping in 1-R will results in decline in water tables. Water budget results shows that if farmers or Punjab Irrigation Department manage to reduce pumping by increasing canal water use efficiencies or cultivation of low delta crops in 1-R distributary command area, the net groundwater storage will be zero, which is -0.88 MCM/yr according to BAU scenario (Scenario 1).

Table 9.15: Water balance for 1-R case study for the scenario 5

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	0.01	-16.89	-16.89
East-flow	28.75	0.00	28.75
North-flow	9.06	-4.73	4.33
South-flow	17.98	-0.01	17.97
Recharge	13.26	0.00	13.26
River	4.26	0.00	4.26
Well	0	-50.85	-50.85
ET	0	-0.85	-0.85
	73.33	**-73.33**	**0.00**

Table 9.16 shows the water balance for 11-L distributary command for scenario 5. Main inflows includes recharge, river and boundary inflows from north boundary and major outflows include pumping and outflows from south boundary. The values for recharge and canals inflows are 15.63 MCM/yr and 55.17 MCM/yr respectively. Results shows that farmers pumping groundwater of -115.06 MCM/yr, which is 4.48 MCM/yr less than BAU scenario. It reveal that in 11-L command area there is potential of increase in groundwater pumping and decrease in pumping will increase groundwater storage in the aquifer by 6.34 MCM/yr.

Table 9.16: Water balance for 11-L case study for the scenario 5

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West-flow	24.27	-18.38	5.89
East-flow	11.81	-18.53	-6.72
North-flow	119.49	0.00	119.49
South-flow	0.00	-68.05	-68.05
Recharge	15.63	0.00	15.63
River	55.17	0.00	55.17
Well	0	-115.06	-115.06
ET	0	0.00	0.00
	226.36	**-220.02**	**6.34**

9.6 Scenario 6: Climate change scenario-R.C.P 4.5

As a basis for the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report, the Representative Concentration Pathways (RCPs) was developed to capture the full range of possible future scenarios. These future scenarios are categorized into four RCPs (2.6, 4.5, 6.0 and 8.5), according to their approximate radiative forcing in the year 2100. The numerical values of RCPs refer to the concentrations in year 2100. We use data from RCP 4.5 and RCP 8.5 model simulations to study the projected future changes for the mean and extreme variability of rainfall and its subsequent impact on groundwater. RCP 4.5 corresponds to the concentration of carbon which delivers an average global warming of 4.5 W/m^2 (Watts per square meter) in 2100. Similarly, RCP 8.5 states the concentration of carbon which delivers an average global warming of 8.5 W/m^2 across the Globe. Rainfall was simulated using RCP 4.5 and RCP 8.5 scenarios for the period September 2015 to October 2047 on monthly basis using the NorESM global circulation model

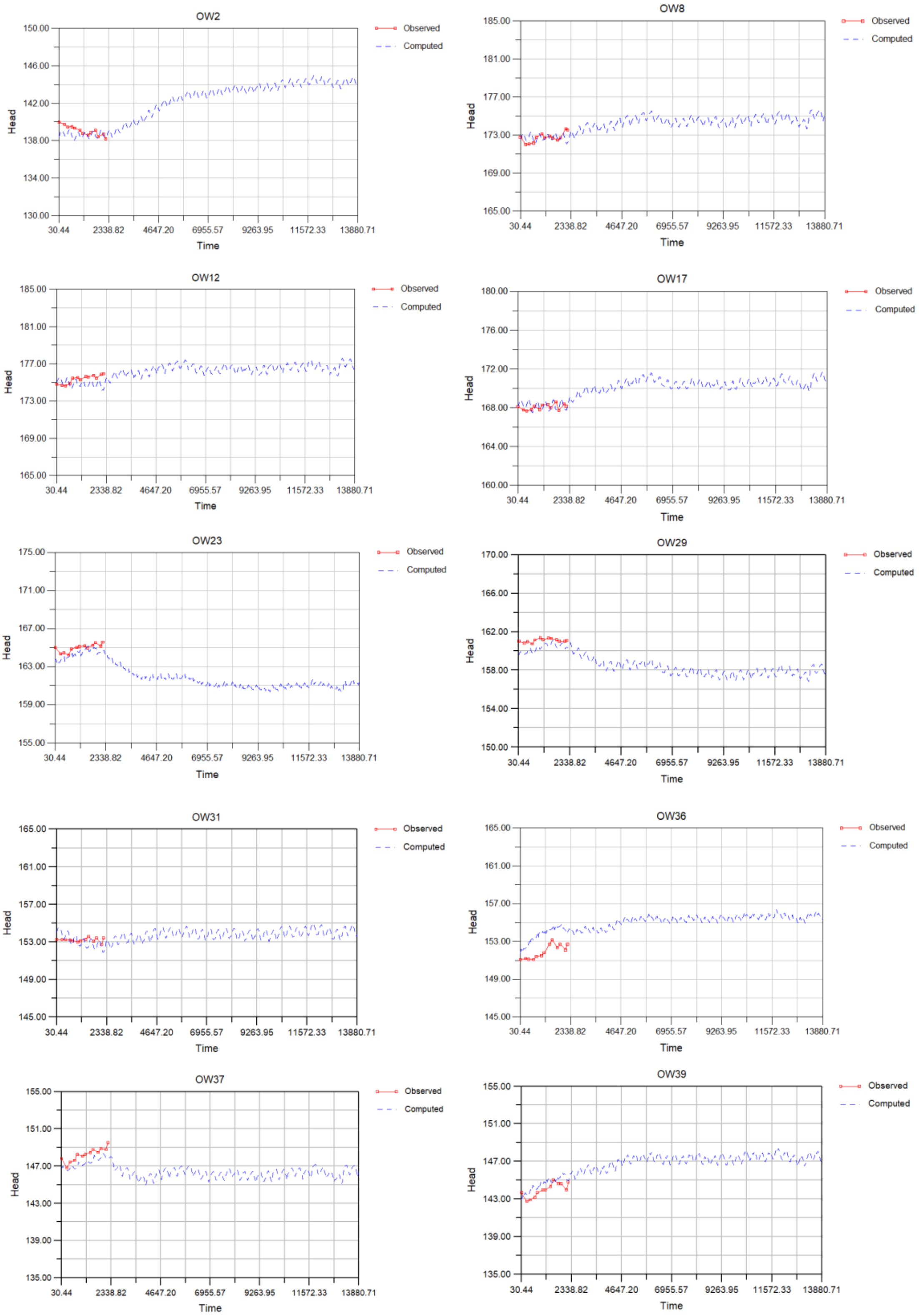
This scenario was simulated to observe the impacts of climate change in the study area for the period from October 2009 to September 2047. Representative concentration pathways (R.C.P) 4.5 data was used for this purpose. Table 9.17 present the water balance for this scenario. All the values are in MCM/yr.

Table 9.17: Water balance for all model layers for scenario 6 from October 2009 to September 2047

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	3033.42	0	3033.42
River	1532.10	-8.15	1523.95
Well	0	-4321.72	-4321.72
ET	0	-201.40	-201.40
	4565.52	**-4531.27**	**34.25**

The water balance for the RCP 4.5 scenario in Table 9.17 indicates recharge has decreased by about 1% in comparison to the BAU scenario. This decrease is due to the variation of rainfall in the study region, which results in decreased recharge from the agriculture fields as some of the crop water requirements were met by rainfall. The average net storage for LBDC command area is 34.25 MCM/yr. The increase in rainfall under RCP 4.5 will reduce irrigation as crop water requirement will be fulfilled by surface water supplies and rainfall.

Figure 9.6. shows the hydrographs of observation wells for scenario 6 – RCP 4.5.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Computed
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Head
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6955.57
9263.95
11572.33
13880.71
Time
OW8
Observed
Computed
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177.00
173.00
169.00
165.00
Head
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OW12
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Computed
185.00
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OW17
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OW23
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OW29
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Computed
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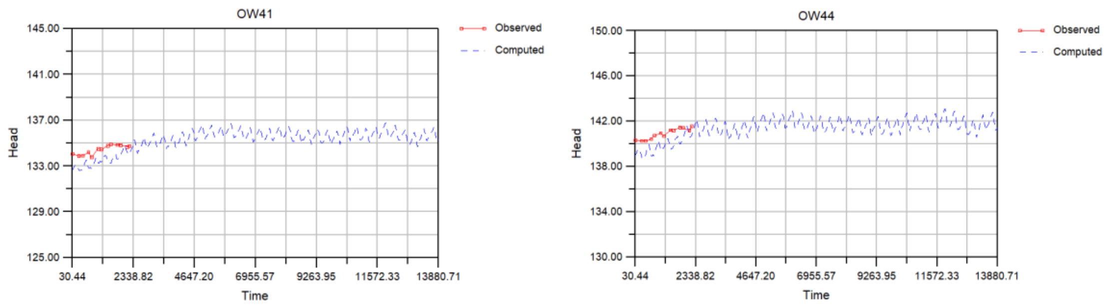


Figure 9.6: Simulated heads (mMSL) for piezometers for Scenario 6

9.6.1 Scenario 6: Water Balance for case studies 1-R and 11-L

This analysis is depicting the impacts of climate change on groundwater aquifer of 1-R and 11-L distributaries command area for October 2009 to September 2047 (38 years). The water balance is presented in Table 9.18 for scenario 6. All values are in MCM/yr and are averaged over the 38 years of simulation.

Table 9.18 shows the water balance results for 1-R command for climate scenario RCP 4.5 (scenario 6). This scenario was simulated to predict climate change impacts, which indicates inflows from recharge and rivers are 41.84 MCM/yr and 4.16 MCM/yr, the net storage will be 0.92 MCM/yr, which is higher than -0.88 MCM/yr precited in the business as usual scenario for 1-R case study. This net water increase is due to an increase in rainfall which translates to an increase of an average of 44 mm/yr of depth across the 1-R command. Additionally if pumping increases the aquifer will start depleting. Groundwater levels are already deep enough (>30 m) in much of the study area, so any increase in groundwater pumping results in decline in groundwater levels and poor groundwater quality as well.

Table 9.18: Water balance for 1-R case study for the scenario 6

	Inflow	Outflow	Net MCM/yr
West-flow	0.12	-17.04	-16.92
East-flow	19.37	-0.02	19.35
North-flow	3.51	-5.06	-1.55
South-flow	10.68	-0.48	10.20
Recharge	41.84	0.00	41.84
River	4.16	0.00	4.16
Well	0	-53.33	-53.33
ET	0	-2.83	-2.83
	79.68	**-78.76**	**0.92**

In the water budget for 11-L command (Table 9.19), the total groundwater inflows and outflows for 11-L command are 253.69 MCM/yr and -247.39 MCM/yr, respectively. Inflows from field recharge has increased from 15.63 MCM/yr to 76.03 MCM/yr, which is 60.40 MCM/yr increase in recharge. The reason for this increase in recharge are several high rainfall events occurring in the study area, according to RCP 4.5 data set. Whereas groundwater pumping is the same as the Business as Usual (BAU) scenario. This average an increase in recharge results in restoring groundwater aquifers by 6.30 MCM/yr equivalent to an average gain of 149 mm/yr in groundwater levels.

Table 9.19: Water balance for 11-L case study for the scenario 6

	Inflow	Outflow	Net MCM/yr
West-flow	11.73	-46.12	-34.39
East-flow	15.74	-11.55	4.19
North-flow	95.51	-0.41	95.10
South-flow	0.00	-69.39	-69.39
Recharge	76.03	0.00	76.03
River	54.68	0.00	54.68
Well	0	-119.91	-119.91
ET	0	0.00	0.00
	253.69	**-247.39**	**6.30**

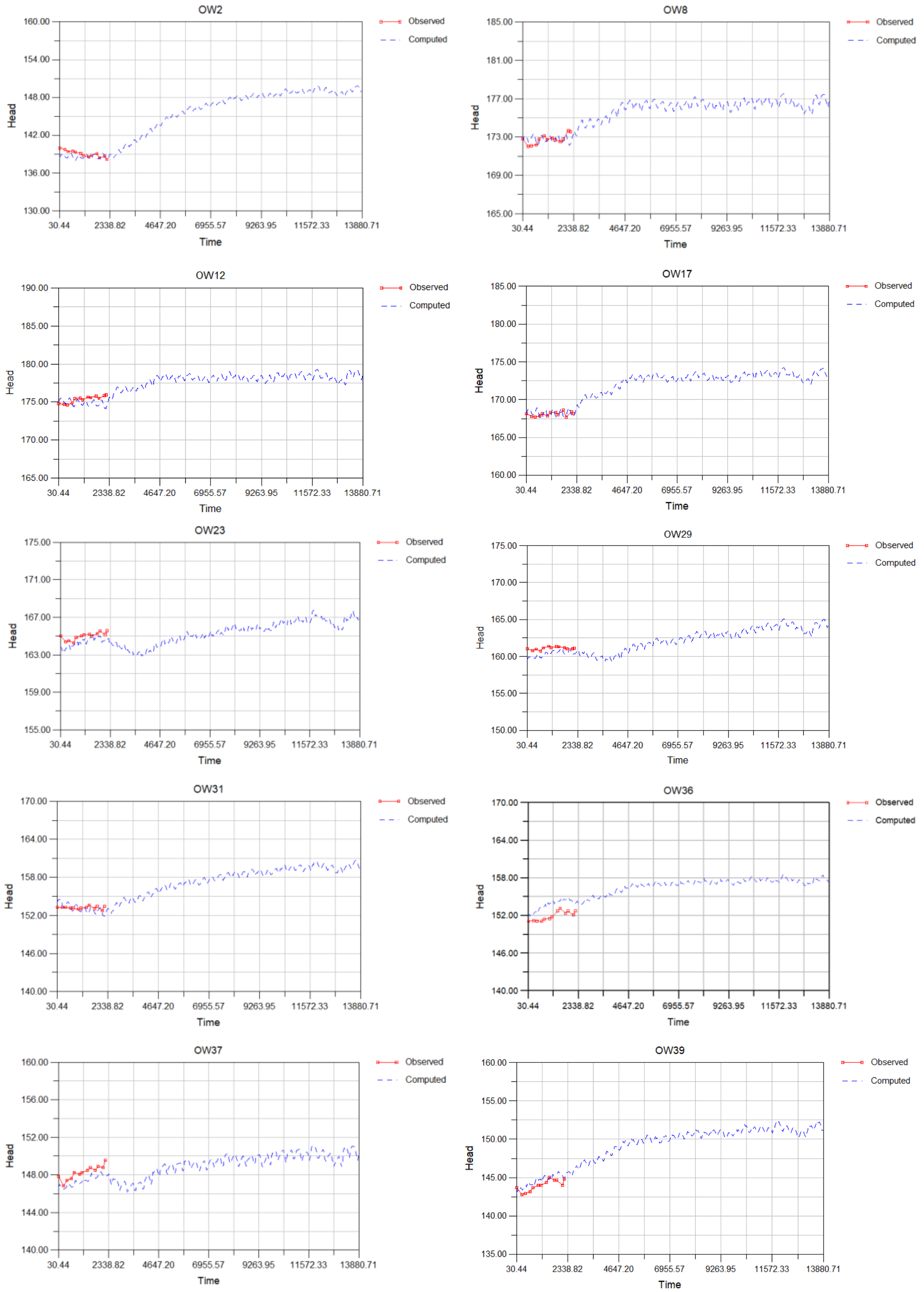
9.7 Scenario 7: Climate change scenario-R.C.P 8.5

The RCP database aims at documenting the emissions, concentrations, and land-cover change projections of the so-called "Representative Concentration Pathways" (RCPs). Information about the RCPs 8.5 is focused on warming climate scenarios. Table 9.20 present the water balance for this scenario. All the values are in MCM/yr. The results of water balance (Table 9.20) shows that recharge increased by 460.70 in LBDC area, due to the extreme rainfall events in the study region, which also results in increase of ET (190.59 MCM/yr increase) from the groundwater. The net groundwater storage increased at a rate of 179.20 MCM/yr which is a gain in groundwater levels by 127 mm/year. The increase in groundwater levels has also resulted in decrease net seepage as the head gradient between the canal water level and the groundwater levels have decreased.

