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the People of Japan

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Issues and Options: Reallocating Canal Water in Punjab Province, Pakistan

Final Report

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List of Abbreviations

ADB	-	Asian Development Bank
CCI	-	Council of Common Interest
EPA	-	Environment Protection Agency
EPCO	-	Environmental Pollution Control Organization
EPD	-	Environment Protection Dept
IWMI	-	International Water Management Institute (Lahore)
IRSA	-	Indus River System Authority
IWRM	-	Integrated Water Resources Management
NPPMCL	-	National Power Park Management Company
NWP	-	National Water Policy
PEPA	-	Punjab Environment Protection Act
PWP	-	Punjab Water Policy
PHED	-	Public Health Engineering Dept
PMD	-	Pakistan Meteorological Dept
PWSRA	-	Punjab Water Services Regulatory Authority
PWRC	-	Punjab Water Resources Commission
PID	-	Punjab Irrigation Department
RDWWF	-	Returned Domestic Wastewater Fraction
WAPDA	-	Water and Power Development Authority
WASA	-	Water and Sanitation Agency
WCAP	-	Water Capacity Advisory Project (World Bank)
WRC	-	Water Resource Commission

Acronyms/Units

MAF	-	Million Acre-Feet
BCM	-	Billion Cubic Metre (1 BCM = 0.810 MAF)
TA	-	Technical Assistance

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2 Executive Summary

The Punjab Water Policy (2018) aims to balance productivity and conservation and requires adopting Integrated Water Resource Management (IWRM) across the province. The Punjab Water Act (2019), enacted by the Provincial Assembly, is the legal instrument of the Government of Punjab to comprehensively manage and regulate water resources in Punjab in the interest of conservation and sustainability. Allocating water in the order of priority will be the responsibility of the Water Resources Commission (WRC).

There are three sources of water, namely, canal water, rainfall, and groundwater, which ought to be allocated to domestic, livestock, industrial, agricultural, and environmental demands across the canal commands of Punjab. Although canal and rainfall data are available, data on net groundwater use is not. Estimating net groundwater extraction is complicated by continuous recharging from canal and rainfall and discharge from pumping. This deficiency is addressed in this study, using post-monsoon groundwater level data from 846 observation wells from 2007 and 2019. Canal command-wise net discharge and discharge have been determined. Net discharge determined from observation well data is compared with net discharge estimated from GRACE and GRACE FO anomalies.

The comparison showed that Net Recharge for the canal command estimated from observation-well data (0.7943 BCM/y) and GRACE data (0.7886 BCM/y) are very similar. Both GRACE data and observation-well data estimated groundwater decline in 22 canal commands and groundwater level rise in three canal commands. However, GRACE estimated that the decrease in all 22 canal commands is statistically significant, whereas the observation-well data estimated only 14 of the canal commands had a statistically significant decline. Furthermore, the observation-well data estimated a statistically significant rise in one of the three canal commands. In contrast, GRACE estimated none of the three had a significant increase in groundwater levels.

There is a strong correlation between TWS anomalies and Groundwater Anomalies within the canal command. Hence, TWS anomalies may be used as a surrogate for Groundwater anomalies when data from observation wells are unavailable to monitor groundwater behavior.

The net discharge of groundwater, leading to aquifer depletion, is not sustainable. Therefore, net groundwater discharge should not be considered in allocating water to meet various demands. Instead, only the recharge to groundwater from the canal and rainfall should be considered for allocation.

Spatial units for water allocation within irrigated areas of the Province is Canal Commands. The order of priority for a water allocation proposed is a follows: (1) domestic and industrial from which a fraction will be returned for reallocation; (2) water supplied to livestock and to arrest aquifer decline will not be returned for reuse; (3) remaining water is allocated for agriculture.

Canal Commands' water balance BIG PICTURE informs two significant water sources, the canal (river) and rainfall. According to the Water Apportionment Act (1991), the Canal Water available for Punjab is 69 BCM. Gross rainfall within the canal commands is 34 BCM, of which an estimated 16.8 BCM is effective. The difference between 34 BCM and 16.8 BCM (17.2 BCM) is considered the water cannot be used in practice (floods, environmental flows, etc.)

The total volume of water required to meet domestic, industrial, livestock, and crop water demand are 3.4 BCM, 1.99 BCM, 0.56 BCM, and 87.6 BCM. To replenish the aquifers at the rate they are being depleted over the past 13 years, the annual environmental demand is 0.7943 BCM.

Consequently, the Canal Commands endure a net deficit of 7.73 BCM. This deficit may be reduced when a fraction of water supplied to the Domestic and Industrial sectors is returned to agriculture, preferably after treatment.

The central question for WRC for allocating water to Punjab's 26 canal commands is what objectives should shape water (re) allocation? More specifically, once the aims are defined for a particular hydrological system, how can they be achieved?

As a finite resource, water needs to be used (deterioration of water quality), treated and reused in domestic/industrial sectors, and finally consumed in agriculture (liquid to vapor). Noting that water is a finite resource, planners must maximize water productivity in all sectors as a continuum of use-use… and, finally, consumption. This paradigm will shift investments in water treatment, which will have added health and labor productivity benefits in addition to water productivity benefits.

It appears that WRC may consider three different objectives, which are not necessarily mutually exclusive.

The first objective is to implement the recent promulgation of the Government of Punjab's rules for the Adjustment of Canal Command Areas ((Rule 3-a, b, c, d) and the provision to reduce canal water allowance (Clause 4 Rule 4(2).

The second objective may be to supply canal water to meet all domestic, industrial, livestock, and environmental demands of every canal, and then reallocate remaining canal water to ensure equitable deficit to meet crop water requirements within the canal command.

The third objective may be to supply canal water to meet all domestic, industrial, livestock, and environmental demands of every canal, and then reallocate remaining canal water to ensure equitable supply per unit land area, consistent with warabandi principles.

Three Linear Programming Models are developed to assess reallocation options to meet each one of the three objectives.

The results are as follows if the first objective is pursued under the best-case scenario (in addition to canal water supplies, effective rainfall estimated by the modified SCS method, and return of wastewater from domestic and industrial sectors). This scenario assumes that all excess water in Lower Bahawal and Panjnad canal commands after meeting all requirements within the canal command is available for reallocation to canal commands in water deficit to meet Crop Water Requirement (CWR). Excess water available in Lower Bahawal and Panjnad canal is 2.1895 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. Total Water Available (TWA) in canal commands ranged between 658 mm and 1473 mm with a Gini Coefficient of 0.13. % CWR met in canal commands averaged 92% and ranged between 65% and 128% with a Gini Coefficient of 0.11.

Following reallocation, water available in canal commands ranged between 698 mm and 1200 mm with a Gini Coefficient of 0.10. %CWR met in all canal commands averaged 93% and ranged between 65% and 100% with a Gini Coefficient of 0.08. A total volume of 2.1895 BCM was transferred from Lower Bahawal, and Panjnad canal commands to Abbasia, Central Bari Doab, CRBC, D.G. Khan, Haveli, Upper Dipalpur, and Upper Pakpattan canal commands.

If the second objective is pursued, under the best-case scenario, the results are as follows. This scenario assumes that the effective rain estimated using the simplified SCS method, and wastewater from domestic (99% of the domestic demand) and industrial sector (10% of the industrial demand) and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The TWA for this scenario is 82.26 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. Water Available in canal command ranged between 658 mm and 1474 mm, with a Gini Coefficient of 0.10. % CWR met in canal commands ranged between 65% and 128% with a Gini Coefficient of 0.08.

Following reallocation, water available in canal commands ranged between 784 mm and 1146 mm, with a Gini Coefficient of 0.06. %CWR met in all canal commands was 94% due to imposing equity in deficit, resulting in a Gini Coefficient of zero. A total volume of 4.05 BCM was to be transferred from canal commands where %CWR met before reallocation is more than 94% to canal commands where the %CWR met before reallocation is less than 94%.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Mailsi, Lower Pakpattan, Qaim + UBC, Sindhnai, Upper Dipalpur, and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed are CRBC D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Jhelum, Marala Ravi, Muzaffargarh, Panjnad, Rangpur, Sadiqia, Thal, Upper Chenab, and Upper Jhelum canal commands.

If the third objective is pursued, under the best-case scenario, the results are as follows. This scenario assumes that the effective rain estimated using the simplified SCS method, and wastewater from domestic (99% of the domestic demand) and industrial sector (10% of the industrial demand) and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The TWA for this scenario is 82.26 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. TWA in canal command ranged between 658 mm and 1474 mm with a Gini Coefficient of 0.1. The % CWR met in canal commands ranged between 65% and 128%, with a Gini Coefficient of 0.08.

Following reallocation, water available in canal commands ranged between 0.32 BCM and 12.42 BCM, with a Gini Coefficient of 0.43. The depth of water available in all canal commands is 962 mm due to imposing equity in supply, resulting in a Gini Coefficient of zero. A total volume of 5.87 BCM was to be transferred from canal commands where TWA was greater than 962 mm to canal commands where the TWA was less than 962 mm.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Lower Mailsi, Marala Ravi, Qaim + UBC, Rangpur, Sadiqia, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum and Upper Pakpattan.

Under this scenario, Canal Commands to which water needs to be removed are Central Bari Doab, CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, Panjnad, and Upper Chenab canal commands.

3 Introduction: Changing Water Architecture in Punjab

To address water sector challenges, Pakistan developed the National Water Policy (NWP) in 2018. Simultaneously, the Punjab Province also embarked on fundamental changes to the Province's governance architecture of water resources institutions. Key developments in Punjab include developing the Punjab Water Policy (PWP) and the Punjab Water Act 2019. Although direct links between the NWP and the PWP are not self-evident, both policies aim to manage Pakistan's water resources to sustain the long-term water productivity of domestic, industrial, agricultural, and environmental sectors.

3.1 National Water Policy

The CCI approved the National Water Policy in 2018. The National Water Policy's objective is to take cognizance of the emerging water crisis and provide an overall policy framework and guidelines for a comprehensive plan of action. Pakistan has a federal government system, and the provinces enjoy a considerable degree of autonomy under the 18thAmendment to the Constitution. Thus, this Policy is only a national framework, guiding provinces to develop their Policy.

The National Water Policy has high-level political support as a national imperative. It creates an institutional framework to address present deficiencies; provides national targets for water conservation, water storage, water treatment, and clean drinking water; and substantially requires a sustained commitment to increasing public and private resources for the water sector.

3.2 Punjab Water Policy

The Punjab Water Policy (2018) aims to balance productivity and conservation within the Province. The Policy requires the adoption of Integrated Water Resource Management (IWRM) across the Province. Integration of (1) Water Resources Institutions (PID, PHED, EPD, MAF), (2) Sources of water (Rain, canal, groundwater, wastewater, drainage water, etc.), at (3) various spatial units to reflect upstream/downstream, hydrology, canal commands, and administrative units. Integration across all water sectors and affiliated institutions will be facilitated by establishing a Punjab Water Resources Commission (PWRC) and a Punjab Water Regulatory Services Authority (PWRSA).

3.3 The Water Act

The Punjab Water Act (2019), enacted by the Provincial Assembly, is the legal instrument of the Government of Punjab to comprehensively manage and regulate water resources in Punjab in the interest of conservation and sustainability. It is expedient to provide for comprehensive management of all water resources in Punjab and control their use in conservation and sustainability and matters connected with and ancillary to it.

3.4 Role of Water Resources Commission

The WRC will allocate water and issue licenses to different water sectors based on the Act's Priority. The Commission must take all such actions as it may, from time to time, consider necessary or expedient for:

- conserving, redistributing or otherwise augmenting water resources in the Punjab;
- allocating water resources for domestic, agricultural, ecological, industrial, or other purposes in different areas of the Punjab; and
- of securing the proper use of water resources in Punjab.

3.5 Role of Water Sector Regulatory Authority

The WSRA is mandated to (1) ensure that the undertakers discharge their duties and perform their functions under the Act; (2) revise tariffs set by water and sewerage undertakers, if deemed necessary, as per procedure; (3) ensure proper operations of water and sewage undertakers; (4) ensure water and or sewerage undertakers are financially viable to deliver required services; (5) ensure that the activities authorized under the license to abstract or dispose of water are correctly carried out.

4 Historical and Present Context for Water Allocation in Punjab

4.1 Historical Context

In 1961, the Indus Water Treaty gave India over the three "eastern rivers," the Beas, Ravi, and Sutlej, while the three "western rivers," the Indus, Chenab, and Jhelum, to Pakistan. Consequently, Pakistan built dams, barrages, and link canals that carry water from western rivers to eastern rivers. Despite the influx of water via the Lahore Siphon and link canals, the Indus Water Treaty's net effect reduces flow in eastern rivers.

The loss of Eastern rivers and reduced flows gradually increased friction between the provinces resulting in complete discord to construct the Kalabagh dam. An attempt to iron out the differences and achieve consensus resulted in the Water Apportionment Accord (1991). Pakistan's waters were allocated to the Provinces based on the history of use, riparian rights, and climate. Indus River System Authority (IRSA), with one member from the Federation and each Province, was created to implement the Water Apportionment Accord. Punjab, being the most densely populated of all the four provinces (pop. 110 million, Census 2017), is allocated 69 BCM (55.94 MAF) out of a total of 144.75 BCM (117 .24 MAF) on a mean annual basis.

4.2 Water Institutions of Punjab

4.2.1 Punjab Irrigation Department (PID)

Since 1849, PID has managed the water in Punjab by operating, rehabilitating, and maintaining Punjab's water infrastructure. The functions of the Irrigation Department include

- Administer the Canal and Drainage Act, 1873.
- Administer the Soil Reclamation Act, 1952.
- Administer the Land Improvement Tax Act, 1975.
- Administer Flood Plain Act 2016
- Survey of Rivers and Riverine Plains
- Construction, Operation, and Maintenance of Reservoirs
- Construction, Operation, and Maintenance of Barrages
- Construction, Operation, and Maintenance of Irrigation canals
- Construction, Operation, and Maintenance of Drainage canals.
- Conduct basic and applied research in irrigation, hydraulics, groundwater, and land reclamation
- Distribute canal water equitably.
- Assess water rates.

The major component of the water infrastructure in Punjab is the Indus Basin Irrigation System (IBIS). In Punjab, IBIS is serving 8.41 m ha (20.78 million acres) of culturable command area through 58,000 outlets and has gradually achieved an average cropping intensity of 120 % – 150 %. Irrigated agriculture employs 50% of the Punjab workforce,

directly or indirectly, and generates 20% of the provincial GDP. Irrigation infrastructure includes:

- Inter-river link canals (528 miles with a total off-take capacity of 110,000 cusecs);
- 13 barrages, and their headworks, and 57 small dams;
- 25 main canals (3593 miles with a total off-take capacity of 120,000 cusecs);
- 2,794 distributary and minor canals (21385 miles long);
- An extensive network of surface drains;
- Two thousand eighty-three miles of flood embankments, etc.

4.2.2 Punjab Agriculture Department

The main functions of the agriculture department are:

- Legislation, policy formulation, and sectoral planning regarding:
    - Improvement of agricultural and water management methods
    - Protection against insects, pests, prevention of plants diseases, and quality control of pesticides
    - Soil Fertility and Soil Conservation
- Monitoring of agriculture inputs like fertilizers, pesticides, and irrigation through field extension staff
- Promotion of modern agriculture technologies and other extension activities through method/result demonstration, farmers gatherings, print and electronic media, etc.
- On-Farm Water Management Operations, Planning, Research, and Coordination
- Coordination and Strengthening of Research activities in Agriculture, Livestock, Irrigation, Water Management, Forest and Fisheries sectors through Punjab Agricultural Research Board
- Plant Protection:
    - Standardization of local and imported pesticides
    - Plant quarantine
- Soil survey, a comprehensive inventory of soil resources of Province and their proper utilization
- Introduction of different crops like jute, tea, olive etc.
- Under-development areas:
    - Identification of under-development areas
    - Identification of the fields in which an area is under-developed
    - Measures necessary to remove the causes of under-development in different areas
- Pest Scouting, Pest Survey, Pest Warning, Quality Control of Pesticides. Research on Plant Protection, training of pesticides dealers, farmers, and extension workers in plant protection

4.2.3 Public Health Engineering Department, Water Supply and Sanitation Agencies, Local Governments

Provision of drinking water supply and sanitation is the Public Health Engineering Dept (a co-department of Housing and Urban Development Department). For large cities where Development Authorities have been created, Water Supply and Sanitation Agencies (WASA)

perform the same function. In areas not covered by a WASA or and PHED, this task is performed by the Local Government. These agencies are responsible for planning, designing, and constructing new water supply, sewerage & drainage facilities; rehabilitation and augmentation of the existing systems; operation and maintenance of water supply, sewerage & drainage systems; billing and collection of rates, fees, and charges for the services provided to consumers.

4.2.4 Environmental Protection Department (EPD)

In 1975, Environmental Pollution Control Organization (EPCO) was created in the PHED to control pollution. In 1983, Pakistan Environmental Ordnance was passed with a provision for creating the Provincial Environmental Protection Agency. In 1987, EPA Punjab was created, which was then merged with the EPD in 1996. In 1997 Environmental Protection Act (PEPA) was enacted, and EPD now functions under this Act. EPA is responsible for the protection, conservation, rehabilitation, and improvement of the environment, the prevention and control of pollution, and promotion of sustainable development in the Province.

The EPA has passed effective regulations, PEQs, quality and quantity standards of discharge of effluents, waste, air emissions, and noise pollution. EPA has certified laboratories for testing. Recently, the World Bank has approved a $200 million loan to strengthen EPA.

4.2.5 Forestry, Fishery and Wildlife Department (FWF)

FWF Department is mandated to conserve, protect, and manage the Forestry, Fishery, and Wildlife resources. Out of a total area of 50.96 mil acres (20.6 m ha) of Punjab Province, forest resources cover an area of 1.66 million acres (0.67 ha or 3.26 %). The forest resources consist of Compact (area) plantations and linear plantations along canals, roads, and rail. Besides this, tree cover exists in farmlands along field boundaries and watercourses.

The department also ensures conservation and sustainable development of wildlife resources in the form of National Parks, Wildlife sanctuaries, Wildlife Parks, Game reserves, Zoos, and a Safari Zoo,

Fish in Punjab constitute an extensive resource in rivers, canals, reservoirs, lakes, waterlogged areas covering about 7.5 million acres. Besides this resource, fish culture activities in the private sector have increased significantly in the last two decades. Approximately 56.54 acres (22.9 ha) are under fish culture, with 50% investments from the private sector.

4.3 Water Resources of Punjab

According to Apportionment Accord 1991, based on historical pattern use (1977-1982), Punjab is allocated 69 BCM (55.94 MAF) out of a total of 144.75 BCM (117 .24 MAF) on a mean annual basis. The water is then distributed to canal commands. Also, rainfall-runoff within the canal commands is 19 BCM. Spatially, the rainfall varies from south to north with

the increasing trend while the temperatures increase towards the south affecting the crop water requirements for most crops.

The actual surface water withdrawals for the three years 2011-2014 by Punjab through its 26 canal systems were 70.06 BCM (56.75 MAF; Kharif 37.23, Rabbi 19.52,), 59.17 BCM (47.93 MAF; 29.99, 17.94), and 60.32 BCM (48.86 MAF; 30.75, 18.11.) respectively (PID). The higher withdrawals in the year 2011 by 15 % reflect the higher rainfall and floods that year. Historically, the minimum withdrawals may be half of the maximum withdrawals.

Estimates of Net groundwater withdrawal in the Province vary widely. World Bank estimates that Punjab's total water withdrawals from all three sources are 118 BCM, exceeding availability by 20 %, thus reflecting unsustainable groundwater abstraction and depletion[1]

On the other hand, ACE et al. estimate that recharge to groundwater in Punjab is 69.67 BCM (rainfall 9.73, canal system 40.2, return flow 12, rivers 2.96, transboundary 4.78) with discharge equal to 69.07 BCM (tube-wells 60, domestic 3.7, evaporation 3.48, outflow 1.86)[2].

In areas outside canal commands, Potohar Plateau in the north generates runoff of 4.4 BCM (3.6 MAF), and DG Khan hill torrents in the south generate runoff of 3.35 BCM (2.71 MAF).

Under the Irrigation and Drainage Act 1860, all river waters were allocated to agriculture. Hence, almost all water used in the domestic and industrial sectors is withdrawn from groundwater unregulated being tied to private property under the Indian Easements Act of 1892. Despite pumping costs, groundwater is extensively withdrawn for irrigation as well. Despite substantial recharge from canals and monsoon rains, groundwater levels are declining in and around urban centers and areas where canal water is not supplied for irrigation.

The variability in crop water requirements and supply in different Canal commands from north to south affects groundwater recharge proportionally. The groundwater levels in upper areas appear to be more in equilibrium or rising than those in the south, where a significant decrease in groundwater levels is observed.

Net mining of fossil groundwater in the Province is estimated as 2.5 BCM (2 MAF). Furthermore, pumping in relatively small urban areas with limited opportunity for recharge has caused deep drawdowns, lowering the water table and risking the aquifer's sustainability.

Further, compounding the problem is the discharge of untreated wastewater and industrial effluent directly into the irrigation network.

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[1] Young, et. al (World Bank IBIS Study) 'Pakistan Getting more from Water' 2018 Table 3.3, 3.4 basing their estimates on GOP 2017 data and their calculations.

[2] 'National Study of Groundwater Availability & Conjunctive Management'2011, Associated Consulting Engineers(ACE), Engineering General Consultants (EGC) & SMEC International Ltd.

4.4 Water Allocation in Practice

4.4.1 Water Allocation Plans

IRSA was mandated under WAA-1991 to distribute water to the Provinces according to their share. Seasonal water availability before each cropping season; Kharif and Rabi for the two systems; Indus-and Jhelum-Chenab Zones is assessed at rim stations, and provinces are informed of their allocation on the 10-daily basis for the maximum, minimum, and most likely inflow scenarios. The provinces then make a Water Allocation Plan for each canal command based on its share/entitlement for maximum, minimum, and likely inflows. Expected shortages/surpluses are uniformly distributed.

4.4.2 Modification of Command Area

A 'Command Area Modification Policy' has been approved by the Government of Punjab. The Policy outlines the reallocation procedure when there is a change in canal command areas (both addition and exclusion). Key features of this Policy are explained below:

The total Command area (in terms of acreage and physical limits) can be modified in the following cases:

- Where water allowance of a command area is re-determined
- Where water allowance is readjusted by 10%
- Where additional irrigation supplies become available

The physical limits of a command area without affecting the total acreage can be modified in the following cases:

- Where an area in the command area is excluded because its irrigation supply has been withdrawn
- Where an area under command is removed from cultivation permanently, or its supply has been stopped permanently

4.4.3 Re-determining Water Allowance

Water Allowance may be re-determined in the following cases:

- Where cropping pattern had significantly changed from the time when the allowance was originally determined
- Where agricultural practices have significantly changed
- Where groundwater is available on economic terms and can be sustainably managed
- Where regulations regarding 'cropping patterns' have been made and enforced

4.4.4 Adjustment in water allowance

The water allowance of the main canal may be adjusted once by up to ten percent provided in the view of relevant expert agronomists and canal engineers; it has no practical effect on the existing irrigators' agriculture.

4.4.5 Irrigation supplies explained

In principle, each Canal in Punjab has a given water allowance and a sanctioned command area. The share of an individual irrigator from the overall irrigation supply in a canal is fixed based on his holding size. This share is his water-right. The total irrigation supply of a canal is generally a function of its water allowance and command area. However, additional supplies may be provided if water is available or demand for non-agricultural purposes increased. Hence, there appears no correlation between water allowances and water supplies to canal commands. Provision of extra water requires the approval of the Water Resources Commission.

4.4.6 Modifications in total command area due to additional irrigation supplies

Modification in CCA may be carried out under the following conditions:

- Additional irrigation supplies become available regularly in a command area without affecting the rights of other command areas.
- Additional water supplies become available due to downward adjustment of the water allowance or redetermination of the water allowance.

Where a case is placed before the Water Resources Commission (WRC) under this clause, the Irrigation Department will place options for additional water use.

4.4.7 Modification in limits of canal command area due to the exclusion of an area

CCA may be reduced under the following conditions:

- If an area's irrigation supply has been permanently withdrawn or where agriculture has been abandoned, the Divisional Canal Officer may exclude the said area from the command.
- If an area has been excluded from the command, the Divisional Canal Officer may add land equal to the land excluded through re-appropriation.
- The additional area may be included in command of an outlet (instead of the excluded area) without permission of the Water Resources Commission, provided that it does not entail any change in outlet size (including by way of splitting or shifting of the outlet) under this Policy.
- New outlets or minors or sub minors for purposes of commanding land instead of the excluded area shall only be allowed where the Water Resources Commission has granted permission for continued water use within the command area's allocation for agricultural purposes.

4.4.8 **Adjustment of Canal Command Areas Rules, April 2021**

Recently, the Government of Punjab has promulgated rules for the Adjustment of Canal Command Areas. Under Rule 3(a,b,c,d), the irrigation supply of a canal can only become surplus in one or more of the following situations:

a. An area included in the command area of the canal no longer remains under agriculture or is rendered unfit for agriculture, and the water supplied to it is cut-off under the Act;
b. Whole or a part of the sanctioned irrigation supply of an existing irrigator of the canal is withdrawn permanently under the Act;
c. Water allowance of the canal is reduced by the Cabinet in terms of Rule 4; or
d. Irrigation supplies over and above the previously sanctioned irrigation supplies become available for the canal in terms of Clause (4) of Rule 4

Under Rule 4(2), ' The Cabinet may reduce water allowance of a canal by not more than ten percent of its existing water allowance where, in majority view of the following, such reduction has no practical effect on the agriculture of the existing irrigators.' Under Rule 4(4), 'in the event of irrigation supply in excess of Punjab's allocation under paragraph 2 of the Water Apportionment Accord 1991 becoming available, the decision as to its allocation to an existing or a new canal shall be taken by the Cabinet, and any such additional irrigation supply shall be the surplus irrigation supply for that canal for the purpose of the Rules.

5 Emerging Issues in Punjab

5.1 Emerging Demands

A summary has been submitted for the Chief Minister's approval to supply cooling water to a Government-owned Power Utility Company for two Power Plants. The demand is 800 and 650 cusecs for 1230MW and 1223 MW installed capacity.

Water and Sanitation Agency, Lahore, has also placed a demand of 1500 cusecs (1.35 BCM/annum) to supply drinking water. There are similar demands from other big cities like Gujranwala, Faislabad, Multan, etc.

5.2 Revisiting Water Allocation in Punjab

The Punjab Water Policy was formulated in 2018, and the Punjab Water Act 2019 was enacted by the Provincial Assembly. The Act has mandated the newly constituted Water Resource Commission (WRC) to reallocate water.

The Punjab Water Policy (2018) requires Key Policy Actions for Water Allocation in section 2.4 below.

a) Assign priority for water allocation for various sub-sectors of water use in the order of domestic water, stock water, water for agriculture, water for industrial and commercial uses, water for environmental and recreational uses based on the current uses and future demand.
b) Allocate water to various sub-sectors of water use and different regions (Canal commands, Pothwar, Thal and Cholistan deserts, Suleiman ranges, riverine areas) towards establishing water entitlements the regions and for sources of water (surface water and groundwater).
c) Enforce measures to reduce, reuse, and recycle water in domestic, commercial, and industrial sub-sectors to manage part of future water demand in these sub-sectors by recycling wastewater.
d) Introduce water-efficient technologies and 'best practices' for optimal land use for irrigated agriculture to enhance water productivity and save water for reallocations to other sub-sector water use.

Furthermore, Clause 4 of the Punjab Water Act (Act XXI of 2019) empowers the Water Resources Commission as below:

It shall be the duty of the Commission to take all such actions as it may, from time to time, consider necessary or expedient for the purpose of:

a) conserving, redistributing or otherwise augmenting water resources in the Punjab;
b) allocating water resources for domestic, agricultural, ecological, industrial, or other purposes in different areas of the Punjab; and
c) of securing the proper use of water resources in Punjab.

Further, compounding the problem is the discharge of untreated wastewater and industrial effluent directly into river streams. The only source of alleviating this situation was the reallocation of water from its largest consumer, the agriculture sector, for which a new Water Act was required.

The inequitable supply of water between canal commands, non-optimal cropping patterns, reduction of culturable command areas (CCA) due to urbanization, induction of new areas into canal commands, and demand for water demands in areas outside canal commands require reallocation of canal water within the Province (outside the domain of WRC).

6 Water Allocation Framework

6.1 Introduction- why allocate water?

Effective water resources management includes the management of water as an economic resource. The interaction of three critical factors, the value of water, the use cost of water, and the resource's opportunity cost, determine how water is used or consumed[3]. The value of irrigation water for food grains is meager, typically orders of magnitude less than the value for urban water supply and high-value crops' irrigation.

The relative magnitudes of "use costs" and "opportunity costs" show that the implications of treating water as an economic resource vary quite widely depending on the sector.

Urban water supply, for example, is a low-volume, high-value use. The "use costs" (incurred in financing and operating the abstraction, transmission, treatment, and distribution systems) are relatively high. In contrast, the "opportunity costs" (imposed on others due to water use) are often relatively low. The situation is quite different for irrigation, which is a high-volume, low-value user of water. The "use cost" of irrigation water is often modest, but the opportunity cost is high when there is competition with urban uses (Briscoe, 1996).

In recent decades, it has been widely recognized that human society's impact on the environment is beginning to threaten the basic foundation upon which we depend for food, shelter, and a sense of well-being. Of all the resources that are important to people, perhaps the one most under pressure is water. Traditionally, the focus has been on water quantity, getting enough to do what we want. The concern is about the health of our aquatic ecosystems and human needs, both dependent on the availability and quality of water. Water is essential to a large number of values that are important to people. In addition to its direct and immediate life-supporting attributes, it is also necessary for most other ecosystems' continued functioning in the natural environment. The level of human impact on the natural world is now so great that in many situations, it has become necessary to deliberately set aside a proportion of the available water so that the environment and its ecosystems can continue to function (Schofield et al. 2003).

Observations above show that water has a 'value' and urban (domestic & industrial), agriculture (crops & livestock), and the environment is critical sectors, which require water.

The central questions for managers responsible for allocating water in a hydrological basin are: what values should shape water management? More specifically, once the aims are defined for a particular hydrological system, how can they be achieved?

While objectives and approaches have evolved, ultimately, water resource allocation has fundamentally remained the process of determining how much water is available for human

[3]. The use of water changes its quality, but water remains in a liquid state (e.g., Washing). Consumption refers to when the state of water changes from liquid to vapor. (e.g. Evaporation).

use and how that water should be shared between competing regions (spatial component) and sectors.

Several related challenges that developed have led to a significant evolution in basin allocation planning. These challenges have included: growth in water abstractions, basin 'closure' and the lack of availability of more sites for water infrastructure, development, and change in the economy, leading to a wider variety of water users with different water demands, the decline of freshwater ecosystems and the loss of river system functions and climate change (Speed et al. 2103).

Hence, modern basin allocation planning now focuses more on prioritizing, recycling non-consumed fractions of recoverable water, e.g. (recharge to freshwater aquifers), and reusing (un)treated wastewater. Consequently, water allocation approaches are founded on complex rules for dealing with variability and balancing different water allocation scenarios' environmental, social, political, and economic implications.

6.2 Water Allocation Process

The allocation process typically culminates in the granting of water entitlements to individual abstractors. The process can involve allocating water at various administrative and geographic levels, such as Provinces, Districts, or Canal Commands.

Water allocation planning involves considering the total water resources available from rain, canal and groundwater supplies, and water from inter-basin transfers. The amount of water available for allocation will be a function of this total volume, less water that cannot in practice be used. Examples are water that cannot be stored or used and passes during uncontrolled flooding and water retained in the river system to meet ecological needs (i.e., environmental flows).

Establishing a water allocation plan involves a detailed situation assessment to identify water availability, existing water use and expected future demand, and water requirements for environmental purposes. This information is used to develop different allocation scenarios, which can be assessed based on their social, economic, and ecological consequences.

6.3 Objectives of Water Allocation

Basin water allocation planning is typically undertaken to achieve a series of overarching policy objectives. In many jurisdictions, these now include:

- Development priorities: allocating water in a way that supports and promotes economic and social development. This can include supporting strategic priorities and protecting existing dependencies.
- Balancing supply and demand: water allocation plans need to balance water supplies with demands, particularly to manage the natural variability of water availability and to avoid frequent or unexpected water shortfalls.

- Promote practices that minimize the nonrecoverable fraction[4] of water applied.
- Equity: allocating water in a way that is fair and equitable amongst different regions.
- Environmental protection: allocating water in a way that recognizes the needs of freshwater-dependent ecosystems and protects essential freshwater services such as sediment transport, groundwater recharge, waste assimilation, and estuarine functioning.

6.4 Water Use vs. Consumption of Sectors in the Order of Priority

Approaches to water allocation for spatial units are based on:

- Proportionality – Population, area, climate
- History of use - levels of dependency, or current efficiency and productivity
- Future use - based on growth projections or to align with development planning.

Before discussing the priorities, it is prudent to recall the distinction between water use and consumption by different sectors5 and the priority set in the Punjab Water Policy (3:3a). In the domestic sector, most of the water will be used (will stay as a liquid, but with changed water quality, and therefore available for reuse). Most of the water will be beneficially consumed by the livestock in the livestock sector, and negligible amounts will be reusable. Water supplied to the agricultural sector will be consumed beneficially or non-beneficially (evapotranspiration), recoverable and consumed, or, not consumed but lost to a sink. Most livestock is reared in rural agricultural areas, and water allocated to them is 'çonsumed' and not returned for reuse.

The fate of water provided to the industry will be similar to the water supply for the domestic sector – a fraction will change its state from liquid to vapor. Still, most will be of changed water quality and therefore reusable after treatment. Furthermore, since most industries are placed within urban and semi-urban areas and supplied water by a common water supply network, it is prudent to allocate water for domestic & industrial needs collectively.

A fraction of the water for the environmental sector will be evaporated by natural vegetation. The key environmental issue within the canal commands is groundwater decline. Hence water needs to be allocated to arrest the rate of decline.

Water used for recreational purposes is often not consumed, as the recreational activities take place along water bodies, such as the flood plain of the river or banks of a lake.

[4] Perry, C.J. 2007. "Efficient Irrigation; Inefficient Communication; Flawed Recommendations." Irrigation and Drainage 56 (4): 367–78.

[5] Water available for agriculture is either consumed or non-consumed. Water may be consumed for beneficial purposes (crop evapotranspiration), or non-beneficial purposes (bare soil evaporation). Non consumed fraction may be recoverable and reused (recharge to freshwater aquifers) or non-recoverable for reuse (recharge to saline aquifers). Agricultural water managers need to minimize non-beneficial consumption, and non-recoverable non consumed fractions to realize true water savings.

In summary, the order of priority for a water allocation proposed is a follows: (1) domestic and industrial from which a fraction between 0 and 1 will be returned for reallocation; (2) water supplied to livestock and to arrest aquifer decline will not be returned for reuse; (3) remaining water is allocated for agriculture.

7 Role of groundwater on determining canal water allocation

The concept of sustainable development was brought to the forefront in 1987 by the United Nations World Commission on Environment and Development. The Brundtland Commission, as it came to be known, broadly defined sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their needs. The California Sustainable Groundwater Management Act defines sustainable groundwater management as a basin operated in such a way so as not to cause "undesirable results," such as chronic depletion of groundwater, seawater intrusion, or land subsidence. The definition used in U.S. Geological Survey Circular 1186, Sustainability of Ground-Water Resources, is the "development and use of groundwater resources to meet current and future beneficial uses without causing unacceptable environmental or socioeconomic consequences." The precursor to undesirable results such as the saltwater intrusion or land subsidence in depletion of groundwater, indicated by a decline in groundwater levels.

The three uses that dominate demand for water in Pakistan are agriculture, industry, and domestic. Groundwater is a constituent of all three. The alluvial aquifers of the Indus basin contain large quantities of fresh and marginal quality groundwater, and irrigators turn to groundwater use where and when surface water is (or becomes) unavailable, installing tube wells when the need arises.

The development of the initial canal irrigation system between 1870 and 1930 led to a rise in the water table, reaching 3.0 to 4.5 meters below ground level by 1940 in some areas. A survey conducted from 1953 to 1954 (the Colombo Plan Survey) reported that rising water tables had caused waterlogging across an area of more than 5 million hectares.