Table 9.20: Water balance for all model layers for scenario 7 from October 2009 to September 2047

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	3610.77	0	3610.77
River	1385.04	-26.80	1358.24
Well	0	-4321.72	-4321.72
ET	0.00	-468.08	-468.08
	4995.80	**-4816.60**	**179.20**

This scenario indicates the impacts of extreme climate change on the study area from October 2015 to September 2035 period. This is shown in hydrographs of selected piezometers which is shown in Figure 9.7. The effect of high rainfall events can be observed by the trends in hydrograph.


OW2
Observed
Computed
Head
160.00
154.00
148.00
142.00
136.00
130.00
30.44
2338.82
4647.20
6955.57
9263.95
11572.33
13880.71
Time
OW8
185.00
181.00
177.00
173.00
169.00
165.00
OW12
190.00
185.00
180.00
175.00
170.00
165.00
OW17
160.00
OW23
171.00
167.00
163.00
159.00
155.00
OW29
155.00
150.00
OW31
164.00
158.00
152.00
146.00
140.00
OW36
OW37
156.00
152.00
148.00
144.00
OW39
145.00
140.00
135.00

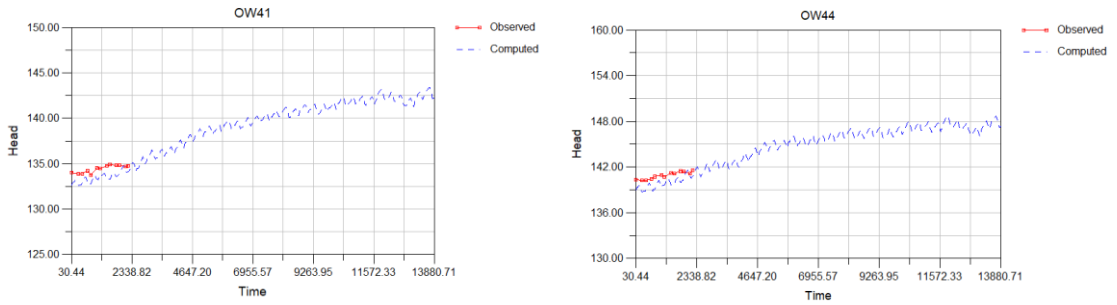


Figure 9.7: Simulated heads (mMSL) for piezometers for Scenario 7

9.7.1 Scenario 7: Water Balance for case studies 1-R and 11-L

This analysis is depicting the impacts of extreme climate change on the groundwater aquifer of 1-R and 11-L distributaries command area for October 2009 to September 2047 (38 years). The water balance is present in Table 9.21 for scenario 7. All values are in MCM/yr and are averaged over the 38 years of simulation.

Table 9.21 shows the water balance results for 1-R command for climate scenario RCP 8.5 (scenario 7). This scenario predicts that for the RCP 8.5 scenario inflows from recharge and rivers are 51.30 MCM/yr and 3.24 MCM/yr, and the net storage will be 1.67 MCM/yr, which is -0.88 MCM/yr in business as usual scenario for 1-R case study. This net water increase is due to the increase in groundwater recharge due to high rainfall events, which results in rise in groundwater levels on an average of 80 mm/yr across the 1-R command.

Table 9.21: Water balance for 1-R case study for the scenario 7

	Inflow	**Outflow**	**Net MCM/yr**
West-flow	0.37	-14.29	-13.92
East-flow	17.50	-0.01	17.48
North-flow	5.59	-3.74	1.85
South-flow	7.52	-1.16	6.37
Recharge	51.30	0.00	51.30
River	3.24	-0.07	3.16
Well	0	-53.33	-53.33
ET	0	-11.24	-11.24
	85.52	**-83.84**	**1.67**

The results of water budget for 11-L command are presented in Table 9.22, show the total groundwater inflows and outflows for 11-L command are 259.39 MCM/yr and -232.75 MCM/yr, respectively. Inflows from field recharge is increased from 15.63 MCM/yr (BAU scenario) to 87.69 MCM/yr, which is 72.06 MCM/yr increase in recharge. The reason for this increase in recharge are several high rainfall events occurring in the study area, according to the RCP 8.5 data set. This average increase in recharge results in restoring groundwater aquifers by 26.65 MCM/yr. This reflects an average gain of 628 mm/yr in groundwater levels.

Table 9.22: Water balance for 11-L case study for the scenario 7

	Inflow	**Outflow**	**Net MCM/yr**
West-flow	10.58	-37.64	-27.07
East-flow	16.49	-6.92	9.57
North-flow	89.95	-1.31	88.65
South-flow	0.00	-66.96	-66.96
Recharge	87.69	0.00	87.69
River	54.68	0.00	54.68
Well	0	-119.91	-119.91

ET	0	0.00	0.00
	259.39	**-232.75**	**26.65**

The RCP 8.5 scenario indicates that pumping can increases further in response to increases in cropping intensity, but farmers are likely to face greater difficulties under a climate regime where flooding and damage to crops may be more frequent due to severity of rainfall events. Under this scenario, groundwater levels are likely to rise rapidly in response to higher rainfall in the upper aquifer (<30 m) in study area, and PID would need to manage waterlogging in some areas which had largely abated due to the increase in pumping in the Lower Bari Doab.

10 Conclusions and Recommendation

10.1 Monitoring Strategy for Lower Bari Doab

Accurate records of groundwater extraction are essential in developing and calibrating a groundwater model. There are about 60,000 tubewells in use in Lower Bari Doab however, none of these have any recorded usage figures. We recommend that PID consider metering groundwater usage at strategic monitoring sites in the doab, and instrument key monitoring sites with loggers to record water levels and salinity concentrations on a daily basis.

At present PID is monitoring water levels in several hundred piezometers. Improving and better targeting the monitoring strategy would be more cost effective and also provide improved understanding of groundwater conditions which could then provide a framework for sustainable management of the surface and groundwater for Lower Bari Doab. We recommend that PID take the lead on establishing a groundwater monitoring strategy for regular and strategic monitoring of groundwater resources in Punjab. Spatial and temporal groundwater information are key elements for improving understanding of groundwater resources and for governments to make informed decisions.

A lack of knowledge of which layer the pumping is occurring from is another potential source of error which can be rectified by implementing a strategic metering and monitoring program. To manage the water resources of Lower Bari Doab requires an accurate assessment of the water balance. Improving the quality and reliability of the data will reduce the number of assumptions and as a consequence decrease the uncertainty in modelling results. There is an old adage in business “you can't manage what you don't measure”. Unless key stresses on the system are measured, Resource Managers cannot ascertain accurately if the condition of the resource is improving or deteriorating. Thus improving the management of the system or indeed achieving sustainable management of the system becomes a difficult task for Resource Managers if they do not have access to reliable data to evaluate if the system is improving or not.

10.2 Sustainable Groundwater Use for LBDC command area

The two major components of the water balance are recharge from rainfall, river and canal seepage and irrigation recharge which account for 93 percent of inputs to the system. The net gain in storage over the simulation period is 78.12 MCM/yr. The water balance also indicates that river discharge or flows from the aquifer to the river system are negligible which has important implications for salt transport out of the LBDC command area. Higher water tables may increase the possibility of outflows to the rivers, thus a sustainable level of pumping for irrigation would provide improved livelihood outcomes as well as environmental benefits.

Ideally, pumping should be managed around 4300±215 MCM/yr which depend on the need for groundwater pumping in reaction to lack of surface water supplies and or drought. The groundwater pumping should be decreased so that the aquifer gets recharged with freshwater especially when surface water supplies are plentiful. Additionally, in specific suitable areas of LBDC command area PID should consider the establishment of managed aquifer recharge (MAR) schemes, especially where water tables are significantly deep and soil conditions are favourable. This would be particularly useful for ensuring that salinity does not encroach into freshwater resources.

The water balance for 1-R and 11-L case studies shows the main inputs are recharge and canal seepage, and the main outputs are pumping and boundary outflows. It is important to note here there is significant pumping occurring in 1-R and this should be verified by farmer surveys, and monitoring and metering at key sites. Pumping in 1-R case study area causes a decline of -41 mm/yr in groundwater levels. Whereas in 11-L there an estimate of 7.14 MCM/yr is added in groundwater aquifer. Thus monitoring and managing pumping in 1-R is needed more than in the 11-L case study area.

10.3 Scenario Analysis for LBDC command area

Five scenarios including climate scenarios were undertaken from September 2015 to October 2035 and two climate scenarios from September 2015 to October 2047, to assess aquifer status and availability of groundwater for irrigation and to provide the future recommendations for PID indicated below:

i. The Business as Usual scenario indicates that if conditions remained similar to the September 2015 to October 2035 period then pumping of 4316 MCM/yr will not result in significant drawdowns.
ii. When groundwater usage increase by 20 percent the net groundwater storage will reduce by 146 MCM/yr, which is 78 MCM/yr in business as usual scenario, this will result in declining groundwater levels. This net water reduced due to increase in groundwater pumping translates to an average of -104 mm of depth across the Lower Bari Doab.
iii. If in future with the increase in 20 percent groundwater usage the surface water supplies also reduce by 5 percent then the net change in groundwater storage will be -144 MCM/yr over the whole LBDC area. The increase in pumping and decrease in surface water supplies will results in average decline of 102 mm/yr in groundwater levels in LBDC. This scenario depicts the condition of the groundwater resource in response to lower surface water supplies and increased groundwater pumping and . increased cropping intensities in response to food security needs.
iv. When pumping increases only 10 percent due to limited surface water supplies the groundwater pumping will be 4491 MCM/yr, which is 178 MCM/yr more than Business as Usual scenario. Results shows that an estimated total water savings of 44 MCM/yr is possible. However if we look at the case study if 1-R distributary command for scenario 4 the net groundwater storage is decreased at rate of -1.28 MCM/yr. This results in decline in groundwater levels by 128 mm/yr which is due to increase in groundwater pumping in 1-R case study area.
v. Comparing scenario 5 with scenario 1 (Business as Usual) we find that if groundwater pumping was reduced by 176 MCM/yr and an estimated total water savings of 162 MCM/yr is possible. We find that improved controls on pumping will achieve greater water savings. Thus PID will need to focus effort on significantly enhancing the level of groundwater management.
vi. Water balance for climate scenarios R.C.P 4.5 shows that there is gain in net groundwater storage by 0.94 MCM/yr and 6.30 MCM/yr in case study area of 1-R and 11-L respectively as compared to -0.88 MCM/yr in Business as Usual scenario.
vii. Comparing scenario 7 (climate change scenario R.C.P 8.5) with scenario 1 (Business as Usual) we find that if climate conditions remain as defined in R.C.P 8.5 data an estimation of 179 MCM/yr of water will be stored in underlying aquifers of LBDC. The RCP 8.5 scenario indicates that farmers are likely to face greater difficulties under a climate regime where flooding and damage to crops may be more frequent. Under this scenario, groundwater levels are likely to rise rapidly in response to higher rainfall in the upper aquifer (>30 m) in study area, and PID would need to manage waterlogging in some areas which had largely abated due to the increase in pumping in the Lower Bari Doab

PID has already recognized the importance of groundwater management and since 2008 has executed a monitoring program of water quality and water levels parameters from hundreds of tubewells and piezometers. This monitoring program should be rationalized, to make a significant change in management of groundwater and key bores (observation wells) need to be instrumented with data loggers which monitors the salinity and water levels. For future improvement of the groundwater model and management of LBDC command area, the targeted monitoring of key tubewells need to be executed. When there is inequity of surface water supplies, it results in less canal water for farmers located at tail end reaches. Thus it is critical to access the canal water supplies for farmers located at mid and tail end reaches in combination with advice to those farmers on use of groundwater for irrigation and for improved monitoring and governance of groundwater in study area.

10.4 Recommendations for sustainable groundwater Management

We encourage the PID to consider establishing a Water Resources Management cell with the specific mandate to improve management of surface and groundwater resources in the Punjab and particularly for the four major doabs (Sindh Sagar, Chah, Rechna and Bari). The Water Resources Management Cell would need to integrate the management and monitoring of water resources especially groundwater resources to support implementation of the National Water Policy 2018 and by setting allocation limits for groundwater management zones and improved management of pumping in vulnerable zones.

An important recommendation is that an investment in collecting, storing and making available monitoring data on water levels, salinity and other water quality parameters be implemented at the earliest possible time so that the work undertaken in this project is continued for improved sustainable management of groundwater resources. We understand that the PID is already monitoring water levels and salinity in the Lower Bari Doab in case studies area (1-R and 11-L). However, we are recommending the monitoring program be upgraded with water level and salinity loggers at strategic sites not only in Lower Bari Doab but also in the other doabs.

There are no records of groundwater pumping in Lower Bari Doab nor in the other doabs as groundwater usage is not being monitored. We recommend metering of tubewells at strategic locations within the doab to provide good spatial coverage of the doab as well as identify screen lengths so that it can be ascertained from which depth the groundwater is being pumped. We would recommend to PID to consider extending the flow model and developing a solute transport model for monitoring and better understanding of groundwater quality in Lower Bari Doab.

The monitoring program should be carried out alongside hydrogeological investigations and a groundwater mapping program to develop an in depth understanding of groundwater conditions and to provide accurate information for future groundwater studies.

Establishment of Groundwater Management Zones is needed in the Lower Bari Doab to ensure that groundwater extraction from the middle and tail of the Lower Bari Doab where groundwater levels are lowest is minimized. However, to reduce groundwater usage may not be an easy task and PID will need to offer farmers viable alternatives such as increase in surface water supply and/or crops that are water efficient and advice on improved irrigation practices.

Introducing water saving technologies amongst progressive farmers should be encouraged and for this PID needs dedicated staff with up-to-date knowledge of modern water savings technologies. The use of Managed Aquifer Recharge (MAR) at specific suitable sites in Lower Bari Doab would enhance recharge to the aquifer during the monsoon period.

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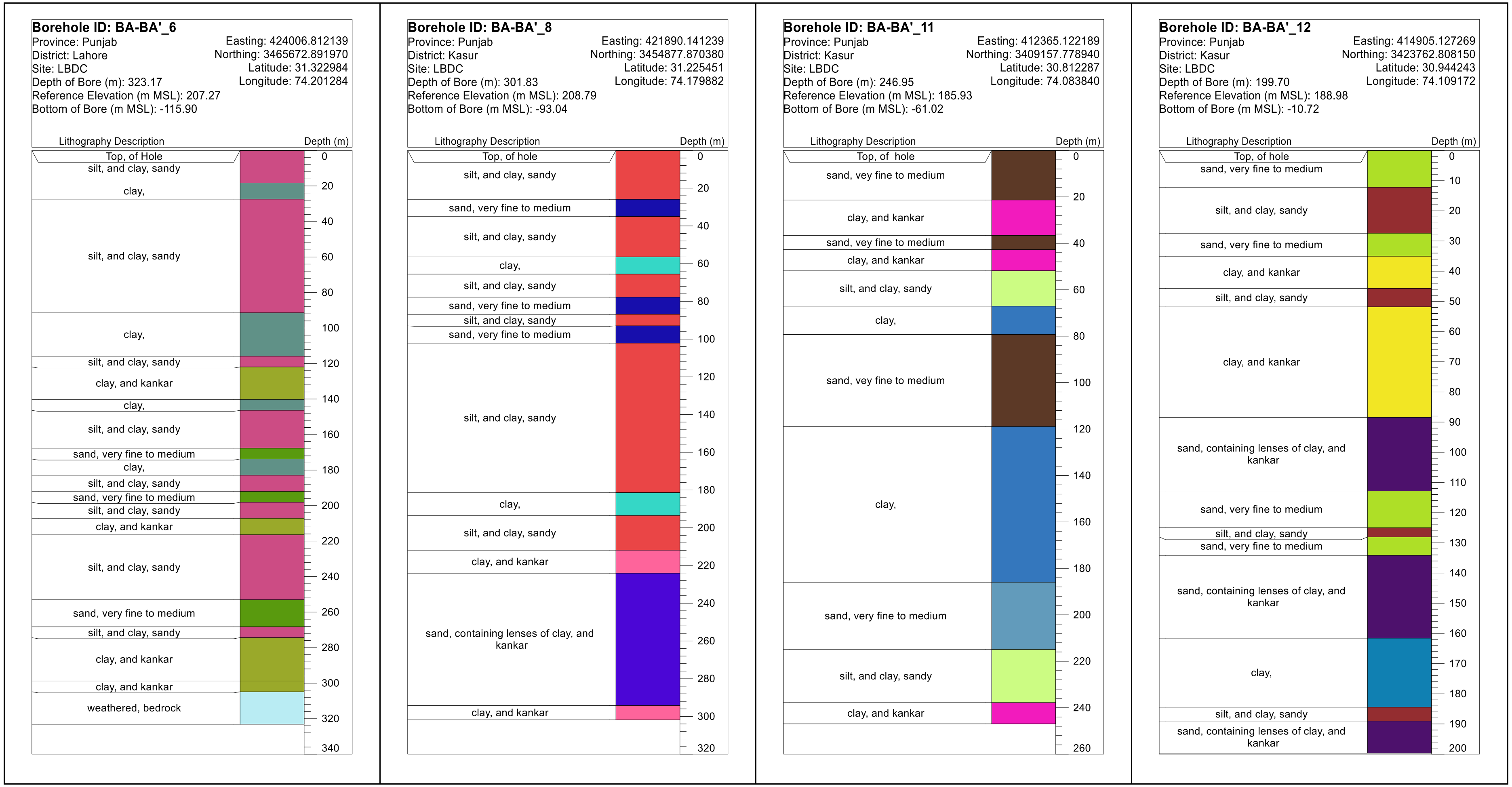
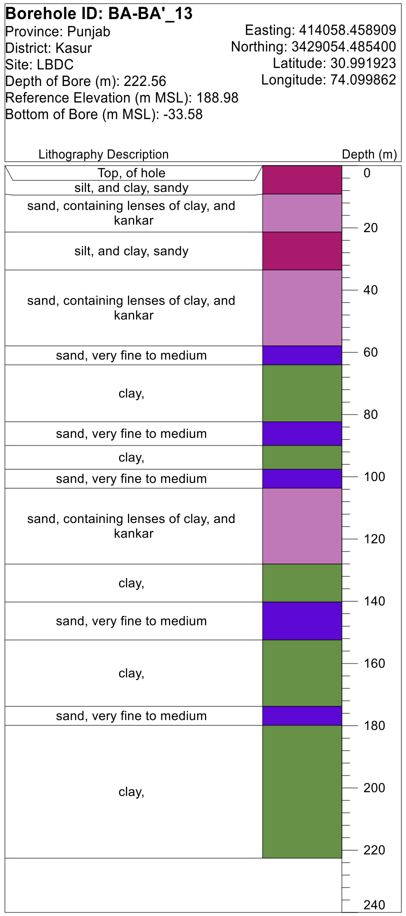
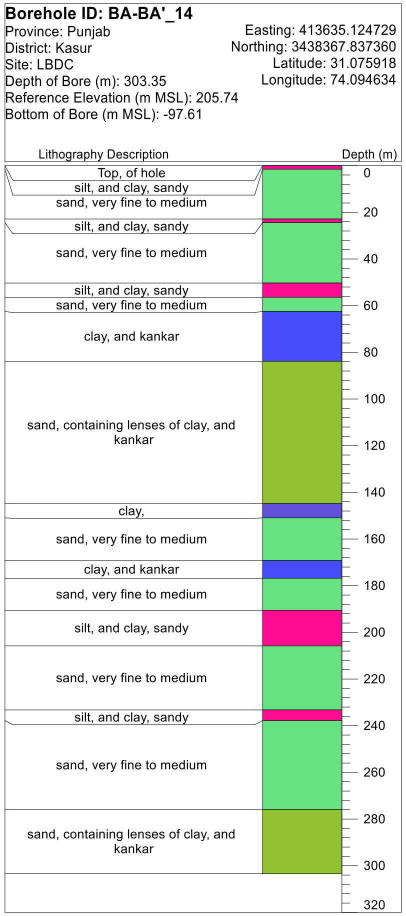
12 Appendix I – Bore Log Information

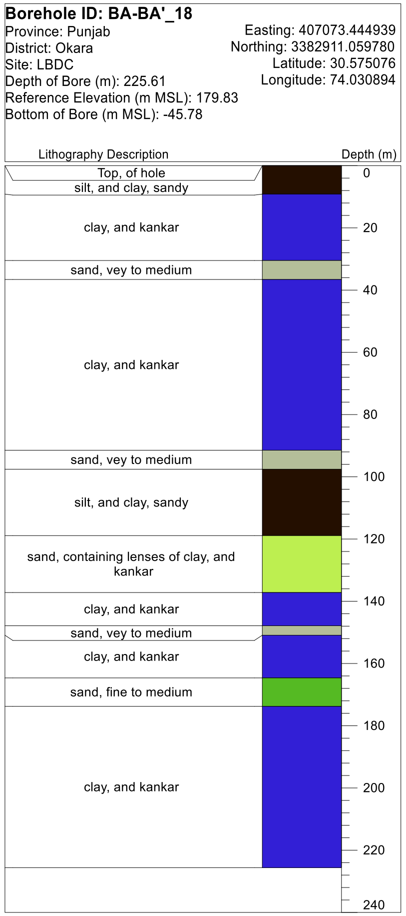
Well Hole ID	Depth (m)	Page	Well Hole ID	Depth (m)	Page	Well Hole ID	Depth (m)	Page
BA-BA'_6	323.17	3	BC-BC'_TW_11	60.98	9	BG-BG'_52	170.73	15
BA-BA'_8	301.83	3	BD-BD'_100	201.22	9	BG-BG'_57	182.93	15
BA-BA'_11	246.95	3	BD-BD'_106	189.02	9	BG-BG'_60	179.88	16
BA-BA'_12	199.70	3	BD-BD'_107	198.17	10	BG-BG'_75	185.98	16
BA-BA'_13	222.56	4	BD-BD'_108	198.17	10	BG-BG'_TW_13	73.17	16
BA-BA'_14	303.35	4	BD-BD'_113	198.17	10			
BA-BA'_18	225.61	4	BD-BD'_114	189.02	10			
BB-BB'_25	179.88	4	BD-BD'_116	192.07	11			
BB-BB'_26	182.93	5	BD-BD'_TW_17	128.02	11			
BB-BB'_28	179.88	5	BD-BD'_TW_20	76.22	11			
BB-BB'_33	185.98	5	BE-BE'_63	185.98	11			
BB-BB'_36	187.50	5	BE-BE'_73	170.73	12			
BB-BB'_42	179.88	6	BE-BE'_80	170.73	12			
BB-BB'_45	189.02	6	BE-BE'_84	131.07	12			
BB-BB'_53	189.02	6	BE-BE'_103	204.27	12			
BB-BB'_123	182.93	6	BE-BE'_105	198.17	13			

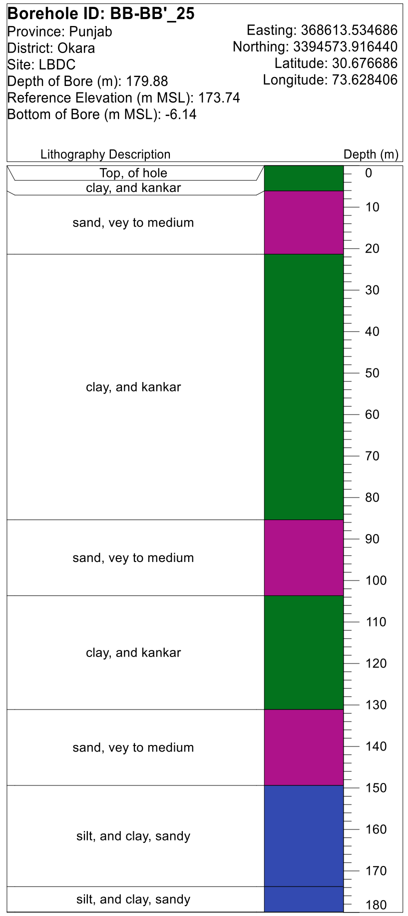
BB-BB'_125	182.93	7	BE-BE'_TW_14	207.32	13
BC-BC'_49	189.02	7	BF-BF'_7	265.24	13
BC-BC'_51	161.59	7	BF-BF'_15	265.24	13
BC-BC'_64	185.98	7	BF-BF'_16	259.15	14
BC-BC'_71	185.98	8	BF-BF'_22	253.05	14
BC-BC'_72	125.00	8	BF-BF'_34	192.07	14
BC-BC'_126	195.12	8	BF-BF'_TW_3	79.27	14
BC-BC'_127	155.49	8	BG-BG'_40	176.83	15
BC-BC'_TW_10	82.32	9	BG-BG'_48	182.93	15