The Indus Waters Treaty of 1960 resulted in a gradual reduction in the three eastern rivers' flows as they entered Pakistan. The transfer of water from the western rivers (Chenab, Indus, and Jhelum) to the eastern rivers (Beas, Ravi, and Sutlej) via link canals originated in the Indus Waters Treaty, with control of the waters of the three eastern rivers vested in India. As a result, Pakistan transfers surface water from the Indus basin's western rivers to support flow in the eastern rivers once they have entered Pakistan. This massive transfer of water via linked canals, the expansion of the canal network, and irrigated areas contributed to the recharge to the aquifers, rising groundwater levels, and the associated problems of waterlogging secondary salinity.

Since the 1970s, and with the SCARP program to control salinity and waterlogging, fresh groundwater became accessible to complement surface water to meet the water demand. It led to the control of groundwater levels. Simultaneously, farmers too installed wells to supplement irrigation water, which led to a rapid expansion of conjunctive use of water for irrigation. Despite the rapid expansion of groundwater irrigation in Pakistan over the past 30 years, systematic long-term monitoring and archiving of groundwater data are mostly absent. Limited long-term groundwater monitoring has been undertaken by federal and state agencies in Pakistan from the mid-1970s to 2015 and more recently (since 2007) by

the Punjab Irrigation Department in Punjab's eastern doabs. There's a widespread view that groundwater depletion in Punjab is unsustainable. Young et al. (2019) report that current groundwater withdrawals in Pakistan's Indus basin exceed the recharge rate by about 1 billion cubic meters per year.

Although groundwater level decline is evident in the eastern part, groundwater resource overexploitation does not occur over Punjab. Water tables are shallower at the heads of the canals and deeper (yet in higher demand) at the tail end of canals. The decline is understood locally through its effects on users. Accurate assessment of the depletion extent is limited because data on groundwater extraction, levels, and quality are scarce or unreliable.

7.1 Determining long term changes to groundwater stored

As a part of this CDTA, data from 846 observation bores across 25 canal commands in Punjab from 2007 till 2019 has been used to assess the sustainability of groundwater use in Punjab (Figure 1). The study identifies canal commands where groundwater levels are significantly falling, remain stable, or rising. Within canal commands where groundwater levels are falling significantly, localities where decline is statistically significant (Hotspots) are identified. These hotspots will require management interventions to prevent further decline.

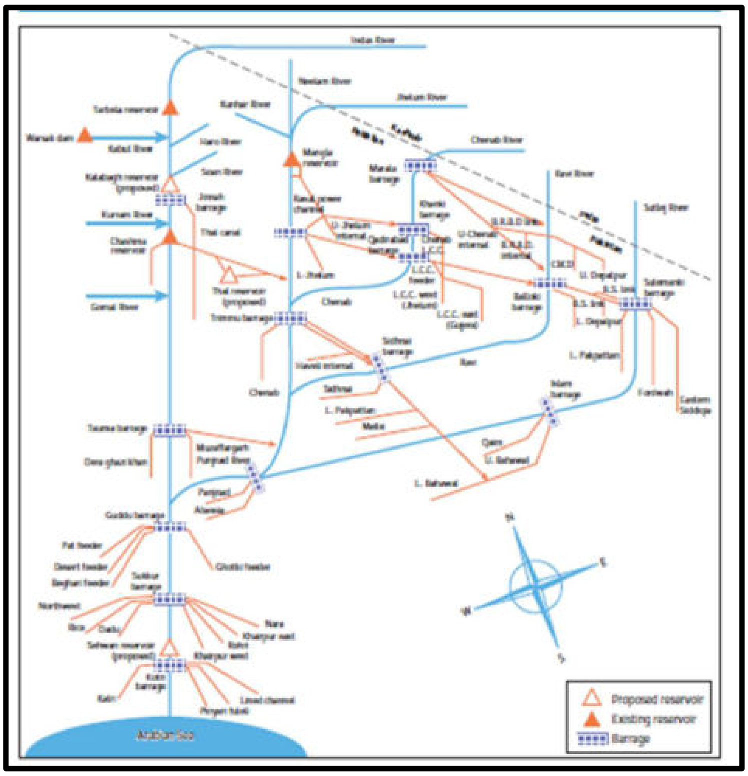

Figure 1: Schematic of Canal Network within the Indus Basin of Pakistan

7.1.1 Testing for statistically significant change in groundwater levels

This study recognizes that the aquifer is a reservoir to supply water for human use and consumption throughout the year. Unlike the use and consumption, which occur daily, significant recharge levels occur in Punjab only during the monsoon. Therefore, sustainable groundwater management practices need to permit a decline in groundwater levels during the year, as long as they are recovered at the monsoon's end. Thus, the groundwater levels observed immediately after the annual monsoon are analyzed to determine whether the changes between 2007 until 2019 are structural and statistically significant or fluctuations due to random factors.

Furthermore, not all monsoons are equal in rainfall amounts and intensity, resulting in a recharge variation annually. In dry years, groundwater extraction will be more than in dry years. Similarly, recharge to groundwater will be more in wet years than in dry years. Therefore, a reasonable number of years need to be analyzed to conclude whether changes to groundwater levels are significant or not. In this study, groundwater levels observed from 2007 till 2019 are used.

Initially, groundwater levels at 846 observation bores at the end of the monsoon were used to interpolate groundwater levels across all canal commands each year using an inverse distance weighted method. A representative groundwater level for each canal command was estimated by averaging all interpolated pixel values within the respective canal command. Subsequently, the annual estimate of post-monsoon groundwater level (one per year per canal command) is linearly regressed against time (2007 – 2019) to obtain an equation for the trend line. A positive slope of the trend line is an indicator of groundwater levels increasing, and a negative slope is an indicator that the groundwater level is declining. Invariably, all linear regression equations will have a slope (unless the trend line is a horizontal line), indicating groundwater rise or fall. Therefore, the regression equation slope is tested statistically using ANOVA to determine if it is significant.

Based on the above, canal commands with a negative slope and a P-value less than 0.05 were confirmed as canal commands where groundwater levels are falling significantly. Canal commands with a positive slope and a P-value less than 0.05 were confirmed as canal commands where groundwater levels are rising significantly. Canal commands with slopes positive or negative, but the P-value is greater than 0.05 were acknowledged as a command where groundwater levels have not changed statistically, and the use is sustainable.

7.1.2 Estimating net recharge in canal commands

Net recharge is the difference between recharge and discharge to the water table. Change in groundwater levels due to net recharge (or net discharge) is a function of the aquifer's specific yield. The level of fluctuation in a year is the slope of the trendline, and the net recharge will be the product of the slope by the specific yield. The effective specific yield of a canal command was determined from specific yield data derived from the lithology logs by

JF Punthakey (Personnel Communication). Specific yield values used to estimate net recharge for canal commands are presented in Table 1.

No.	Canal Command	Specific Yield	No	Canal Command	Specific Yield
1	Abbasia Canal	0.14	14	Lower Pakpattan	0.17
2	Central Bari Doab Canal	0.14	15	Marala Ravi Canal	0.15
3	CRBC	0.15	16	Muzaffargarh Canal	0.16
4	D.G. Khan Canal	0.15	17	Panjnad Canal	0.17
5	Forwah Canal	0.09	18	QaimCanal+ Upper Bahawal Canal	0.15
6	Geater Thal Canal	0.16	19	Rangpur Canal	0.17
7	Haveli Canal	0.18	20	Sadiqia Canal	0.09
8	LBDC	0.19	21	Sindhnai Canal	0.15
9	Lower Bhawal Canal	0.15	22	Thal Canal	0.17
10	Lower Chenab Canal	0.18	23	Upper Chenab Canal	0.18
11	Lower Dipalpur Canal	0.17	24	Upper Dipalpur Canal	0.13
12	Lower Jhelum Canal	0.13	25	Upper Jhelum Canal	0.12
13	Lower Mailsi	0.18	26	Upper Pakpattan Canal	0.18

Table 1: Estimated Specific Yield for Canal Commands

Data used to estimate the specific yield of a canal command is presented in Figure 2. The average specific yield is 0.15, with a standard deviation of 0.03, a maximum of 0.19, and a minimum of 0.09. The specific yields are higher within the river basins than outside, confirming sediment deposition due to river flows.

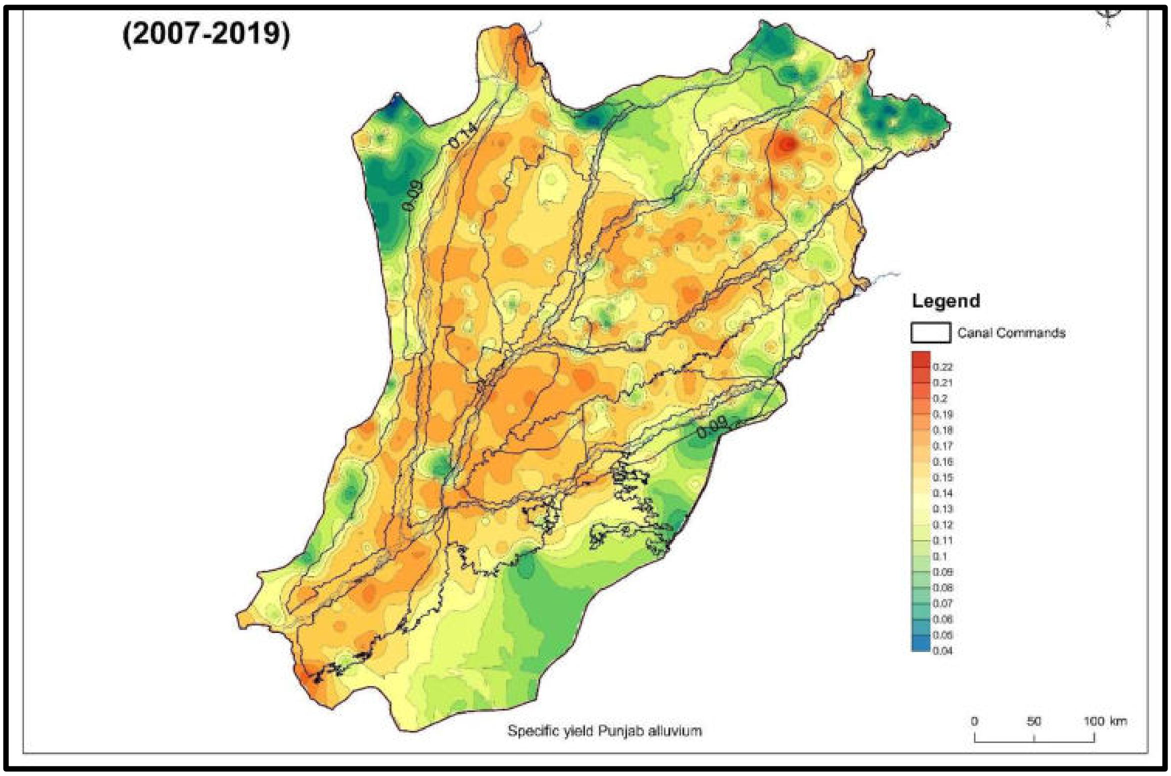

Figure 2: Specific Yield of Punjab Alluvium (JF Punthakey. Pers Corr.)

7.1.3 Identifying Hotspots within canal commands

Considering the vastness of canal commands, it is imperative that locales within canal commands where groundwater decline is significant need to be identified to implement management initiatives to arrest and restore groundwater levels. Areas requiring restoration efforts are referred to as ***Hotspots*** in this report.

Initially, to identify hotspots, post-monsoon groundwater levels from 2007 till 2019 at all piezometers within the canal commands were identified. They constitute 13 observations per piezometer. Subsequently, the average for the 13 years and the deviation from the average for the 13 years for each piezometer were determined. Estimating deviations at each bore independently from other bores eliminated potential biases introduced by variation in topography. Afterward, all deviations (13 per bore) from all bores were pooled and fitted with a normal probability distribution. A decline corresponding to a probability of 0.10 and 0.05 was adopted as thresholds for potential hotspots. Areas showing groundwater decline greater than the threshold in any 13 years is a potential hotspot site. The hotspots identified with $P < 0.05$ need to be considered for rectification as a matter of priority. The hotspots identified between $P < 0.1$ and $P < 0.05$ should be monitored closely, and extraction patterns need to be changed to avoid a structural decline in groundwater levels.

7.1.4 Changes to post-monsoon groundwater levels

Data available for Greater Thal Canal Command is inadequate for statistical analyses. Hence it is excluded from further analysis. Figures illustrating observed post-monsoon groundwater levels, trendline determined for the canal command from annual average, the probability distribution of groundwater level deviation from the mean, and the cumulative probability density function of deviations from the mean for the 25 canal commands are presented in Appendices A, B, C, and D respectively. Tables 2, 3, and 4 summarise the results of canal commands where groundwater levels are falling significantly; canal commands where groundwater levels have not changed significantly since 2007; and canal commands where groundwater levels are rising significantly. Results are graphically presented in Figure 3.

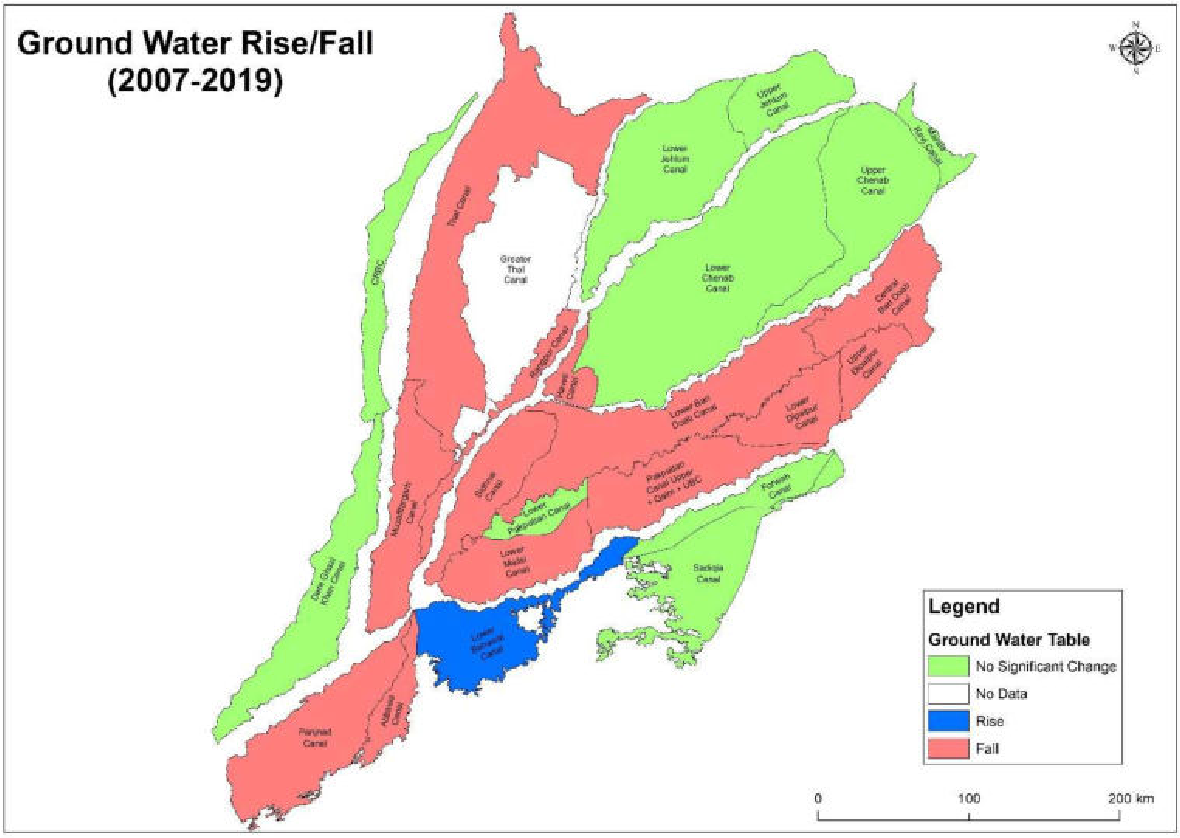

Figure 3: Canal commands with groundwater levels falling, steady, and rising.

No	Name	No of Bores	P	Change m/a	P=0.10	P=0.05
1	CBDC	20	0.0001	-0.24	-1.83	-2.31
2	Sidhnai	47	0.0000	-0.16	-3.77	-4.82
3	Qaim + UBC	8	0.0000	-0.15	-1.35	-1.73
4	Upper Pakpattan	8	0.0000	-0.15	-1.56	-2
5	Panjnad	18	0.0182	-0.14	-1.06	-1.36
6	UDC Multan	4	0.0044	-0.13	-1.11	-1.42
7	LBDC	64	0.0001	-0.13	-1.6	-2.05
8	Rangpur	14	0.0309	-0.11	-0.55	-0.73
9	Haveli	37	0.0054	-0.1	-1.18	-1.51
10	Lower Dipalpur	2	0.0003	-0.1	-0.62	-0.79
11	Abbasia	29	0.0032	-0.09	-0.81	-1.04
12	Lower Maisli	47	0.0413	-0.08	-1.97	-2.52
13	Muzzafargah	29	0.0032	-0.07	-1.07	-1.38
14	Thal	85	0.0155	-0.04	-0.89	-1.14

Table 2: Canal Commands with significant fall in groundwater levels.

Groundwater levels are falling significantly in fourteen canal commands. The low P values of the trendlines informs that the decline in these canal commands is steady over the years. Most of the canal commands where groundwater levels are falling are in the eastern part of Punjab, where the river flow is negligible following the Indus Water Treaty. Despite the water transfers from the western rivers, long stretches of the rivers do not transfer water most of the year, and hence there's no opportunity for them to contribute to recharge.

The decline is severe in CBDC at 0.24 m per annum. The rate of decrease is lowest in the Thal canal command at 0.04 m per annum. However, the lowest threshold values at P<0.05 and P<0.1 (-4.82 m and 3.77 m respectively) were at the Sidhnai canal command, which informs that pockets are within the canal command experience a severe decline. The highest threshold values of deviation from the mean at p< 0.05 and P<0.1 (-0.73 m and -0.55 m) were at Rangpur canal command.

No	Name	No of Bores	P	Change m/a	P=0.10	P=0.05
1	Saddiqia	43	0.0823	-0.04	-0.51	-0.65
2	Lower Pakpattan	9	0.2347	-0.04	-2.52	-3.24
3	DGKhan	38	0.3285	-0.05	-0.93	-1.19
4	CRBC	27	0.1206	-0.03	-0.78	-1.00
5	LJC Sarghodha	87	0.4294	-0.02	-0.58	-0.75
6	MRLC	7	0.6164	-0.01	-0.87	-1.12
7	Upper Chenab	47	0.068	-0.01	-1.55	-1.99
8	Fordwah	48	0.8505	-0.01	-1.31	-1.68
9	LCC Faislabad	47	0.8477	0.01	-1.56	-2.01
10	UJC Sarghoda	41	0.2919	0.04	-0.74	-0.95

Table 3: Canal Commands with non-significant changes to groundwater levels

Ten of the 25 canal commands do not experience a significant change in groundwater levels. Annual changes are ranged between -0.05 m and 0.04 m. Groundwater use patterns in these canal commands may be considered sustainable.

No	**Name**	**No of Bores**	**P-value of trendline**	**Change m/a**	**P=0.10**	**P=0.05**
1	Lower Bahawal	40	0.0007	0.18	-1.43	-1.83

Table 4: Canal Commands with a significant rise in groundwater levels

Only one canal command show a significant rise in groundwater levels, which is adjacent to all five tributaries' confluence to the Indus. However, groundwater levels may be falling in parts of these canal commands that are away from the confluence. It is noted that the piezometers in these canal commands are closer to the confluence, and therefore not necessarily represent areas away from the confluence.

7.1.5 Estimated Net Recharge

Table 5 summarises the estimated annual net recharge (+) and net discharge (-) rates between 2007 and 2019. The mean net recharge is -10.12 mm, with a standard deviation of 12.9 mm. The maximum and the minimum net recharge are 26.10 mm and – 32.4 mm at Lower Bahawal and CBDC commands, respectively. Net recharge in BCM was estimated by multiplying the area with estimated recharge, presented in Table 5. In sum, -0.7943 BCM is the net loss pa within canal commands of Punjab.

No	Canal Command	Slope	Specific Yield	NR (mm/a)	Area (ha)	NR (BCM)
1	Abbasia Canal	-0.09	0.14	-12.78	93078	-0.0119
2	Central Bari Doab Canal	-0.24	0.14	-32.40	202343	-0.0656
3	CRBC	-0.03	0.15	-4.35	97125	-0.0042
4	D.G. Khan Canal	-0.05	0.15	-7.60	364217	-0.0277
5	Forwah Canal	-0.01	0.09	-0.85	174015	-0.0015
6	Geater Thal Canal		0.16	0.00	619170	0.0000
7	Haveli Canal	-0.10	0.18	-17.50	66045	-0.0116
8	LBDC	-0.13	0.19	-24.05	538232	-0.1294
9	Lower Bhawal Canal	0.18	0.15	26.10	218530	0.0570
10	Lower Chenab Canal	0.01	0.18	1.80	1290948	0.0232
11	Lower Dipalpur Canal	-0.10	0.17	-16.50	249853	-0.0412
12	Lower Jehlum Canal	-0.02	0.13	-2.50	615123	-0.0154
13	Lower Mailsi	-0.08	0.18	-14.40	279233	-0.0402
14	Lower Pakpattan	-0.04	0.17	-6.60	121406	-0.0080
15	Marala Ravi Canal	-0.01	0.15	-2.03	64750	-0.0013
16	Muzaffargarh Canal	-0.07	0.16	-10.85	331843	-0.0360
17	Panjnad Canal	-0.14	0.17	-23.45	546326	-0.1281
18	QaimCanal+ UBC + LPC	-0.15	0.15	-22.05	44515	-0.0098
19	Rangpur Canal	-0.11	0.17	-18.92	141640	-0.0268
20	Sadiqia Canal	-0.04	0.09	-3.60	441108	-0.0159
21	Sindhnai Canal	-0.16	0.15	-24.00	346735	-0.0832
22	Thal Canal	-0.04	0.17	-6.70	857934	-0.0575
23	Upper Chenab Canal	-0.01	0.18	-1.75	586795	-0.0103
24	Upper Dipalpur Canal	-0.13	0.13	-16.58	146739	-0.0243
25	Upper Jehlum Canal	0.04	0.12	4.70	218530	0.0103
26	Upper Pakpattan Canal	-0.15	0.18	-26.25	513951	-0.1349

Table 5: Estimated Net Recharge in Canal Commands

7.1.6 Identified hotspots in Canal Commands with a significant decline in groundwater level

Based on the coordinates of piezometers with decline corresponding to $p<0.05$, an average coordinate of hotspot for each canal command is presented in Table 6. Management

interventions for these canal commands may be focussed at or around these locations. Priority should be given to canal commands with steadiest declines, as indicated by the trendline's lowest P-value (Table 2). Based on their coordinates of piezometers corresponding to 0.05< p<0.1, an average coordinates of areas where groundwater use need to be reduced is presented in Table 7.

Summary of Hotspots with p<0.05			
No	Canal	North	East
1	Abbasia	70.82	28.64
2	CBDC	74.20	31.38
3	Haveli	72.11	30.79
4	LBDC	72.50	30.43
5	LPCMultan	72.12	29.88
6	UPCMultan	72.50	30.04
7	UDCMultan	74.36	30.99
8	Sidhnai	71.57	30.03
9	Panjnad	70.52	28.81
10	Muzaffargarh	71.02	29.74
11	Mailsi	71.65	29.62
12	Thal	71.24	31.57
13	Sadiqia	73.39	29.99

Table 6: Coordinates of Hotspots within Canal Commands where decline corresponds to p<0.05

No	**Canal**	**North**	**East**
1	Abbasia	70.77	28.52
2	CBDC	74.21	31.44
3	Haveli	72.08	30.74
4	LBDC	72.60	30.48
5	UPCMultan	72.45	30.05
6	UDCMultan	74.01	30.95
7	Sidhnai	71.42	30.08
8	Panjnad	70.77	28.54
9	Muzaffargarh	70.96	29.79
10	Thal	71.18	31.64
11	Sadiqia	73.35	29.96

Table 7: Coordinates of Hotspots within Canal Commands where decline corresponds to 0.05<p<0.1

7.2 Assessment of Groundwater Use from changes to watertable

An analysis of data collected at 846 piezometers across 25 canal commands of Punjab between 2007 and 2019 has been carried out to determine groundwater use sustainability. Noting that groundwater is used throughout the year, but significant recharge occurs during monsoon, post-monsoon groundwater levels were analyzed to evaluate whether they recover fully during monsoon. Annual average groundwater level values for a period 2007 until 2019 for each canal command were estimated and regressed against time. The slope of the regression line was tested to determine if it is statistically significant.

Results showed that groundwater levels are declining significantly in 14 of the 25 canal commands. Most of the canal commands where groundwater levels are falling are in the eastern part of Punjab, where the river flow is negligible following the Indus Water Treaty. The decline rate is severe in CBDC at 0.24 m per annum; and mild in Thal at 0.04 m per annum.

The regression line slope was multiplied by an effective specific yield and the area to estimate net recharge to groundwater in each canal command. A net decline of 0.7943CM was calculated for all canal commands in the Province.

Additional analyses were carried out to determine hotspots within canal commands where groundwater levels are declining. Two levels of threshold values are estimated, The first at $p < 0.1$ and the second at $p < 0.05$. Groundwater extraction between the thresholds needs to be reduced to prevent unsustainable use in such locales. In areas where groundwater decline is more than the threshold for $p < 0.05$, rectification measures such as managed aquifer recharge needs to be initiated.

7.3 Assessment of Groundwater Use from GRACE and GRACE FO Anomalies

Groundwater monitoring is a fundamental requirement to manage it sustainably. Traditionally, observation wells and piezometers are installed in aquifers of interest, and the groundwater level in them is monitored periodically. The cost of installing, monitoring and processing data is prohibitive, resulting in a lack of groundwater data in space and time. For example, the Province of Punjab has installed over 5000 observation wells within its canal command over the years. However, reliable data is available from 2007 till 2019 and is available only in 846 observation wells. Furthermore, the groundwater level data in regions East, North, and West of the Canal Commands is very sparse and unreliable.

To complement the analysis made with data from observation wells, groundwater anomalies available from the Gravity Recovery And Climate Experiment (GRACE) and GRACE-FO Missions managed by NASA have been used to assess groundwater behavior within the province. The methodology for groundwater assessment involved estimating groundwater storage changes from GRACE satellite data for the study period of 2002 to 2020, only for the month of October, which is the peak post-monsoon month of the region.

Subsequently, groundwater anomalies were extracted for canal commands and three regions: East, North, and West, to the canal commands (Figure 4).

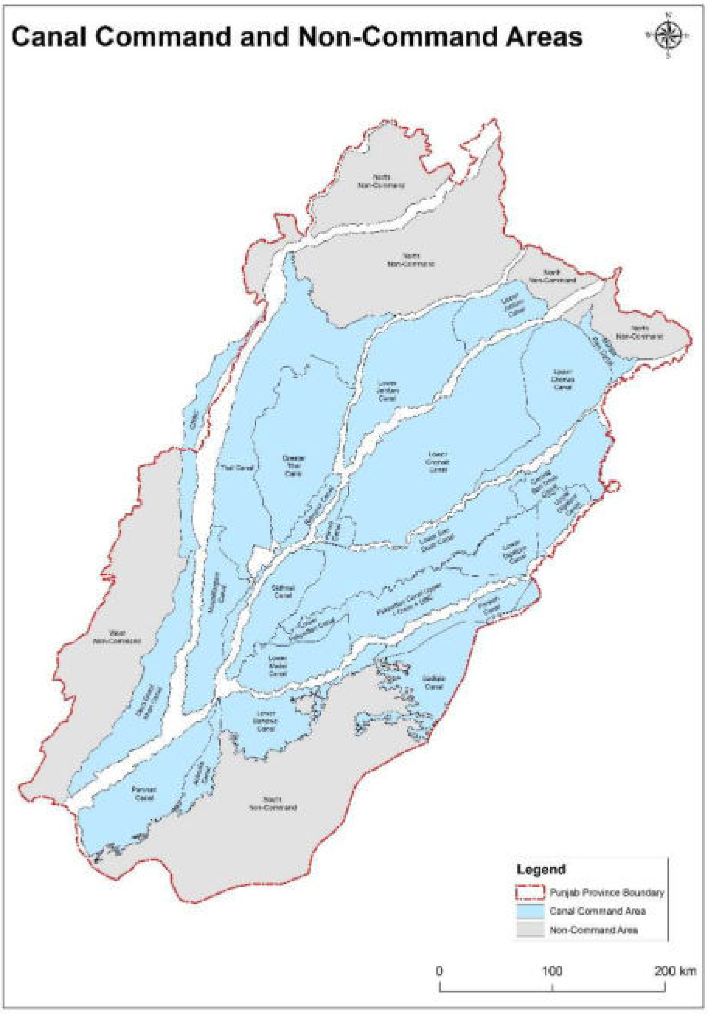

Figure 4: Canal *command, North, West, and East Regions of Punjab, Pakistan.*

No	Region	Area (ha)	Approximate # of MASCONS
1	Canal Command	9170185	30
2	East Region	2017545	7
3	North Region	2785578	9
4	West Region	1441140	5

Table 8: Area and Number of MASCONS in Regions and Canal Commands in Punjab, Pakistan

7.3.1 Terrestrial Water Storage Anomaly (TWS) data from GRACE and GRACE-FO

The Gravity Recovery And Climate Experiment (GRACE) and GRACE Follow On (GRACE-FO) mission data were used to calculate spatiotemporal changes trends in TWS and groundwater (GW) storage across the Province of Punjab in this study.

The GRACE and GRACE-FO mission is combined operation by the National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) of the German Aerospace Agency. The first mission, a pair of GRACE satellites, was launched on March 17, 2002. GRACE is the first and the only remote sensing satellite with the potential of estimating global gravity anomalies, which can be converted to changes in Terrestrial Water Storage (TWS), which is the sum of changes to surface and groundwater on a monthly time scale.

GRACE anomalies show how much the Earth's actual gravity field differs from the gravity field of a uniform, featureless Earth surface. The anomalies highlight variations in the strength of the gravitational force over the surface of the Earth. For example, mountain ranges will usually cause the gravitational force to be more than it would be on a featureless planet — a positive gravity anomaly. Conversely, the presence of ocean trenches or even the depression of the landmass that was caused by the presence of glaciers millennia ago can cause negative gravity anomalies.

The GRACE-FO mission is a successor to the original GRACE mission, which orbited Earth from 2002-2017. GRACE-FO was launched on May 22, 2018, and continues the work of GRACE in tracking water storage changes in terrestrial and groundwater compartments. GRACE-FO carries on the highly successful work of its predecessor while testing a new technology designed to dramatically improve the already remarkable precision of its measurement system on the same principle, with updated technologies.

GRACE satellites work on recording changes in gravitational pull on the satellites due to spatial mass changes on the Earth. At a particular location, the differences between gravitational pull observed after a time interval is due to the change in total mass. Assuming that the mass of solids does not change during the time interval and the mass of gases is negligible, the difference is attributable to the change in TWS. The TWS will comprise changes to snow and glacier deposits, storage in lakes, dams, soils, and aquifers.

In brief, the changes in mass between months (temporal) are primarily attributable to water mass changes. The GRACE team at NASA then convert these results to monthly TWS anomalies after removing a baseline (2004 to 2009) average (Swenson & Wahr 2006; Landerer & Swenson 2012).

Over the years, there have been different processing algorithms for processing raw GRACE data to TWS anomalies. Research units, such as GFZ (Geoforschungs Zentrum Potsdam - Germany), CSR (Center for Space Research at University of Texas, Austin USA), and JPL (Jet Propulsion Laboratory, NASA), have released different solutions of GRACE. JPL has a higher

version of GRACE solutions called Mass Concentration blocks (MASCONS), which have fewer signal leakage errors. These are different gravity field basis functions to which raw GRACE's inter-satellite data are fit. The essential advantage of using the GRACE MASCON solutions includes less noise in data and a more rigorous (Level 2) processing when compared to the empirical approach (Watkins et al., 2015). The MASCONS data also consists of a Coastline Resolution Improvement (CRI) filter with few errors on data sharing boundaries between ocean and land, i.e., coastal regions[6].

These algorithms and data products are used in the current assessment at a spatial resolution of 0.5×0.5° grids (55440 * 55440 m or 307359.4 ha at Lahore) and monthly temporal resolutions. The approximate number of MASCONS for which data is available for the four regions are provided in Table 8. It is to be noted that the shape of the MASCONS and regional boundaries will not overlay exactly on top of each other, resulting in a degree of inclusions or exclusion of surrounding areas.

The algorithms are rigorously tested; however, there are some errors associated with the physical conversions and mathematical models. Hence, scaling coefficients are needed that can incorporate adjustments to the errors. These coefficients were developed by Landerer & Swenson (2012) and the NASA team and recommended using GRACE products to reduce errors. These GRACE scaling coefficients were employed in this study. The scaling factors corrected the GRACE data errors, i.e., leakage errors (caused by GRACE signal leakage from neighboring land and ocean grids) and measurement errors (caused by errors in processing the raw GRACE data).

GRACE MASCON CRI data, available at monthly time scales, in 0.5×0.5° grid-cells format (CRI version RL06), were accessed from the NASA Jet Propulsion Laboratory's GRCTellus Land grids website[7]. The website also had the scaling factors (Landerer & Swenson 2012), which were discussed earlier. The GRCTellus Land grids were multiplied by the corresponding scaling coefficients (also as grids) to estimate TWS. Also, it is recalled that the GRACE data were only available as monthly anomalies with a baseline average (i.e., mean actual monthly TWS from January 2004 to December 2009) removed. The GRACE data processing team defines this baseline period (i.e., January 2004–December 2009), and hence any studies using other data with the GRACE data should incorporate this baseline average. For the current study, data from October 2002 to October 2020 were used.

GRACE-derived TWS includes contributions from snow accumulation, canopy storage, and soil moisture. In addition to groundwater, these are terrestrial components of the mass water balance. Therefore, groundwater storage anomalies were estimated by subtracting these storage components (collectively called Total Soil Moisture (SM) in this study) from the TWS. The storage components other than groundwater were derived from the Global Land Data Assimilations System (GLDAS) 's Land surface models.

[6] https://gracefo.jpl.nasa.gov/mission/grace-tellus/.

[7] https://opendap.jpl.nasa.gov/opendap/GeodeticsGravity/tellus/L3/mascon/RL06/JPL/CRI/contents.html.

7.3.2 Total Soil Moisture (SM) data – GLDAS

The Global Land Data Assimilations System (GLDAS) program was started and maintained to archive information on land and ocean mass fluxes by the NASA's Goddard Space Flight Centre (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) of USA (Rodell et al. 2009). This team uses Land Surface Models (LSMs) to calculate global soil moisture at different spatial and temporal resolutions. It is noted that remote sensing data are used to drive LSMs. Widely used LSM models are NOAH Common Land Model (CLM), Mosaic, and the Variable Infiltration Capacity (VIC) model. In the archive, GLDAS-2.1 NOAH 1.0 degree monthly is generated through temporal averaging of GLDAS-2.1 NOAH 3-hourly data simulated with the NOAH Model 3.3 in Land Information System (LIS) Version 7. The output dataset contains thirty-six parameters from January 2000 to the present.

In this study, NOAH version 2.7.1 was used to estimate soil moisture (SM4) ranging from 0 to 200 cm in depth, snow water (SW), and canopy storage (CS) as equivalent water thickness in mm, which was later converted to cm to be consistent with GRACE data. NOAH was chosen as it was widely used in the Asian Region (e.g., Rodell et al. 2009; Chinnasamy et al. 2013; Chinnasamy 2016). NOAH data (and LSMs) and information on the methodology can be accessed from the Goddard Earth Sciences Data and Information Services Centre[8].

For the current study, NOAH data in a gridded format at relevant spatial and temporal scales (1° grid-cells/monthly resolution) were accessed while the GRACE data was accessed at 0.5°. The total soil moisture (SM) estimates (sum of soil moisture, snow water, and canopy storage) were then converted to an anomaly by subtracting the baseline period (2004 to 2009 monthly average). These SM anomalies will then be deducted from TWS anomaly data to arrive at groundwater storage anomalies.