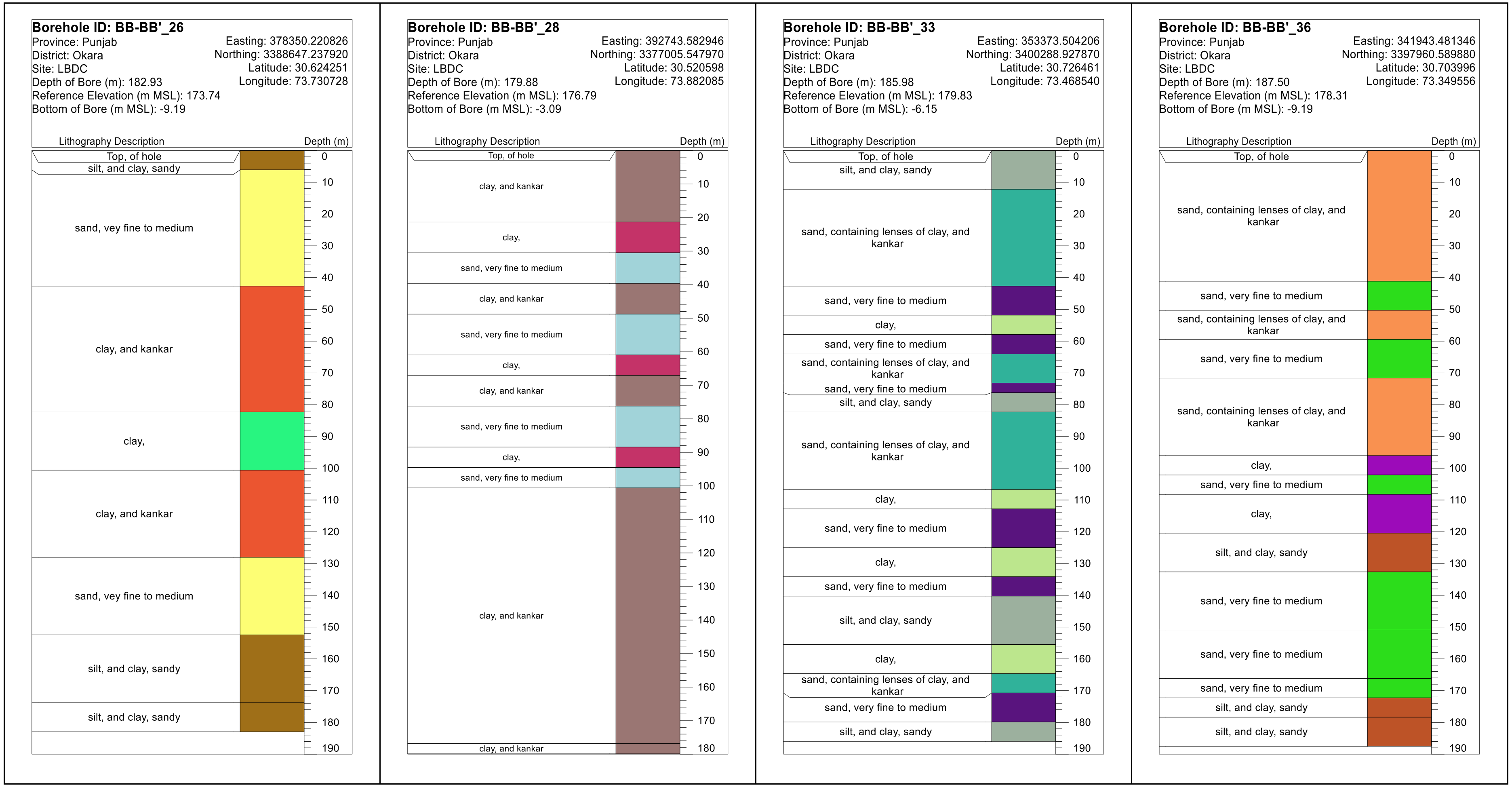

Borehole ID: BA-BA'_6
Province: Punjab
District: Lahore
Site: LBDC
Depth of Bore (m): 323.17
Reference Elevation (m MSL): 207.27
Bottom of Bore (m MSL): -115.90
Easting: 424006.812139
Northing: 3465672.891970
Latitude: 31.322984
Longitude: 74.201284
Lithography Description
Depth (m)
Top, of Hole
silt, and clay, sandy
clay,
silt, and clay, sandy
clay,
silt, and clay, sandy
clay, and kankar
clay,
silt, and clay, sandy
sand, very fine to medium
clay,
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
clay, and kankar
weathered, bedrock
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
Borehole ID: BA-BA'_8
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 301.83
Reference Elevation (m MSL): 208.79
Bottom of Bore (m MSL): -93.04
Easting: 421890.141239
Northing: 3454877.870380
Latitude: 31.225451
Longitude: 74.179882
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
clay,
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
clay,
silt, and clay, sandy
clay, and kankar
sand, containing lenses of clay, and kankar
clay, and kankar
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
Borehole ID: BA-BA'_11
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 246.95
Reference Elevation (m MSL): 185.93
Bottom of Bore (m MSL): -61.02
Easting: 412365.122189
Northing: 3409157.778940
Latitude: 30.812287
Longitude: 74.083840
Lithography Description
Depth (m)
Top, of hole
sand, vey fine to medium
clay, and kankar
sand, vey fine to medium
clay, and kankar
silt, and clay, sandy
clay,
sand, vey fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Borehole ID: BA-BA'_12
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 199.70
Reference Elevation (m MSL): 188.98
Bottom of Bore (m MSL): -10.72
Easting: 414905.127269
Northing: 3423762.808150
Latitude: 30.944243
Longitude: 74.109172
Lithography Description
Depth (m)
Top, of hole
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
clay, and kankar
sand, containing lenses of clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
sand, containing lenses of clay, and kankar
clay,
silt, and clay, sandy
sand, containing lenses of clay, and kankar
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

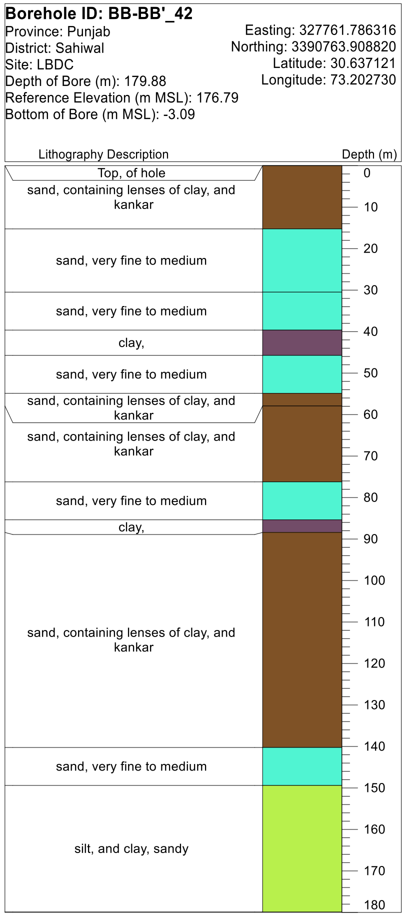

Borehole ID: BA-BA'_13
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 222.56
Reference Elevation (m MSL): 188.98
Bottom of Bore (m MSL): -33.58
Easting: 414058.458909
Northing: 3429054.485400
Latitude: 30.991923
Longitude: 74.099862
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, containing lenses of clay, and kankar
silt, and clay, sandy
sand, containing lenses of clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
sand, containing lenses of clay, and kankar
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay,
0
20
40
60
80
100
120
140
160
180
200
220
240

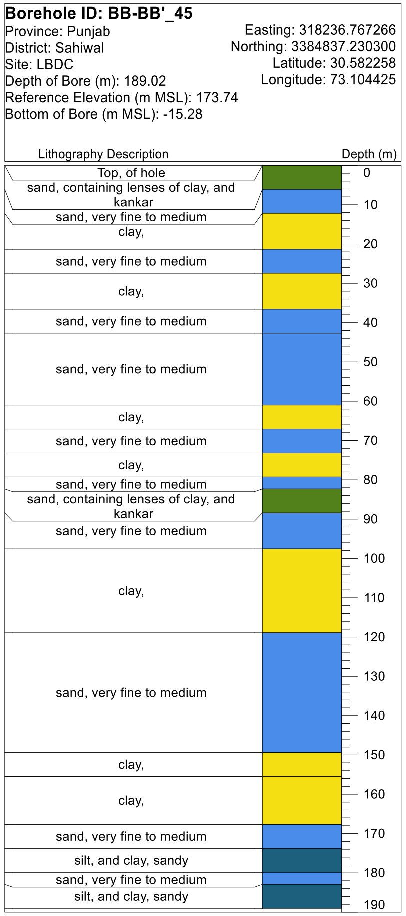

Borehole ID: BA-BA'_14
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 303.35
Reference Elevation (m MSL): 205.74
Bottom of Bore (m MSL): -97.61
Easting: 413635.124729
Northing: 3438367.837360
Latitude: 31.075918
Longitude: 74.094634
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, containing lenses of clay, and kankar
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
sand, containing lenses of clay, and kankar
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320

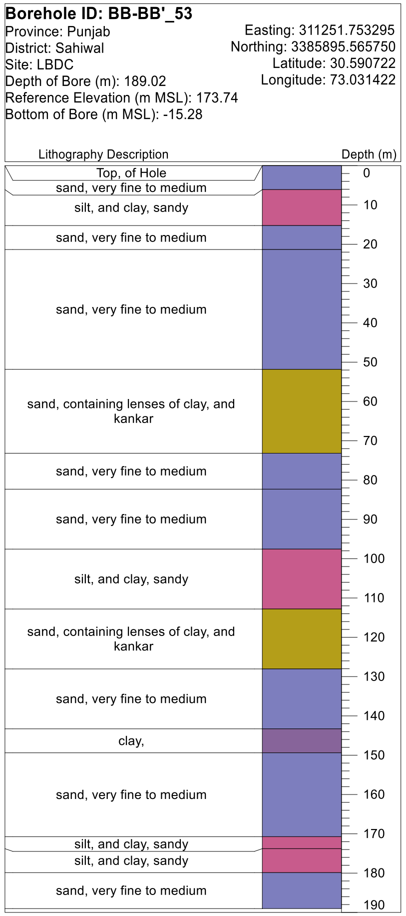

Borehole ID: BA-BA'_18
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 225.61
Reference Elevation (m MSL): 179.83
Bottom of Bore (m MSL): -45.78
Easting: 407073.444939
Northing: 3382911.059780
Latitude: 30.575076
Longitude: 74.030894
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
clay, and kankar
sand, vey to medium
clay, and kankar
sand, vey to medium
silt, and clay, sandy
sand, containing lenses of clay, and kankar
clay, and kankar
sand, vey to medium
clay, and kankar
sand, fine to medium
clay, and kankar
0
20
40
60
80
100
120
140
160
180
200
220
240


Borehole ID: BB-BB'_25
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 179.88
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -6.14
Easting: 368613.534686
Northing: 3394573.916440
Latitude: 30.676686
Longitude: 73.628406
Lithography Description
Depth (m)
Top, of hole
clay, and kankar
sand, vey to medium
clay, and kankar
sand, vey to medium
clay, and kankar
sand, vey to medium
silt, and clay, sandy
silt, and clay, sandy
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180


Borehole ID: BB-BB'_26
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 182.93
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -9.19
Easting: 378350.220826
Northing: 3388647.237920
Latitude: 30.624251
Longitude: 73.730728
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, vey fine to medium
clay, and kankar
clay,
clay, and kankar
sand, vey fine to medium
silt, and clay, sandy
silt, and clay, sandy
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
Borehole ID: BB-BB'_28
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 179.88
Reference Elevation (m MSL): 176.79
Bottom of Bore (m MSL): -3.09
Easting: 392743.582946
Northing: 3377005.547970
Latitude: 30.520598
Longitude: 73.882085
Lithography Description
Depth (m)
Top, of hole
clay, and kankar
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
clay, and kankar
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Borehole ID: BB-BB'_33
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 185.98
Reference Elevation (m MSL): 179.83
Bottom of Bore (m MSL): -6.15
Easting: 353373.504206
Northing: 3400288.927870
Latitude: 30.726461
Longitude: 73.468540
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, containing lenses of clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
sand, containing lenses of clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, containing lenses of clay, and kankar
clay,
sand, very fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
clay,
sand, containing lenses of clay, and kankar
sand, very fine to medium
silt, and clay, sandy
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
Borehole ID: BB-BB'_36
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 187.50
Reference Elevation (m MSL): 178.31
Bottom of Bore (m MSL): -9.19
Easting: 341943.481346
Northing: 3397960.589880
Latitude: 30.703996
Longitude: 73.349556
Lithography Description
Depth (m)
Top, of hole
sand, containing lenses of clay, and kankar
sand, very fine to medium
sand, containing lenses of clay, and kankar
sand, very fine to medium
sand, containing lenses of clay, and kankar
clay,
sand, very fine to medium
clay,
silt, and clay, sandy
sand, very fine to medium
sand, very fine to medium
sand, very fine to medium
silt, and clay, sandy
silt, and clay, sandy
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190


Borehole ID: BB-BB'_42
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 179.88
Reference Elevation (m MSL): 176.79
Bottom of Bore (m MSL): -3.09
Easting: 327761.786316
Northing: 3390763.908820
Latitude: 30.637121
Longitude: 73.202730
Lithography Description
Depth (m)
Top, of hole
sand, containing lenses of clay, and kankar
sand, very fine to medium
sand, very fine to medium
clay,
sand, very fine to medium
sand, containing lenses of clay, and kankar
sand, containing lenses of clay, and kankar
sand, very fine to medium
clay,
sand, containing lenses of clay, and kankar
sand, very fine to medium
silt, and clay, sandy
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180


Borehole ID: BB-BB'_45
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 189.02
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -15.28
Easting: 318236.767266
Northing: 3384837.230300
Latitude: 30.582258
Longitude: 73.104425
Lithography Description
Depth (m)
Top, of hole
sand, containing lenses of clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
sand, containing lenses of clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
clay,
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190


Borehole ID: BB-BB'_53
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 189.02
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -15.28
Easting: 311251.753295
Northing: 3385895.565750
Latitude: 30.590722
Longitude: 73.031422
Lithography Description
Depth (m)
Top, of Hole
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
sand, very fine to medium
sand, containing lenses of clay, and kankar
sand, very fine to medium
sand, very fine to medium
silt, and clay, sandy
sand, containing lenses of clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
silt, and clay, sandy
sand, very fine to medium
0
10
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70
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90
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120
130
140
150
160
170
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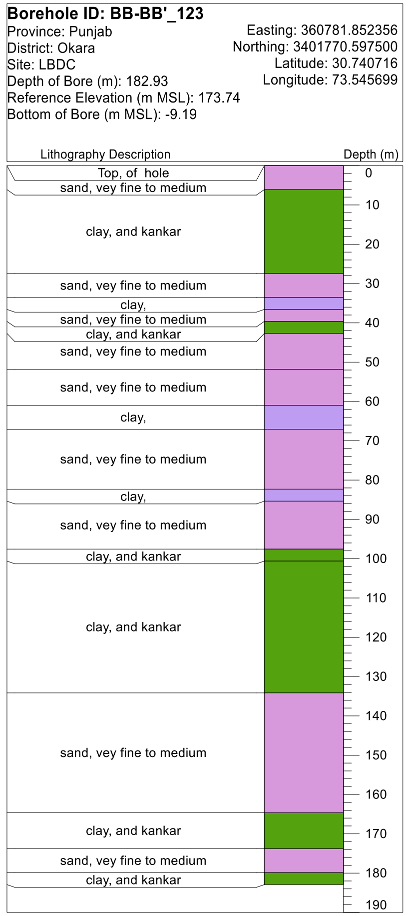
190