7.3.3 Groundwater storage (GW)

As per the methodology used in past investigations (e.g., Rodell et al. 2009; Chinnasamy et al. 2013), groundwater storage was estimated as:

$$GW = TWS - SM$$

$$SM = SM4 + CS + SW$$

where TWS is GRACE based terrestrial water storage (cm), SM is GLDAS based total soil moisture (cm), GW is groundwater storage (cm), SM4 is the total soil moisture of four layers (0 to 200 cm), CS is the canopy storage (cm) and SW is the snow water (cm). Since the intent of this study was to study long-term trends, monthly GRACE and GLDAS grids from October 2002 to 2020 were used to estimate GW for each month. Like TWS, the GW data will also be anomalies, with a long-term average (2004 to 2009) removed. Estimates of TWS, SM, and GW were made for each MASCON within each region, and average values of the variables were obtained for each region from respective MASCON values.

[8] https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH10_M_V2.1/summary?keywords=GLDAS.

7.3.4 Results for Canal Commands

The GRACE analysis for the Canal Commands (Figure 5) indicated that for TWS, 2019 had the lowest anomaly (-13.50 cm), and 2015 had the highest (4.30 cm), while for SM, 2016 had the lowest anomaly (-3.44 cm), and 2011 had the highest (8.55 cm). 2020 had the lowest GW anomaly (-16.1 cm), while 2002 had the highest (4.87 cm). Overall, the TWS (-0.68 cm/y) and GW (-0.86 cm/y) decreased while SM increased (0.18 cm/y) between 2002 and 2020. ANOVA on annual GRACE anomalies showed that the decline in TWS and GW were statistically significant ($P<0.05$), but changes in SM were not. Therefore it may be postulated groundwater pumping in excess to recharge from rain and canals has contributed to a decline in groundwater (and TWS).

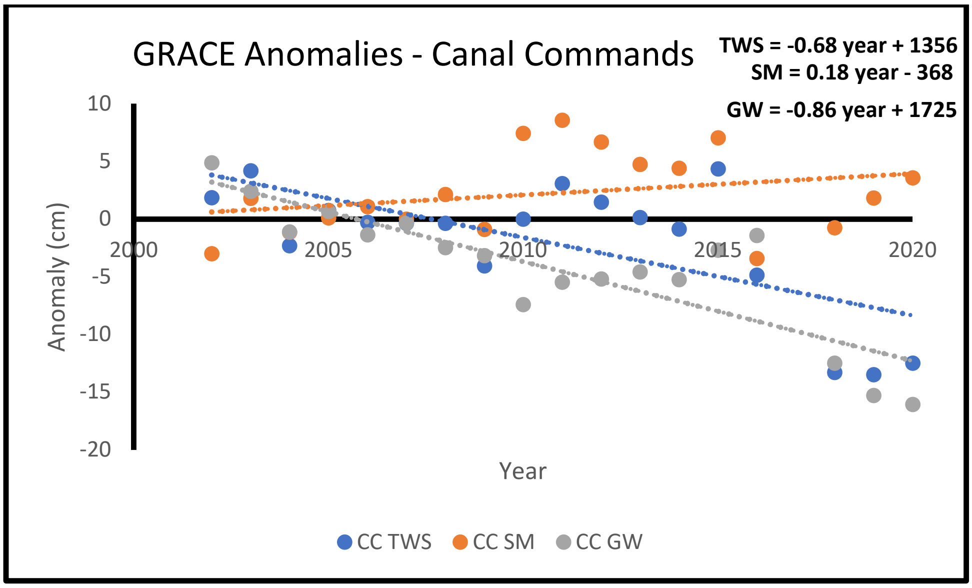

Figure 5: TWS, SM, and GW anomalies (cm) for the canal command, Punjab, Pakistan (2002-2020)

7.3.5 Results for East Region

The GRACE analysis for the Region east of Canal Commands (Figure 6) indicated that for TWS, 2018 had the lowest anomaly (-4.10 cm), and 2011 had the highest (4.41 cm), while for SM, 2002 had the lowest anomaly (-4.86 cm), and 2012 had the highest (9.95 cm). The year 2019 had the lowest GW anomaly (-7.78 cm), while 2002 had the highest (5.09 cm). Overall, the TWS (-0.16 cm/y) and GW (-0.36 cm/y) decreased while SM increased (0.2 cm/y) between 2002 and 2020. ANOVA on annual GRACE anomalies showed that the decline in GW was statistically significant ($P<0.05$), but changes in TWS and SM were not. Low rainfall in this region is inadequate to recharge the aquifer but sufficient to increase soil moisture storage insignificantly.

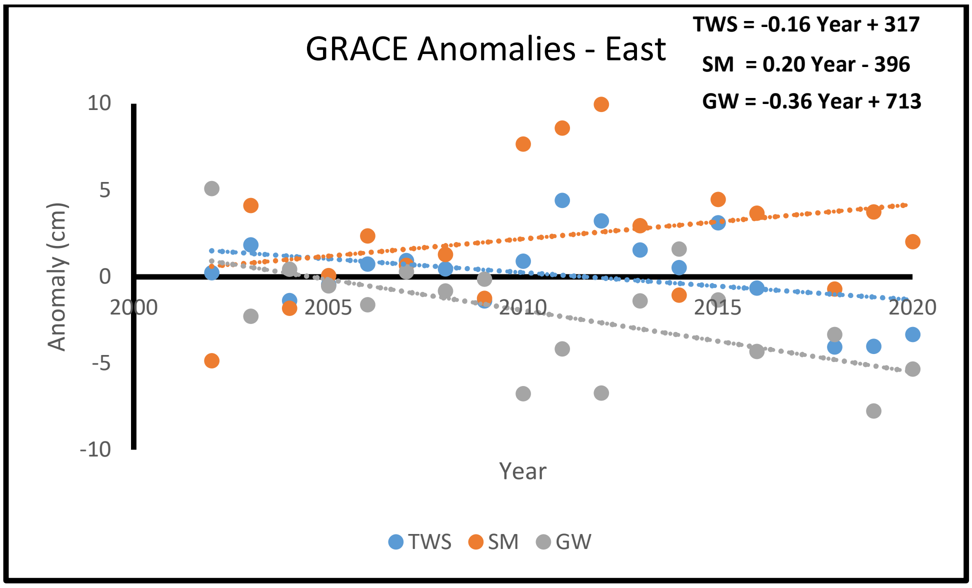

Figure 6: TWS, SM, and GW anomalies (cm) for the East Region, Punjab, Pakistan (2002-2020)

7.3.6 Results for North Region

The GRACE analysis for the North Region (north of Canal Commands) in Figure 7 indicated that for TWS, 2019 had the lowest anomaly (-15.05 cm), and 2015 had the highest (6.47 cm), while for SM, 2009 had the lowest anomaly (-5.46 cm), and 2013 had the highest (8.47 cm). 2020 had the lowest GW anomaly (-20.89 cm), while 2002 had the highest (4.24 cm). Overall, the TWS (-0.79 cm/y) and GW (-1.07 cm/y) decreased while SM increased (0.28 cm/y) between 2002 and 2020. ANOVA on annual GRACE anomalies showed that the decline in TWS and GW were statistically significant ($P<0.05$), but changes in SM were not. A plausible reason for the decline in groundwater is its flow towards canal commands, downstream of the North Region, and lower elevation.

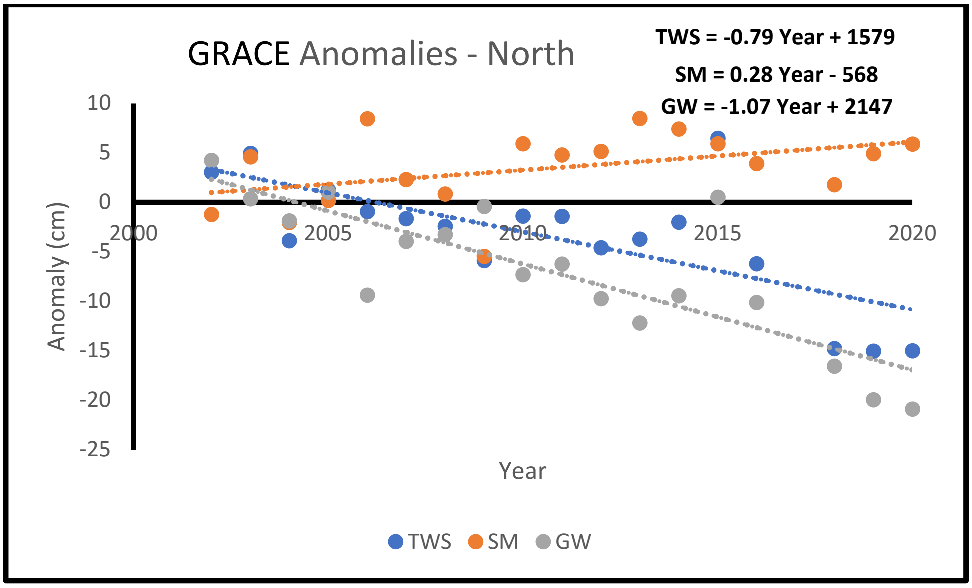

Figure 7: TWS, SM, and GW anomalies (cm) for the North Region, Punjab, Pakistan (2002-2020)

7.3.7 Results for West Region

The GRACE analysis for the Region west of Canal Commands (Figure 8) indicated that for TWS, 2019 had the lowest anomaly (-14.16 cm), and 2015 had the highest (5.74 cm), while for SM, 2002 had the lowest anomaly (-3.19 cm), and 2012 had the highest (11.94 cm). 2020 had the lowest GW anomaly (-16.05 cm), while 2002 had the highest (4.74 cm). Overall, the TWS (-0.66 cm/y) and GW (-0.93 cm/y) decreased while SM increased (0.26 cm/y) between 2002 and 2020. ANOVA on annual GRACE anomalies showed that the decline in TWS and GW were statistically significant ($P<0.05$), but changes in SM were not.

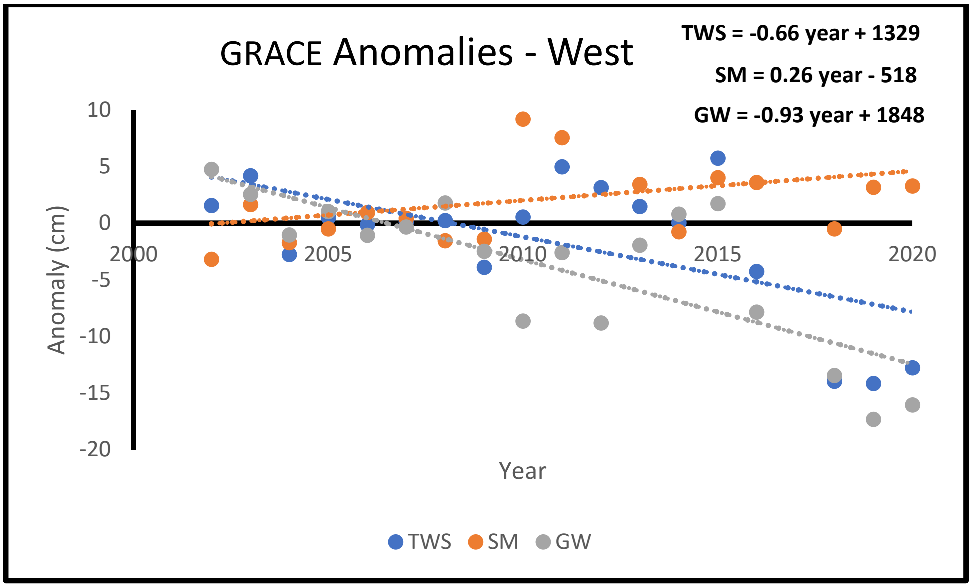

Figure 8: TWS, SM, and GW anomalies (cm) for the West Region, Punjab, Pakistan (2002-2020)

7.3.8 Discussions

A comparison of critical results for the four regions is presented in Table 9.

Parameter	**Canal Command**	**East**	**North**	**West**
Area (ha)	9170185	2017545	2785578	1441140
Max TWS (cm)	4.33	4.40	6.47	5.74
Max TWS Year	2015	2011	2015	2015
Min TWS (cm)	-13.49	-4.07	-15.05	-14.16
Min TWS Year	2019	2018	2019	2019
Max SM (cm)	8.55	9.95	8.47	11.95
Max SM Year	2011	2012	2013	2012
Min SM (cm)	-3.44	-7.77	-5.46	-3.20
Min SM Year	2016	2002	2009	2002
Max GW (cm)	4.87	5.09	4.24	4.74
Max GW Year	2002	2002	2002	2002
Min GW (cm)	-16.07	-7.77	-20.89	-17.33
Min GW Year	2020	2019	2020	2019
Slope TWS (cm/y)	-0.68*[9]	-0.16	-0.79*	-0.66*
Slope SM (cm/y)	0.18	0.2	0.28	0.26
Slope GW (cm/y)	-0.86*	-0.36*	-1.07*	-0.93*
Range TWS (cm)	17.83	8.48	21.52	19.90
Range SM (cm)	11.99	17.72	13.93	15.14
Range GW (cm)	20.93	12.86	25.13	22.07
Rate of change in TWS (BCM/y)	-0.6236	-0.0323	-0.2201	-0.0951
Rate of change in SM (BCM/y)	0.1651	0.0404	0.0780	0.0375
Rate of change in GW (BCM/y)	-0.7886	-0.0726	-0.2981	-0.1340

Table 9: Key Results for the Canal Command and the Regions

7.3.9 Terrestrial Water Storage Anomaly

TWS has declined in all four regions during the study period. The rate of change is highest in the North and the lowest in the East. TWS has fluctuated between the maximum and the minimum in each region, resulting in a range of 17.83 cm, 8.48 cm, 21.52 cm, and 19.9 cm in Canal Command, East, North, and West Regions, respectively. The decline in TWS is statistically significant in all regions except the East. Low rainfall has resulted in the lowest

[9] * indicates statistically significant slopes ($p<0.05$)

range for the East Region. The storage change rate annually is -0.6236 BCM, -0.0323 BCM, -0.2201 BCM, and -0.0951 BCM in Canal Command, East, North, and West Regions.

7.3.10 **Soil Moisture Anomaly**

SM has fluctuated between the maximum and the minimum in each region, resulting in a range of 11.99 cm, 17.72 cm, 13.93 cm, and 15.14 cm in Canal Command, East, North, and West Regions, respectively. SM has increased in all four regions during the study period. The rate of change is highest in the North and the lowest in the Canal Command. Although the slope was positive in all regions, the rise is not statistically significant. Possible reasons for the positive slope include an increase in the unsaturated zone due to the decline in groundwater levels and lower depths of the unsaturated zones remaining closer to saturation. The storage change rate annually is 0.1651 BCM, 0.0404 BCM, 0.0780 BCM, and 0.0375 BCM in Canal Command, East, North, and West Regions.

7.3.11 **Groundwater Anomaly**

GW has declined in all four regions during the study period. The rate of change is highest in the North and the lowest in the East. GW has fluctuated between the maximum and the minimum in each region, resulting in a range of 20.93 cm, 12.86 cm, 25.13 cm, and 22.07 cm in Canal Command, East, North, and West Regions, respectively. GW has declined significantly in all regions. The storage change rate annually is -0.7886 BCM, -0.0726 BCM, -0.2981 BCM, and -0.1340 BCM in Canal Command, East, North, and West Regions.

The annual rate of storage change estimated by Prathapar et al. 2021 using observed-well data between 2007 and 2019 for the Canal Command is 0.7943 BCM, which is very close to the estimate using GRACE anomalies (0.7886).

Both GRACE data and observation-well data estimated groundwater decline in 22 canal commands and groundwater level rise in three canal commands. However, GRACE estimated that the decrease in all 22 canal commands is statistically significant, whereas the observation-well data estimated only 14 of the canal commands had a statistically significant decline. Furthermore, the observation-well data estimated a statistically significant rise in one of the three canal commands. In contrast, GRACE estimated none of the three had a significant increase in groundwater levels.

Hence, it may be appropriate to use GRACE Anomalies for a region where observed groundwater level data are unavailable to understand changes to groundwater storage.

7.3.12 **Correlation among anomalies in each region**

Statistical correlation among the three anomalies, TWS, SM, and GW, is presented in Table 10.

	East TWS	East SM	East GW	North TWS	North SM	North GW	West TWS	West SM	West GW	CC TWS	CC SM	CC GW
East TWS	1.00											
East SM	0.52	1.00										
East GW	0.11	-0.79	1.00									
North TWS				1.00								
North SM				0.01	1.00							
North GW				0.85	-0.51	1.00						
West TWS							1.00					
West SM							0.21	1.00				
West GW							0.80	-0.42	1.00			
CC TWS										1.00		
CC SM										0.32	1.00	
CC GW										0.79	-0.33	1.00

Table 10: Correlation among anomalies

Following inferences can be made from the correlation analysis. In the East, the TWS anomaly is strongly correlated to the SM anomaly (Pearson Correlation Coefficient is 0.52). Low rainfall in this region is inadequate to recharge the aquifer but sufficient to vary soil moisture storage. The correlation between TWS and GW anomaly in the East is very poor, informing minimal groundwater development in the East. In the North (Pearson Coefficient 0.85), the West (Pearson Correlation Coefficient is 0.8), and in the Canal Command (Pearson Correlation Coefficient is 0.79), the TWS anomaly is strongly correlated to GW anomaly. Among correlation, the correlation between TWS and SM is weaker than the others. Therefore, the TWS anomalies may be used as surrogates to estimate changes in SM in the East and changes in the GW in North, West, and the Canal Commands.

7.4 Changes in TWS within Canal Commands

TWS anomalies are available at 0.5^o by 0.5^o (approximately 55 km by 55 km at the study site), and data necessary to estimate SM to be used in GLDAS is drawn from five data sets with a spatial resolution of 1^o by 1^o (approximately 111 km by 111 km). On the other hand, the canal commands are not ***square***. Hence the spatial units at which data available from GRACE and for GLDAS do not neatly fit with the shape of the canal commands. Hence, further data processing to downscale and interpolate SM and GW at the Canal Command level will introduce mathematical artifacts. Therefore, in the following analysis, we have determined changes to TWS only at the centroid of each canal command. Subsequently, we

have determined the linear regression line of TWS at centroids of each canal command and tested whether the slope is significantly different to zero.

Results are presented in Table 11. TWS has declined significantly in all canal commands, except in Chasma Right Bank Canal, Panjnad, and Thal. In these three canal commands, TWS has increased insignificantly.

Canal Name	***02***	***03***	***04***	***05***	***06***	***07***	***08***	***09***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***18***	***19***	***20***	***Slope***	***P***	***F/R***	***S/NS***
Abbasia	1.6	4.1	-2.2	0.5	-0.1	0.0	0.1	-3.6	0.4	4.3	2.7	1.2	-0.2	5.0	-4.0	-12.7	-12.9	-11.7	-0.62	0.01	F	S
Central Bari Doab	19.9	26.6	9.4	10.5	0.3	-5.6	-5.6	-17.1	-8.1	-10.4	-13.4	-18.8	-25.8	-16.4	-35.6	-60.5	-62.6	-63.8	-4.52	0.00	F	S
Chasma Right Bank	-2.3	-2.3	-3.6	-0.6	-1.6	-0.7	-0.7	-1.7	0.0	0.0	0.9	0.3	1.2	1.3	-1.4	-1.7	-1.5	-0.8	0.10	0.09	R	NS
Dera Ghazi Khan	2.1	5.4	-2.9	0.7	-0.1	0.0	0.1	-4.7	0.5	5.7	3.6	1.6	-0.2	6.6	-5.2	-16.7	-17.0	-15.4	-0.82	0.01	F	S
Fordwah	1.2	1.7	0.6	0.7	0.0	-0.3	-0.4	-1.1	-0.5	-0.6	-0.8	-1.2	-1.6	-1.0	-2.2	-3.8	-3.9	-4.0	-0.28	0.00	F	S
Greater Thal	5.0	12.5	-6.7	1.6	-0.2	-0.1	0.3	-11.0	1.2	13.3	8.3	3.7	-0.5	15.4	-12.2	-38.9	-39.5	-35.9	-1.90	0.01	F	S
Haveli Canal	1.7	4.2	-2.3	0.5	-0.1	0.0	0.1	-3.7	0.4	4.5	2.8	1.3	-0.2	5.2	-4.1	-13.1	-13.3	-12.1	-0.64	0.01	F	S
Lower Bahawal	1.7	4.2	-2.3	0.5	-0.1	0.0	0.1	-3.7	0.4	4.5	2.8	1.2	-0.2	5.1	-4.1	-13.0	-13.2	-12.0	-0.64	0.01	F	S
Lower Bari Doab	1.7	4.2	-2.3	0.5	-0.1	0.0	0.1	-3.7	0.4	4.5	2.8	1.3	-0.2	5.2	-4.1	-13.1	-13.3	-12.1	-0.64	0.01	F	S
Lower Chenab	1.9	4.8	-2.6	0.6	-0.1	0.0	0.1	-4.2	0.5	5.1	3.2	1.4	-0.2	5.9	-4.6	-14.8	-15.0	-13.7	-0.72	0.01	F	S
Lower Dipalpur	1.2	1.7	0.6	0.7	0.0	-0.3	-0.4	-1.1	-0.5	-0.6	-0.8	-1.2	-1.6	-1.0	-2.2	-3.8	-3.9	-4.0	-0.28	0.00	F	S
Lower Jhelum	1.8	2.9	-2.3	0.7	-0.5	-0.9	-1.4	-3.4	-0.8	-0.8	-2.7	-2.2	-1.2	3.8	-3.6	-8.6	-8.7	-8.7	-0.46	0.00	F	S
Lower Mailsi	1.7	4.2	-2.3	0.5	-0.1	0.0	0.1	-3.7	0.4	4.5	2.8	1.2	-0.2	5.1	-4.1	-13.0	-13.2	-12.0	-0.64	0.01	F	S
Lower Pakpattan	1.7	4.2	-2.3	0.5	-0.1	0.0	0.1	-3.7	0.4	4.5	2.8	1.2	-0.2	5.1	-4.1	-13.0	-13.2	-12.0	-0.64	0.01	F	S

Marala Ravi	6.2	10.1	-7.9	2.5	-1.9	-3.3	-4.9	-12.0	-2.8	-2.9	-9.3	-7.6	-4.1	13.2	-12.6	-30.1	-30.7	-30.6	-1.60	0.00	F	S
Muzafffargarh	2.1	5.4	-2.9	0.7	-0.1	0.0	0.1	-4.7	0.5	5.7	3.6	1.6	-0.2	6.6	-5.2	-16.7	-17.0	-15.4	-0.82	0.01	F	S
Upper Pakpattan + Qaim + UBC	1.7	4.2	-2.3	0.5	-0.1	0.0	0.1	-3.7	0.4	4.5	2.8	1.3	-0.2	5.2	-4.1	-13.1	-13.3	-12.1	-0.64	0.01	F	S
Panjnad	-0.4	1.2	-1.2	-1.0	1.3	1.6	0.7	-0.7	1.3	5.3	4.1	2.0	0.9	2.8	0.7	-0.9	-0.7	-0.1	0.02	0.80	R	NS
Rangpur	1.7	4.2	-2.2	0.5	-0.1	0.0	0.1	-3.7	0.4	4.4	2.8	1.2	-0.2	5.1	-4.1	-12.9	-13.1	-11.9	-0.63	0.01	F	S
Sadiqia	0.4	0.9	-0.5	0.1	0.0	0.0	0.0	-0.8	0.1	1.0	0.6	0.3	0.0	1.1	-0.9	-2.9	-3.0	-2.7	-0.14	0.01	F	S
Sidhnai	1.7	4.2	-2.2	0.5	-0.1	0.0	0.1	-3.7	0.4	4.4	2.8	1.2	-0.2	5.1	-4.1	-12.9	-13.1	-11.9	-0.63	0.01	F	S
Thal	-2.3	-2.3	-3.5	-0.6	-1.6	-0.7	-0.7	-1.6	0.0	0.0	0.9	0.3	1.2	1.3	-1.4	-1.7	-1.5	-0.8	0.09	0.09	R	NS
Upper Chenab	2.4	3.9	-3.0	1.0	-0.7	-1.3	-1.9	-4.6	-1.1	-1.1	-3.6	-2.9	-1.6	5.0	-4.8	-11.5	-11.7	-11.7	-0.61	0.00	F	S
Upper Dipalpur	9.4	12.6	4.5	5.0	0.1	-2.6	-2.7	-8.1	-3.9	-5.0	-6.4	-8.9	-12.2	-7.8	-16.9	-28.7	-29.7	-30.3	-2.14	0.00	F	S
Upper Jhelum	1.6	2.6	-2.1	0.7	-0.5	-0.9	-1.3	-3.1	-0.7	-0.8	-2.5	-2.0	-1.1	3.5	-3.3	-7.9	-8.0	-8.0	-0.42	0.00	F	S

Table 11: TWS Anomalies (cm) at Centroids of Canal Commands

7.5 Potential use of GRACE and GRACE FO in Punjab

In many regions for Pakistan and Punjab in particular, the cost of installation and periodic monitoring of groundwater levels is prohibitive, resulting in a lack of historical groundwater data in space and time. An alternative means to measure changes to groundwater storage is to use GRACE Anomalies. The GRACE and GRACE-FO mission is combined operation by the National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum für Luft- und Raumfahrt (DLR) of the German Aerospace Agency. GRACE is the first and the only remote sensing satellite with the potential of estimating global gravity anomalies, which can be converted to changes in Terrestrial Water Storage (TWS), which is the sum of changes to surface and groundwater on a monthly time scale. The GRACE-FO mission, launched on May 22, 2018, is a successor to the original GRACE mission, which orbited Earth from 2002-2017.

This study explored the potential to use GRACE gravity anomalies to monitor historical changes to Terrestrial Water Storage (TWS), Soil Moisture (SM), and Groundwater (GW) behavior in the Punjab Province of Pakistan.

Results are compared with results obtained from observation-well data within canal commands. The comparison showed that estimates of Net Recharge for the canal command from o-well data (0.7943 BCM/y) and GRACE data (0.7886 BCM/y) are very similar. Both GRACE data and observation-well data estimated groundwater decline in 22 canal commands and groundwater level rise in three canal commands.

There is a strong correlation between TWS anomalies and Groundwater Anomalies within the canal command. Hence, TWS anomalies may be used as a surrogate for Groundwater anomalies when data from observation wells are unavailable to monitor groundwater behavior.

Primary advantages of using GRACE anomalies to assess groundwater storage are:

- Data obtainable from remote, inaccessible regions
- Data available at regular spatial and temporal resolutions
- Inexpensive

Disadvantages are:

- Coarse spatial resolution. Specialized training of staff may overcome this limitation. Typically, TWS data is readily downloadable at a spatial scale of 3^o by 3^o. In this study, we have processed GRACE data at 0.5^o resolution, which requires the necessary processing skills.

8 Principles adapted to Allocate Water in Punjab

8.1 Sustainable Use of Water

We propose to allocate water within total water available sustainably, from rainfall and canals. Groundwater is excluded because it is recharged by rain and Canal water and recycled. We consider aquifers as are underground reservoirs, (1) able to recycle recharging rain and canal water, seasonally and annually (2) meet seasonal or annual water deficits due to climate variation. This implies that the groundwater levels may fluctuate due to seasonal or annual climate variability but not decline significantly during a reasonable period.

8.2 Balancing supply and demand

For prioritized sectors, seasonal and annual demands will be estimated, the allocation will be made in priority. The potential for reuse of water will also be factored as potential supplies for the subsequent sectors. For example, treated wastewater from domestic and industrial sectors will be considered as potential supplies for Agriculture.

8.3 Development priorities

The Government's plans to promote economic and social development will be given priority during allocation assessments. For example, priority will be given to Lahore's request for canal water and water required for cooling towers of proposed power plants.

8.4 Equity

Equity implies allocating water in a way that is fair and equitable amongst different canal commands. A general water balance assessment for canal commands shows that domestic, industrial, livestock, and environmental demands can easily be met with available rain and canal water. However, the remaining fresh water in canal commands and the water available for reuse are insufficient to meet crop water requirements.

In this study, two alternative objectives will be considered. The first is to allocate the same depth of water per unit area in each canal command for agriculture after meeting domestic, industrial, livestock, and environmental demands irrespective of cropping patterns. This is consistent with PID's mandate and is the basis of *warabandi*. The second is to permit the same depth of crop water stress in all canal commands based on cropping patterns.

8.5 Methodology for Water (Re) Allocation

Spatial units for water allocation will be (1) Canal Commands, (2) Pothwar, (3) Thal, (4) Cholistan deserts, (5) Suleiman ranges, and (6) riverine areas. Water demands for domestic, industrial, livestock, agriculture, and the environment (groundwater decline) in each selected region will be estimated from primary and secondary data. Concurrently, total water available for each region from rainfall and canal water will also be estimated from secondary sources.

For areas outside the canal commands, the total available water will be estimated from rainfall and the capacity to store rainwater on the surface (surface storages) or in the aquifer. The smallest of the two (adequate rainfall or storage) will determine the water available for allocation.

9 Assessing Demand in Canal Commands

9.1 Domestic Demand

Administratively, Punjab is divided into 9 Divisions, 36 Districts and 145 Tehsils. Tehsil-wise demand based on latest water supply criteria by Govt. of Punjab based on population is given in Appendix E. District-wise and Tehsil-wise Demand based on population (Census 2017) and Canal Command- wise and tehsil-wise domestic demand are given in Appendix E

Groundwater is the primary water source for domestic water. There are 25 Tehsils where groundwater quality is unacceptable and where surface supplies are needed. In another 38 tehsils, a combination of groundwater and surface water is required. In the remaining 45 tehsils, groundwater is available for domestic supply on a long-term basis, and in the remaining 38 tehsils, groundwater is available presently in the short term. A fraction of water supplied for domestic requirements will become wastewater and is expected to be reused by other sectors after appropriate treatment. This fraction will be referred to as Returned Domestic Waster Water Fraction (RDWWF).

9.2 Industries

Four RLNG based Punjab Government-owned Combined Power Plants, namely Haveli Bahadar Shah (1230 MW), Balloki Power Plant (1230 MW), Qaid e Azam Power Plant (1180 MW), and Punjab Power Plant(1263 MW), have placed a demand of 800, 800, 645 and 817 cusecs for Haveli Bahadar Shah (HBS), Balloki, Qaid e Azam and Punjab Power Plant respectively. Trimmu-Sidhnai Link (TS Link) is supposed to supply 800 each to HBS and Balloki, 817 cusecs to Punjab Power (800 + 800 +817), and 645 cusecs by Qadirabad- Balloki Link (QB Link) to Qaid e Azam Power Plant.

The water will be used for cooling and returned to canals at a downstream at higher temperatures with some evaporation losses. National Power Parks Management Company Limited (NPPMCL), owned by the Government of Pakistan, owns HBS and Balloki Power Plants and Energy Dept; the Government of Punjab owns the other two Plants. NPPMCL has already signed an agreement with the Government of Punjab, and the water use tariff is determined. It is expected that similar demand may be forthcoming from private sector power plants.

The industrial demand data, which primarily relies on groundwater by other sectors, is generally not available. World Bank Report (Young 2017) estimates total country demand at less than one BCM. Another report (Amer, 2017) puts this at 8.5% (103/1211 BCM)of total demand using neighboring India's industrial data. Census (2005-2006) gives Punjab share at 56% of Industries for over 3550 industrial units out of 6339 units, which is shared by Lahore (774 units), Gujrat (190), Sheikhupura (229), Faislabad (418), Gujranwala (440), Sialkot (215), Kasur (158), Multan (116), Bahawalpur (114), and Rahimyarkhan (106). WWF (2014) estimated groundwater abstraction for industrial water use for Lahore at 0.92 MCM per day.

Commercial and institutional sectors use another 0.76 MCM per day. The total industrial and commercial water use for 300 working days per annum, for 6339 units is ((0.92+0.76)*300/774*6339 = 4.127 BCM. District-wise industrial water use based on the above methodology is given in Appendix E.

9.3 Livestock Demand

The livestock demand is based on the livestock Census of 2005 for each district with unit consumption rates for different animal types (horses, cattle, sheep, poultry, etc.). The livestock water demand in Canal Command areas was estimated proportionally and is given in Appendix E. Water provided for livestock is assumed to have 'consumed', and none is expected to return for reuse in other sectors.

9.4 Crop Water Requirement

Punjab canal irrigated area is about 22.6 m acres fed through 26 Canal Commands, including Chasma Right Bank Canal (CRBC) and Greater Thal Canal, through a contiguous network system. Initial estimates of Crop water demand for the 26 Canal Commands were assessed for three years; 2015-2016, 2016-2017, and 2017-2018. Monthly crop water requirements for Kharif (October-March) and Rabi (April-September) for each of the three years were calculated using the Penman-Monteith equation (FAO56). Crop data was obtained from published Crop Reporting Service(P&D Dept., GOPjb) data for each Punjab District for the three years. It was proportionally distributed through GIS overlay to Canal Command Areas based on a percentage of Canal command area lying in each district. The CCAs of Canal Commands with CCA and its distribution in each district are shown in Appendix B, C, and D (Volume 2) Crop coefficients used were based on G1-G10 canal categorization by PCRWR-FAO study (19…) for Punjab based on agro-climatic zonation. Climatic parameters (min, max temperature, relative humidity, wind speed, cloud cover, sunshine hours, rainfall) for 40 meteorological stations in Punjab were obtained from PMD, SUPARCO, and international websites. The data used for some selected stations is shown in Appendix B, C, and D.

The total cropped area for the three years 2015-16, 2016-17, and 2017-18 was 13.91 (34.4), 12.97 (32.05) and 13.21 (32.64) m-ha (m-ac), respectively. The Kharif:Rabi ratio for these years was 6.31:7.6 (15.6:18.79), 6.16:6.8 (15.25:16.80) and 6.28:6.93 (15.53:17.11) m-ha (m-ac) respectively. Since crop area is reported District-wise, included non-command areas, they excluded with the help of satellite images. Still, the cropped area shows a marked increase over the previous three decades, probably due to the recycling of canal water through aquifers. A 1993-94 study by IWMI calculated total cropped area as 11.08 m-ha (26.64 m-ac) with Kharif:Rabi ratio of 5.54:5.54 (13.32:13.32) m-ha (m-ac) with cropping intensities also registering a marked increase. Almost all increase came in the wheat crop whose area increased from 3.38 mha in 1993-94 (IWMI) to 5.56 mha in 2017-2018 (Appendix D) which is also reflected in increased wheat production from 11.22ln tons to

19.18 mln tons in 2017-2018 (www.aims.pk). Groundwater supplies also accounted for an increase in per hectare yield of wheat crop.

Based on the above crop areas, the total crop water requirements for each of the three years were calculated as 83.1 (67.42), 81.4 (65.99), and 83.41 (67.62) BCM (MAF), respectively. The Kharif-Rabi requirement in each year was calculated as 40.13:20.80 (32.53:16.87), 44.88:19.65 (36.39:15.93) and 43.81:16.60(35.51:13.46) BCM (MAF) respectively. The Canal-wise crop areas and CWR is shown in Appendix B, C, and D. A Summary of estimates showing Eto and Etc depths of each Canal Command for three years is shown in the above Appendices.

Subsequently, initial estimates of crop water requirements were calibrated to ensure that the final estimates meet fundamental principles of water balance. More credence was given to monitored data (rainfall, change in groundwater levels, and canal supplies) than estimated agricultural demand, underlained by several assumptions.

9.5 Environment

Demand for the environment includes waters required for maintaining min environmental flows in rivers, channels, streams, etc., to maintain its ecology. Under IWT, River Ravi and Sutlej were allocated to India, and since the construction of Thein Dam on Ravi and Hakra dam on Sutlej by India, the flows in these rivers have drastically reduced. Besides, industrial and sewage discharge within Pakistan and India have further aggravated these rivers' ecology. Pakistan also has one of the world's highest diversions for its rivers, which adversely affect the river ecology.

Despite a lack of estimation of environmental flows within Punjab's Rivers, it is noted that they carry water for Sindh. At this stage, it is assumed that flow in Punjab's rivers at critical nodes (dams and barrages) exceeds the environmental flows at these nodes, except north of Balloki and Sulemanqi barrages, because of the Indus Water Treaty. MAR structures to capture opportunistic floods between the Indian Border and the respective barrages need to be considered.

The municipal wastewater discharged into rivers/channels in Punjab is 111.5 m3/s, equal to 3.5 BCM annually (WCAP, 2011). The industrial wastewater being discharged into irrigation channels/drains in Punjab is 13.59m3/s (WCAP, 2011), equal to 0.353 BCM annually.

10 Assessing Water Availability in Canal Commands

10.1 Canal Water Supplies

Canal supplies for the three years on 10-daily basis was obtained from PID for all 26 Canal Commands (including CRBC and Greater Thal Canal). They were summed up on a monthly basis, and supplies were computed for each Canal Command for Kharif and Rabi seasons. The total canal supplies in the three years were 60.94 (49.41), 64.53 (52.32) and 60.41 (48.97) BCM (MAF), respectively. The Kharif : Rabi supplies were 40.13:20.81(32.53: 16.87), 44.88:19.64(36.39:15.93) and 43.81:16.6(35.51:13.36) BCM(MAF) respectively.

A Summary of canal supplies depth (volume/CCA) for each canal is shown in Table 12. For the three years studied, the average annual allocation is 64 BCM, while the allocation to Punjab vide the Water Apportionment Accord is 69 BCM. Hence average canal water supply for each canal command was multiplied by 69/64, to make water available consistent with the Accord without changing the existing proportionality.

10.2 Effective Rainfall

Monthly rainfall data for each of the three years was obtained from SUPARCO for each of the 40 PMD weather stations. The canal command area was assigned proportionally to the respective weather station falling in the same district. The total rainfall received within the canal command is approximately 33.9 BCM per annum.

Effective rainfall was estimated using two methods. The first is a modified SCS method, assuming 10% of the total rainfall is unavailable due to interception losses, and a fraction equal to a runoff coefficient has left the canal command. The assumed runoff coefficient for CBDC, Haveli, LCC, LJC, MRC, UCC, UDC, and UJC was 0.43. For the remaining canal commands, the assumed runoff coefficient was 0.37[10]. This results in a total rainfall available for use and consumption to be approximately 16.81 BCM per annum.

The second method was based on the USDA Method, assuming 5% interception losses, and 10% run off, when monthly rainfall exceeded 80 mm. For the three years, Effective Rainfall (Re) was computed as 14.83(12.03), 12.63(10.24) and 9.88 (8.01) bcm (maf), respectively.

The results are summarized in Appendix A.

[10]Shereif Mahmoud and Alazba. 2015. Hydrological Response to Land Cover Changes and Human Activities in Arid Regions Using a Geographic Information System and Remote Sensing. Article in PLoS ONE · April 2015. DOI: 10.1371/journal.pone.0125805 · Source: PubMed

10.3 Groundwater

Prathapar[11] et al. (2021) determined the sustainability of groundwater use in Punjab's Irrigation Canal Commands. The study showed that groundwater levels are declining significantly in 14 of the 25 canal commands. The decline rate is highest at CBDC (-0.24 m/y), the lowest in Thal (-0.04 m/y) canal command. The estimated annual net discharge for all canal commands is 0.7943 BCM. Using an independent methodology using GRACE anomalies, Chinnasamy and Prathapar (2021)[12] estimated the net groundwater discharge as 0.7886 BCM per annum. (Appendix J)

In comparison to our estimates, as reported in section 2.3 of this report, ACE et al. (2011) reported negligible net discharge, and an Anonymous source reported a net discharge of 2.5 BCM for Punjab. Concurrently, Young et al. 2019 reported 1 BCM net discharge for IBIS.

Prathapar et al. (2021) identified two levels ($P<0.1$ and $P<0.05$) of threshold values of groundwater decline for each canal command. Groundwater extraction at sites between the thresholds needs to be reduced to prevent unsustainable use. In areas where groundwater decline is more than the threshold for $p < 0.05$, rectification measures such as managed aquifer recharge needs to be initiated.

Although the above analysis addressed net changes to groundwater levels, in reality, aquifers are recharged continuously by canal seepage and rainfall while discharged continuously due to groundwater pumping and water table evaporation.

Total required groundwater abstraction for agriculture use (assuming crop water requirements are fully met) has been computed by subtracting the sum of total canal supplies and effective rainfall (estimated by the second method) from total crop water requirements. Total system losses have been assumed at 61.75% (canal and distribution system 16.75%, watercourses 20%, field application 25%). Additionally, 4.1% of system losses have been assumed as non-beneficial losses.

Consequently, the total required groundwater abstraction for the three years is 45.42 BCM (36.82 MAF), 44.52 BCM (36.09 MAF), and 50.80 BCM (41.19 MAF), respectively. The Kharif: Rabi fractions of the totals are 37.39 & 8.03 BCM (30.31 & 6.5 MAF), 36.56 &7.96 BCM (29.64&6.45 MAF) and 40.31 &10.49 BCM (32.68&8.51 MAF), respectively. Accounting for domestic, industrial, and livestock demand, the total abstraction is 41.81, 41.08, and 46.18 MAF. Canal-wise distribution of abstraction for the three years is given in Appendix A.

Suppose all crop water requirement has to be met, the net required groundwater withdrawal will be 10.88 BCM (8.33 MAF, and 7.8 BCM (6.32 MAF) and 16.38 BCM (13.28 MAF). The fractions of Kharif & Rabi ratio will be 8.19 &2.79 BCM (6.56 &2.27 MAF), 10.73

[11] S.A. Prathapar, Bahaudin Hashmi, Mansoor Hashmi and Muhammad Arslan. 2021. Determining Sustainability of Groundwater Use in Punjab's Irrigation Canal Commands. A Statistical Assessment. Report submitted to PID as a part of the Water Allocation Study.

[12] P. Chinnasamy and S.A. Prathapar (2021). Assessing Changes To Groundwater Storage Using Grace Anomalies: A Case Study for Punjab, Pakistan.

& -2.93 BCM (8.68 & -2.37 MAF) and 15.08 & 1.32 BCM (12.23 & 1.05 MAF) respectively. Accounting for domestic, industrial, and livestock, the net abstraction is 13.82, 11.32, and 18.29 BCM.

11 Water Balance/Surplus and Deficits

11.1 Canal Commands

Estimated water balance components for the 26 canal commands are presented in Table 12. The CCA of Greater Thal, Marala Ravi, and Upper Chenab Canal were reduced to 104361, 33010, and 510402 ha from their design values of 619170, 64750, 586795 ha, respectively, to reflect the area served with canal water.

Effective rainfall estimated by the SSCS method and the USDA method is reported in Table 12. The simplified SCS method assumes that 10% of the total rainfall is unavailable due to interception losses, and a fraction equal to a runoff coefficient has left the canal command. The assumed runoff coefficient for CBDC, Haveli, LCC, LJC, MRC, UCC, UDC, and UJC was 0.43. For the remaining canal commands, the assumed runoff coefficient was 0.37. The estimated effective rainfall is considered available within respective canal commands to meet various demands. The s USDA Method assumes 5% interception losses and 10% runoff when monthly rainfall exceeded 80 mm. Effective rainfall is then drawn from a Table available on the FAO website[13]

The average rainfall for the canal commands is 379 mm, which ranges between104 mm and 983 mm. The Gini Coefficient, which is a measure of statistical dispersion within the group, is 0.36.

The Effective Rainfall estimated by the USDA method is considerably lower than the estimate obtained with the SSCS method. The estimated mean effective rainfall from the SSCS and USDA methods is 188 (~50% of Gross Rainfall) and 123 (~33% of Gross Rainfall) mm respectively. The Gini Coefficients of both are about the same, implying a systematic bias between the methods. We propose a sensitivity analysis for effective rainfall to assess how this variation affects water (re)allocation.

Canal Water Supply during the three years averaged 64 BCM, while the apportioned volume for Punjab is 69 BCM. Hence average canal water supplies for each canal command were multiplied by 69/64 to make water available consistent with the Accord without changing the existing proportionality. After correction, the average canal water supply is 807 mm, with a maximum of 1443 mm to Panjnad canal and a minimum of 460 mm to Upper Dipalpur Canal. Despite a wide range, the Gini Coefficient is 0.16, implying that most canals' water supplies are equitable.

Maximum net groundwater discharge was 32.4 mm/a at CBDC, and maximum net groundwater recharge was 26.1mm at Lower Bahawal Canal. The average net discharge is 8.7 mm across the canal commands, equivalent to 0.7943 BCM per annum.

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[13] National Engineering Handbook (USDA 1970) Part 623 Table 2-43 ‘ Average monthly effective precipitation as related to mean monthly precipitation and average monthly crop evapotranspiration’

Domestic water demand ranged from 6.5 mm/ha at Greater Thal Canal Command to 287.0 mm/ha at CBDC, reflecting the range in population density among these canal commands. The average demand was 47 mm/ha, and the Gini Coefficient was 0.48.

Industrial water demand ranged between 0.0 mm/ha at Greater Thal Canal to 292.5 mm/ha at CBDC, reflecting industrialization among canal commands. The average demand was 26.7 mm/ha, and the Gini Coefficient was 0.71, the highest among all variables.

Livestock demand ranged between 1.8 mm/ha at Greater Thal Canal to 35.7 mm/ha at Marala Ravi Canal command. The average demand was 7.6 mm/ha, and the Gini Coefficient was 0.34.

The Reference Evapotranspiration (ET_0) ranged between 1333 mm at Marala Ravi Canal Command and 1817 mm at Fordwah canal. The average was 1676 mm, and the Gini Coefficient was 0.04, the least among all variables.

Checks were made to ascertain if there are any canal commands where piezometric data show that groundwater levels are declining but, there's a surplus of surface water with estimated Ag Demand. If True, then there's an error in the initial estimate of crop water requirements. This was the case in CBDC (941 mm), Haveli (932 mm), LBDC(899 mm), Lower Jhelum(876 mm), Muzaffargarh(943 mm), Panjnad(1031 mm), Sadiqia (947 mm), Thal (856 mm), and Upper Jhelum(799 mm). The crop water requirement in these Canal Commands is revised by multiplying the current estimate by a factor. The factors are: CBDC(1.27), Haveli(1.15), LBDC(1.27), Lower Jhelum(1.08), Muzaffargarh(1.13), Panjnad (1.20), Sadiqia(1.01), Thal (1.09) and Upper Jhelum(1.20).

Revised values of Crop Water Requirements (CWR) are presented in Table 12. It ranged between 836 mm to 1222 mm, averaged 1032 mm with a Gini Coefficient of 0.06. The average CET approximates 62% of the average ET_0, reflecting an effective crop coefficient of 0.62 across Punjab's canal commands. A small increment of the Gini Coefficient of CWR, compared to the Gini Coefficient of ET_0 reflects variation in cropping pattern across the canal commands.

Compared to values of CWR estimated by Young et al. 2017[14], this estimate is about 6% high.

11.2 The Big Picture

The water balance BIG PICTURE informs two significant water sources, the canal (river) and rainfall. The Canal Water Supply is 69 BCM. Gross rainfall 34 BCM, of which an estimated 16.8 BCM is effective. Together, the total water available within the canal command is 85.8 BCM. A minor source is stored groundwater, and it is estimated to be 0.7943 BCM. Aquifers

[14] Young, William J., Arif Anwar, Touseef Bhatti, et. al 2019. Pakistan: Getting More from Water. Water Security Diagnostics. World Bank, Washington DC. 161 pp.

within the canal command play a critical role in recycling recharge from canal water and rainfall. The net discharge from aquifers of 0.7943 BCM will deplete the stored water in the future if it continues.

Our estimate differs from Young et al. 2019's estimate that Punjab uses 118 BCM, exceeding the supplies by 20%. Under best of circumstances, total water consumed from the three sources, canal, rain, and groundwater, in Punjab is 69+16.8+0.7943 = 86.59 BCM (not 118 BCM). In our estimates, a contributor to this difference is that runoff from a canal command is excluded for water use or consumption within the canal command. However, it does not explain the entire difference (31.41 BCM) between the two estimates.

In order to increase water availability, effective rainfall needs to be improved. Punjab should adopt a widespread rainwater harvesting program, especially in urbanized areas. Depleting fossil water in aquifers needs to be avoided, and measures should be taken to replenish depleted groundwater.

The total volume of water required to meet domestic, industrial, livestock, and crop water demand are 3.4 BCM, 1.99 BCM, 0.56 BCM, and 87.6 BCM. To replenish the aquifers at the rate they are being depleted over the past 13 years, and the annual environmental demand is 0.7943 BCM. In sum, demand from all sectors is 94.32 BCM. This compares with total water consumed at 86.59 BCM, a maximum net deficit of 7.73 BCM. This deficit will be reduced when a fraction of water supplied to the Domestic and Industrial sectors is returned to agriculture.

Assuming only canal and effective rainfall is available to meet all demands, the initial estimate of the water deficit within Punjab's canal commands is 94.32 – 85.8 = 8.52 BCM. However, the deficit will be further reduced depending on the wastewater returned from domestic and industrial sectors to agriculture. The total demand for domestic and industrial sectors is 5.39 BCM (3.4 +1.99). Previous studies have shown that 99% of water withdrawn for domestic use is returned as water for agriculture (3.37 BCM). Another 10% of water supplied for industries is returned as wastewater for agriculture (0.2 BCM). Assuming that returning wastewater quality is acceptable for agriculture, the deficit will be reduced from 8.52 BCM to 4.95 BCM.

No	Canal	Area ha	Gross Rainfall (mm)	SCS Rainfall (mm)	USDA Rainfall (mm)	CWS (mm)	GW Net Discharge (mm)	Env Demand[15] (mm)	Domestic Demand (mm)	Industrial Demand (mm)	Livestock Demand (mm)	CWR (mm)
1	Abbasia	93078	124	66	40	734	13	13	25	14	6	1051
2	Central Bari Doab	202343	623	293	271	1027	32	32	287	293	16	1195
3	Chasma Right Bank	97125	223	118	88	944	4	4	29	3	5	1007
4	Dera Ghazi Khan	364217	145	77	74	967	8	8	38	16	4	1049
5	Fordwah	174015	207	110	82	739	1	1	15	1	5	939
6	Greater Thal	104361	472	250	4	554	0	0	7	0	2	1200
7	Haveli	66045	492	231	154	838	18	18	17	10	8	1072
8	Lower Bari Doab	538232	290	154	127	1068	24	24	35	21	9	1222
9	Lower Bhawal	218530	104	55	78	1435	-26	0	47	34	7	1135
10	Lower Chenab	1290948	535	251	217	695	-2	0	50	37	7	1012
11	Lower Dipalpur	249853	324	172	127	641	17	17	26	10	8	836
12	Lower Jhelum	615123	741	348	186	586	3	3	25	4	5	946
13	Lower Mailsi	279233	158	84	75	831	14	14	18	10	5	1100
14	Lower Pakpattan	121406	158	84	72	932	7	7	13	16	3	1070
15	Marala Ravi	33010	935	439	105	596	2	2	211	103	36	920
16	Muzaffargarh	331843	237	126	72	927	11	11	39	8	5	1066
17	Panjnad[16]	546326	128	68	39	1443	23	23	29	10	5	1200
18	Qaim Canal+ UBC	44515	104	55	78	897	22	22	31	0	4	1135
19	Rangpur	141640	443	235	133	743	19	19	23	10	7	912
20	Sadiqia	441108	203	107	80	825	4	4	19	2	5	956
21	Sindhnai	346735	237	126	87	622	24	24	76	21	5	1072
22	Thal	857934	466	247	150	674	7	7	23	3	5	929
23	Upper Chenab	510402	712	335	318	725	2	2	22	51	7	1050
24	Upper Dipalpur	146739	567	267	237	460	17	17	33	1	10	908
25	Upper Jhelum	218530	983	462	236	497	-5	0	67	13	14	958
26	Upper Pakpattan	513951	231	122	79	571	26	26	21	4	5	879

[15] Net groundwater decline is assumed equal to environmental demand. This implies that groundwater decline is an environmental issue, which needs to be addressed.
[16] Panjnad has two parts; Panjnad and Abbasia Link Canal (also called Panjnad Perennial). It is the latter which has surplus. Due to unavailability of CCA separated for the two, Panjnad Perennial and Panjnad are combined in this analysis.

Table 12: Water Balance Components of Canal Commands

Statistics	*Area ha*	*Gross Rainfall*	*SCS Effective Rainfall*	*USDA Effective Rainfall*	*Revised CWS*	*GW Decline*	*Env Demand*	*Domestic Demand*	*Industrial Demand*	*Livestock Demand*	*Revised CWR*
Mean	328740	379	188	123	807	10	11	47	27	8	1032
Median	234192	264	140	87	741	9	9	27	10	5	1050
Standard Deviation	285758	257	118	78	249	12	10	62	58	7	109
Range	1257939	879	407	314	984	59	32	280	293	34	386
Minimum	33010	104	55	4	460	-26	0	7	0	2	836
Maximum	1290948	983	462	318	1443	32	32	287	293	36	1222
Count	26	26	26	26	26	26	26	26	26	26	26
Gini Coefficient	0.43	0.36	0.34	0.33	0.16	0.66	0.48	0.48	0.71	0.34	0.06

Table 13: Summary of Canal Water Balance Statistics

11.3 Estimating Surplus or Deficit in each canal command

Data presented in Tables 12 and 13 are considered the best estimates made using existing data and established scientific methods. It is acknowledged that there's a possibility of minor variations to these estimates. The impact of such errors on the outcome is discussed below.

We consider three variables, actual values of Effective Rainfall, Returned flow from Domestic & Industrial, and the Agricultural demand may differ from the base. Of these, our estimate of Crop Water Requirement is about 5% more than other published estimates. Hence, adapting our estimates will lead to conservative estimates of water reallocation. For the other two variables, a sensitivity analysis is required to estimate the impact of potential errors on estimates of surplus or deficit in each canal command. Details are presented in Table 12.

This chapter illustrated the variability among key water balance components across canal commands. Overall, there's a water deficit within the canal commands. After meeting domestic, industrial, livestock, and environmental demands, water available is inadequate to meet crop water requirements within the canal commands.

12 Allocating/Reallocating Water in Canal Commands

12.1 Objectives of Allocation/Reallocation

This chapter aims to quantify reallocation options subject to Rule 4 (Section 2.4.8). Subsequently, it aims to quantify the volumes of water to be reallocated for two different objectives. The first objective is to provide an equal depth of water for each unit area within the canal command. The second objective is to ensure that the CWR deficit experienced is the same in all canal commands. Three Linear Programming models have been developed to evaluate these objectives.

The first model, named Modified_Rule-4, identifies water in excess to current demands for domestic, industrial, livestock, and environmental demands, and allocates the excess to canal commands where there's a deficit. The second model is the Equitable-Supply model (ES), and the third is the Equitable-Deficit (ED) model.

All models are subjected to supply and demand constraints, which are presented in Table 12. The supply of water for CWR will be water available in each canal command after meeting domestic, industrial, livestock, and environmental demands presented in Table 12.

Before being available to agriculture, it is assumed that available water in a canal command is used directly or indirectly (recycling through aquifers) to meet domestic, industrial, livestock, and environmental demands.

12.2 Modified_Rule-4 Model Description

Recently, the Government of Punjab promulgated rules for the Adjustment of Canal Command Areas. Under Rule 4(2), 'The Cabinet may reduce water allowance of a canal by not more than ten percent of its existing water allowance ***where such reduction has no practical effect on the agriculture of the existing irrigators***.' Based on the water balance calculations made earlier, water is in excess of all demands available only in two canal commands, Lower Bahawal and Panjnad (Table 14).

Source(s) of Water	Lower Bahawal	Panjnad
Canal Water Only	0.4640	0.9599
Canal Water + Effective Rainfall (SCS)	0.5844	1.3319
Canal Water + Effective Rainfall (USDA)	0.6339	1.1714
Canal Water + Effective Rainfall (SCS) + Returned Waste Water	0.6931	1.4965
Canal Water + Effective Rainfall (USDA) + Returned Waste Water	0.7425	1.3360

Table 14: Excess water available in Lower Bahawal and Panjnad Canal Commands (BCM)

Current canal water allowance to Lower Bahawal and Panjnad Canal Commands are 3.1367 and 7.8852 BCM, respectively. Ten percent of these volumes will be 0.3137 and 0.7885 BCM, respectively, which are less than excess water available in the canal commands (Table 14). As per Rule 4, 0.3137 and 0.7885 BCM (Totaling 1.1022 BCM) may be reallocated to canal commands with severe crop water deficit. Under the best of conditions, only 65% of the CWR is met in Sindhnai canal command, and the deficit is 1.2936 BCM. Therefore, excess water in Lower Bahawal and Panjnad may be appropriated to Sindhnai Canal Command.

Suppose the 10% limit is not enforced (Modified_Rule-4), allowing all excess water in Lower Bahawal and Panjnad to be reallocated. In that case, the following LP Model may be used to assess options under different water availability conditions.

Modified_Rule-4 Model

Objective Function

$$Min\ Z = \sum_{i=0}^{n} Add_i + \ Remove_i$$

Equation 1

Subject to:

$$Target_i = CWR_i$$

Equation 2

$$Target_i = Water\ Available\ _i + Add_i - \ Remove_i$$

Equation 3

$$Add_i \ \geq 0$$

Equation 4

$$Remove_i \ \geq 0$$

Equation 5

$$\sum_{i=0}^{n} Add_i = \sum_{i=0}^{n} Remove_i$$

Equation 6

$$TWA\ before\ Allocation = TWA\ after\ Reallocation$$

Equation 7

Where,

Z: Objective variable

Add: Water to be added from canal command *i* to ensure equity in deficit (BCM)
Remove: Water to be removed from canal command *i* to ensure equity in deficit (BCM)
Target: Final volume of water after reallocation (BCM)
TWA: Total Water Available in Canal Commands (BCM)
CWR: Crop Water Requirement (BCM)
i = 1,..., 26 (Number of Canal Commands)

12.3 Variation in Total Water Available to meet CWR for ED & ES Models

Total water available to meet CWR under varying conditions is tabulated below. Total CWR (Demand for Agriculture) is 87.71 BCM, higher than water available for crops under all conditions in Table 15.

Source(s) of Water	Volume (BCM)	Code
Canal Water Only	61.88	C
Canal Water + Effective Rainfall (SCS)	78.69	CS
Canal Water + Effective Rainfall (USDA)	74.03	CU
Canal Water + Effective Rainfall (SCS) + Returned Waste Water	82.26	CSWW
Canal Water + Effective Rainfall (USDA) + Returned Waste Water	77.60	CUWW

Table 15: Water available to meet CWR in Punjab''s Canal Commands

12.4 Equitable Deficit (ED) Model description

Objective Function

$$Min\ Z = \sum_{i=0}^{n} Add_i + Remove_i$$

Equation 8

Subject to:

$$Target_i = \frac{TWA}{Total\ CWR} * CWR_i$$

Equation 9

$$Target_i = Water\ Available_{\ i} + Add_i - Remove_i$$

Equation 10

$$Add_i \geq 0$$

Equation 11

$$Remove_i \geq 0$$

Equation 12

$$\sum_{i=0}^{n} Add_i = \sum_{i=0}^{n} Remove_i$$

Equation 13

$$TWA\ before\ Allocation = TWA\ after\ Reallocation$$

Equation 14

Where,

Z: Objective variable
Add: Water to be added from canal command *i* to ensure equity in deficit (BCM)
Remove: Water to be removed from canal command *i* to ensure equity in deficit (BCM)
Target: Final volume of water after reallocation (BCM)
TWA: Total Water Available in Canal Commands (BCM)
CWR: Crop Water Requirement (BCM)
i = 1,…, 26 (Number of Canal Commands)

12.5 Equitable Supply (ES) Model description

Objective Function

$$Min\ Z = \sum_{i=0}^{n} Add_i + Remove_i$$

Equation 15

Subject to:

$$Target_i = \frac{TWA}{TCA} * Command\ Area_i$$

Equation 16

$$Target_i = Water\ Available_{\ i} + Add_i - Remove_i$$

Equation 17

$$Add_i \geq 0$$

Equation 18

$$Remove_i \geq 0$$

Equation 19

$$\sum_{i=0}^{n} Add_i = \sum_{i=0}^{n} Remove_i$$

Equation 20

$$TWA\ before\ Allocation = TWA\ after\ Reallocation$$

Equation 21

Where,

Z: Objective variable
Add: Water to be added from canal command i to ensure equity in deficit (BCM)
Remove: Water to be removed from canal command i to ensure equity in deficit (BCM)
Target: Final volume of water after reallocation (BCM)
TWA: Total Water Available in Canal Commands (BCM)
TCA: Total Command Area (ha)
Command Area: Command Area of the Canal (ha)
i = 1,…, 26 (Number of Canal Commands)

12.6 Modified Rule 4 Scenarios Evaluated

Each model, modified_Rule-4, ES, and ED simulated water allocation under the five total water available conditions. Results of modified_Rule-4 are discussed below.

12.6.1 Rule4-C

This scenario assumes that all excess water in Lower Bahawal and Panjnad canal commands after meeting all requirements within the canal command is available for reallocation to canal commands in water deficit to meet CWR. Excess water available in Lower Bahawal and Panjnad canal is 1.4239 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. TWA in canal commands ranged between 245 mm and 1376 mm with a Gini Coefficient of 0.20. % CWR met in canal commands averaged 68% and ranged between 27% and 119% with a Gini Coefficient of 0.17.

Following reallocation, water available in canal commands ranged between 245 mm and 1200 mm with a Gini Coefficient of 0.18. %CWR met in all canal commands averaged 70% and ranged between 27% and 100% with a Gini Coefficient of 0.15. A total volume of 1.4239 BCM was to be transferred from Lower Bahawal and Panjnad canal commands to Abbasia and Central Bari Doab canal commands.

Canal-wise results are presented in Table 16.

12.6.2 Rule4-CS

This scenario assumes that all excess water in Lower Bahawal and Panjnad canal commands after meeting all requirements within the canal command is available for reallocation to canal commands in water deficit to meet CWR. Excess water available in Lower Bahawal and Panjnad canal is 1.9163 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. TWA in canal commands ranged between 621 mm and 1443 mm with a Gini Coefficient of 0.14. % CWR met in canal commands averaged 87% and ranged between 58% and 124% with a Gini Coefficient of 0.12.

Following reallocation, water available in canal commands ranged between 621 mm and 1200 mm with a Gini Coefficient of 0.13. %CWR met in all canal commands averaged 89% and ranged between 58% and 100% with a Gini Coefficient of 0.10. A total volume of 1.9163

BCM was to be transferred from Lower Bahawal and Panjnad canal commands to Abbasia, Central Bari Doab, CRBC, D.G. Khan, Fordwah, and Greater Thal canal commands.

Canal-wise results are presented in Table 17.

12.6.3 **Rule4-CU**

This scenario assumes that all excess water in Lower Bahawal and Panjnad canal commands after meeting all requirements within the canal command is available for reallocation to canal commands in water deficit to meet CWR. Excess water available in Lower Bahawal and Panjnad canal is 1.8053 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. TWA in canal commands ranged between 350 mm and 1425 mm with a Gini Coefficient of 0.15. % CWR met in canal commands averaged 87% and ranged between 38% and 126% with a Gini Coefficient of 0.13.

Following reallocation, water available in canal commands ranged between 350 mm and 1200 mm with a Gini Coefficient of 0.14. %CWR met in all canal commands averaged 82% and ranged between 62% and 100% with a Gini Coefficient of 0.11. A total volume of 1.8053 BCM was to be transferred from Lower Bahawal and Panjnad canal commands to Abbasia, Central Bari Doab, CRBC, D.G. Khan, Fordwah canal commands.

Canal-wise results are presented in Table 18.

12.6.4 **Rule4-CSWW**

This scenario assumes that all excess water in Lower Bahawal and Panjnad canal commands after meeting all requirements within the canal command is available for reallocation to canal commands in water deficit to meet CWR. Excess water available in Lower Bahawal and Panjnad canal is 2.1895 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. TWA in canal commands ranged between 658 mm and 1473 mm with a Gini Coefficient of 0.13. % CWR met in canal commands averaged 92% and ranged between 65% and 128% with a Gini Coefficient of 0.11.

Following reallocation, water available in canal commands ranged between 698 mm and 1200 mm with a Gini Coefficient of 0.10. %CWR met in all canal commands averaged 93% and ranged between 65% and 100% with a Gini Coefficient of 0.08.

A total volume of 2.1895 BCM was transferred from Lower Bahawal, and Panjnad canal commands to Abbasia, Central Bari Doab, CRBC, D.G. Khan, Haveli, Upper Dipalpur, and Upper Pakpattan canal commands.

Canal-wise results are presented in Table 19.

12.6.5 **Rule4-CUWW**

This scenario assumes that all excess water in Lower Bahawal and Panjnad canal commands after meeting all requirements within the canal command is available for reallocation to canal commands in water deficit to meet CWR. Excess water available in Lower Bahawal

and Panjnad canal is 2.0785 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. TWA in canal commands ranged between 556 mm and 1475 mm with a Gini Coefficient of 0.13. % CWR met in canal commands averaged 85% and ranged between 46% and 130% with a Gini Coefficient of 0.10.

Following reallocation, water available in canal commands ranged between 569 mm and 1200 mm with a Gini Coefficient of 0.12. %CWR met in all canal commands averaged 88% and ranged between 62% and 100% with a Gini Coefficient of 0.07.

A total volume of 2.0785 BCM was to be transferred from Lower Bahawal, and Panjnad canal commands to Abbasia, Central Bari Doab, CRBC, D.G. Khan, Fordwah, Greater Thal, Haveli, and LBDC canal commands.

Canal-wise results are presented in Table 20.

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R(mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6293	676	0.9785	0.3493	0.0000	0.9785	1051	64%	100%
2	Central Bari Doab	202343	2.4185	0.8080	399	2.4185	1.0746	0.0000	1.8825	930	33%	78%
3	CRBC	97125	1.0271	0.8775	903	1.0271	0.0000	0.0000	0.8775	903	85%	85%
4	D.G. Khan	364217	3.8209	3.2806	901	3.8209	0.0000	0.0000	3.2806	901	86%	86%
5	Fordwah	174015	1.6333	1.2486	718	1.6333	0.0000	0.0000	1.2486	718	76%	76%
6	Greater Thal	104361	1.2523	0.5693	546	1.2523	0.0000	0.0000	0.5693	546	45%	45%
7	Haveli	66045	0.7078	0.5193	786	0.7078	0.0000	0.0000	0.5193	786	73%	73%
8	LBDC	538232	6.5784	5.2677	979	6.5784	0.0000	0.0000	5.2677	979	80%	80%
9	Lower Bhawal	218530	2.4804	2.9444	1347	2.4804	0.0000	0.4640	2.4804	1135	119%	100%
10	Lower Chenab	1290948	13.0688	7.7457	600	13.0688	0.0000	0.0000	7.7457	600	59%	59%
11	Lower Dipalpur	249853	2.0888	1.4506	581	2.0888	0.0000	0.0000	1.4506	581	69%	69%
12	Lower Jhelum	615123	5.8199	3.3782	549	5.8199	0.0000	0.0000	3.3782	549	58%	58%
13	Lower Mailsi	279233	3.0708	2.1891	784	3.0708	0.0000	0.0000	2.1891	784	71%	71%
14	Lower Pakpattan	121406	1.2991	1.0853	894	1.2991	0.0000	0.0000	1.0853	894	84%	84%
15	Marala Ravi	33010	0.3038	0.0810	245	0.3038	0.0000	0.0000	0.0810	245	27%	27%
16	Muzaffargarh	331843	3.5365	2.8701	865	3.5365	0.0000	0.0000	2.8701	865	81%	81%
17	Panjnad	546326	6.5559	7.5158	1376	6.5559	0.0000	0.9599	6.5559	1200	115%	100%
18	Qaim + UBC	44515	0.5053	0.3743	841	0.5053	0.0000	0.0000	0.3743	841	74%	74%
19	Rangpur	141640	1.3568	0.9684	684	1.3568	0.0000	0.0000	0.9684	684	71%	71%
20	Sadiqia	441108	4.2175	3.5104	796	4.2175	0.0000	0.0000	3.5104	796	83%	83%
21	Sindhnai	346735	3.7167	1.7193	496	3.7167	0.0000	0.0000	1.7193	496	46%	46%
22	Thal	857934	7.9673	5.4621	637	7.9673	0.0000	0.0000	5.4621	637	69%	69%
23	Upper Chenab	510402	5.3618	3.2771	642	5.3618	0.0000	0.0000	3.2771	642	61%	61%
24	Upper Dipalpur	146739	1.3320	0.5851	399	1.3320	0.0000	0.0000	0.5851	399	44%	44%
25	Upper Jhelum	218530	2.0942	0.8815	403	2.0942	0.0000	0.0000	0.8815	403	42%	42%
26	Upper Pakpattan	513951	4.5178	2.6453	515	4.5178	0.0000	0.0000	2.6453	515	59%	59%

Table 16: Canal wise Results - Modified Rule-4 -C Water Allocation

No	Canal	Area ha	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6903	742	0.9785	0.2883	0.0000	0.9785	1051	71%	100%
2	Central Bari Doab	202343	2.4185	1.4002	692	2.4185	1.0183	0.0000	2.4185	1195	58%	100%
3	CRBC	97125	1.0271	0.9924	1022	1.0271	0.0347	0.0000	1.0271	1058	97%	100%
4	D.G. Khan	364217	3.8209	3.5613	978	3.8209	0.2596	0.0000	3.8209	1049	93%	100%
5	Fordwah	174015	1.6333	1.4393	827	1.6333	0.1940	0.0000	1.6333	939	88%	100%
6	Greater Thal	104361	1.2523	0.8302	795	1.2523	0.1215	0.0000	0.9517	912	66%	76%
7	Haveli	66045	0.7078	0.6721	1018	0.7078	0.0000	0.0000	0.6721	1018	95%	95%
8	LBDC	538232	6.5784	6.0953	1132	6.5784	0.0000	0.0000	6.0953	1132	93%	93%
9	Lower Bhawal	218530	2.4804	3.0649	1402	2.4804	0.0000	0.5844	2.4804	1135	124%	100%
10	Lower Chenab	1290948	13.0688	10.9908	851	13.0688	0.0000	0.0000	10.9908	851	84%	84%
11	Lower Dipalpur	249853	2.0888	1.8803	753	2.0888	0.0000	0.0000	1.8803	753	90%	90%
12	Lower Jhelum	615123	5.8199	5.5211	898	5.8199	0.0000	0.0000	5.5211	898	95%	95%
13	Lower Mailsi	279233	3.0708	2.4234	868	3.0708	0.0000	0.0000	2.4234	868	79%	79%
14	Lower Pakpattan	121406	1.2991	1.1868	978	1.2991	0.0000	0.0000	1.1868	978	91%	91%
15	Marala Ravi	33010	0.3038	0.2260	685	0.3038	0.0000	0.0000	0.2260	685	74%	74%
16	Muzaffargarh	331843	3.5365	3.2868	990	3.5365	0.0000	0.0000	3.2868	990	93%	93%
17	Panjnad	546326	6.5559	7.8878	1444	6.5559	0.0000	1.3319	6.5559	1200	120%	100%
18	Qaim + UBC	44515	0.5053	0.3988	896	0.5053	0.0000	0.0000	0.3988	896	79%	79%
19	Rangpur	141640	1.3568	1.3008	918	1.3568	0.0000	0.0000	1.3008	918	96%	96%
20	Sadiqia	441108	4.2175	3.9844	903	4.2175	0.0000	0.0000	3.9844	903	94%	94%
21	Sindhnai	346735	3.7167	2.1548	621	3.7167	0.0000	0.0000	2.1548	621	58%	58%
22	Thal	857934	7.9673	7.5791	883	7.9673	0.0000	0.0000	7.5791	883	95%	95%
23	Upper Chenab	510402	5.3618	4.9850	977	5.3618	0.0000	0.0000	4.9850	977	93%	93%
24	Upper Dipalpur	146739	1.3320	0.9764	665	1.3320	0.0000	0.0000	0.9764	665	73%	73%
25	Upper Jhelum	218530	2.0942	1.8909	865	2.0942	0.0000	0.0000	1.8909	865	90%	90%
26	Upper Pakpattan	513951	4.5178	3.2742	637	4.5178	0.0000	0.0000	3.2742	637	72%	72%