Borehole ID: BB-BB'_123
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 182.93
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -9.19
Easting: 360781.852356
Northing: 3401770.597500
Latitude: 30.740716
Longitude: 73.545699
Lithography Description
Depth (m)
Top, of hole
sand, vey fine to medium
clay, and kankar
sand, vey fine to medium
clay,
sand, vey fine to medium
clay, and kankar
sand, vey fine to medium
sand, vey fine to medium
clay,
sand, vey fine to medium
clay,
sand, vey fine to medium
clay, and kankar
clay, and kankar
sand, vey fine to medium
clay, and kankar
sand, vey fine to medium
clay, and kankar
0
10
20
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50
60
70
80
90
100
110
120
130
140
150
160
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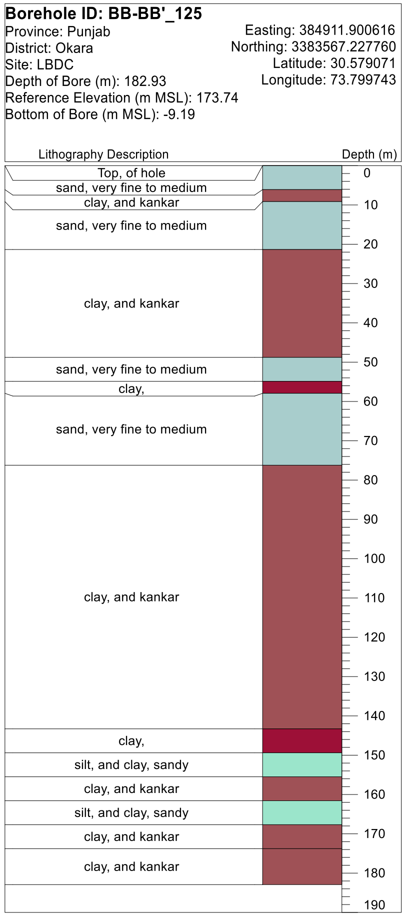
Borehole ID: BB-BB'_125
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 182.93
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -9.19
Easting: 384911.900616
Northing: 3383567.227760
Latitude: 30.579071
Longitude: 73.799743
Lithography Description
Depth (m)
Top, of hole
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
clay,
silt, and clay, sandy
clay, and kankar
silt, and clay, sandy
clay, and kankar
clay, and kankar
0
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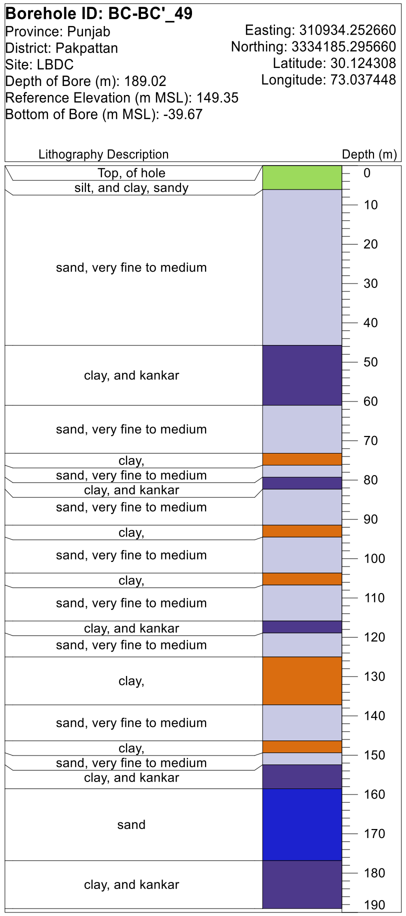
Borehole ID: BC-BC'_49
Province: Punjab
District: Pakpattan
Site: LBDC
Depth of Bore (m): 189.02
Reference Elevation (m MSL): 149.35
Bottom of Bore (m MSL): -39.67
Easting: 310934.252660
Northing: 3334185.295660
Latitude: 30.124308
Longitude: 73.037448
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand
clay, and kankar
0
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120
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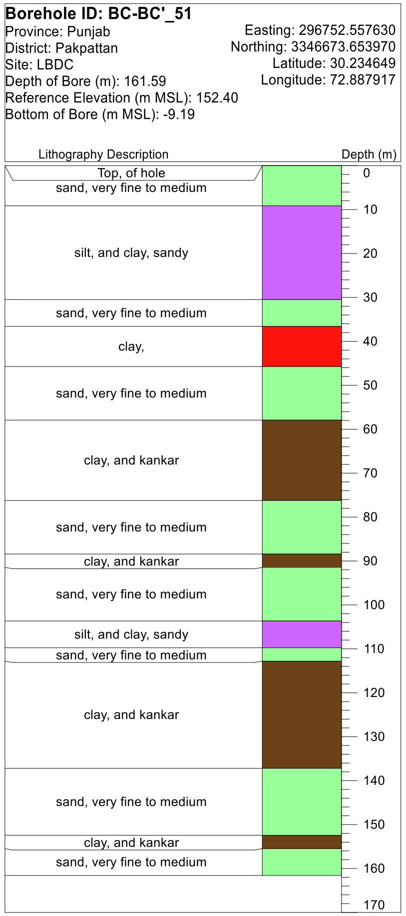
Borehole ID: BC-BC'_51
Province: Punjab
District: Pakpattan
Site: LBDC
Depth of Bore (m): 161.59
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): -9.19
Easting: 296752.557630
Northing: 3346673.653970
Latitude: 30.234649
Longitude: 72.887917
Lithography Description
Depth (m)
Top, of hole
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
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120
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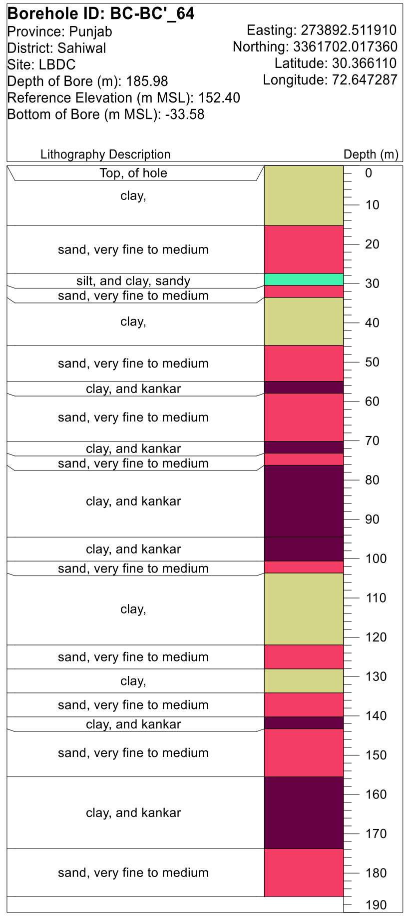
140
150
160
170


Borehole ID: BC-BC'_64
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 185.98
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): -33.58
Easting: 273892.511910
Northing: 3361702.017360
Latitude: 30.366110
Longitude: 72.647287
Lithography Description
Depth (m)
Top, of hole
clay,
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
0
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130
140
150
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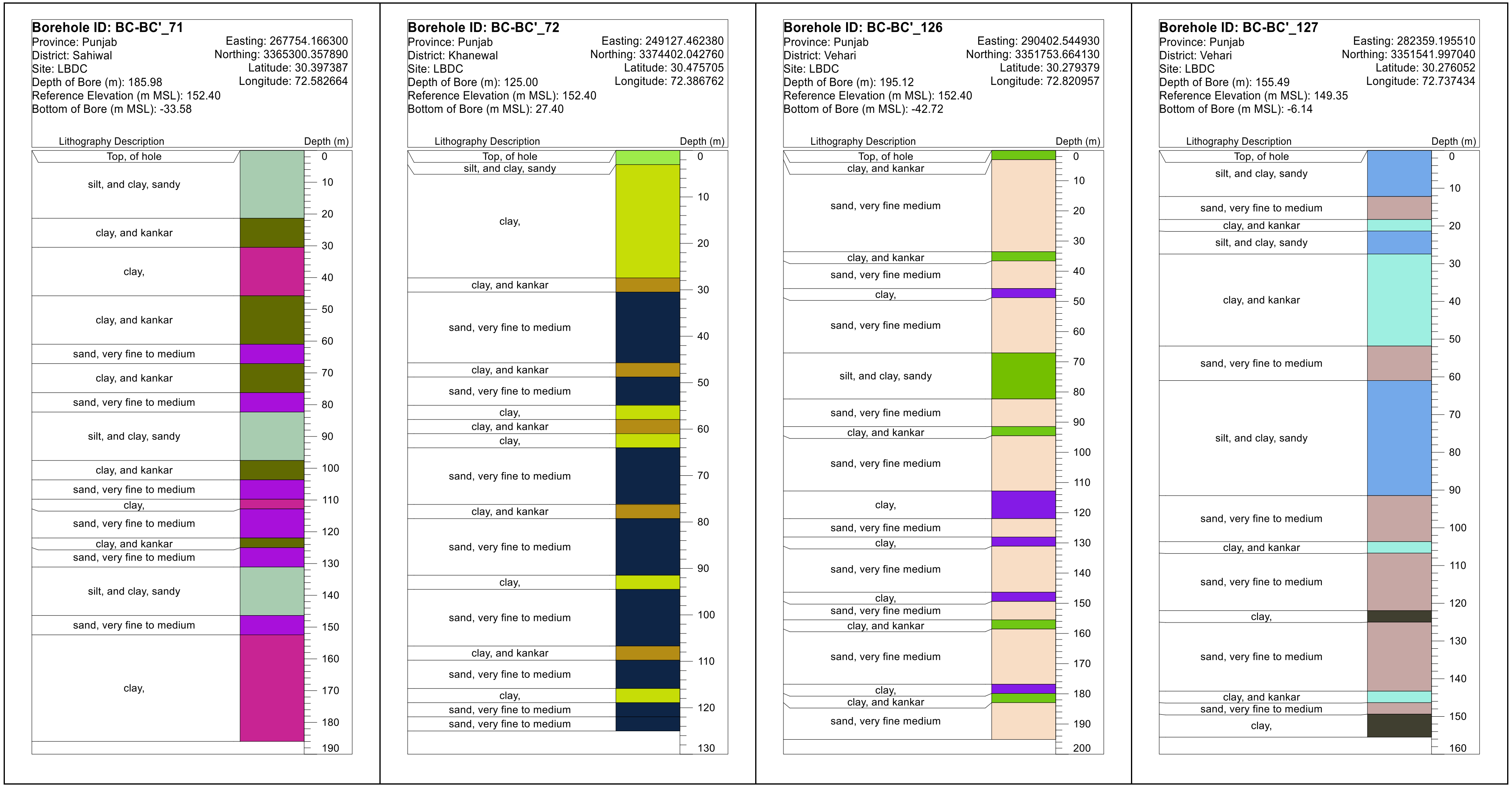
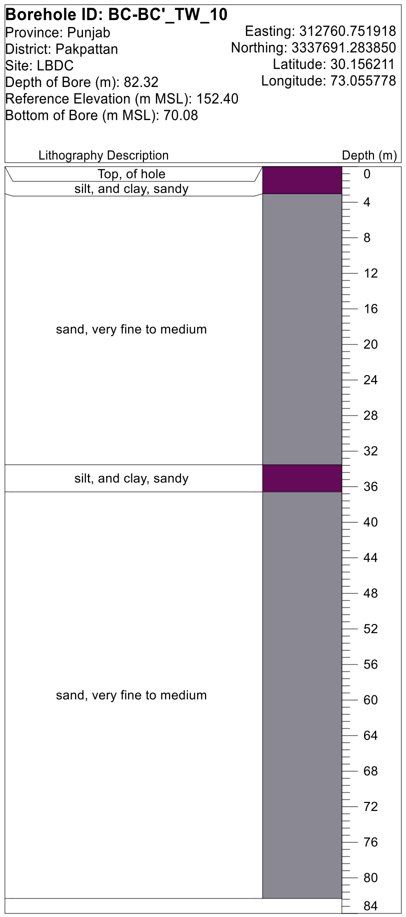
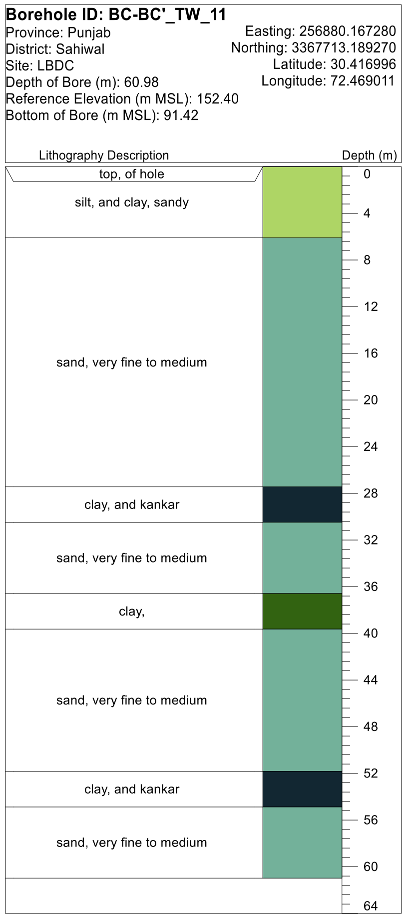
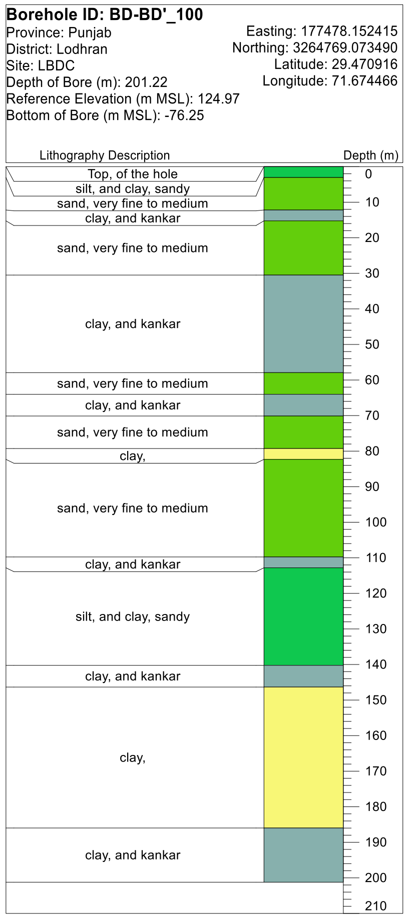
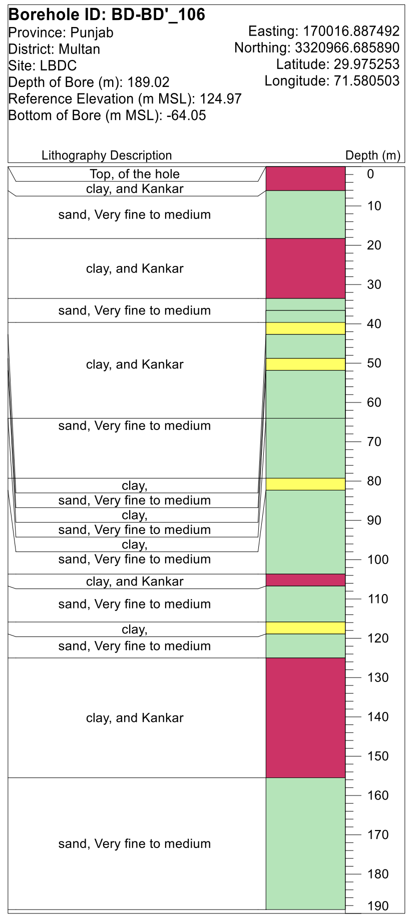
170
180
190