Table 17: Canal wise Results - Modified Rule-4 -CS Water Allocation

No	Canal	Area ha	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6667	716	0.9785	0.3119	0.0000	0.9785	1051	68%	100%
2	Central Bari Doab	202343	2.4185	1.3563	670	2.4185	1.0623	0.0000	2.4185	1195	56%	100%
3	CRBC	97125	1.0271	0.9626	991	1.0271	0.0645	0.0000	1.0271	1058	94%	100%
4	D.G. Khan	364217	3.8209	3.5493	975	3.8209	0.2716	0.0000	3.8209	1049	93%	100%
5	Fordwah	174015	1.6333	1.3906	799	1.6333	0.0950	0.0000	1.4856	854	85%	91%
6	Greater Thal	104361	1.2523	0.5735	550	1.2523	0.0000	0.0000	0.5735	550	46%	46%
7	Haveli	66045	0.7078	0.6211	940	0.7078	0.0000	0.0000	0.6211	940	88%	88%
8	LBDC	538232	6.5784	5.9489	1105	6.5784	0.0000	0.0000	5.9489	1105	90%	90%
9	Lower Bhawal	218530	2.4804	3.1143	1425	2.4804	0.0000	0.6339	2.4804	1135	126%	100%
10	Lower Chenab	1290948	13.0688	10.5532	817	13.0688	0.0000	0.0000	10.5532	817	81%	81%
11	Lower Dipalpur	249853	2.0888	1.7672	707	2.0888	0.0000	0.0000	1.7672	707	85%	85%
12	Lower Jhelum	615123	5.8199	4.5247	736	5.8199	0.0000	0.0000	4.5247	736	78%	78%
13	Lower Mailsi	279233	3.0708	2.3972	858	3.0708	0.0000	0.0000	2.3972	858	78%	78%
14	Lower Pakpattan	121406	1.2991	1.1730	966	1.2991	0.0000	0.0000	1.1730	966	90%	90%
15	Marala Ravi	33010	0.3038	0.1156	350	0.3038	0.0000	0.0000	0.1156	350	38%	38%
16	Muzaffargarh	331843	3.5365	3.1100	937	3.5365	0.0000	0.0000	3.1100	937	88%	88%
17	Panjnad	546326	6.5559	7.7273	1414	6.5559	0.0000	1.1714	6.5559	1200	118%	100%
18	Qaim + UBC	44515	0.5053	0.4089	919	0.5053	0.0000	0.0000	0.4089	919	81%	81%
19	Rangpur	141640	1.3568	1.1562	816	1.3568	0.0000	0.0000	1.1562	816	85%	85%
20	Sadiqia	441108	4.2175	3.8628	876	4.2175	0.0000	0.0000	3.8628	876	92%	92%
21	Sindhnai	346735	3.7167	2.0219	583	3.7167	0.0000	0.0000	2.0219	583	54%	54%
22	Thal	857934	7.9673	6.7508	787	7.9673	0.0000	0.0000	6.7508	787	85%	85%
23	Upper Chenab	510402	5.3618	4.8986	960	5.3618	0.0000	0.0000	4.8986	960	91%	91%
24	Upper Dipalpur	146739	1.3320	0.9331	636	1.3320	0.0000	0.0000	0.9331	636	70%	70%
25	Upper Jhelum	218530	2.0942	1.3978	640	2.0942	0.0000	0.0000	1.3978	640	67%	67%
26	Upper Pakpattan	513951	4.5178	3.0525	594	4.5178	0.0000	0.0000	3.0525	594	68%	68%

Table 18: Canal wise Results - Modified Rule-4 -CU Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA Before (mm)	Target (BCM)	Add (mm)	Remove (mm)	TWA-R (BCM)	TWA After (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.7144	768	0.9785	0.2641	0.0000	0.9785	1051	73%	100%
2	Central Bari Doab	202343	2.4185	2.0344	1005	2.4185	0.3345	0.0000	2.3689	1171	84%	98%
3	CRBC	97125	1.0271	1.0203	1051	1.0271	0.0068	0.0000	1.0271	1058	99%	100%
4	D.G. Khan	364217	3.8209	3.7051	1017	3.8209	0.1158	0.0000	3.8209	1049	97%	100%
5	Fordwah	174015	1.6333	1.4653	842	1.6333	0.0000	0.0000	1.4653	842	90%	90%
6	Greater Thal	104361	1.2523	0.8370	802	1.2523	0.0000	0.0000	0.8370	802	67%	67%
7	Haveli	66045	0.7078	0.6836	1035	0.7078	0.0242	0.0000	0.7078	1072	97%	100%
8	LBDC	538232	6.5784	6.2917	1169	6.5784	0.0000	0.0000	6.2917	1169	96%	96%
9	Lower Bhawal	218530	2.4804	3.1735	1452	2.4804	0.0000	0.6931	2.4804	1135	128%	100%
10	Lower Chenab	1290948	13.0688	11.6833	905	13.0688	0.0000	0.0000	11.6833	905	89%	89%
11	Lower Dipalpur	249853	2.0888	1.9461	779	2.0888	0.0000	0.0000	1.9461	779	93%	93%
12	Lower Jhelum	615123	5.8199	5.6736	922	5.8199	0.0000	0.0000	5.6736	922	97%	97%
13	Lower Mailsi	279233	3.0708	2.4748	886	3.0708	0.0000	0.0000	2.4748	886	81%	81%
14	Lower Pakpattan	121406	1.2991	1.2042	992	1.2991	0.0000	0.0000	1.2042	992	93%	93%
15	Marala Ravi	33010	0.3038	0.2982	903	0.3038	0.0000	0.0000	0.2982	903	98%	98%
16	Muzaffargarh	331843	3.5365	3.4163	1029	3.5365	0.0000	0.0000	3.4163	1029	97%	97%
17	Panjnad	546326	6.5559	8.0524	1474	6.5559	0.0000	1.4965	6.5559	1200	123%	100%
18	Qaim + UBC	44515	0.5053	0.4123	926	0.5053	0.0000	0.0000	0.4123	926	82%	82%
19	Rangpur	141640	1.3568	1.3346	942	1.3568	0.0000	0.0000	1.3346	942	98%	98%
20	Sadiqia	441108	4.2175	4.0679	922	4.2175	0.0000	0.0000	4.0679	922	96%	96%
21	Sindhnai	346735	3.7167	2.4232	699	3.7167	0.0000	0.0000	2.4232	699	65%	65%
22	Thal	857934	7.9673	7.7780	907	7.9673	0.0000	0.0000	7.7780	907	98%	98%
23	Upper Chenab	510402	5.3618	5.1231	1004	5.3618	0.0000	0.0000	5.1231	1004	96%	96%
24	Upper Dipalpur	146739	1.3320	1.0248	698	1.3320	0.3072	0.0000	1.3320	908	77%	100%
25	Upper Jhelum	218530	2.0942	2.0378	933	2.0942	0.0000	0.0000	2.0378	933	97%	97%
26	Upper Pakpattan	513951	4.5178	3.3809	658	4.5178	1.1369	0.0000	4.5178	879	75%	100%

Table 19: Canal wise Results - Modified Rule-4 -CSWW Water Allocation

No	Canal	Area ha	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R(mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6908	742	0.9785	0.2877	0.0000	0.9785	1051	71%	100%
2	Central Bari Doab	202343	2.4185	1.9904	984	2.4185	0.4281	0.0000	2.4185	1195	82%	100%
3	CRBC	97125	1.0271	0.9905	1020	1.0271	0.0366	0.0000	1.0271	1058	96%	100%
4	D.G. Khan	364217	3.8209	3.6931	1014	3.8209	0.1278	0.0000	3.8209	1049	97%	100%
5	Fordwah	174015	1.6333	1.4166	814	1.6333	0.2167	0.0000	1.6333	939	87%	100%
6	Greater Thal	104361	1.2523	0.5802	556	1.2523	0.6721	0.0000	1.2523	1200	46%	100%
7	Haveli	66045	0.7078	0.6325	958	0.7078	0.0753	0.0000	0.7078	1072	89%	100%
8	LBDC	538232	6.5784	6.1453	1142	6.5784	0.2341	0.0000	6.3794	1185	93%	97%
9	Lower Bhawal	218530	2.4804	3.2229	1475	2.4804	0.0000	0.7425	2.4804	1135	130%	100%
10	Lower Chenab	1290948	13.0688	11.2457	871	13.0688	0.0000	0.0000	11.2457	871	86%	86%
11	Lower Dipalpur	249853	2.0888	1.8330	734	2.0888	0.0000	0.0000	1.8330	734	88%	88%
12	Lower Jhelum	615123	5.8199	4.6772	760	5.8199	0.0000	0.0000	4.6772	760	80%	80%
13	Lower Mailsi	279233	3.0708	2.4486	877	3.0708	0.0000	0.0000	2.4486	877	80%	80%
14	Lower Pakpattan	121406	1.2991	1.1903	980	1.2991	0.0000	0.0000	1.1903	980	92%	92%
15	Marala Ravi	33010	0.3038	0.1878	569	0.3038	0.0000	0.0000	0.1878	569	62%	62%
16	Muzaffargarh	331843	3.5365	3.2394	976	3.5365	0.0000	0.0000	3.2394	976	92%	92%
17	Panjnad	546326	6.5559	7.8919	1445	6.5559	0.0000	1.3360	6.5559	1200	120%	100%
18	Qaim + UBC	44515	0.5053	0.4224	949	0.5053	0.0000	0.0000	0.4224	949	84%	84%
19	Rangpur	141640	1.3568	1.1900	840	1.3568	0.0000	0.0000	1.1900	840	88%	88%
20	Sadiqia	441108	4.2175	3.9463	895	4.2175	0.0000	0.0000	3.9463	895	94%	94%
21	Sindhnai	346735	3.7167	2.2902	661	3.7167	0.0000	0.0000	2.2902	661	62%	62%
22	Thal	857934	7.9673	6.9497	810	7.9673	0.0000	0.0000	6.9497	810	87%	87%
23	Upper Chenab	510402	5.3618	5.0366	987	5.3618	0.0000	0.0000	5.0366	987	94%	94%
24	Upper Dipalpur	146739	1.3320	0.9814	669	1.3320	0.0000	0.0000	0.9814	669	74%	74%
25	Upper Jhelum	218530	2.0942	1.5448	707	2.0942	0.0000	0.0000	1.5448	707	74%	74%
26	Upper Pakpattan	513951	4.5178	3.1591	615	4.5178	0.0000	0.0000	3.1591	615	70%	70%

Table 20:Canal wise Results - Modified Rule-4 -CUWW Water Allocation

12.7 ED Scenarios Evaluated

12.7.1 ED-C

This scenario assumes that only the remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. Spatial variation in effective rainfall or potential for recycling wastewater in respective canal commands is excluded in this scenario. Consequently, the TWA for this scenario is 61.88 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43.

TWA in canal commands ranged between 245 mm and1376 mm, with a Gini Coefficient of 0.20. % CWR met in canal commands ranged between 27% and 119% with a Gini Coefficient of 0.17.

Following reallocation, water available in canal commands ranged between 590 mm and 862 mm, with a Gini Coefficient of 0.06. %CWR met in all canal commands was 71% due to imposing equity in deficit, resulting in a Gini Coefficient of zero. A total volume of 6.69 BCM was to be transferred from canal commands where %CWR met is more than 71% to canal commands where the %CWR met is less than 71% before reallocation.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Marala Ravi Sindhnai, Thal, Upper Chenab, Upper Dipalpur, Upper Jhelum, and Upper Pakpattan.

Under this scenario, Canal Commands to which water needs to be removed from are CRBC, D.G. Khan, Fordwah, Haveli, LBDC, Lower Bhawal, Lower Mailsi, Lower Pakpattan, Muzaffargarh, Panjnad, Qaim + UBC, Rangpur, Sadiqia canal commands.

Canal-wise results are presented in Table 21.

12.7.2 ED-CS

This scenario assumes that the effective rain estimated using the simplified SCS method and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The potential for recycling wastewater is excluded in this scenario. The TWA for this scenario is 78.69 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. Water Available in canal command ranged between 621 mm and 1443 mm, with a Gini Coefficient of 0.12. % CWR met in canal commands ranged between 58% and 124% with a Gini Coefficient of 0.09.

Following reallocation, water available in canal commands ranged between 750 mm and 1097 mm, with a Gini Coefficient of 0.06. %CWR met in all canal commands was 90% due to imposing equity in deficit, resulting in a Gini Coefficient of zero. A total volume of 4.62 BCM was to be transferred from canal commands where %CWR met before reallocation is more than 90% to canal commands where the %CWR met before reallocation is less than 90%.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Mailsi, Marala Ravi, Qaim + UBC, Sindhnai, Upper Dipalpur, and Upper Pakpattan.

Under this scenario, Canal Commands to which water needs to be removed from being, CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Dipalpur, Lower Jhelum, Lower Pakpattan, Muzaffargarh, Panjnad, Rangpur, Sadiqia, Thal, Upper Chenab, and Upper Jhelum canal commands.

Canal-wise results are presented in Table 22.

12.7.3 **ED-CU**

This scenario assumes that the effective rain estimated using the simplified USDA method and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The potential for recycling wastewater is excluded in this scenario. The TWA for this scenario is 74.03 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. Water Available in canal command ranged between 350 mm and 1425 mm, with a Gini Coefficient of 0.15. % CWR met in canal commands ranged between 38% and 126% with a Gini Coefficient of 0.13.

Following reallocation, water available in canal commands ranged between 706 mm and 1032 mm, with a Gini Coefficient of 0.06. %CWR met in all canal commands was 84% due to imposing equity in deficit, resulting in a Gini Coefficient of zero. A total volume of 4.98 BCM was to be transferred from canal commands where %CWR met before reallocation is more than 84% to canal commands where the %CWR met before reallocation is less than 84%.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Greater Thal, Lower Chenab, Lower Jhelum, Lower Mailsi, Marala Ravi, Qaim + UBC, Sindhnai, Upper Dipalpur, Upper Jhelum and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed are CRBC, D.G. Khan, Fordwah, Haveli, LBDC, Lower Bhawal, Lower Dipalpur, Lower Pakpattan, Muzaffargarh, Panjnad, Rangpur, Sadiqia, Thal, and Upper Chenab canal commands.

Canal-wise results are presented in Table 23.

12.7.4 **ED-CSWW**

This scenario assumes that the effective rain estimated using the simplified SCS method, and wastewater from domestic (99% of the domestic demand) and industrial sector (10% of the industrial demand) and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The TWA for this scenario is 82.26 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and

13.06 BCM with a Gini Coefficient of 0.43. Water Available in canal command ranged between 658 mm and 1474 mm, with a Gini Coefficient of 0.10. % CWR met in canal commands ranged between 65% and 128% with a Gini Coefficient of 0.08.

Following reallocation, water available in canal commands ranged between 784 mm and 1146 mm, with a Gini Coefficient of 0.06. %CWR met in all canal commands was 94% due to imposing equity in deficit, resulting in a Gini Coefficient of zero. A total volume of 4.05 BCM was to be transferred from canal commands where %CWR met before reallocation is more than 94% to canal commands where the %CWR met before reallocation is less than 94%.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Mailsi, Lower Pakpattan, Qaim + UBC, Sindhnai, Upper Dipalpur, and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed are CRBC D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Jhelum, Marala Ravi, Muzaffargarh, Panjnad, Rangpur, Sadiqia, Thal, Upper Chenab, and Upper Jhelum canal commands.

Canal-wise results are presented in Table 24.

12.7.5 **ED-CUWW**

This scenario assumes that the effective rain estimated using the USDA method, and wastewater from domestic (99% of the domestic demand) and industrial sector (10% of the industrial demand) and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The TWA for this scenario is 77.60 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. Water Available in canal commands ranged between 556 mm and 1475 mm, with a Gini Coefficient of 0.13. % CWR met in canal commands ranged between 46% and 130% with a Gini Coefficient of 0.10.

Following reallocation, water available in canal commands ranged between 740 mm and 1081 mm, with a Gini Coefficient of 0.06. %CWR met in all canal commands was 88% due to imposing equity in deficit, resulting in a Gini Coefficient of zero. A total volume of 4.51 BCM was to be transferred from canal commands where %CWR met before reallocation is more than 88% to canal commands where the %CWR met before reallocation is less than 88%.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Lower Mailsi, Marala Ravi, Qaim + UBC, Rangpur, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed are CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, Panjnad, Sadiqia, and Upper Chenab canal commands. Canal-wise results are presented in Table 25.

No	Canal	Area ha	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6293	676	0.6904	0.0611	0.0000	0.6904	742	64%	71%
2	Central Bari Doab	202343	2.4185	0.8080	399	1.7064	0.8984	0.0000	1.7064	843	33%	71%
3	CRBC	97125	1.0271	0.8775	903	0.7247	0.0000	0.1528	0.7247	746	85%	71%
4	D.G. Khan	364217	3.8209	3.2806	901	2.6958	0.0000	0.5847	2.6958	740	86%	71%
5	Fordwah	174015	1.6333	1.2486	718	1.1523	0.0000	0.0963	1.1523	662	76%	71%
6	Greater Thal	104361	1.2523	0.5693	546	0.8836	0.3143	0.0000	0.8836	847	45%	71%
7	Haveli	66045	0.7078	0.5193	786	0.4994	0.0000	0.0199	0.4994	756	73%	71%
8	LBDC	538232	6.5784	5.2677	979	4.6414	0.0000	0.6263	4.6414	862	80%	71%
9	Lower Bhawal	218530	2.4804	2.9444	1347	1.7501	0.0000	1.1943	1.7501	801	119%	71%
10	Lower Chenab	1290948	13.0688	7.7457	600	9.2207	1.4750	0.0000	9.2207	714	59%	71%
11	Lower Dipalpur	249853	2.0888	1.4506	581	1.4737	0.0231	0.0000	1.4737	590	69%	71%
12	Lower Jhelum	615123	5.8199	3.3782	549	4.1062	0.7280	0.0000	4.1062	668	58%	71%
13	Lower Mailsi	279233	3.0708	2.1891	784	2.1666	0.0000	0.0225	2.1666	776	71%	71%
14	Lower Pakpattan	121406	1.2991	1.0853	894	0.9166	0.0000	0.1687	0.9166	755	84%	71%
15	Marala Ravi	33010	0.3038	0.0810	245	0.2143	0.1333	0.0000	0.2143	649	27%	71%
16	Muzaffargarh	331843	3.5365	2.8701	865	2.4952	0.0000	0.3749	2.4952	752	81%	71%
17	Panjnad	546326	6.5559	7.5158	1376	4.6255	0.0000	2.8903	4.6255	847	115%	71%
18	Qaim + UBC	44515	0.5053	0.3743	841	0.3565	0.0000	0.0178	0.3565	801	74%	71%
19	Rangpur	141640	1.3568	0.9684	684	0.9573	0.0000	0.0111	0.9573	676	71%	71%
20	Sadiqia	441108	4.2175	3.5104	796	2.9756	0.0000	0.5348	2.9756	675	83%	71%
21	Sindhnai	346735	3.7167	1.7193	496	2.6223	0.9031	0.0000	2.6223	756	46%	71%
22	Thal	857934	7.9673	5.4621	637	5.6213	0.1592	0.0000	5.6213	655	69%	71%
23	Upper Chenab	510402	5.3618	3.2771	642	3.7830	0.5059	0.0000	3.7830	741	61%	71%
24	Upper Dipalpur	146739	1.3320	0.5851	399	0.9398	0.3546	0.0000	0.9398	640	44%	71%
25	Upper Jhelum	218530	2.0942	0.8815	403	1.4776	0.5961	0.0000	1.4776	676	42%	71%
26	Upper Pakpattan	513951	4.5178	2.6453	515	3.1875	0.5422	0.0000	3.1875	620	59%	71%

Table 21: Canal-wise Results - ED-C Water allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6903	742	0.8779	0.1877	0.0000	0.8779	943	71%	90%
2	Central Bari Doab	202343	2.4185	1.4002	692	2.1699	0.7697	0.0000	2.1699	1072	58%	90%
3	CRBC	97125	1.0271	0.9924	1022	0.9215	0.0000	0.0709	0.9215	949	97%	90%
4	D.G. Khan	364217	3.8209	3.5613	978	3.4281	0.0000	0.1332	3.4281	941	93%	90%
5	Fordwah	174015	1.6333	1.4393	827	1.4654	0.0261	0.0000	1.4654	842	88%	90%
6	Greater Thal	104361	1.2523	0.8302	795	1.1236	0.2934	0.0000	1.1236	1077	66%	90%
7	Haveli	66045	0.7078	0.6721	1018	0.6351	0.0000	0.0370	0.6351	962	95%	90%
8	LBDC	538232	6.5784	6.0953	1132	5.9021	0.0000	0.1932	5.9021	1097	93%	90%
9	Lower Bhawal	218530	2.4804	3.0649	1402	2.2254	0.0000	0.8394	2.2254	1018	124%	90%
10	Lower Chenab	1290948	13.0688	10.9908	851	11.7253	0.7345	0.0000	11.7253	908	84%	90%
11	Lower Dipalpur	249853	2.0888	1.8803	753	1.8740	0.0000	0.0062	1.8740	750	90%	90%
12	Lower Jhelum	615123	5.8199	5.5211	898	5.2216	0.0000	0.2995	5.2216	849	95%	90%
13	Lower Mailsi	279233	3.0708	2.4234	868	2.7552	0.3318	0.0000	2.7552	987	79%	90%
14	Lower Pakpattan	121406	1.2991	1.1868	978	1.1655	0.0000	0.0213	1.1655	960	91%	90%
15	Marala Ravi	33010	0.3038	0.2260	685	0.2726	0.0466	0.0000	0.2726	826	74%	90%
16	Muzaffargarh	331843	3.5365	3.2868	990	3.1730	0.0000	0.1138	3.1730	956	93%	90%
17	Panjnad	546326	6.5559	7.8878	1444	5.8820	0.0000	2.0059	5.8820	1077	120%	90%
18	Qaim + UBC	44515	0.5053	0.3988	896	0.4533	0.0545	0.0000	0.4533	1018	79%	90%
19	Rangpur	141640	1.3568	1.3008	918	1.2173	0.0000	0.0835	1.2173	859	96%	90%
20	Sadiqia	441108	4.2175	3.9844	903	3.7839	0.0000	0.2005	3.7839	858	94%	90%
21	Sindhnai	346735	3.7167	2.1548	621	3.3347	1.1798	0.0000	3.3347	962	58%	90%
22	Thal	857934	7.9673	7.5791	883	7.1482	0.0000	0.4309	7.1482	833	95%	90%
23	Upper Chenab	510402	5.3618	4.9850	977	4.8106	0.0000	0.1744	4.8106	943	93%	90%
24	Upper Dipalpur	146739	1.3320	0.9764	665	1.1950	0.2186	0.0000	1.1950	814	73%	90%
25	Upper Jhelum	218530	2.0942	1.8909	865	1.8790	0.0000	0.0119	1.8790	860	90%	90%
26	Upper Pakpattan	513951	4.5178	3.2742	637	4.0533	0.7791	0.0000	4.0533	789	72%	90%

Table 22: Canal-wise Results ED-CS Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9782	0.6667	716	0.8258	0.1591	0.0000	0.8258	887	68%	84%
2	Central Bari Doab	202343	2.4180	1.3563	670	2.0411	0.6848	0.0000	2.0411	1009	56%	84%
3	CRBC	97125	1.0276	0.9626	991	0.8674	0.0000	0.0952	0.8674	893	94%	84%
4	D.G. Khan	364217	3.8206	3.5493	975	3.2251	0.0000	0.3243	3.2251	885	93%	84%
5	Fordwah	174015	1.6340	1.3906	799	1.3793	0.0000	0.0113	1.3793	793	85%	84%
6	Greater Thal	104361	1.2523	0.5735	550	1.0571	0.4837	0.0000	1.0571	1013	46%	84%
7	Haveli	66045	0.7080	0.6211	940	0.5976	0.0000	0.0234	0.5976	905	88%	84%
8	LBDC	538232	6.5772	5.9489	1105	5.5520	0.0000	0.3970	5.5520	1032	90%	84%
9	Lower Bhawal	218530	2.4803	3.1143	1425	2.0937	0.0000	1.0382	2.0761	950	126%	84%
10	Lower Chenab	1290948	13.0644	10.5532	817	11.0279	0.4747	0.0000	11.0279	854	81%	84%
11	Lower Dipalpur	249853	2.0888	1.7672	707	1.7632	0.0000	0.0040	1.7632	706	85%	84%
12	Lower Jhelum	615123	5.8191	4.5247	736	4.9120	0.3872	0.0000	4.9120	799	78%	84%
13	Lower Mailsi	279233	3.0716	2.3972	858	2.5928	0.1956	0.0000	2.5928	929	78%	84%
14	Lower Pakpattan	121406	1.2990	1.1730	966	1.0965	0.0000	0.0764	1.0965	903	90%	84%
15	Marala Ravi	33010	0.3037	0.1156	350	0.2564	0.1407	0.0000	0.2564	777	38%	84%
16	Muzaffargarh	331843	3.5374	3.1100	937	2.9860	0.0000	0.1239	2.9860	900	88%	84%
17	Panjnad	546326	6.5559	7.7273	1414	5.5340	0.0000	2.1933	5.5340	1013	118%	84%
18	Qaim + UBC	44515	0.5053	0.4089	919	0.4265	0.0176	0.0000	0.4265	958	81%	84%
19	Rangpur	141640	1.3569	1.1562	816	1.1454	0.0000	0.0108	1.1454	809	85%	84%
20	Sadiqia	441108	4.2170	3.8628	876	3.5597	0.0000	0.3032	3.5597	807	92%	84%
21	Sindhnai	346735	3.7170	2.0219	583	3.1376	1.1157	0.0000	3.1376	905	54%	84%
22	Thal	857934	7.9702	6.7508	787	6.7278	0.0000	0.0230	6.7278	784	85%	84%
23	Upper Chenab	510402	5.3592	4.8986	960	4.5238	0.0000	0.3571	4.5414	890	91%	85%
24	Upper Dipalpur	146739	1.3324	0.9331	636	1.1247	0.1916	0.0000	1.1247	766	70%	84%
25	Upper Jhelum	218530	2.0935	1.3978	640	1.7672	0.3693	0.0000	1.7672	809	67%	84%
26	Upper Pakpattan	513951	4.5176	3.0525	594	3.8134	0.7609	0.0000	3.8134	742	68%	84%

Table 23: Canal-wise Results ED-CU Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.7144	768	0.9177	0.2033	0.0000	0.9177	986	73%	94%
2	Central Bari Doab	202343	2.4185	2.0344	1005	2.2681	0.2338	0.0000	2.2681	1121	84%	94%
3	CRBC	97125	1.0271	1.0203	1051	0.9632	0.0000	0.0571	0.9632	992	99%	94%
4	D.G. Khan	364217	3.8209	3.7051	1017	3.5833	0.0000	0.1218	3.5833	984	97%	94%
5	Fordwah	174015	1.6333	1.4653	842	1.5317	0.0664	0.0000	1.5317	880	90%	94%
6	Greater Thal	104361	1.2523	0.8370	802	1.1745	0.3375	0.0000	1.1745	1125	67%	94%
7	Haveli	66045	0.7078	0.6836	1035	0.6638	0.0000	0.0198	0.6638	1005	97%	94%
8	LBDC	538232	6.5784	6.2917	1169	6.1693	0.0000	0.1223	6.1693	1146	96%	94%
9	Lower Bhawal	218530	2.4804	3.1735	1452	2.3262	0.0000	0.8473	2.3262	1064	128%	94%
10	Lower Chenab	1290948	13.0688	11.6833	905	12.2562	0.5729	0.0000	12.2562	949	89%	94%
11	Lower Dipalpur	249853	2.0888	1.9461	779	1.9589	0.0128	0.0000	1.9589	784	93%	94%
12	Lower Jhelum	615123	5.8199	5.6736	922	5.4580	0.0000	0.2155	5.4580	887	97%	94%
13	Lower Mailsi	279233	3.0708	2.4748	886	2.8799	0.4051	0.0000	2.8799	1031	81%	94%
14	Lower Pakpattan	121406	1.2991	1.2042	992	1.2183	0.0141	0.0000	1.2183	1003	93%	94%
15	Marala Ravi	33010	0.3038	0.2982	903	0.2849	0.0000	0.0133	0.2849	863	98%	94%
16	Muzaffargarh	331843	3.5365	3.4163	1029	3.3166	0.0000	0.0996	3.3166	999	97%	94%
17	Panjnad	546326	6.5559	8.0524	1474	6.1483	0.0000	1.9041	6.1483	1125	123%	94%
18	Qaim + UBC	44515	0.5053	0.4123	926	0.4739	0.0616	0.0000	0.4739	1064	82%	94%
19	Rangpur	141640	1.3568	1.3346	942	1.2724	0.0000	0.0622	1.2724	898	98%	94%
20	Sadiqia	441108	4.2175	4.0679	922	3.9552	0.0000	0.1126	3.9552	897	96%	94%
21	Sindhnai	346735	3.7167	2.4232	699	3.4856	1.0625	0.0000	3.4856	1005	65%	94%
22	Thal	857934	7.9673	7.7780	907	7.4719	0.0000	0.3061	7.4719	871	98%	94%
23	Upper Chenab	510402	5.3618	5.1231	1004	5.0284	0.0000	0.0947	5.0284	985	96%	94%
24	Upper Dipalpur	146739	1.3320	1.0248	698	1.2491	0.2244	0.0000	1.2491	851	77%	94%
25	Upper Jhelum	218530	2.0942	2.0378	933	1.9640	0.0000	0.0738	1.9640	899	97%	94%
26	Upper Pakpattan	513951	4.5178	3.3809	658	4.2368	0.8560	0.0000	4.2368	824	75%	94%

Table 24: Canal-wise Results ED-CSWW Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9782	0.6908	742	0.8655	0.1747	0.0000	0.8655	930	71%	88%
2	Central Bari Doab	202343	2.4180	1.9904	984	2.1393	0.1489	0.0000	2.1393	1057	82%	88%
3	CRBC	97125	1.0276	0.9905	1020	0.9091	0.0000	0.0813	0.9091	936	96%	88%
4	D.G. Khan	364217	3.8206	3.6931	1014	3.3803	0.0000	0.3128	3.3803	928	97%	88%
5	Fordwah	174015	1.6340	1.4166	814	1.4457	0.0291	0.0000	1.4457	831	87%	88%
6	Greater Thal	104361	1.2523	0.5802	556	1.1080	0.5278	0.0000	1.1080	1062	46%	88%
7	Haveli	66045	0.7080	0.6325	958	0.6264	0.0000	0.0061	0.6264	948	89%	88%
8	LBDC	538232	6.5772	6.1453	1142	5.8191	0.0000	0.3261	5.8191	1081	93%	88%
9	Lower Bhawal	218530	2.4803	3.2229	1475	2.1944	0.0000	1.0531	2.1698	993	130%	87%
10	Lower Chenab	1290948	13.0644	11.2457	871	11.5586	0.3129	0.0000	11.5586	895	86%	88%
11	Lower Dipalpur	249853	2.0888	1.8330	734	1.8480	0.0150	0.0000	1.8480	740	88%	88%
12	Lower Jhelum	615123	5.8191	4.6772	760	5.1484	0.4712	0.0000	5.1484	837	80%	88%
13	Lower Mailsi	279233	3.0716	2.4486	877	2.7175	0.2690	0.0000	2.7175	973	80%	88%
14	Lower Pakpattan	121406	1.2990	1.1903	980	1.1493	0.0000	0.0410	1.1493	947	92%	88%
15	Marala Ravi	33010	0.3037	0.1878	569	0.2687	0.0809	0.0000	0.2687	814	62%	88%
16	Muzaffargarh	331843	3.5374	3.2394	976	3.1297	0.0000	0.1097	3.1297	943	92%	88%
17	Panjnad	546326	6.5559	7.8919	1445	5.8003	0.0000	2.0916	5.8003	1062	120%	88%
18	Qaim + UBC	44515	0.5053	0.4224	949	0.4470	0.0246	0.0000	0.4470	1004	84%	88%
19	Rangpur	141640	1.3569	1.1900	840	1.2005	0.0105	0.0000	1.2005	848	88%	88%
20	Sadiqia	441108	4.2170	3.9463	895	3.7310	0.0000	0.2153	3.7310	846	94%	88%
21	Sindhnai	346735	3.7170	2.2902	661	3.2886	0.9984	0.0000	3.2886	948	62%	88%
22	Thal	857934	7.9702	6.9497	810	7.0516	0.1019	0.0000	7.0516	822	87%	88%
23	Upper Chenab	510402	5.3592	5.0366	987	4.7415	0.0000	0.2704	4.7662	934	94%	89%
24	Upper Dipalpur	146739	1.3324	0.9814	669	1.1788	0.1974	0.0000	1.1788	803	74%	88%
25	Upper Jhelum	218530	2.0935	1.5448	707	1.8522	0.3074	0.0000	1.8522	848	74%	88%
26	Upper Pakpattan	513951	4.5176	3.1591	615	3.9969	0.8378	0.0000	3.9969	778	70%	88%

Table 25: Canal-wise Results - ED CUWW Water Allocation

12.8 ES Scenarios Evaluated

12.8.1 **ES-C**

This scenario assumes that only the remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. Spatial variation in effective rainfall or potential for recycling wastewater in respective canal commands is excluded in this scenario. Consequently, the TWA for this scenario is 61.88 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. TWA in canal commands ranged between 245 mm and 1376 mm, with a Gini Coefficient of 0.20. % CWR met in canal commands ranged between 27% and 119% with a Gini Coefficient of 0.17.

Following reallocation, water available in canal commands ranged between 0.24 BCM and 9.35 BCM, with a Gini Coefficient of 0.43. %CWR met in all canal commands ranged between 59% and 87%, resulting in a Gini Coefficient of 0.06. Reallocation will result in all canal commands with 724 mm of TWA. A total volume of 8.36 BCM was to be transferred from canal commands TWA is greater than 724 mm to canal commands where the TWA was less than 724 mm, before reallocation.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Marala Ravi, Rangpur, Sindhnai, Thal, Upper Chenab, Upper Dipalpur, Upper Jhelum and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed are CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Mailsi, Lower Pakpattan, Muzaffargarh, Panjnad, Qaim + UBC, and Sadiqia canal commands. Canal-wise results are presented in Table 26.

12.8.2 **ES-CS**

This scenario assumes that the effective rain estimated using the simplified SCS method and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The potential for recycling wastewater is excluded in this scenario. The TWA for this scenario is 78.69 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.07 BCM with a Gini Coefficient of 0.43. Total Water Available in canal command ranged between 621 mm and 1443 mm with a Gini Coefficient of 0.12. % CWR met in canal commands ranged between 58% and 124% with a Gini Coefficient of 0.09.

Following reallocation, water available in canal commands ranged between 0.3 BCM and 11.88 BCM, with a Gini Coefficient of 0.43. The water depth available in all canal commands is 921 mm (Gini Coefficient zero), ensuring equity in supplies. %CWR met in all canal commands ranged between 75% and 110%, resulting in a Gini Coefficient of 0.06. A total volume of 6 BCM was to be transferred from canal commands where TWA is greater than 921 mm to canal commands where TWA is less than 921 mm.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Lower Mailsi, Marala Ravi, Qaim + UBC, Rangpur, Sadiqia, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed from are CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, Panjnad, and Upper Chenab canal commands. Canal-wise results are presented in Table 27.

12.8.3 **ES-CU**

This scenario assumes that the effective rain estimated using the simplified USDA method and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The potential for recycling wastewater is excluded in this scenario. The TWA for this scenario is 74.03 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. Water Available in canal command ranged between 350 mm and 1425 mm, with a Gini Coefficient of 0.15. % CWR met in canal commands ranged between 38% and 126% with a Gini Coefficient of 0.13.

Following reallocation, water available in canal commands ranged between 0.29 BCM and 11.18 BCM, with a Gini Coefficient of 0.43. The depth of water available in all canal commands is 866 mm, resulting in a Gini Coefficient of zero. The %CWR met in all canal commands ranged between 71% and 104%, with a Gini Coefficient of 0.06. A total volume of 6.97 BCM was to be transferred from canal commands where TWA is greater than 866 mm to canal commands where TWA is less than 866 mm.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Central Bari Doab, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Lower Mailsi, Marala Ravi, Rangpur, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum, and Upper Pakpattan.

Under this scenario, Canal Commands to which water needs to be removed are CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, Panjnad, Qaim + UBC, Sadiqia, and Upper Chenab canal commands. Canal-wise results are presented in Table 28.

12.8.4 **ES-CSWW**

This scenario assumes that the effective rain estimated using the simplified SCS method, and wastewater from domestic (99% of the domestic demand) and industrial sector (10% of the industrial demand) and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The TWA for this scenario is 82.26 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. TWA in canal command ranged between 658 mm and 1474 mm with a Gini Coefficient of 0.1. The % CWR met in canal commands ranged between 65% and 128%, with a Gini Coefficient of 0.08.

Following reallocation, water available in canal commands ranged between 0.32 BCM and 12.42 BCM, with a Gini Coefficient of 0.43. The depth of water available in all canal commands is 962 mm due to imposing equity in supply, resulting in a Gini Coefficient of zero. A total volume of 5.87 BCM was to be transferred from canal commands where TWA was greater than 962 mm to canal commands where the TWA was less than 962 mm.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Lower Mailsi, Marala Ravi, Qaim + UBC, Rangpur, Sadiqia, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum and Upper Pakpattan.

Under this scenario, Canal Commands to which water needs to be removed are Central Bari Doab, CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, Panjnad, and Upper Chenab canal commands. Canal-wise results are presented in Table 29.