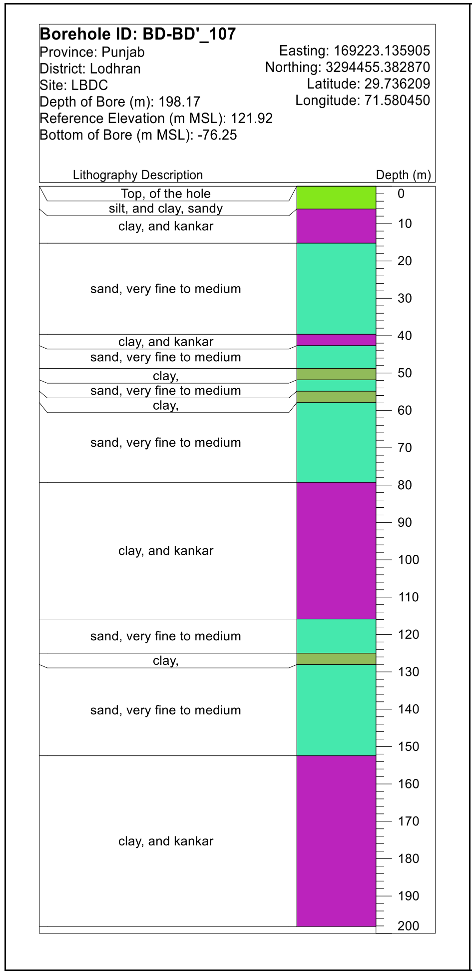

Borehole ID: BC-BC'_71
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 185.98
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): -33.58
Easting: 267754.166300
Northing: 3365300.357890
Latitude: 30.397387
Longitude: 72.582664
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
clay, and kankar
clay,
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
Borehole ID: BC-BC'_72
Province: Punjab
District: Khanewal
Site: LBDC
Depth of Bore (m): 125.00
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): 27.40
Easting: 249127.462380
Northing: 3374402.042760
Latitude: 30.475705
Longitude: 72.386762
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
clay,
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
clay, and kankar
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
sand, very fine to medium
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Borehole ID: BC-BC'_126
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 195.12
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): -42.72
Easting: 290402.544930
Northing: 3351753.664130
Latitude: 30.279379
Longitude: 72.820957
Lithography Description
Depth (m)
Top, of hole
clay, and kankar
sand, very fine medium
clay, and kankar
sand, very fine medium
clay,
sand, very fine medium
silt, and clay, sandy
sand, very fine medium
clay, and kankar
sand, very fine medium
clay,
sand, very fine medium
clay,
sand, very fine medium
clay,
sand, very fine medium
clay, and kankar
sand, very fine medium
clay,
clay, and kankar
sand, very fine medium
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Borehole ID: BC-BC'_127
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 155.49
Reference Elevation (m MSL): 149.35
Bottom of Bore (m MSL): -6.14
Easting: 282359.195510
Northing: 3351541.997040
Latitude: 30.276052
Longitude: 72.737434
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160

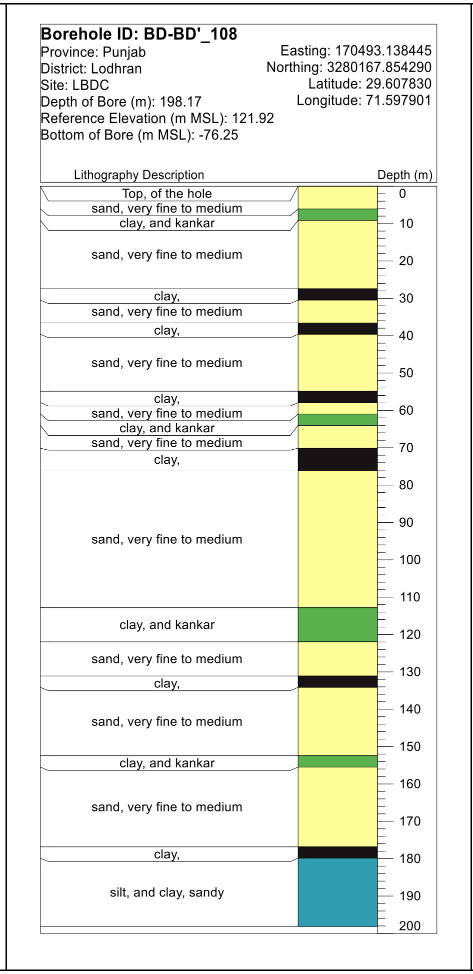

Borehole ID: BC-BC'_TW_10
Province: Punjab
District: Pakpattan
Site: LBDC
Depth of Bore (m): 82.32
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): 70.08
Easting: 312760.751918
Northing: 3337691.283850
Latitude: 30.156211
Longitude: 73.055778
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84

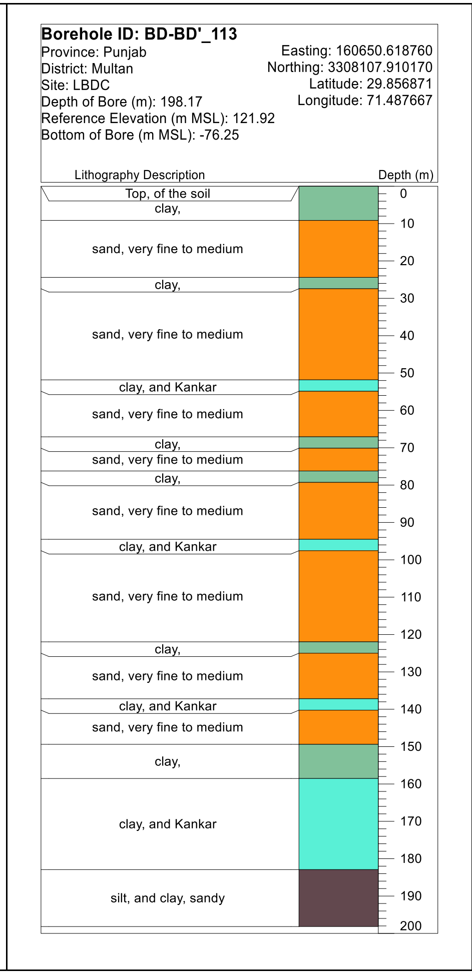

Borehole ID: BC-BC'_TW_11
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 60.98
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): 91.42
Easting: 256880.167280
Northing: 3367713.189270
Latitude: 30.416996
Longitude: 72.469011
Lithography Description
Depth (m)
top, of hole
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64


Borehole ID: BD-BD'_100
Province: Punjab
District: Lodhran
Site: LBDC
Depth of Bore (m): 201.22
Reference Elevation (m MSL): 124.97
Bottom of Bore (m MSL): -76.25
Easting: 177478.152415
Northing: 3264769.073490
Latitude: 29.470916
Longitude: 71.674466
Lithography Description
Depth (m)
Top, of the hole
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
clay, and kankar
clay,
clay, and kankar
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210


Borehole ID: BD-BD'_106
Province: Punjab
District: Multan
Site: LBDC
Depth of Bore (m): 189.02
Reference Elevation (m MSL): 124.97
Bottom of Bore (m MSL): -64.05
Easting: 170016.887492
Northing: 3320966.685890
Latitude: 29.975253
Longitude: 71.580503
Lithography Description
Depth (m)
Top, of the hole
clay, and Kankar
sand, Very fine to medium
clay, and Kankar
sand, Very fine to medium
clay, and Kankar
sand, Very fine to medium
clay,
sand, Very fine to medium
clay,
sand, Very fine to medium
clay,
sand, Very fine to medium
clay, and Kankar
sand, Very fine to medium
clay,
sand, Very fine to medium
clay, and Kankar
sand, Very fine to medium
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190


Borehole ID: BD-BD'_107
Province: Punjab
District: Lodhran
Site: LBDC
Depth of Bore (m): 198.17
Reference Elevation (m MSL): 121.92
Bottom of Bore (m MSL): -76.25
Easting: 169223.135905
Northing: 3294455.382870
Latitude: 29.736209
Longitude: 71.580450
Lithography Description
Depth (m)
Top, of the hole
silt, and clay, sandy
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200


Borehole ID: BD-BD'_108
Province: Punjab
District: Lodhran
Site: LBDC
Depth of Bore (m): 198.17
Reference Elevation (m MSL): 121.92
Bottom of Bore (m MSL): -76.25
Easting: 170493.138445
Northing: 3280167.854290
Latitude: 29.607830
Longitude: 71.597901
Lithography Description
Depth (m)
Top, of the hole
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
silt, and clay, sandy
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200


Borehole ID: BD-BD'_113
Province: Punjab
District: Multan
Site: LBDC
Depth of Bore (m): 198.17
Reference Elevation (m MSL): 121.92
Bottom of Bore (m MSL): -76.25
Easting: 160650.618760
Northing: 3308107.910170
Latitude: 29.856871
Longitude: 71.487667
Lithography Description
Depth (m)
Top, of the soil
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
clay,
clay, and Kankar
silt, and clay, sandy
0
10
20
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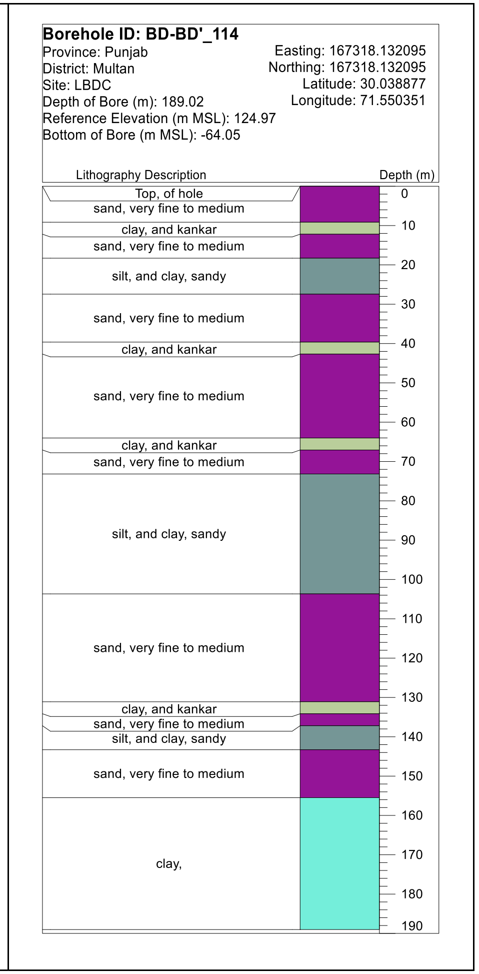
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200


Borehole ID: BD-BD'_114
Province: Punjab
District: Multan
Site: LBDC
Depth of Bore (m): 189.02
Reference Elevation (m MSL): 124.97
Bottom of Bore (m MSL): -64.05
Easting: 167318.132095
Northing: 167318.132095
Latitude: 30.038877
Longitude: 71.550351
Lithography Description
Depth (m)
Top, of hole
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
0
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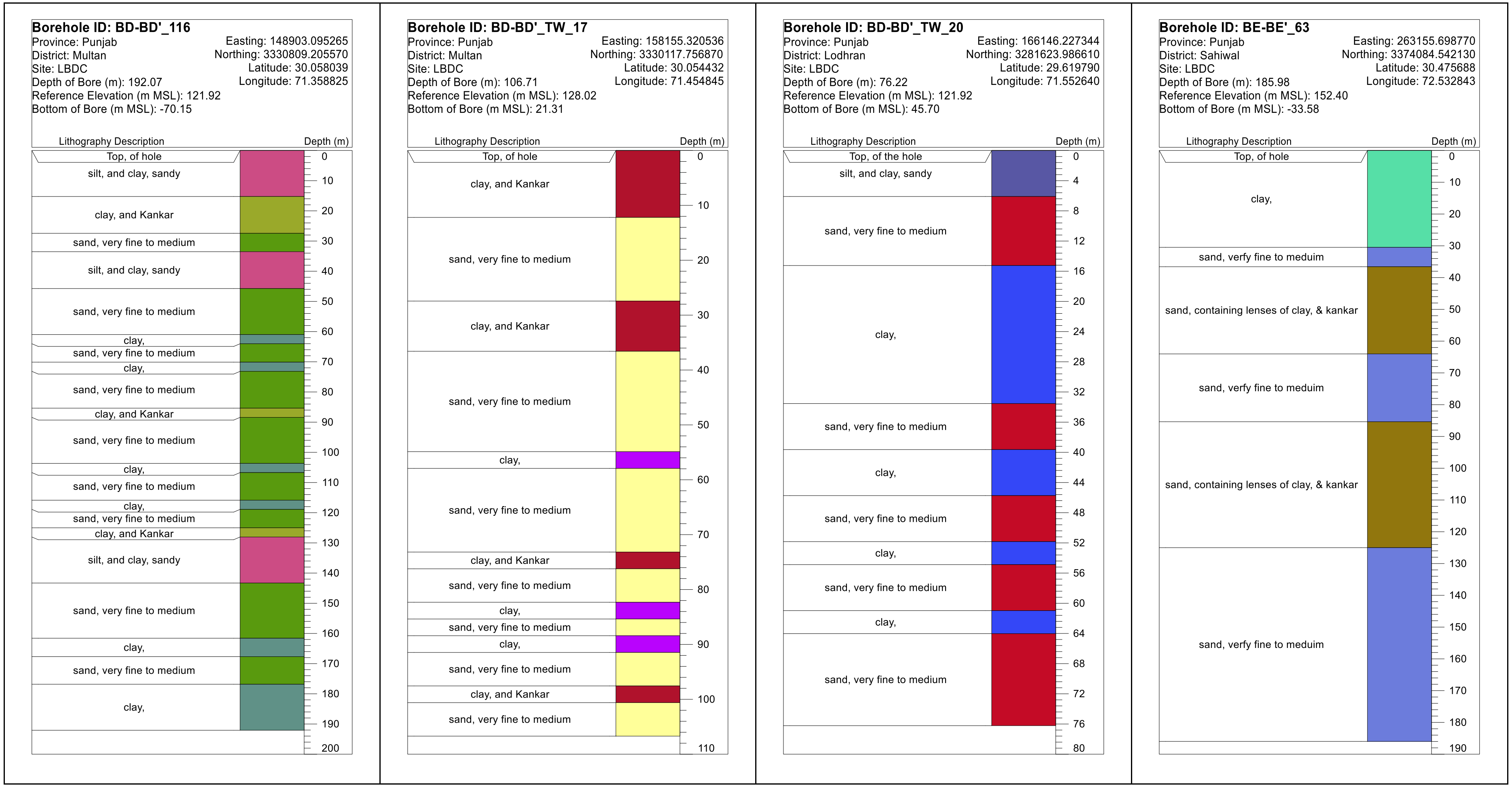
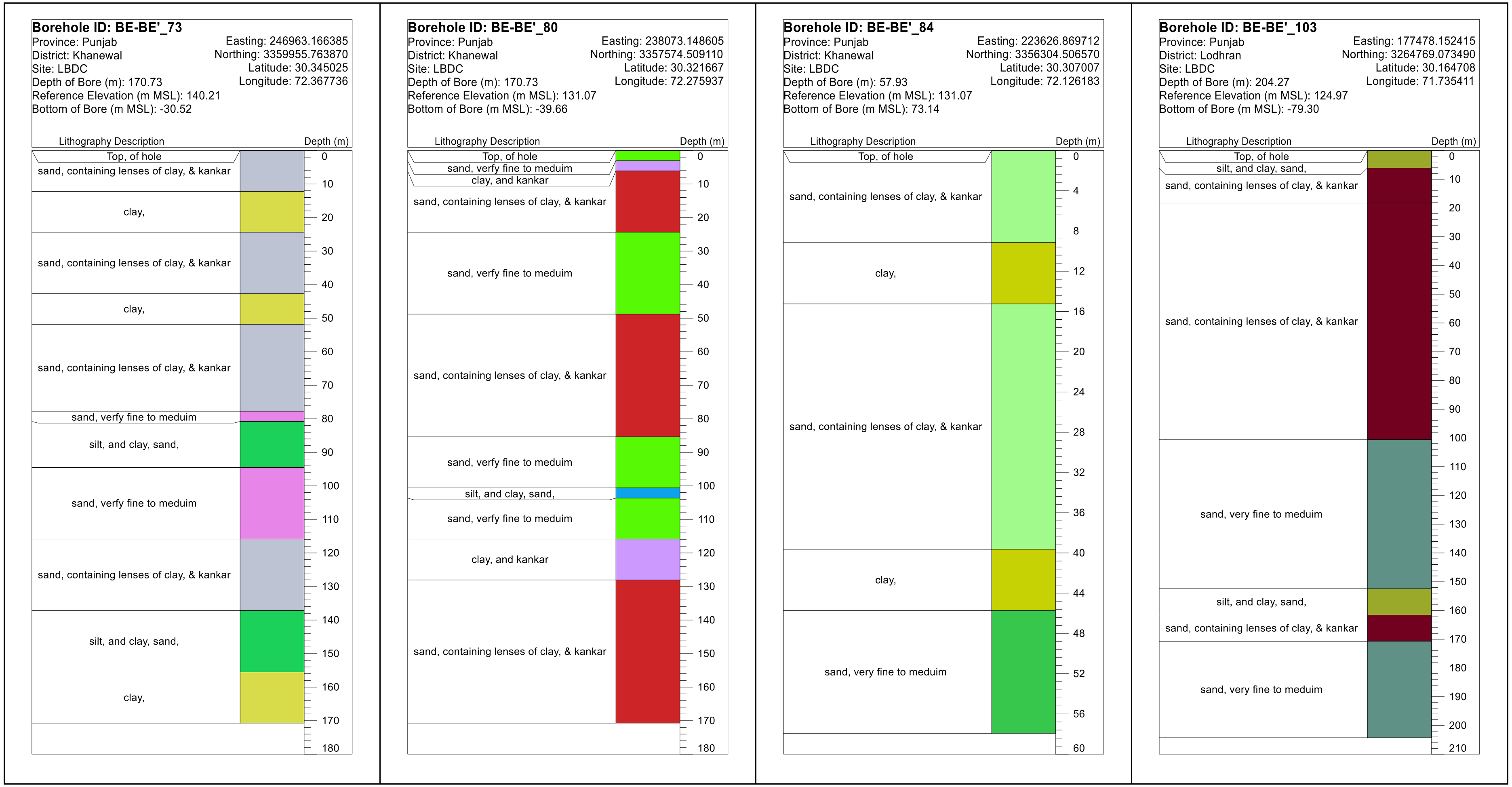