12.8.5 **ES-CUWW**

This scenario assumes that the effective rain estimated using the USDA method, and wastewater from domestic (99% of the domestic demand) and industrial sector (10% of the industrial demand) and remaining canal water after meeting domestic, industrial, environmental, and livestock demands is available for CWR. The TWA for this scenario is 77.60 BCM, while the CWR is 87.71 BCM. CWR in canal commands ranged between 0.3 and 13.06 BCM with a Gini Coefficient of 0.43. Water Available in canal commands ranged between 556 mm and 1475 mm with a Gini Coefficient of 0.13. % CWR met in canal commands ranged between 46% and 130% with a Gini Coefficient of 0.1.

Following reallocation, water available in canal commands ranged between 0.30 BCM and 11.72 BCM, with a Gini Coefficient of 0.43. The depth of water available in all canal commands is 908 mm due to imposing equity in supply, resulting in a Gini Coefficient of zero. %CWR met ranged between 74% and 109%. A total volume of 6.85 BCM was to be transferred from canal commands where TWA is greater than 886 mm to canal commands where the TWA is less than 886 mm.

Under this scenario, Canal Commands to which water needs to be added are Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Lower Mailsi, Marala Ravi, Rangpur, Sadiqia, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum, and Upper Pakpattan canal commands.

Under this scenario, Canal Commands to which water needs to be removed are Central Bari Doab, CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, Panjnad, Qaim + UBC, and Upper Chenab canal commands. Canal-wise results are presented in Table 30.

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6293	676	0.6739	0.0446	0.0000	0.6739	724	64%	69%
2	Central Bari Doab	202343	2.4185	0.8080	399	1.4650	0.6571	0.0000	1.4650	724	33%	61%
3	CRBC	97125	1.0271	0.8775	903	0.7032	0.0000	0.1743	0.7032	724	85%	68%
4	D.G. Khan	364217	3.8209	3.2806	901	2.6370	0.0000	0.6436	2.6370	724	86%	69%
5	Fordwah	174015	1.6333	1.2486	718	1.2599	0.0113	0.0000	1.2599	724	76%	77%
6	Greater Thal	104361	1.2523	0.5693	546	0.7556	0.1863	0.0000	0.7556	724	45%	60%
7	Haveli	66045	0.7078	0.5193	786	0.4782	0.0000	0.0411	0.4782	724	73%	68%
8	LBDC	538232	6.5784	5.2677	979	3.8969	0.0000	1.3707	3.8969	724	80%	59%
9	Lower Bhawal	218530	2.4804	2.9444	1347	1.5822	0.0000	1.3622	1.5822	724	119%	64%
10	Lower Chenab	1290948	13.0688	7.7457	600	9.3467	1.6010	0.0000	9.3467	724	59%	72%
11	Lower Dipalpur	249853	2.0888	1.4506	581	1.8090	0.3584	0.0000	1.8090	724	69%	87%
12	Lower Jhelum	615123	5.8199	3.3782	549	4.4536	1.0754	0.0000	4.4536	724	58%	77%
13	Lower Mailsi	279233	3.0708	2.1891	784	2.0217	0.0000	0.1674	2.0217	724	71%	66%
14	Lower Pakpattan	121406	1.2991	1.0853	894	0.8790	0.0000	0.2063	0.8790	724	84%	68%
15	Marala Ravi	33010	0.3038	0.0810	245	0.2390	0.1580	0.0000	0.2390	724	27%	79%
16	Muzaffargarh	331843	3.5365	2.8701	865	2.4026	0.0000	0.4675	2.4026	724	81%	68%
17	Panjnad	546326	6.5559	7.5158	1376	3.9555	0.0000	3.5603	3.9555	724	115%	60%
18	Qaim + UBC	44515	0.5053	0.3743	841	0.3223	0.0000	0.0520	0.3223	724	74%	64%
19	Rangpur	141640	1.3568	0.9684	684	1.0255	0.0571	0.0000	1.0255	724	71%	76%
20	Sadiqia	441108	4.2175	3.5104	796	3.1937	0.0000	0.3167	3.1937	724	83%	76%
21	Sindhnai	346735	3.7167	1.7193	496	2.5104	0.7912	0.0000	2.5104	724	46%	68%
22	Thal	857934	7.9673	5.4621	637	6.2116	0.7495	0.0000	6.2116	724	69%	78%
23	Upper Chenab	510402	5.3618	3.2771	642	3.6954	0.4184	0.0000	3.6954	724	61%	69%
24	Upper Dipalpur	146739	1.3320	0.5851	399	1.0624	0.4773	0.0000	1.0624	724	44%	80%
25	Upper Jhelum	218530	2.0942	0.8815	403	1.5822	0.7007	0.0000	1.5822	724	42%	76%
26	Upper Pakpattan	513951	4.5178	2.6453	515	3.7211	1.0758	0.0000	3.7211	724	59%	82%

Table 26: Canal-wise Results ES-C Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6903	742	0.8570	0.1667	0.0000	0.8570	921	71%	88%
2	Central Bari Doab	202343	2.4185	1.4002	692	1.8630	0.4628	0.0000	1.8630	921	58%	77%
3	CRBC	97125	1.0271	0.9924	1022	0.8942	0.0000	0.0982	0.8942	921	97%	87%
4	D.G. Khan	364217	3.8209	3.5613	978	3.3533	0.0000	0.2080	3.3533	921	93%	88%
5	Fordwah	174015	1.6333	1.4393	827	1.6021	0.1628	0.0000	1.6021	921	88%	98%
6	Greater Thal	104361	1.2523	0.8302	795	0.9608	0.1307	0.0000	0.9608	921	66%	77%
7	Haveli	66045	0.7078	0.6721	1018	0.6081	0.0000	0.0640	0.6081	921	95%	86%
8	LBDC	538232	6.5784	6.0953	1132	4.9554	0.0000	1.1399	4.9554	921	93%	75%
9	Lower Bhawal	218530	2.4804	3.0649	1402	2.0120	0.0000	1.0529	2.0120	921	124%	81%
10	Lower Chenab	1290948	13.0688	10.9908	851	11.8856	0.8948	0.0000	11.8856	921	84%	91%
11	Lower Dipalpur	249853	2.0888	1.8803	753	2.3004	0.4201	0.0000	2.3004	921	90%	110%
12	Lower Jhelum	615123	5.8199	5.5211	898	5.6634	0.1422	0.0000	5.6634	921	95%	97%
13	Lower Mailsi	279233	3.0708	2.4234	868	2.5709	0.1475	0.0000	2.5709	921	79%	84%
14	Lower Pakpattan	121406	1.2991	1.1868	978	1.1178	0.0000	0.0691	1.1178	921	91%	86%
15	Marala Ravi	33010	0.3038	0.2260	685	0.3039	0.0779	0.0000	0.3039	921	74%	100%
16	Muzaffargarh	331843	3.5365	3.2868	990	3.0552	0.0000	0.2316	3.0552	921	93%	86%
17	Panjnad	546326	6.5559	7.8878	1444	5.0300	0.0000	2.8579	5.0300	921	120%	77%
18	Qaim + UBC	44515	0.5053	0.3988	896	0.4098	0.0110	0.0000	0.4098	921	79%	81%
19	Rangpur	141640	1.3568	1.3008	918	1.3041	0.0032	0.0000	1.3041	921	96%	96%
20	Sadiqia	441108	4.2175	3.9844	903	4.0612	0.0768	0.0000	4.0612	921	94%	96%
21	Sindhnai	346735	3.7167	2.1548	621	3.1924	1.0375	0.0000	3.1924	921	58%	86%
22	Thal	857934	7.9673	7.5791	883	7.8989	0.3198	0.0000	7.8989	921	95%	99%
23	Upper Chenab	510402	5.3618	4.9850	977	4.6992	0.0000	0.2858	4.6992	921	93%	88%
24	Upper Dipalpur	146739	1.3320	0.9764	665	1.3510	0.3746	0.0000	1.3510	921	73%	101%
25	Upper Jhelum	218530	2.0942	1.8909	865	2.0120	0.1211	0.0000	2.0120	921	90%	96%
26	Upper Pakpattan	513951	4.5178	3.2742	637	4.7319	1.4577	0.0000	4.7319	921	72%	105%

Table 27: Canal-wise Results ES-CS Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%Met Before	%Met After
1	Abbasia	93078	0.9785	0.6667	716	0.8062	0.1396	0.0000	0.8062	866	68%	82%
2	Central Bari Doab	202343	2.4185	1.3563	670	1.7526	0.3964	0.0000	1.7526	866	56%	72%
3	CRBC	97125	1.0271	0.9626	991	0.8413	0.0000	0.1213	0.8413	866	94%	82%
4	D.G. Khan	364217	3.8209	3.5493	975	3.1548	0.0000	0.3946	3.1548	866	93%	83%
5	Fordwah	174015	1.6333	1.3906	799	1.5073	0.1167	0.0000	1.5073	866	85%	92%
6	Greater Thal	104361	1.2523	0.5735	550	0.9039	0.3305	0.0000	0.9039	866	46%	72%
7	Haveli	66045	0.7078	0.6211	940	0.5721	0.0000	0.0490	0.5721	866	88%	81%
8	LBDC	538232	6.5784	5.9489	1105	4.6620	0.0000	1.2869	4.6620	866	90%	71%
9	Lower Bhawal	218530	2.4804	3.1143	1425	1.8929	0.0000	1.2215	1.8929	866	126%	76%
10	Lower Chenab	1290948	13.0688	10.5532	817	11.1818	0.6286	0.0000	11.1818	866	81%	86%
11	Lower Dipalpur	249853	2.0888	1.7672	707	2.1642	0.3970	0.0000	2.1642	866	85%	104%
12	Lower Jhelum	615123	5.8199	4.5247	736	5.3280	0.8033	0.0000	5.3280	866	78%	92%
13	Lower Mailsi	279233	3.0708	2.3972	858	2.4186	0.0215	0.0000	2.4186	866	78%	79%
14	Lower Pakpattan	121406	1.2991	1.1730	966	1.0516	0.0000	0.1214	1.0516	866	90%	81%
15	Marala Ravi	33010	0.3038	0.1156	350	0.2859	0.1703	0.0000	0.2859	866	38%	94%
16	Muzaffargarh	331843	3.5365	3.1100	937	2.8743	0.0000	0.2356	2.8743	866	88%	81%
17	Panjnad	546326	6.5559	7.7273	1414	4.7321	0.0000	2.9952	4.7321	866	118%	72%
18	Qaim + UBC	44515	0.5053	0.4089	919	0.3856	0.0000	0.0233	0.3856	866	81%	76%
19	Rangpur	141640	1.3568	1.1562	816	1.2268	0.0706	0.0000	1.2268	866	85%	90%
20	Sadiqia	441108	4.2175	3.8628	876	3.8208	0.0000	0.0420	3.8208	866	92%	91%
21	Sindhnai	346735	3.7167	2.0219	583	3.0033	0.9814	0.0000	3.0033	866	54%	81%
22	Thal	857934	7.9673	6.7508	787	7.4312	0.6803	0.0000	7.4312	866	85%	93%
23	Upper Chenab	510402	5.3618	4.8986	960	4.4210	0.0000	0.4776	4.4210	866	91%	82%
24	Upper Dipalpur	146739	1.3320	0.9331	636	1.2710	0.3380	0.0000	1.2710	866	70%	95%
25	Upper Jhelum	218530	2.0942	1.3978	640	1.8929	0.4950	0.0000	1.8929	866	67%	90%
26	Upper Pakpattan	513951	4.5178	3.0525	594	4.4517	1.3992	0.0000	4.4517	866	68%	99%

Table 28: Canal wise Results - ES CU Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.7144	768	0.8958	0.1813	0.0000	0.8958	962	73%	92%
2	Central Bari Doab	202343	2.4185	2.0344	1005	1.9473	0.0000	0.0871	1.9473	962	84%	81%
3	CRBC	97125	1.0271	1.0203	1051	0.9347	0.0000	0.0856	0.9347	962	99%	91%
4	D.G. Khan	364217	3.8209	3.7051	1017	3.5051	0.0000	0.2000	3.5051	962	97%	92%
5	Fordwah	174015	1.6333	1.4653	842	1.6747	0.2094	0.0000	1.6747	962	90%	103%
6	Greater Thal	104361	1.2523	0.8370	802	1.0043	0.1674	0.0000	1.0043	962	67%	80%
7	Haveli	66045	0.7078	0.6836	1035	0.6356	0.0000	0.0480	0.6356	962	97%	90%
8	LBDC	538232	6.5784	6.2917	1169	5.1798	0.0000	1.1119	5.1798	962	96%	79%
9	Lower Bhawal	218530	2.4804	3.1735	1452	2.1031	0.0000	1.0704	2.1031	962	128%	85%
10	Lower Chenab	1290948	13.0688	11.6833	905	12.4237	0.7404	0.0000	12.4237	962	89%	95%
11	Lower Dipalpur	249853	2.0888	1.9461	779	2.4045	0.4585	0.0000	2.4045	962	93%	115%
12	Lower Jhelum	615123	5.8199	5.6736	922	5.9198	0.2462	0.0000	5.9198	962	97%	102%
13	Lower Mailsi	279233	3.0708	2.4748	886	2.6873	0.2125	0.0000	2.6873	962	81%	88%
14	Lower Pakpattan	121406	1.2991	1.2042	992	1.1684	0.0000	0.0358	1.1684	962	93%	90%
15	Marala Ravi	33010	0.3038	0.2982	903	0.3177	0.0195	0.0000	0.3177	962	98%	105%
16	Muzaffargarh	331843	3.5365	3.4163	1029	3.1936	0.0000	0.2227	3.1936	962	97%	90%
17	Panjnad	546326	6.5559	8.0524	1474	5.2577	0.0000	2.7947	5.2577	962	123%	80%
18	Qaim + UBC	44515	0.5053	0.4123	926	0.4284	0.0161	0.0000	0.4284	962	82%	85%
19	Rangpur	141640	1.3568	1.3346	942	1.3631	0.0285	0.0000	1.3631	962	98%	100%
20	Sadiqia	441108	4.2175	4.0679	922	4.2451	0.1772	0.0000	4.2451	962	96%	101%
21	Sindhnai	346735	3.7167	2.4232	699	3.3369	0.9137	0.0000	3.3369	962	65%	90%
22	Thal	857934	7.9673	7.7780	907	8.2565	0.4786	0.0000	8.2565	962	98%	104%
23	Upper Chenab	510402	5.3618	5.1231	1004	4.9120	0.0000	0.2111	4.9120	962	96%	92%
24	Upper Dipalpur	146739	1.3320	1.0248	698	1.4122	0.3874	0.0000	1.4122	962	77%	106%
25	Upper Jhelum	218530	2.0942	2.0378	933	2.1031	0.0652	0.0000	2.1031	962	97%	100%
26	Upper Pakpattan	513951	4.5178	3.3809	658	4.9461	1.5653	0.0000	4.9461	962	75%	109%

Table 29: Canal wise Results ESCSWW Water Allocation

No	Canal	Area (ha)	CWR (BCM)	TWA (BCM)	TWA (mm)	Target (BCM)	Add (BCM)	Remove (BCM)	TWA-R (BCM)	TWA-R (mm)	%CWR Before	%CWR After
1	Abbasia	93078	0.9785	0.6908	742	0.8450	0.1542	0.0000	0.8450	908	71%	86%
2	Central Bari Doab	202343	2.4185	1.9904	984	1.8370	0.0000	0.1534	1.8370	908	82%	76%
3	CRBC	97125	1.0271	0.9905	1020	0.8818	0.0000	0.1087	0.8818	908	96%	86%
4	D.G. Khan	364217	3.8209	3.6931	1014	3.3066	0.0000	0.3865	3.3066	908	97%	87%
5	Fordwah	174015	1.6333	1.4166	814	1.5798	0.1632	0.0000	1.5798	908	87%	97%
6	Greater Thal	104361	1.2523	0.5802	556	0.9474	0.3672	0.0000	0.9474	908	46%	76%
7	Haveli	66045	0.7078	0.6325	958	0.5996	0.0000	0.0329	0.5996	908	89%	85%
8	LBDC	538232	6.5784	6.1453	1142	4.8864	0.0000	1.2589	4.8864	908	93%	74%
9	Lower Bhawal	218530	2.4804	3.2229	1475	1.9839	0.0000	1.2390	1.9839	908	130%	80%
10	Lower Chenab	1290948	13.0688	11.2457	871	11.7200	0.4742	0.0000	11.7200	908	86%	90%
11	Lower Dipalpur	249853	2.0888	1.8330	734	2.2683	0.4353	0.0000	2.2683	908	88%	109%
12	Lower Jhelum	615123	5.8199	4.6772	760	5.5844	0.9073	0.0000	5.5844	908	80%	96%
13	Lower Mailsi	279233	3.0708	2.4486	877	2.5350	0.0864	0.0000	2.5350	908	80%	83%
14	Lower Pakpattan	121406	1.2991	1.1903	980	1.1022	0.0000	0.0881	1.1022	908	92%	85%
15	Marala Ravi	33010	0.3038	0.1878	569	0.2997	0.1119	0.0000	0.2997	908	62%	99%
16	Muzaffargarh	331843	3.5365	3.2394	976	3.0127	0.0000	0.2267	3.0127	908	92%	85%
17	Panjnad	546326	6.5559	7.8919	1445	4.9599	0.0000	2.9320	4.9599	908	120%	76%
18	Qaim + UBC	44515	0.5053	0.4224	949	0.4041	0.0000	0.0182	0.4041	908	84%	80%
19	Rangpur	141640	1.3568	1.1900	840	1.2859	0.0959	0.0000	1.2859	908	88%	95%
20	Sadiqia	441108	4.2175	3.9463	895	4.0046	0.0584	0.0000	4.0046	908	94%	95%
21	Sindhnai	346735	3.7167	2.2902	661	3.1479	0.8576	0.0000	3.1479	908	62%	85%
22	Thal	857934	7.9673	6.9497	810	7.7888	0.8391	0.0000	7.7888	908	87%	98%
23	Upper Chenab	510402	5.3618	5.0366	987	4.6337	0.0000	0.4029	4.6337	908	94%	86%
24	Upper Dipalpur	146739	1.3320	0.9814	669	1.3322	0.3508	0.0000	1.3322	908	74%	100%
25	Upper Jhelum	218530	2.0942	1.5448	707	1.9839	0.4392	0.0000	1.9839	908	74%	95%
26	Upper Pakpattan	513951	4.5178	3.1591	615	4.6659	1.5068	0.0000	4.6659	908	70%	103%

Table 30: Canal wise Results ES CUWW Water Allocation

12.9 Inferences from Modelling Results

12.9.1 Inferences from Rule4 Modelling

TheRule-4 stipulates reallocation of a maximum of 10% water from canals where all demands are met (without negatively affecting current requirements). This restricts reallocation from Lower Bahawal, and Panjnad canal commands only and will not allow all excess water in these canal commands to be reallocated. Excess water greater than the 10% limit could be better used in other canal commands with CWR deficit and prevent waterlogging and salinity in Lower Bahawal and Panjnad canal commands.

Under all modeling scenarios evaluated, results show that reallocation of all excess canal water from Lower Bahawal and Panjnad canal commands will reduce the CWR deficit in Abbasia and Central Bari Doab Canal Commands. Hence PID may consider reallocating all excess water (instead of 10%) after all demands are met in canal commands.

12.9.2 Inferences from ED Modelling

Suppose the PID wishes to ensure Equity in Deficit (ED) across all canal commands. In that case, canal water supplies may be reduced to CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Muzaffargarh, Panjnad, and Sadiqia canal commands, and increased to Abbasia, Central Bari Doab, Greater Thal, Lower Chenab, Sindhnai, Upper Dipalpur, and Upper Pakpattan canal commands. This objective will equitably meet current demand based on existing cropping patterns.

12.9.3 Inference from ES Modelling

Suppose the PID wishes to ensure Equity in supply (ES), across all canal commands. In that case, canal water supplies may be reduced to CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh and Panjnad canal commands, and increased to Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Marala Ravi, Rangpur, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum, and Upper Pakpattan canal commands. This practice will be consistent to PID's current mandate of distributing water equitably, consistent with Warabandi requirements.

12.9.4 Inference from ED and ES Modelling

Suppose the PID wishes to improve Equity in Supply and Equity in Deficit. In that case, canal water supplies may be reduced to CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh and Panjnad canal commands and increased to Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Marala Ravi, Rangpur, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum and Upper Pakpattan canal commands.

13 Issues and Options: Punjab's Canal Water Allocation Policy

13.1 The Context of Water Allocation in Punjab

The Punjab Water Policy (2018) aims to balance productivity and conservation and requires adopting Integrated Water Resource Management (IWRM) across the province. The Punjab Water Act (2019), enacted by the Provincial Assembly, is the legal instrument of the Government of Punjab to comprehensively manage and regulate water resources in Punjab in the interest of conservation and sustainability.

IWRM embraces the management of water as an economic resource. The interaction of three critical factors, the value of water, the use cost of water, and the resource's opportunity cost, determine how water is used or consumed.

At the National level, the IRSA was mandated under WAA-1991 to distribute water to the provinces according to their share. Seasonal water availability before each cropping season; Kharif and Rabi for the two systems; Indus-and Jhelum-Chenab Zones is assessed at rim stations, and provinces are informed of their allocation on the 10-daily basis for the maximum, minimum, and most likely inflow scenarios. The provinces then make a Water Allocation Plan for each canal command based on its share/entitlement for maximum, minimum, and likely inflows. Expected shortages/surpluses are uniformly distributed.

At the Provincial level, the inequitable supply of water between canal commands, variation in cropping patterns, reduction of culturable command areas (CCA) due to urbanization, induction of new areas into canal commands, and demand for water in areas outside canal commands require reallocation of canal water within the province. This will be the responsibility of the WRC, which will allocate water and issue licenses to different water sectors based on the Act's Priority.

The WRC envisions to adapt modern basin allocation planning with a focus on prioritizing, recycling non-consumed fractions of recoverable water, e.g. (recharge to freshwater aquifers), and reusing (un)treated wastewater. Consequently, its water allocation approaches will be founded on complex rules for dealing with variability and balancing different water allocation scenarios' environmental, social, political, and economic implications.

WRC's water allocation planning will consider the total water resources from rain, canal and groundwater supplies, and water from inter-basin transfers. The amount of water available for allocation will be a function of this total volume, less water that cannot in practice be used. Examples are water that cannot be stored or used and passes during uncontrolled flooding and water retained in the river system to meet ecological needs (i.e., environmental flows).

The Punjab Water Policy (2018) requires Key Policy Actions for Water Allocation in section 2.4 as below.

- Assign priority for water allocation for various sub-sectors of water use in the order of domestic water, stock water, water for agriculture, water for industrial and commercial uses, water for environmental and recreational uses based on the current uses and future demand.
- Allocate water to various sub-sectors of water use and different regions (Canal commands, Pothwar, Thal and Cholistan deserts, Suleiman ranges, riverine areas) towards establishing water entitlements in the regions and for sources of water (surface water and groundwater).
- Enforce measures to reduce, reuse, and recycle water in domestic, commercial, and industrial sub-sectors to manage part of future water demand in these sub-sectors by recycling wastewater.
- Introduce water-efficient technologies and 'best practices for optimal land use for irrigated agriculture to enhance the water productivity and save water for reallocations to other sub-sectors of water use.

Furthermore, Clause 4 of the Punjab Water Act (Act XXI of 2019) empowers the Water Resources Commission as below:

It shall be the duty of the Commission to take all such actions as it may, from time to time, consider necessary or suitable for the purpose of:

- conserving, redistributing or otherwise augmenting water resources in the Punjab;
- allocating water resources for domestic, agricultural, ecological, industrial, or other purposes in different areas of the Punjab; and
- of securing the proper use of water resources in Punjab.

13.2 Water Balance of Punjab's Canal Commands – The Big Picture

Canal Commands' water balance BIG PICTURE informs two significant water sources, the canal (river) and rainfall. According to the Water Apportionment Act (1991), the Canal Water available for Punjab is 69 BCM. Gross rainfall within the canal commands is 34 BCM, of which an estimated 16.8 BCM is effective. The difference between 34 BCM and 16.8 BCM (17.2 BCM) is considered the water cannot be used in practice (floods, environmental flows etc.)

Together, the total water available within the canal command is 85.8 BCM. A minor source is stored groundwater (net discharge), and it is estimated to be 0.7943 BCM. However, reliance on net discharge to support socio-economic activities will be unsustainable because the net discharge from aquifers will deplete the stored water in the future if it continues. Therefore, aquifers within the canal command should be considered as storage of seepage water, facilitating recycling recharge from canal water and rainfall.

The total volume of water required to meet domestic, industrial, livestock, and crop water demand are 3.4 BCM, 1.99 BCM, 0.56 BCM, and 87.6 BCM. To replenish the aquifers at the rate they are being depleted over the past 13 years, and the annual environmental demand

is 0.7943 BCM. In sum, demand from all sectors is 94.32 BCM. This compares with total water consumed at 86.59 BCM, a maximum net deficit of 7.73 BCM. This deficit will be reduced when a fraction of water supplied to the Domestic and Industrial sectors is returned to agriculture.

Assuming only canal and effective rainfall is available to meet all demands, the initial estimate of the water deficit within Punjab's canal commands is 94.32 – 85.8 = 8.52 BCM. However, the deficit will be further reduced depending on the wastewater returned from domestic and industrial sectors to agriculture. The total demand for domestic and industrial sectors is 5.39 BCM (3.4 +1.99). Previous studies have shown that 99% of water withdrawn for domestic use is returned as water for agriculture (3.37 BCM). Another 10% of water supplied for industries is returned as wastewater for agriculture (0.2 BCM). If returning wastewater quality is acceptable for agriculture, the deficit will be reduced from 8.52 BCM to 4.95 BCM.

In sum, water available within Punjab's Canal commands is insufficient to meet all domestic, livestock, industrial, agricultural, and environmental demands for water. To increase water availability, effective rainfall needs to be improved. Punjab should adopt a widespread rainwater harvesting program, especially in urbanized areas. Depleting fossil water in aquifers needs to be avoided, and measures should be taken to replenish depleted groundwater.

13.3 Plausible Objectives of Water Allocation in Punjab

The central question for WRC for allocating water to Punjab's 26 canal commands is what objectives should shape water (re) allocation? More specifically, once the aims are defined for a particular hydrological system, how can they be achieved? It appears that WRC may consider three different objectives, which are not necessarily mutually exclusive.

The first objective is to cause minimal disruption to the status quo, which is reflected in the recent promulgation of the Government of Punjab's rules for the Adjustment of Canal Command Areas ((Rule 3-a, b, c, d), and the provision to reduce canal water allowance (Clause 4 Rule 4(2). Under Clause (4) of Rule 4 (2), 'The Cabinet may reduce water allowance of a canal by not more than ten percent of its existing water allowance where, in majority view of the following, such reduction has no practical effect on the agriculture of the existing irrigators.'

The second objective may be to supply canal water to meet all domestic, industrial, livestock, and environmental demands of every canal, and then reallocate remaining canal water to ensure equitable deficit to meet crop water requirements within the canal command. This objective will support current cropping patterns, which evolved over the years due to agro-climatic and socio-economic factors.

The third objective may be to supply canal water to meet all domestic, industrial, livestock, and environmental demands of every canal, and then reallocate remaining canal water to

ensure equitable supply per unit land area, consistent with warabandi principles. This objective will recognize water as one of the inputs and will allow irrigators to modify their cropping patterns based on water available.

13.4 Meeting the Objectives with Available Water

Recalling that water available within Punjab's Canal commands is insufficient to meet all domestic, livestock, industrial, agricultural, and environmental demands for water, the order of priority for a water allocation proposed is a follows: (1) domestic and industrial from which a fraction between 0 and 1 will be returned for reallocation; (2) water supplied to livestock and to arrest aquifer decline will not be returned for reuse; and (3) remaining water is allocated for agriculture.

13.4.1 Re-Allocation under Rule-4.

Rule-4 stipulates reallocation of a maximum of 10% water from canals where all demands are met (without negatively affecting current requirements). This restricts reallocation from Lower Bahawal, and Panjnad canal commands only and will not allow all excess water in these canal commands to be reallocated. Excess water greater than the 10% limit could be better used in other canal commands with CWR deficit and prevent waterlogging and salinity in Lower Bahawal and Panjnad canal commands.

The total water requirement demand in Lower Bahawal and Panjnad canal commands is 2.6727 and 6.7972 BCM, respectively, which include 2.4804 BCM and 6.5559 BCM. The canal water supplied to the Lower Bahawal and Panjnad Canal Commands are 3.1367 BCM and 7.8852 BCM. Under the best-case scenario (including effective rainfall and reuse of treated wastewater), the total water available for crop water requirements are 3.1735 BCM and 8.0524 BCM.

If only 10% of the canal water can be reallocated, then 0.3137 BCM from Lower Bahawal and 0.6797 BCM from Panjnad can be transferred to canal commands with any other canal commands, as all of them have water deficits.

If all excess water can be transferred, for the modeling scenarios evaluated, results show that reallocation of all excess canal water from Lower Bahawal and Panjnad canal commands will reduce the CWR deficit in Abbasia and Central Bari Doab Canal Commands. Depending on the sources of water considered in Lower Bahawal and Panjnad, additional water from these canal commands may be transferred to water deficit canal commands.

Hence PID may consider reallocating all excess water (instead of 10%) after all demands are met in canal commands.

13.4.2 Reallocation to ensure equity in crop water deficit

Suppose the PID wishes to ensure Equity in Deficit (ED) across all canal commands. In that case, canal water supplies may be reduced to CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Muzaffargarh, Panjnad, and Sadiqia canal commands, and increased to Abbasia, Central Bari Doab, Greater Thal, Lower Chenab, Sindhnai, Upper Dipalpur, and Upper Pakpattan canal

commands. This objective will equitably meet current demand based on existing cropping patterns.

Depending on the sources of water considered in Lower Bahawal and Panjnad, additional water from these canal commands may be transferred to water deficit canal commands.

13.4.3 **Reallocation to ensure equity in water availability**

Suppose the PID wishes to ensure Equity in supply (ES), across all canal commands. In that case, canal water supplies may be reduced to CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh, and Panjnad canal commands, and increased to Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Marala Ravi, Rangpur, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum, and Upper Pakpattan canal commands. This practice will be consistent with PID's current mandate of distributing water equitably, consistent with Warabandi requirements.

Depending on the sources of water considered in Lower Bahawal and Panjnad, additional water from these canal commands may be transferred to water deficit canal commands.

13.4.4 **Reallocation to improve equity in crop water deficit and water availability**

Suppose the PID wishes to improve Equity in Supply and Equity in Deficit. In that case, canal water supplies may be reduced to CRBC, D.G. Khan, Haveli, LBDC, Lower Bhawal, Lower Pakpattan, Muzaffargarh and Panjnad canal commands and increased to Abbasia, Fordwah, Greater Thal, Lower Chenab, Lower Dipalpur, Lower Jhelum, Marala Ravi, Rangpur, Sindhnai, Thal, Upper Dipalpur, Upper Jhelum and Upper Pakpattan canal commands. Depending on the sources of water considered in Lower Bahawal and Panjnad, additional water from these canal commands may be transferred to water deficit canal commands.