Borehole ID: BD-BD'_116
Province: Punjab
District: Multan
Site: LBDC
Depth of Bore (m): 192.07
Reference Elevation (m MSL): 121.92
Bottom of Bore (m MSL): -70.15
Easting: 148903.095265
Northing: 3330809.205570
Latitude: 30.058039
Longitude: 71.358825
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
clay, and Kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay,
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Borehole ID: BD-BD'_TW_17
Province: Punjab
District: Multan
Site: LBDC
Depth of Bore (m): 106.71
Reference Elevation (m MSL): 128.02
Bottom of Bore (m MSL): 21.31
Easting: 158155.320536
Northing: 3330117.756870
Latitude: 30.054432
Longitude: 71.454845
Lithography Description
Depth (m)
Top, of hole
clay, and Kankar
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and Kankar
sand, very fine to medium
0 10 20 30 40 50 60 70 80 90 100 110
Borehole ID: BD-BD'_TW_20
Province: Punjab
District: Lodhran
Site: LBDC
Depth of Bore (m): 76.22
Reference Elevation (m MSL): 121.92
Bottom of Bore (m MSL): 45.70
Easting: 166146.227344
Northing: 3281623.986610
Latitude: 29.619790
Longitude: 71.552640
Lithography Description
Depth (m)
Top, of the hole
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
Borehole ID: BE-BE'_63
Province: Punjab
District: Sahiwal
Site: LBDC
Depth of Bore (m): 185.98
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): -33.58
Easting: 263155.698770
Northing: 3374084.542130
Latitude: 30.475688
Longitude: 72.532843
Lithography Description
Depth (m)
Top, of hole
clay,
sand, verfy fine to meduim
sand, containing lenses of clay, & kankar
sand, verfy fine to meduim
sand, containing lenses of clay, & kankar
sand, verfy fine to meduim
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190


Borehole ID: BE-BE'_73
Province: Punjab
District: Khanewal
Site: LBDC
Depth of Bore (m): 170.73
Reference Elevation (m MSL): 140.21
Bottom of Bore (m MSL): -30.52
Easting: 246963.166385
Northing: 3359955.763870
Latitude: 30.345025
Longitude: 72.367736
Lithography Description
Depth (m)
Top, of hole
sand, containing lenses of clay, & kankar
clay,
sand, containing lenses of clay, & kankar
clay,
sand, containing lenses of clay, & kankar
sand, verfy fine to meduim
silt, and clay, sand,
sand, verfy fine to meduim
sand, containing lenses of clay, & kankar
silt, and clay, sand,
clay,
0
10
20
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40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Borehole ID: BE-BE'_80
Province: Punjab
District: Khanewal
Site: LBDC
Depth of Bore (m): 170.73
Reference Elevation (m MSL): 131.07
Bottom of Bore (m MSL): -39.66
Easting: 238073.148605
Northing: 3357574.509110
Latitude: 30.321667
Longitude: 72.275937
Lithography Description
Depth (m)
Top, of hole
sand, verfy fine to meduim
clay, and kankar
sand, containing lenses of clay, & kankar
sand, verfy fine to meduim
sand, containing lenses of clay, & kankar
sand, verfy fine to meduim
silt, and clay, sand,
sand, verfy fine to meduim
clay, and kankar
sand, containing lenses of clay, & kankar
0
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20
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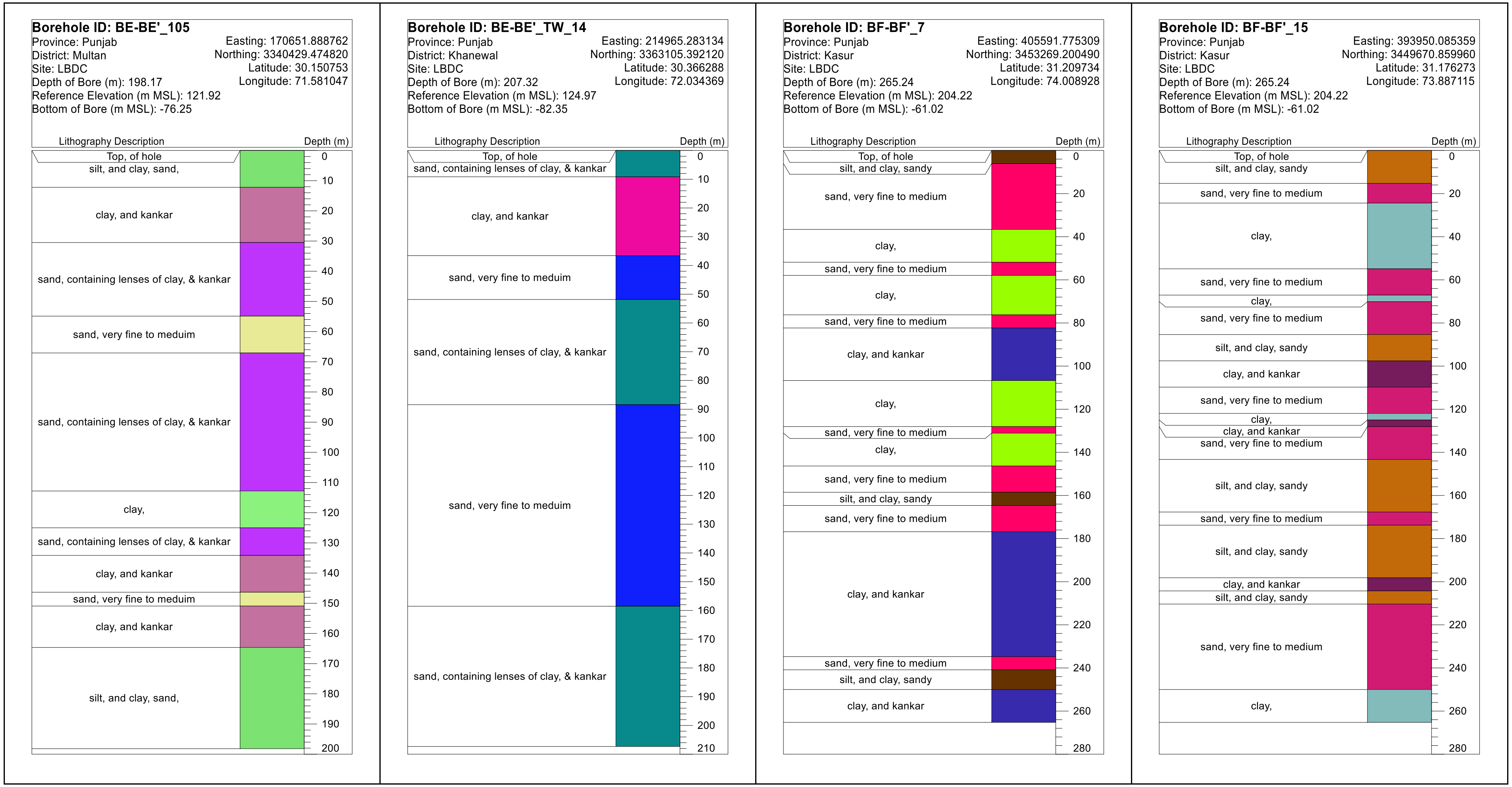
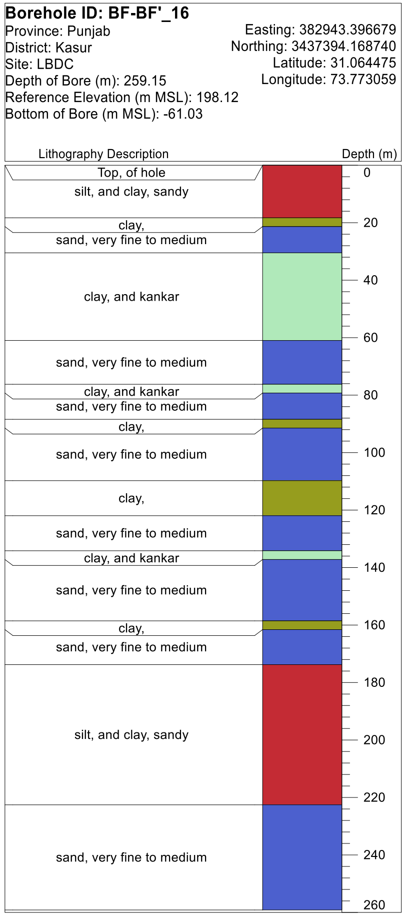
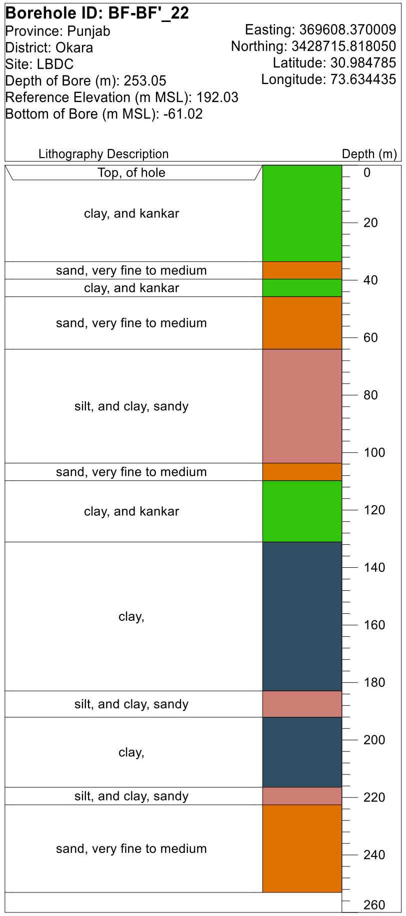
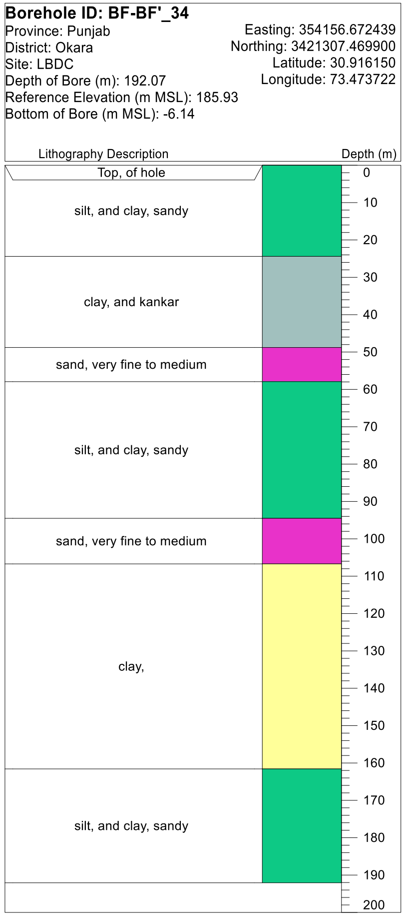
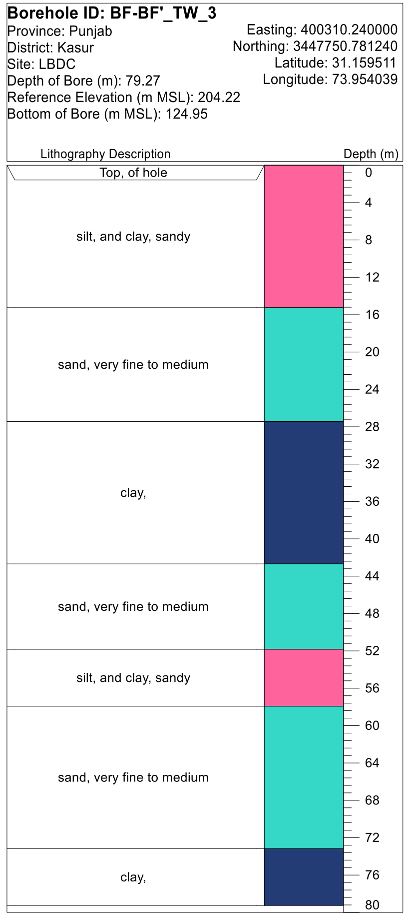
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Borehole ID: BE-BE'_84
Province: Punjab
District: Khanewal
Site: LBDC
Depth of Bore (m): 57.93
Reference Elevation (m MSL): 131.07
Bottom of Bore (m MSL): 73.14
Easting: 223626.869712
Northing: 3356304.506570
Latitude: 30.307007
Longitude: 72.126183
Lithography Description
Depth (m)
Top, of hole
sand, containing lenses of clay, & kankar
clay,
sand, containing lenses of clay, & kankar
clay,
sand, very fine to meduim
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
Borehole ID: BE-BE'_103
Province: Punjab
District: Lodhran
Site: LBDC
Depth of Bore (m): 204.27
Reference Elevation (m MSL): 124.97
Bottom of Bore (m MSL): -79.30
Easting: 177478.152415
Northing: 3264769.073490
Latitude: 30.164708
Longitude: 71.735411
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sand,
sand, containing lenses of clay, & kankar
sand, containing lenses of clay, & kankar
sand, very fine to meduim
silt, and clay, sand,
sand, containing lenses of clay, & kankar
sand, very fine to meduim
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210