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https://www.weatheronline.co.uk/weather/maps/city

15 Appendix A: Post monsoon groundwater levels observed at piezometers within Canal Commands

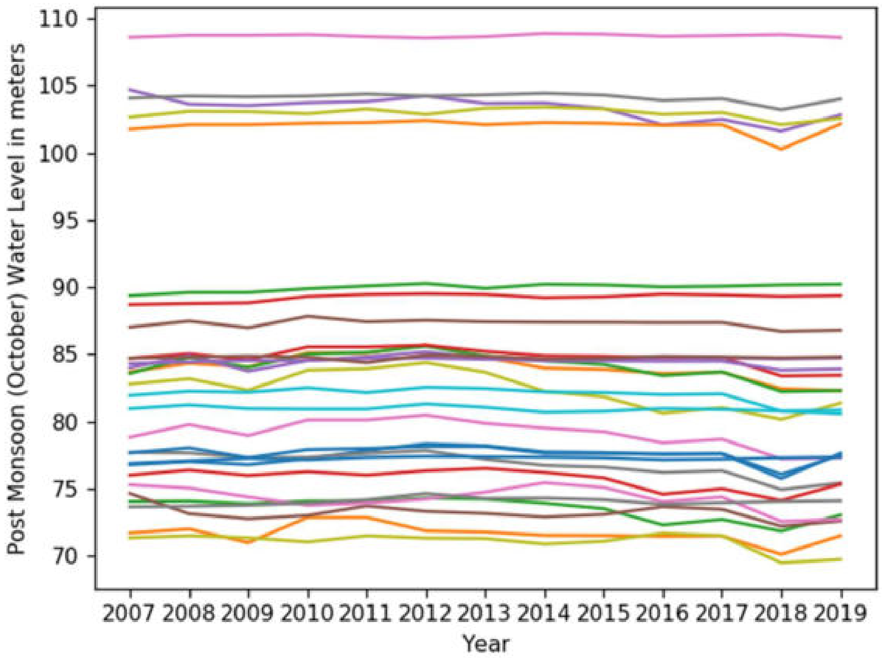

Figure 9: Post monsoon groundwater levels amsl in Abbasia Canal Command

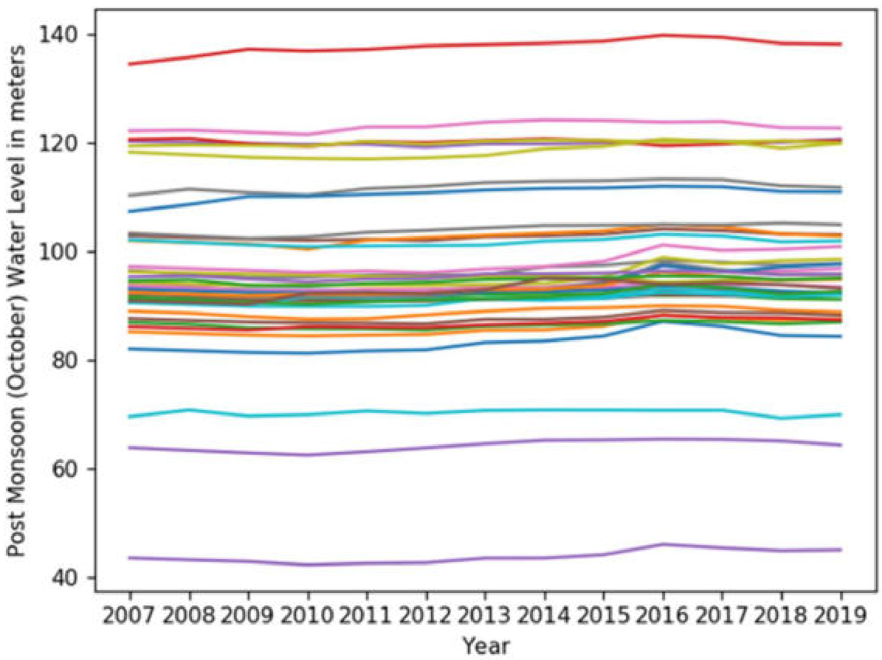

Figure 10: Post monsoon groundwater levels amsl in Bhawal Canal Command

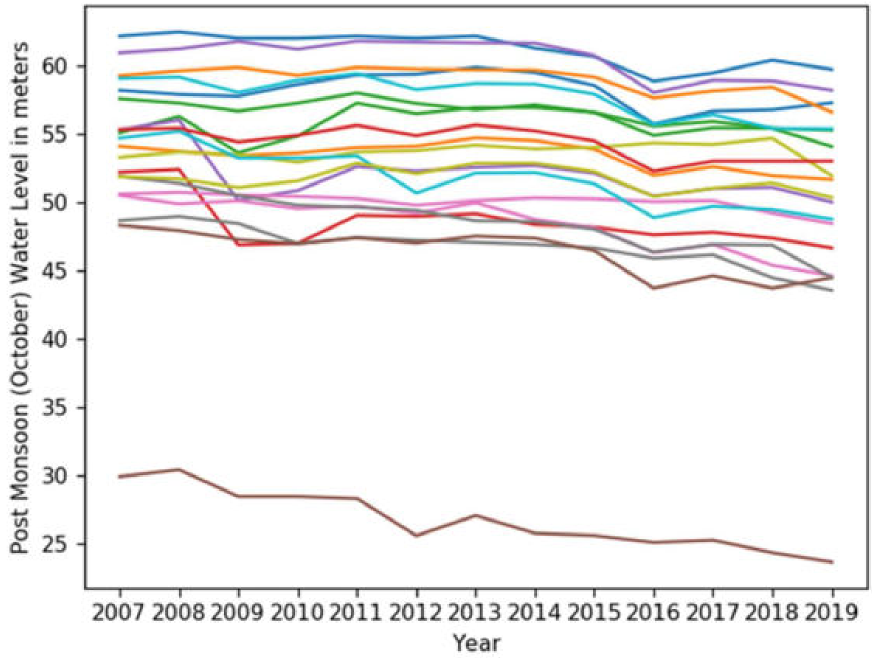

Figure 11: Post monsoon groundwater levels amsl in CBDC Canal Command

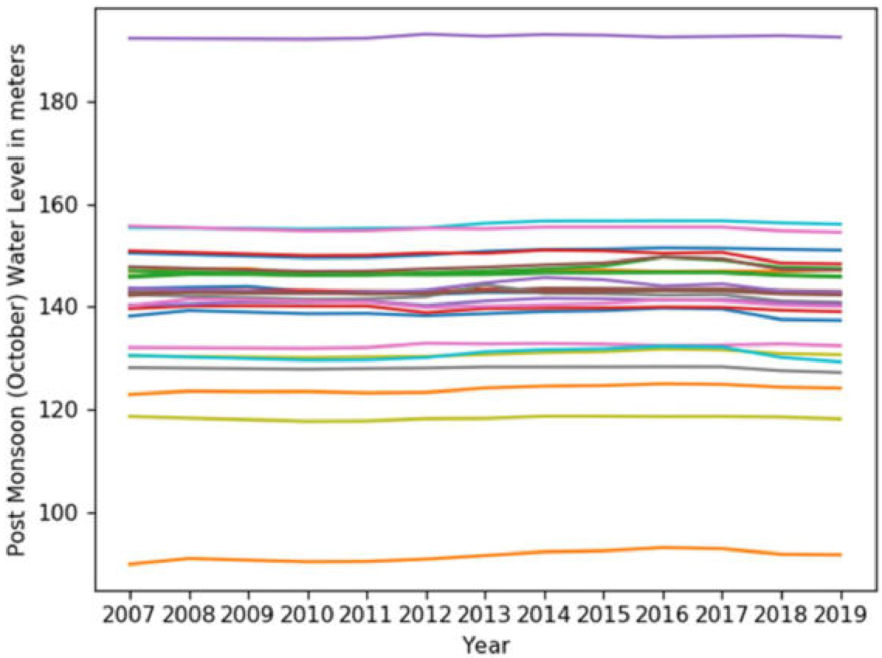

Figure 12: Post monsoon groundwater levels amsl in CRBC Canal Command

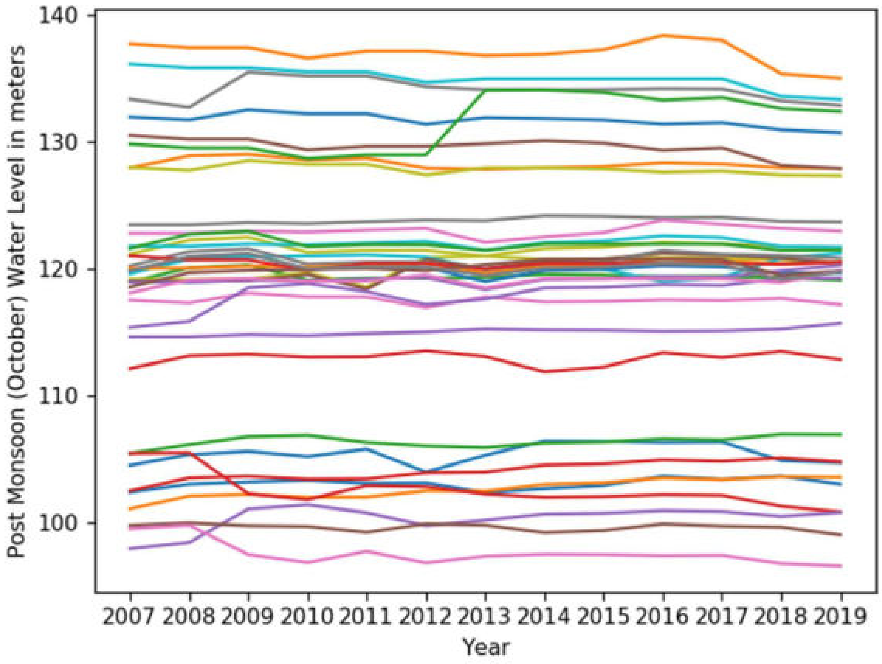

Figure 13: Post monsoon groundwater levels amsl in DG Khan Canal Command

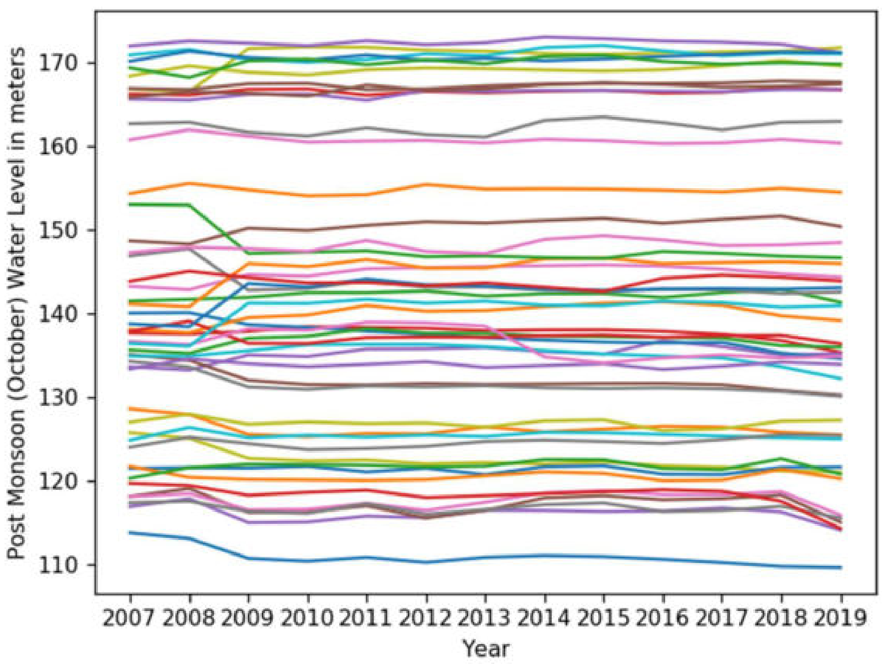

Figure 14: Post monsoon groundwater levels amsl in Fordwah Canal Command

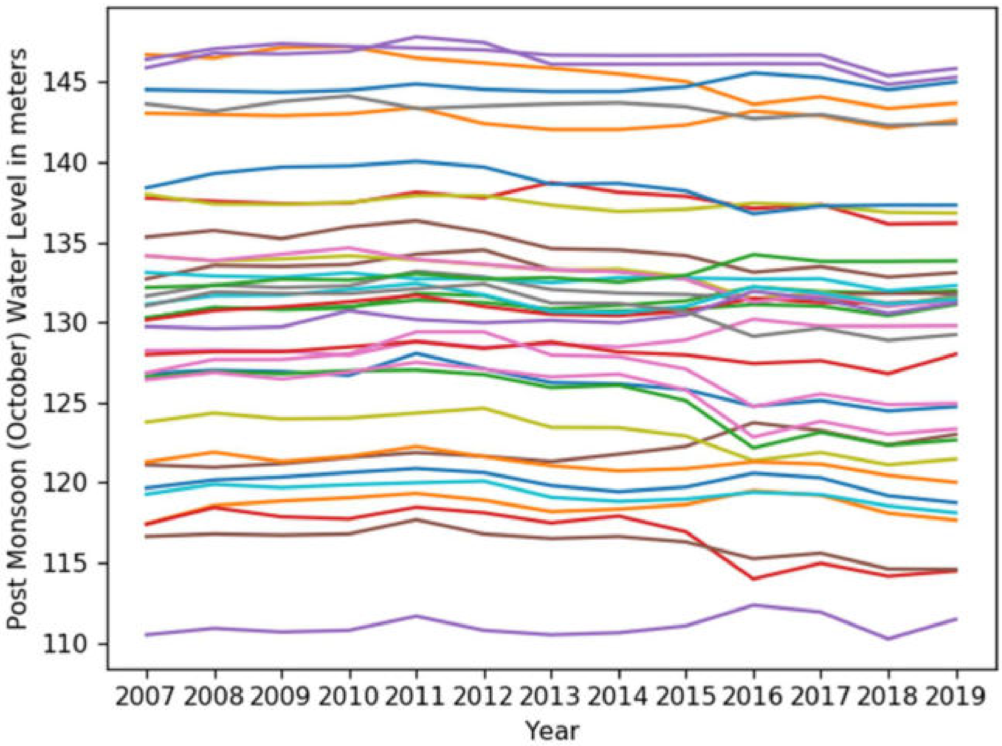

Figure 15: Post monsoon groundwater levels amsl in Haveli Canal Command

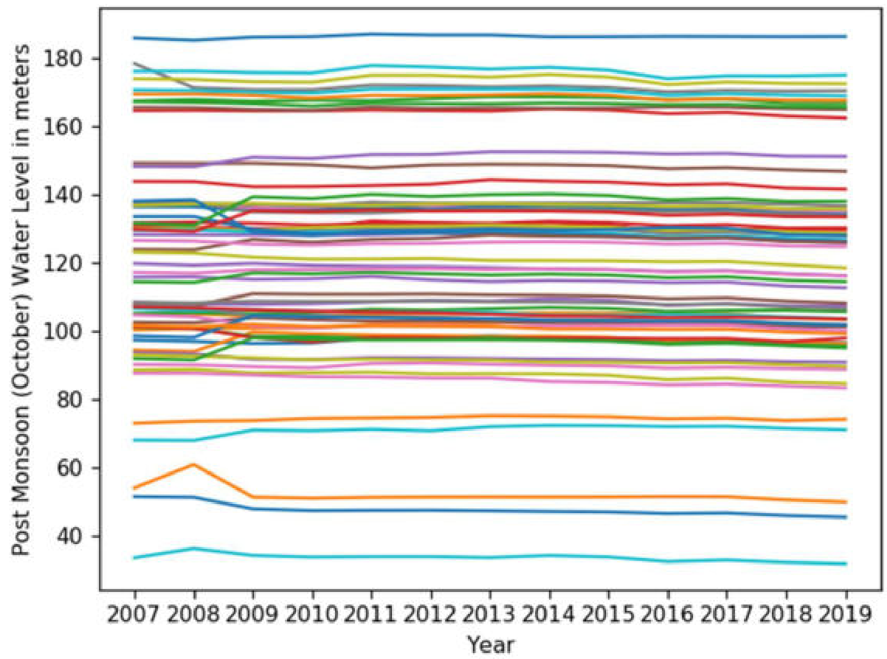

Figure 16: Post monsoon groundwater levels amsl in LBDC Multan Canal Command

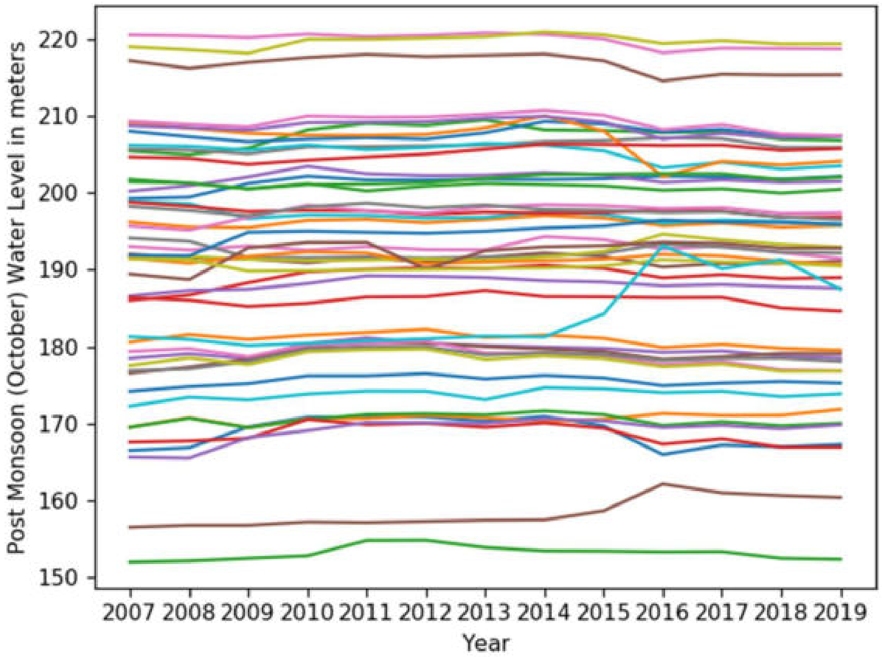

Figure 17: Post monsoon groundwater levels amsl in LCC Faislabad Canal Command

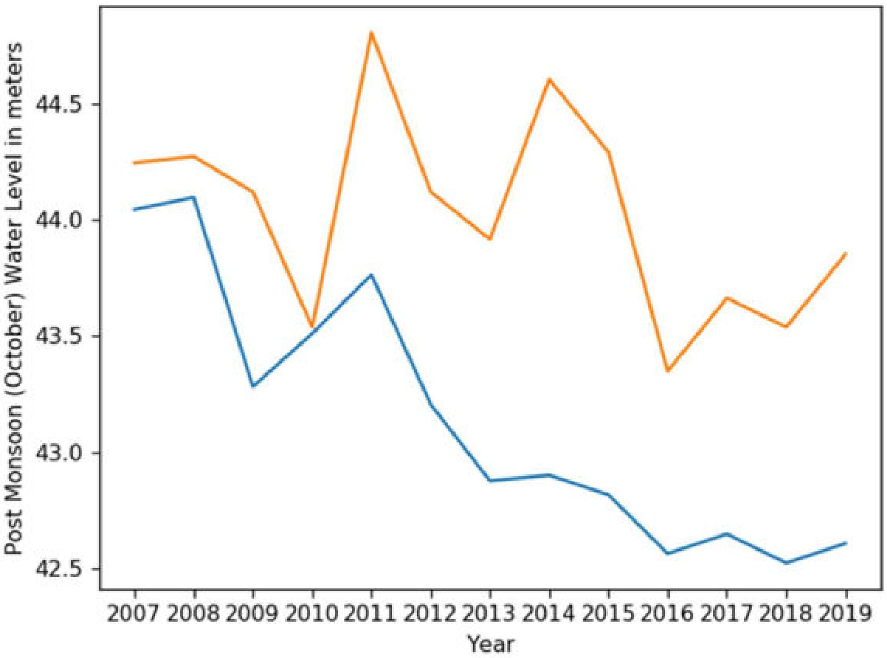

Figure 18: Post monsoon groundwater levels amsl in LDC Lahore Canal Command

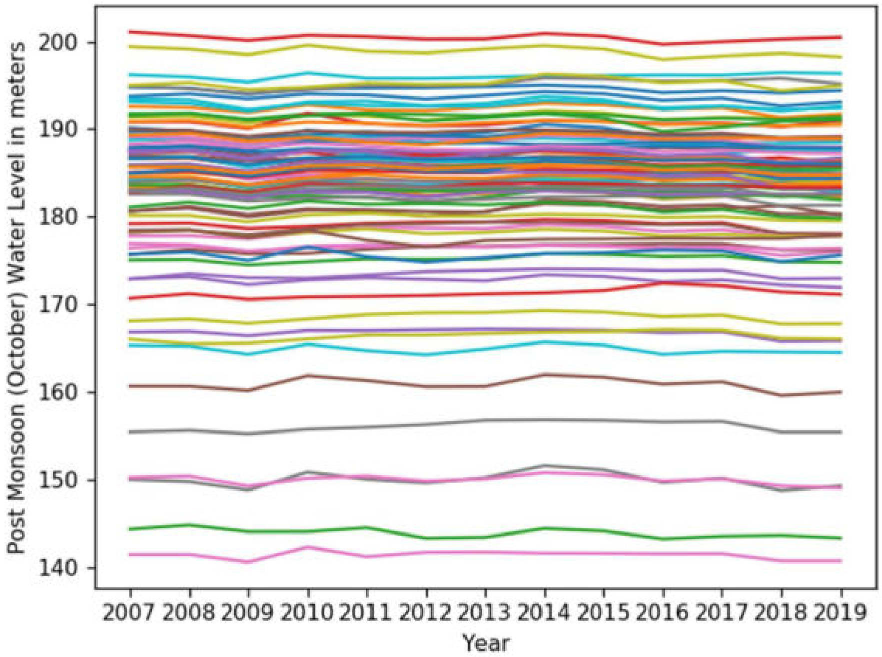

Figure 19: Post monsoon groundwater levels amsl in LJC Sargodha Canal Command

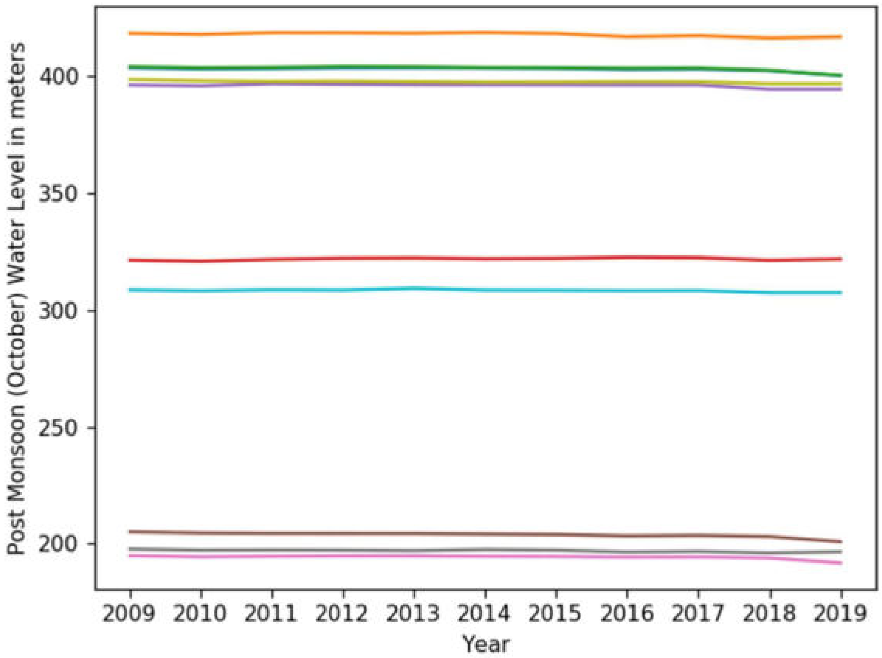

Figure 20: Post monsoon groundwater levels amsl in LPC Multan Canal Command

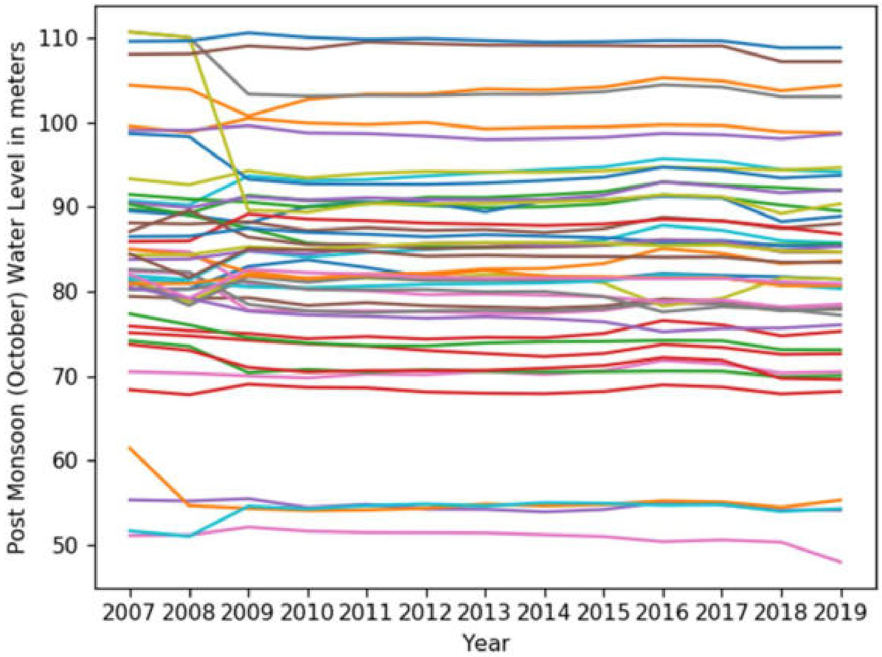

Figure 21: Post monsoon groundwater levels amsl in Mailsi Canal Command

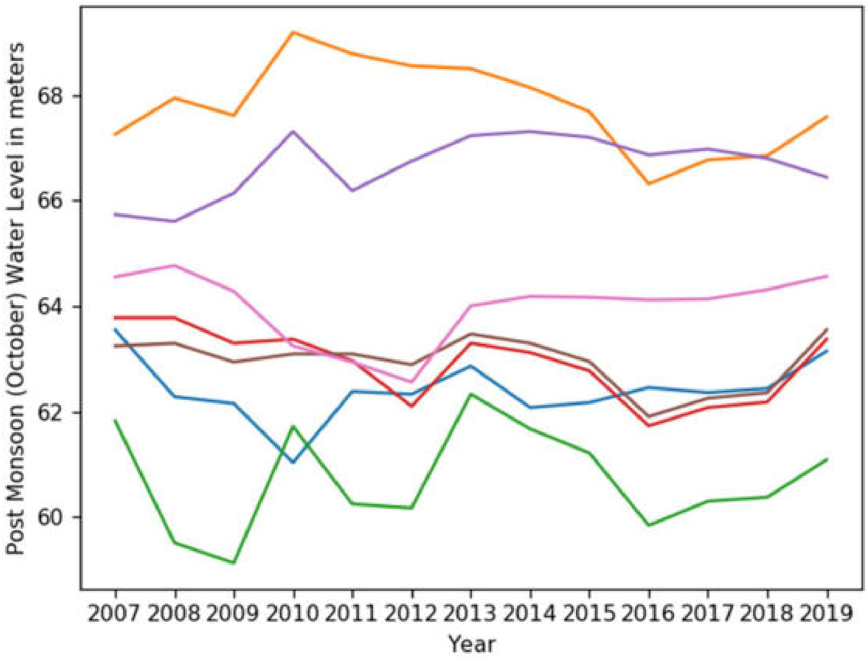

Figure 22: Post monsoon groundwater levels amsl in Marala Ravi Canal Command

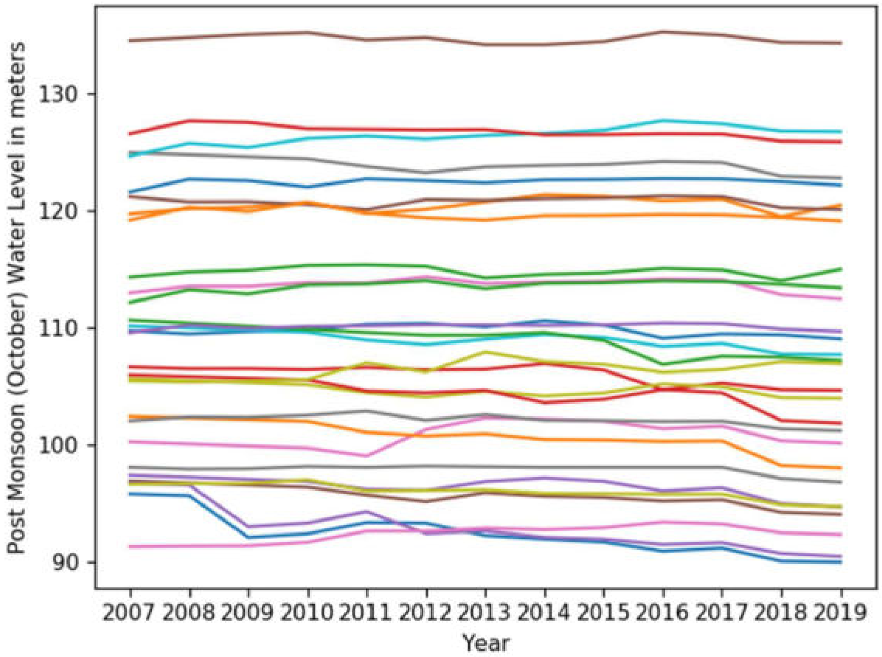

Figure 23: Post monsoon groundwater levels amsl in Muzaffargarh Canal Command

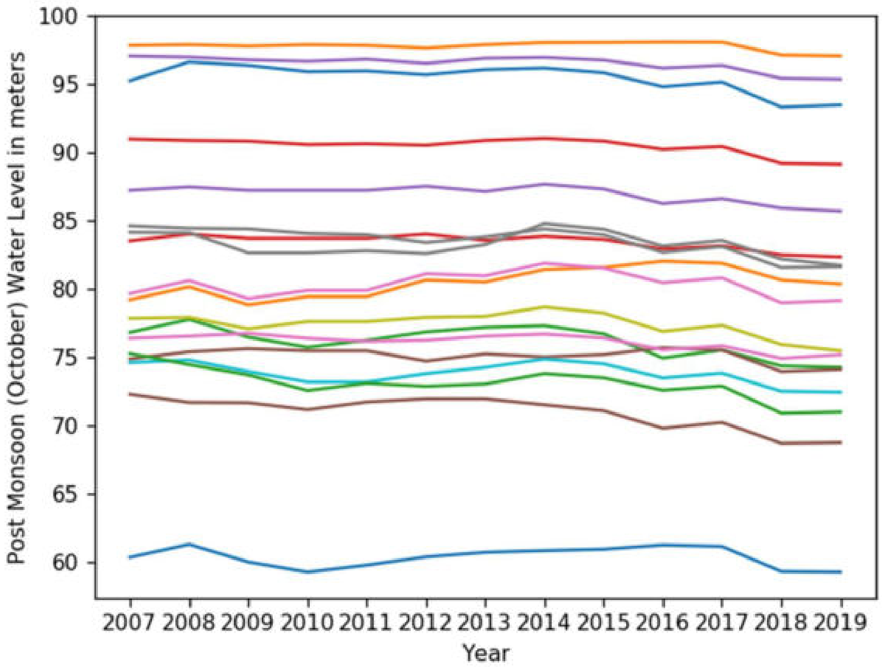

Figure 24: Post monsoon groundwater levels amsl in Panjnad Canal Command

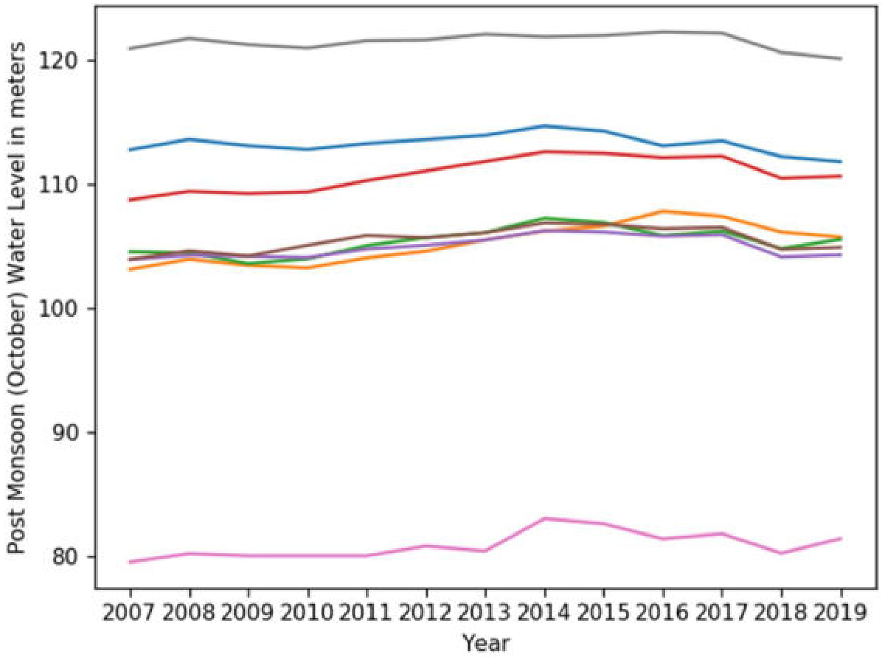

Figure 25: Post monsoon groundwater levels amsl in Qaim Canal Command

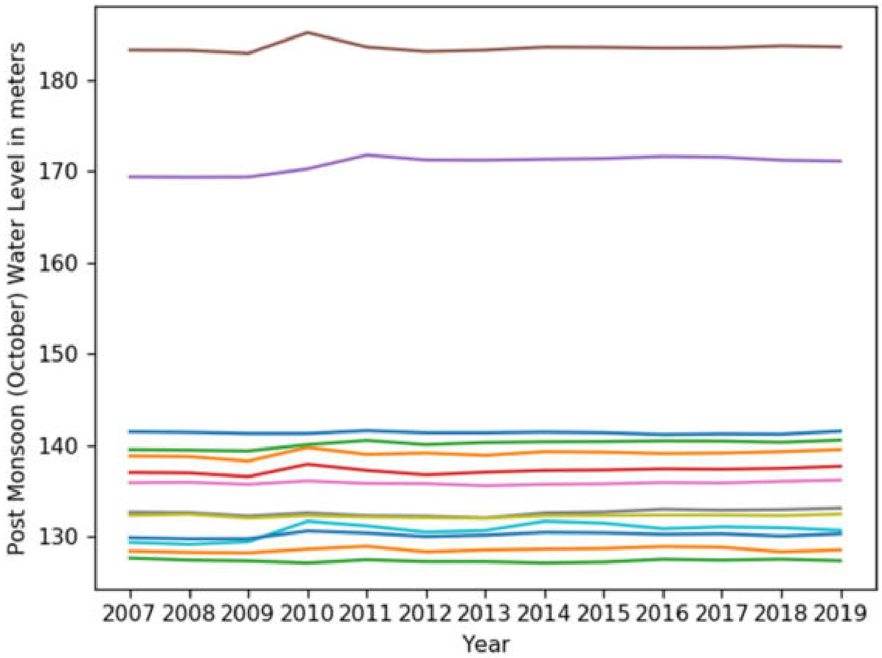

Figure 26: Post monsoon groundwater levels amsl in Rangpur Canal Command

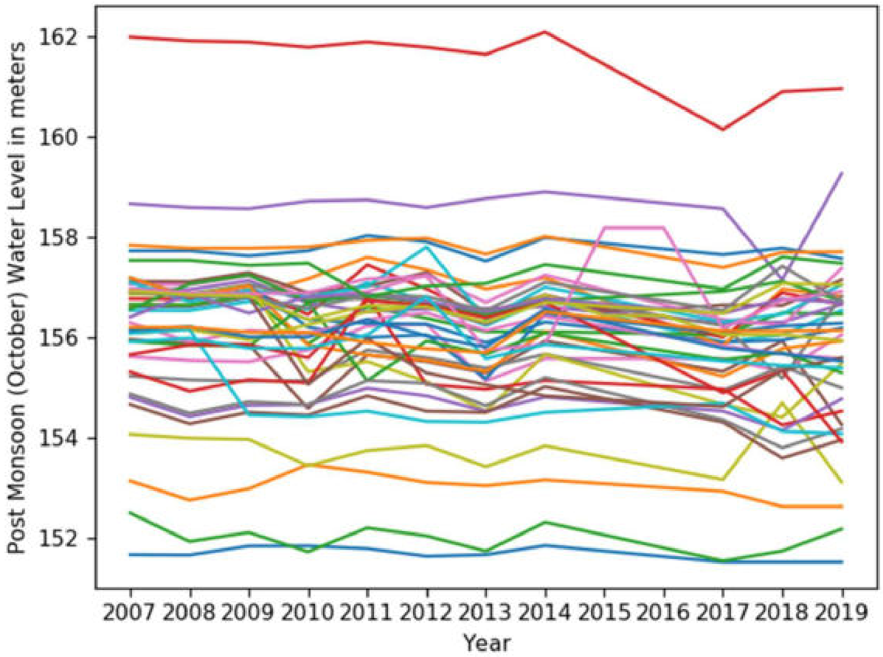

Figure 27: Post monsoon groundwater levels amsl in Sadiqia Canal Command

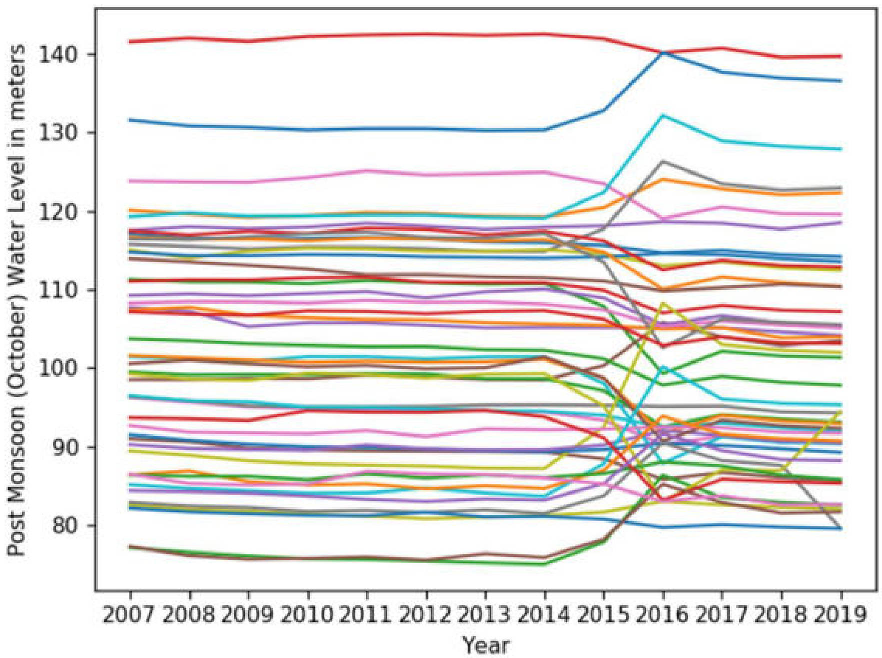

Figure 28: Post monsoon groundwater levels amsl in Sidhnai Canal Command