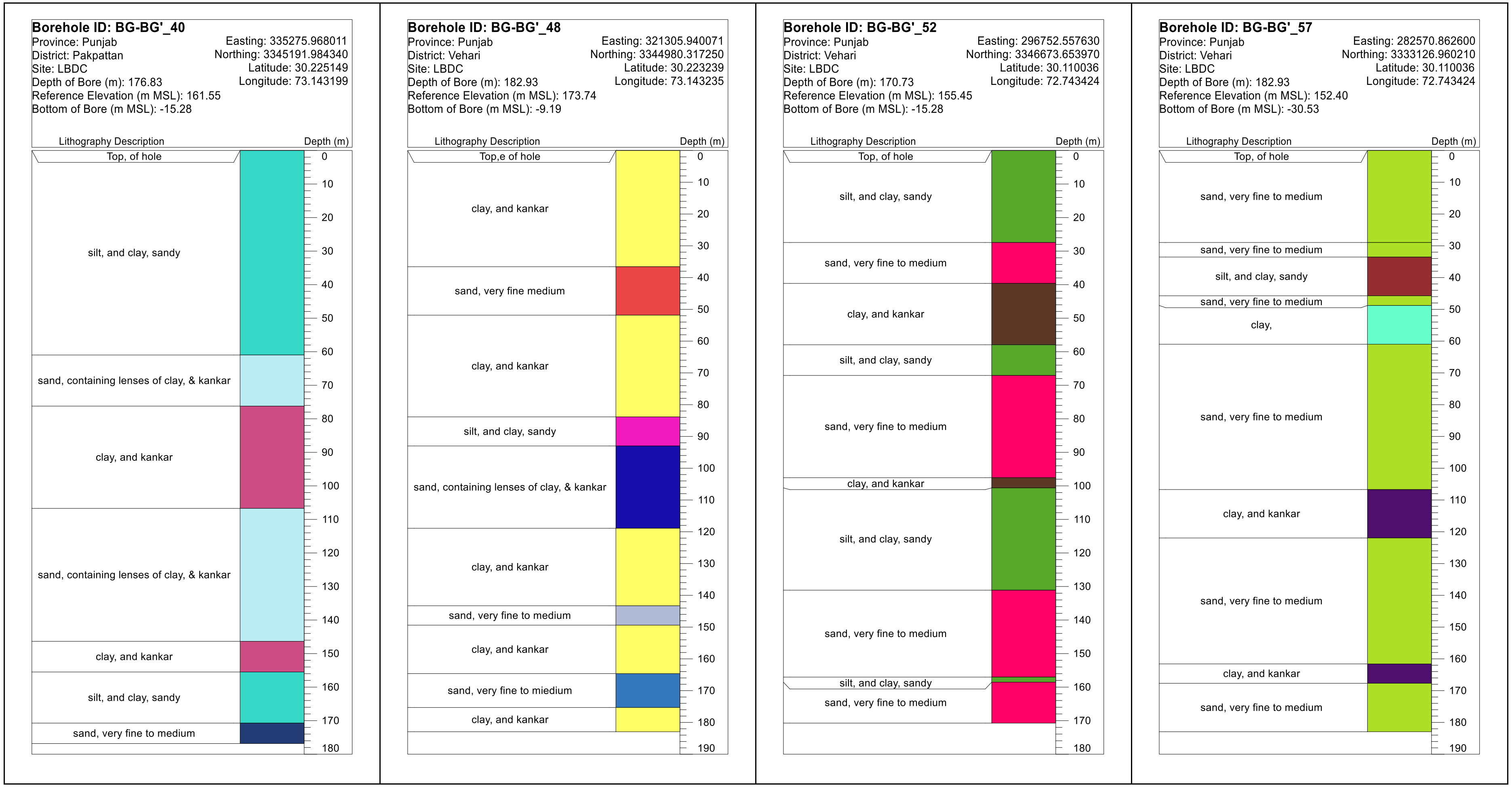

Borehole ID: BE-BE'_105
Province: Punjab
District: Multan
Site: LBDC
Depth of Bore (m): 198.17
Reference Elevation (m MSL): 121.92
Bottom of Bore (m MSL): -76.25
Easting: 170651.888762
Northing: 3340429.474820
Latitude: 30.150753
Longitude: 71.581047
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sand,
clay, and kankar
sand, containing lenses of clay, & kankar
sand, very fine to meduim
sand, containing lenses of clay, & kankar
clay,
sand, containing lenses of clay, & kankar
clay, and kankar
sand, very fine to meduim
clay, and kankar
silt, and clay, sand,
Borehole ID: BE-BE'_TW_14
Province: Punjab
District: Khanewal
Site: LBDC
Depth of Bore (m): 207.32
Reference Elevation (m MSL): 124.97
Bottom of Bore (m MSL): -82.35
Easting: 214965.283134
Northing: 3363105.392120
Latitude: 30.366288
Longitude: 72.034369
Lithography Description
Depth (m)
Top, of hole
sand, containing lenses of clay, & kankar
clay, and kankar
sand, very fine to meduim
sand, containing lenses of clay, & kankar
sand, very fine to meduim
sand, containing lenses of clay, & kankar
Borehole ID: BF-BF'_7
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 265.24
Reference Elevation (m MSL): 204.22
Bottom of Bore (m MSL): -61.02
Easting: 405591.775309
Northing: 3453269.200490
Latitude: 31.209734
Longitude: 74.008928
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
clay,
sand, very fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
Borehole ID: BF-BF'_15
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 265.24
Reference Elevation (m MSL): 204.22
Bottom of Bore (m MSL): -61.02
Easting: 393950.085359
Northing: 3449670.859960
Latitude: 31.176273
Longitude: 73.887115
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
sand, very fine to medium
clay,
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
clay,


Borehole ID: BF-BF'_16
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 259.15
Reference Elevation (m MSL): 198.12
Bottom of Bore (m MSL): -61.03
Easting: 382943.396679
Northing: 3437394.168740
Latitude: 31.064475
Longitude: 73.773059
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
0
20
40
60
80
100
120
140
160
180
200
220
240
260


Borehole ID: BF-BF'_22
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 253.05
Reference Elevation (m MSL): 192.03
Bottom of Bore (m MSL): -61.02
Easting: 369608.370009
Northing: 3428715.818050
Latitude: 30.984785
Longitude: 73.634435
Lithography Description
Depth (m)
Top, of hole
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
clay,
silt, and clay, sandy
clay,
silt, and clay, sandy
sand, very fine to medium
0
20
40
60
80
100
120
140
160
180
200
220
240
260


Borehole ID: BF-BF'_34
Province: Punjab
District: Okara
Site: LBDC
Depth of Bore (m): 192.07
Reference Elevation (m MSL): 185.93
Bottom of Bore (m MSL): -6.14
Easting: 354156.672439
Northing: 3421307.469900
Latitude: 30.916150
Longitude: 73.473722
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
silt, and clay, sandy
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200


Borehole ID: BF-BF'_TW_3
Province: Punjab
District: Kasur
Site: LBDC
Depth of Bore (m): 79.27
Reference Elevation (m MSL): 204.22
Bottom of Bore (m MSL): 124.95
Easting: 400310.240000
Northing: 3447750.781240
Latitude: 31.159511
Longitude: 73.954039
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80


Borehole ID: BG-BG'_40
Province: Punjab
District: Pakpattan
Site: LBDC
Depth of Bore (m): 176.83
Reference Elevation (m MSL): 161.55
Bottom of Bore (m MSL): -15.28
Easting: 335275.968011
Northing: 3345191.984340
Latitude: 30.225149
Longitude: 73.143199
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, containing lenses of clay, & kankar
clay, and kankar
sand, containing lenses of clay, & kankar
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Borehole ID: BG-BG'_48
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 182.93
Reference Elevation (m MSL): 173.74
Bottom of Bore (m MSL): -9.19
Easting: 321305.940071
Northing: 3344980.317250
Latitude: 30.223239
Longitude: 73.143235
Lithography Description
Depth (m)
Top,e of hole
clay, and kankar
sand, very fine medium
clay, and kankar
silt, and clay, sandy
sand, containing lenses of clay, & kankar
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to miedium
clay, and kankar
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
Borehole ID: BG-BG'_52
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 170.73
Reference Elevation (m MSL): 155.45
Bottom of Bore (m MSL): -15.28
Easting: 296752.557630
Northing: 3346673.653970
Latitude: 30.110036
Longitude: 72.743424
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Borehole ID: BG-BG'_57
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 182.93
Reference Elevation (m MSL): 152.40
Bottom of Bore (m MSL): -30.53
Easting: 282570.862600
Northing: 3333126.960210
Latitude: 30.110036
Longitude: 72.743424
Lithography Description
Depth (m)
Top, of hole
sand, very fine to medium
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay,
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
sand, very fine to medium
0
10
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80
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120
130
140
150
160
170
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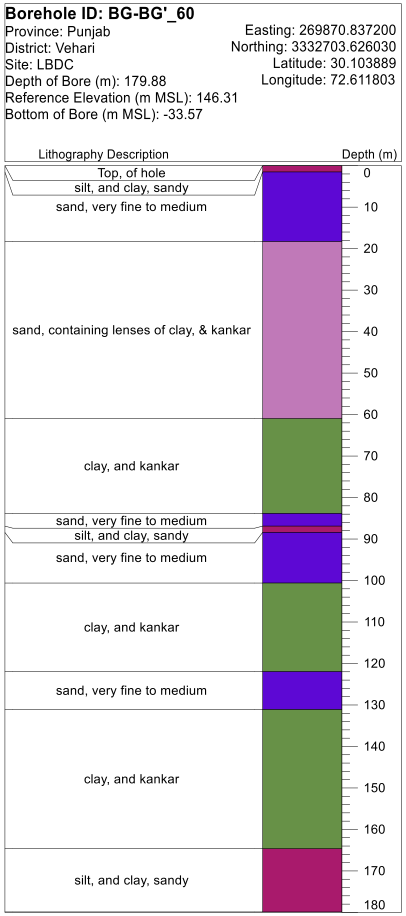
190


Borehole ID: BG-BG'_60
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 179.88
Reference Elevation (m MSL): 146.31
Bottom of Bore (m MSL): -33.57
Easting: 269870.837200
Northing: 3332703.626030
Latitude: 30.103889
Longitude: 72.611803
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, very fine to medium
sand, containing lenses of clay, & kankar
clay, and kankar
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
0
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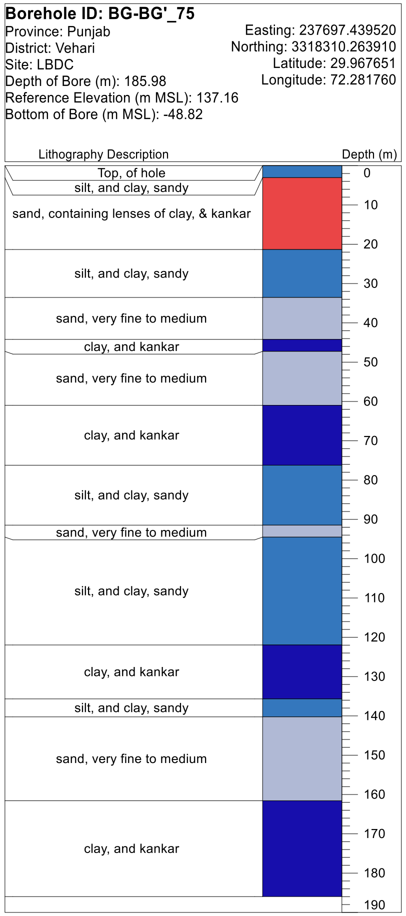
Borehole ID: BG-BG'_75
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 185.98
Reference Elevation (m MSL): 137.16
Bottom of Bore (m MSL): -48.82
Easting: 237697.439520
Northing: 3318310.263910
Latitude: 29.967651
Longitude: 72.281760
Lithography Description
Depth (m)
Top, of hole
silt, and clay, sandy
sand, containing lenses of clay, & kankar
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
sand, very fine to medium
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
clay, and kankar
silt, and clay, sandy
sand, very fine to medium
clay, and kankar
0
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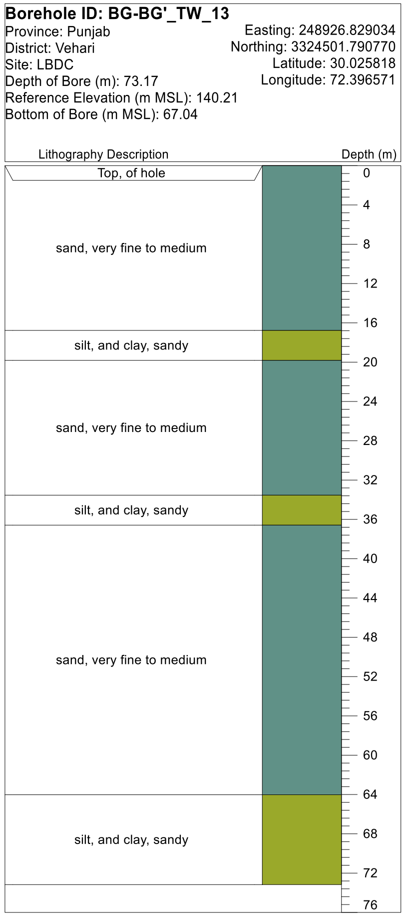
Borehole ID: BG-BG'_TW_13
Province: Punjab
District: Vehari
Site: LBDC
Depth of Bore (m): 73.17
Reference Elevation (m MSL): 140.21
Bottom of Bore (m MSL): 67.04
Easting: 248926.829034
Northing: 3324501.790770
Latitude: 30.025818
Longitude: 72.396571
Lithography Description
Depth (m)
Top, of hole
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
sand, very fine to medium
silt, and clay, sandy
0
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76

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