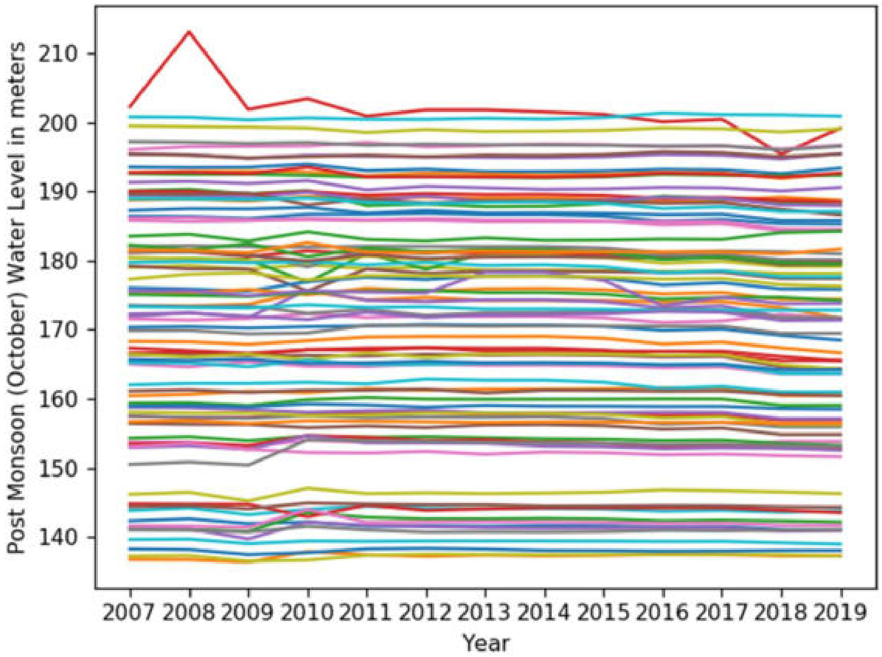

Figure 29: Post monsoon groundwater levels amsl in Thal Canal Command

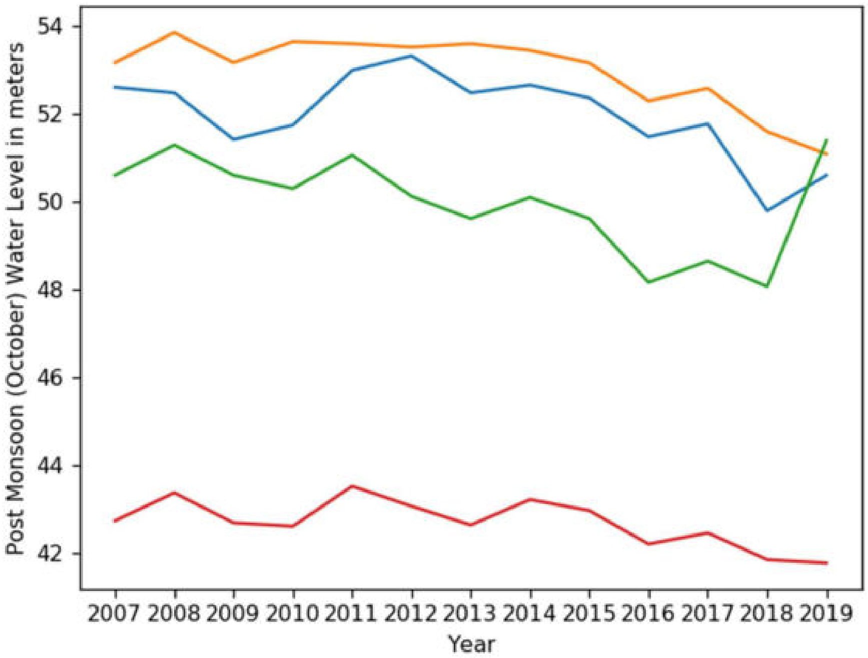

Figure 30: Post monsoon groundwater levels amsl in UDC Multan Canal Command

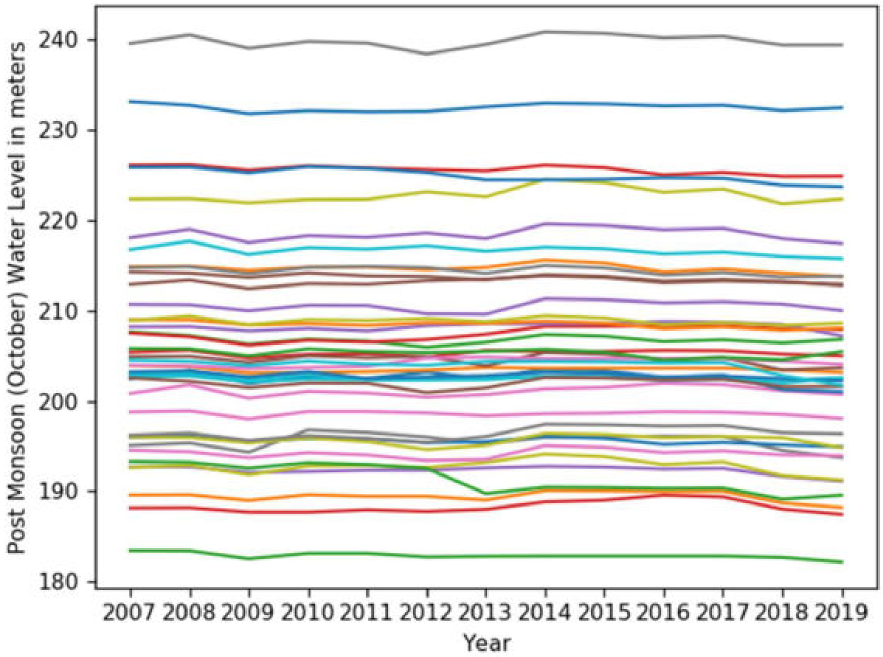

Figure 31: Post monsoon groundwater levels amsl in UJC Sargodha Canal Command

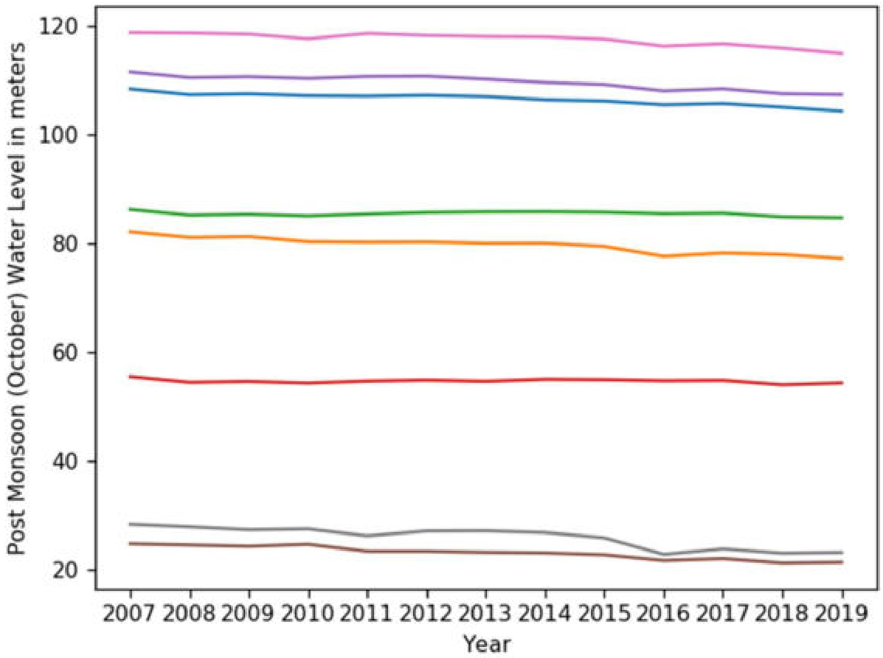

Figure 32: Post monsoon groundwater levels amsl in UPC Multan Canal Command

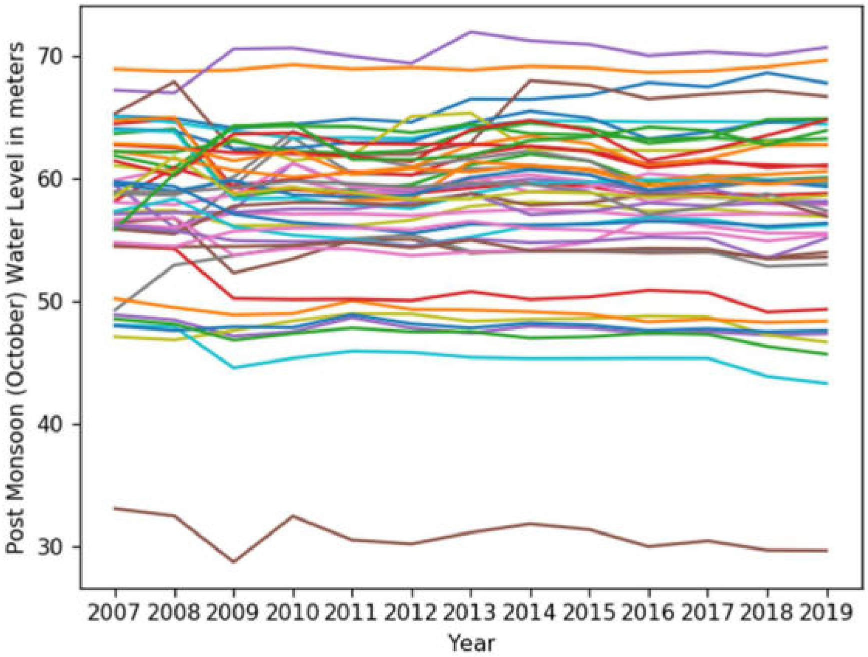

Figure 33: Post monsoon groundwater levels amsl in Upper Chenab Canal Command

16 Appendix B: Trendline of post monsoon Groundwater Level Change in Canal Commands

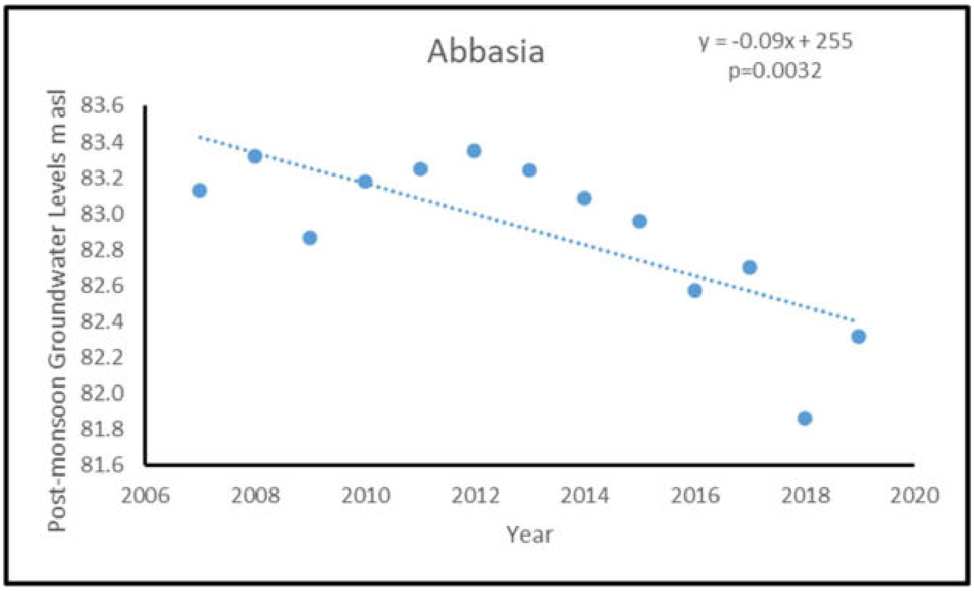

Figure 34: Trendline of changes to post monsoon groundwater levels – Abbasia

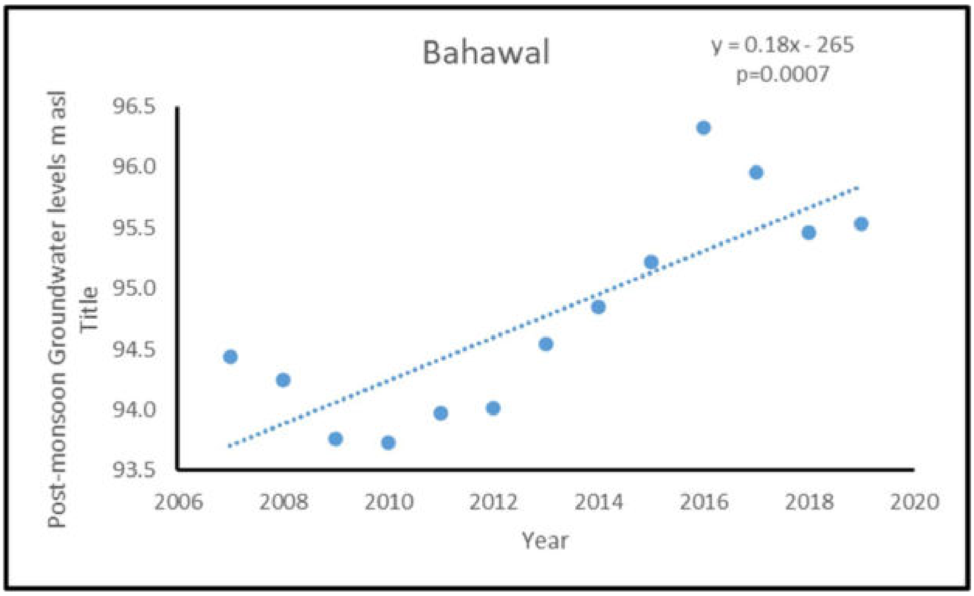

Figure 35: Trendline of changes to post monsoon groundwater levels – Lower Bahawal

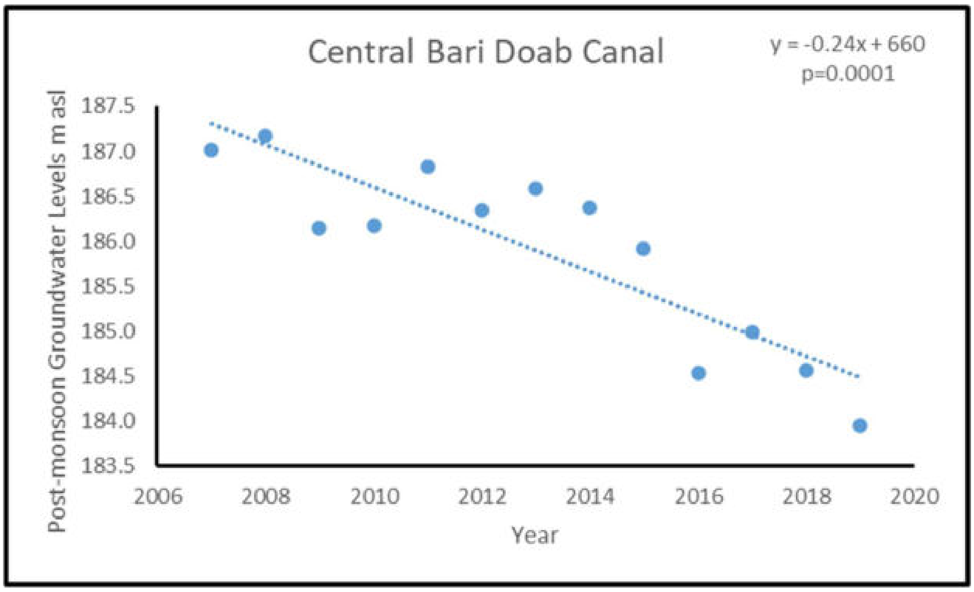

Figure 36: Trendline of changes to post monsoon groundwater levels – CBDC

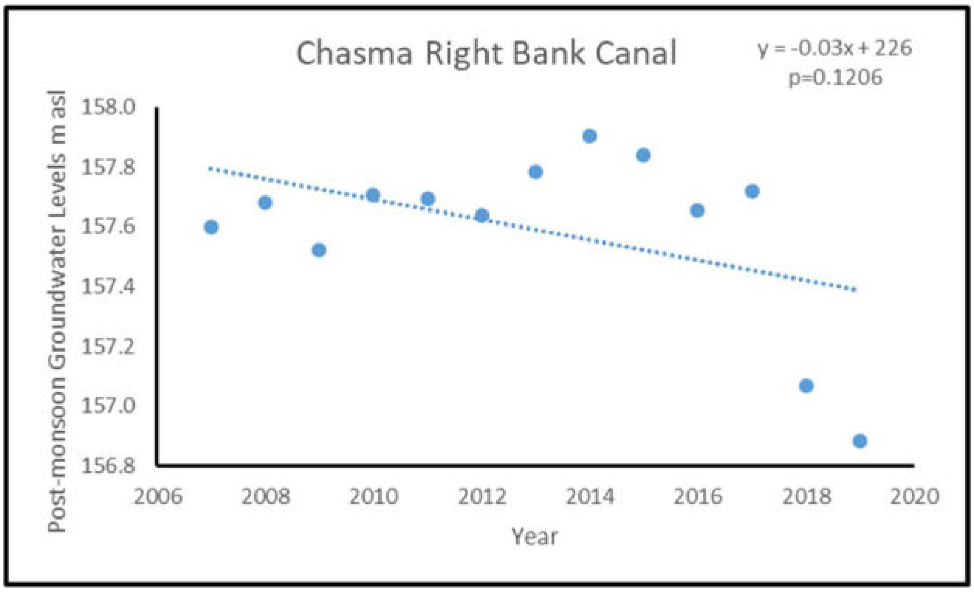

Figure 37: Trendline of changes to post monsoon groundwater levels – CRBC

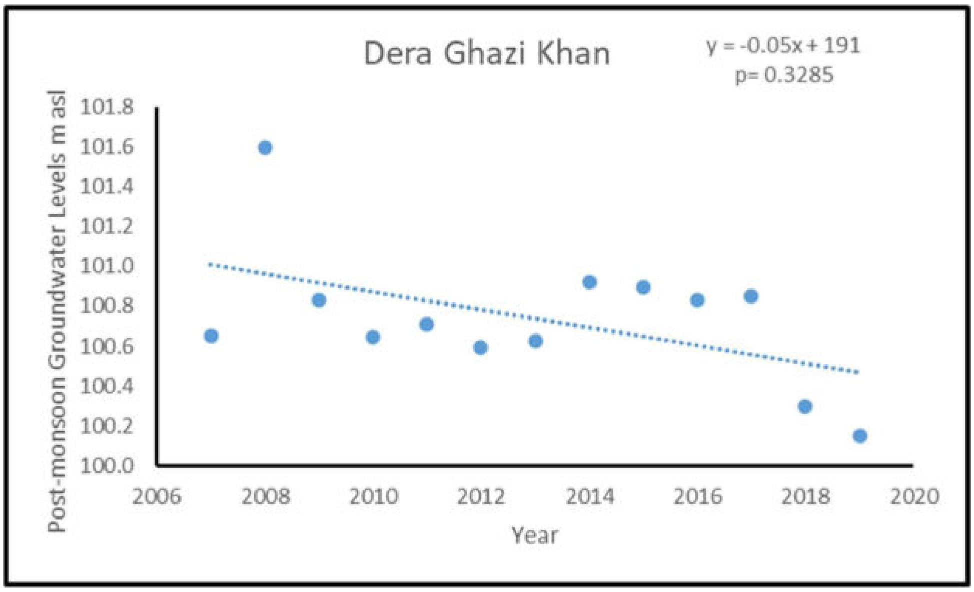

Figure 38: Trendline of changes to post monsoon groundwater levels – DG Khan

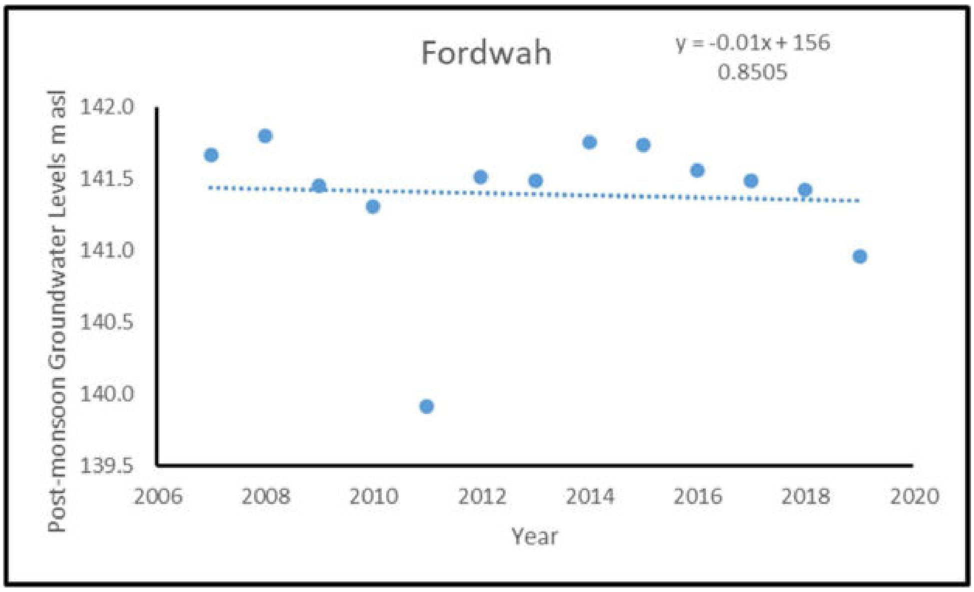

Figure 39: Trendline of changes to post monsoon groundwater levels – Fordwah

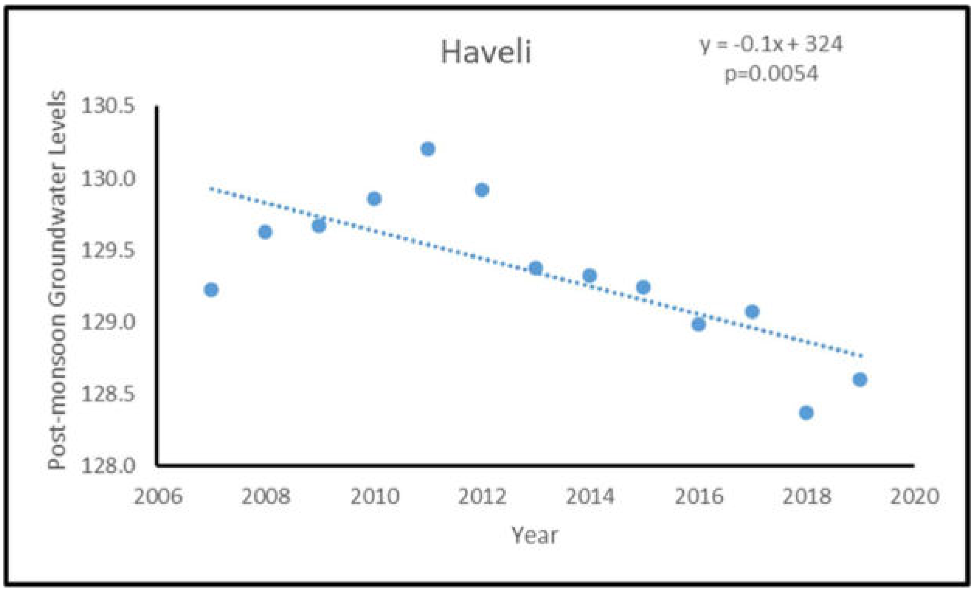

Figure 40: Trendline of changes to post monsoon groundwater levels – Haveli

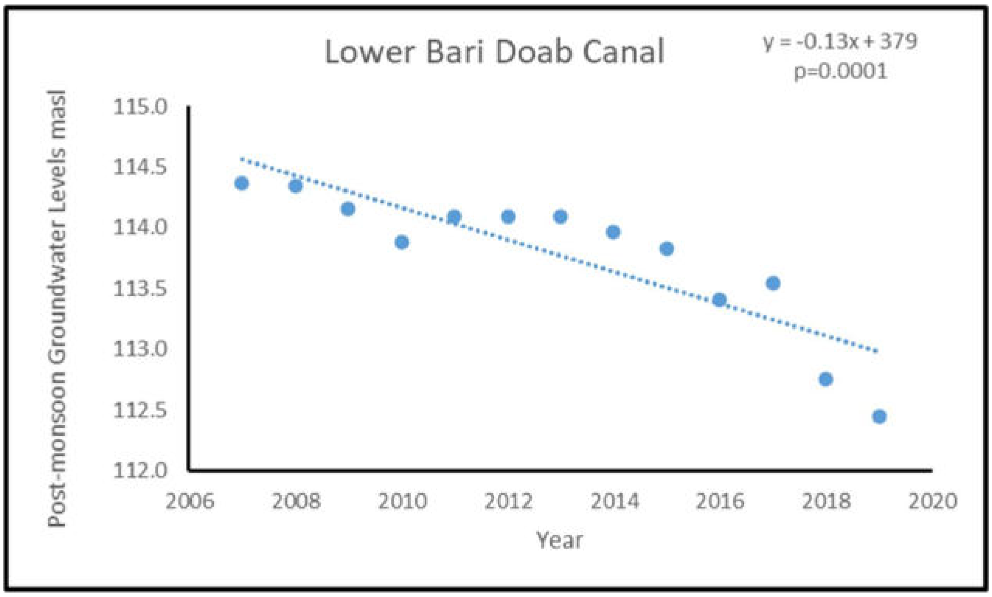

Figure 41: Trendline of changes to post monsoon groundwater levels – LBDC

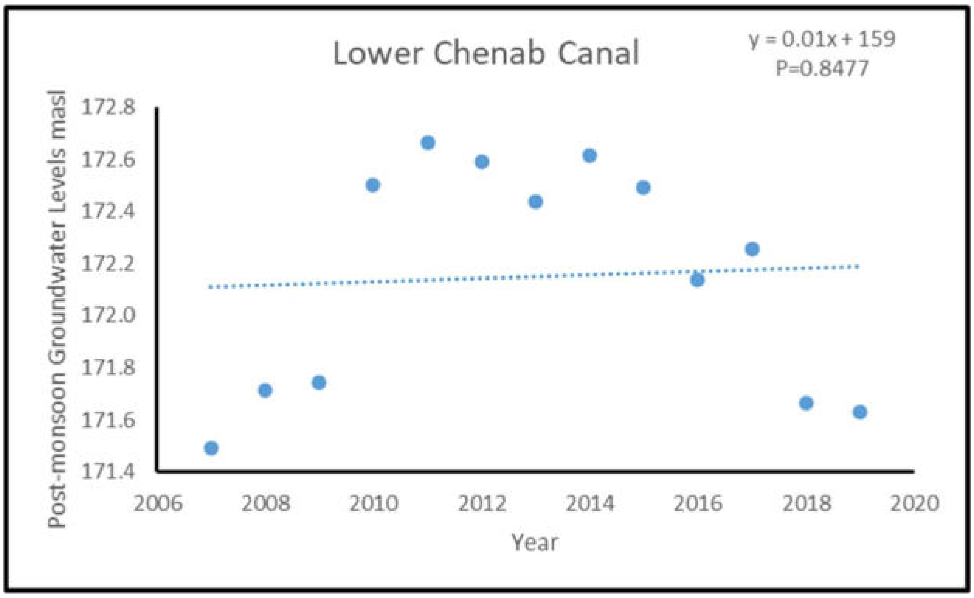

Figure 42: Trendline of changes to post monsoon groundwater levels – LCC

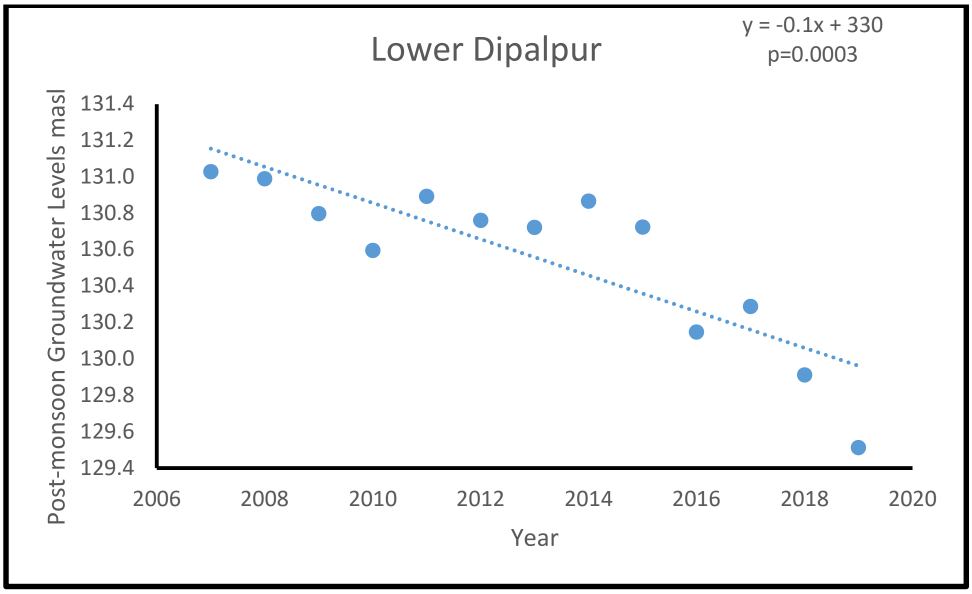

Figure 43: Trendline of changes to post monsoon groundwater levels – LDC

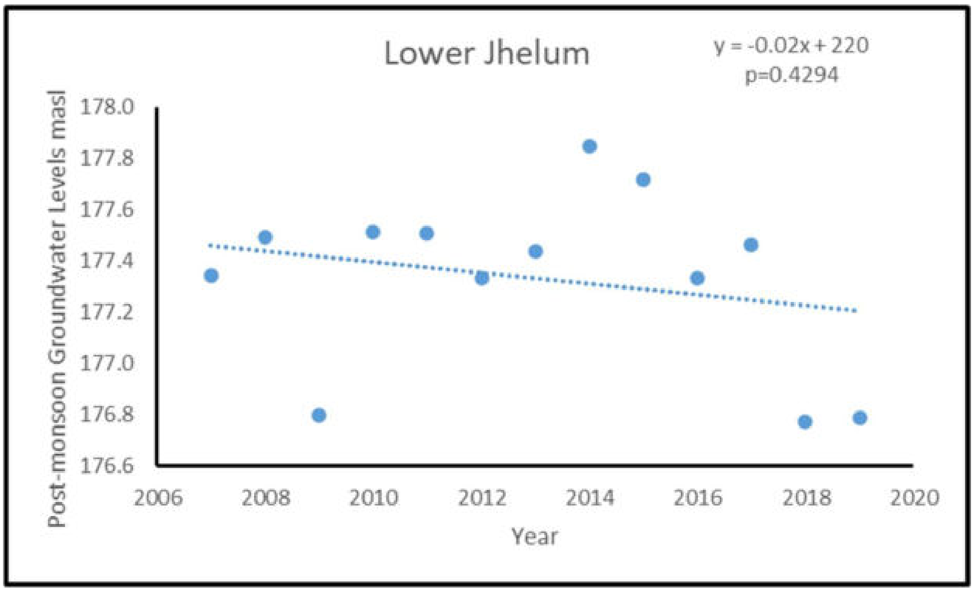

Figure 44: Trendline of changes to post monsoon groundwater levels – LJC Sargodha

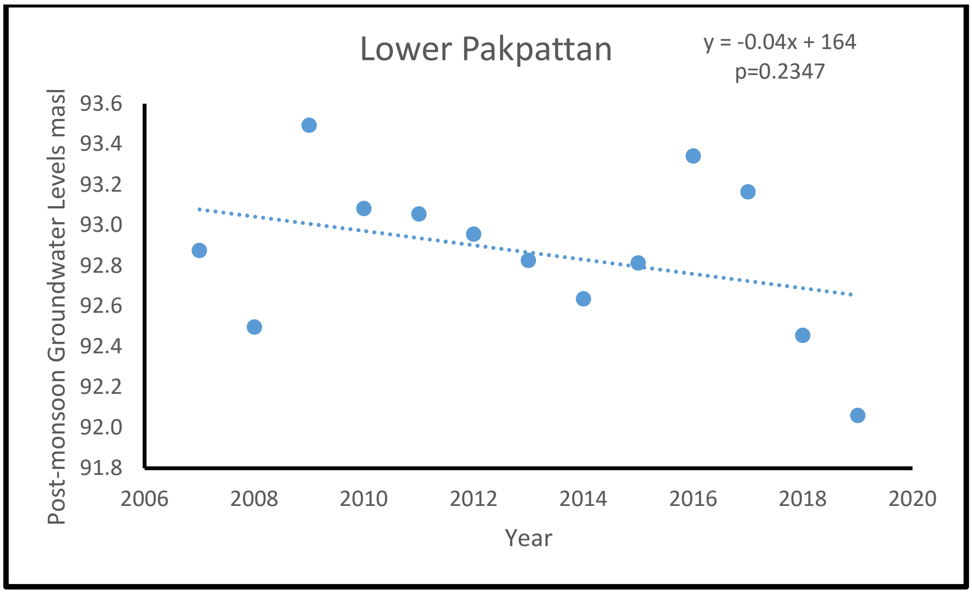

Figure 45: Trendline of changes to post monsoon groundwater levels – Lower Pakpattan

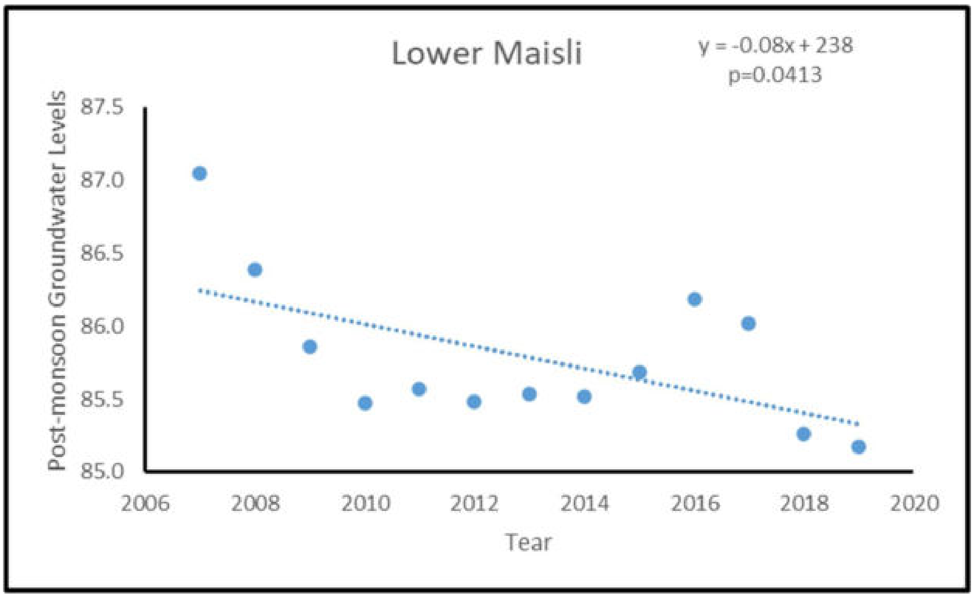

Figure 46: Trendline of changes to post monsoon groundwater levels – Mailsi

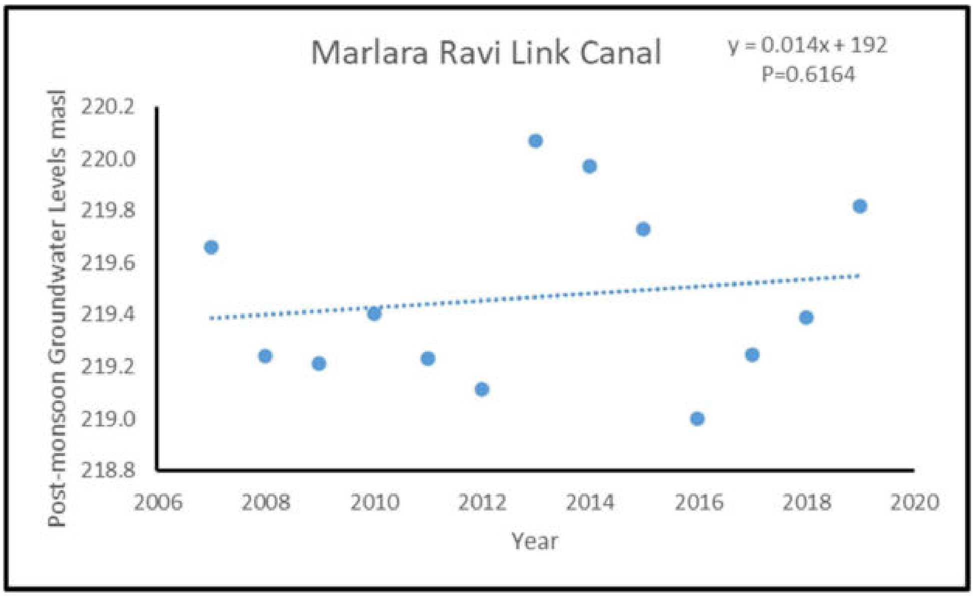

Figure 47: Trendline of changes to post monsoon groundwater levels – Marala Ravi

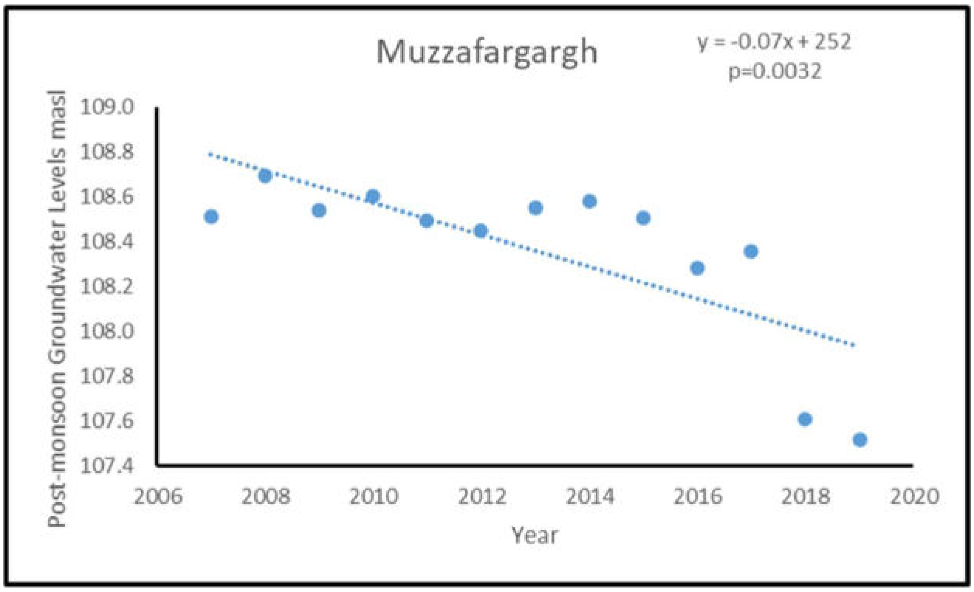

Figure 48: Trendline of changes to post monsoon groundwater levels – Muzaffargarh

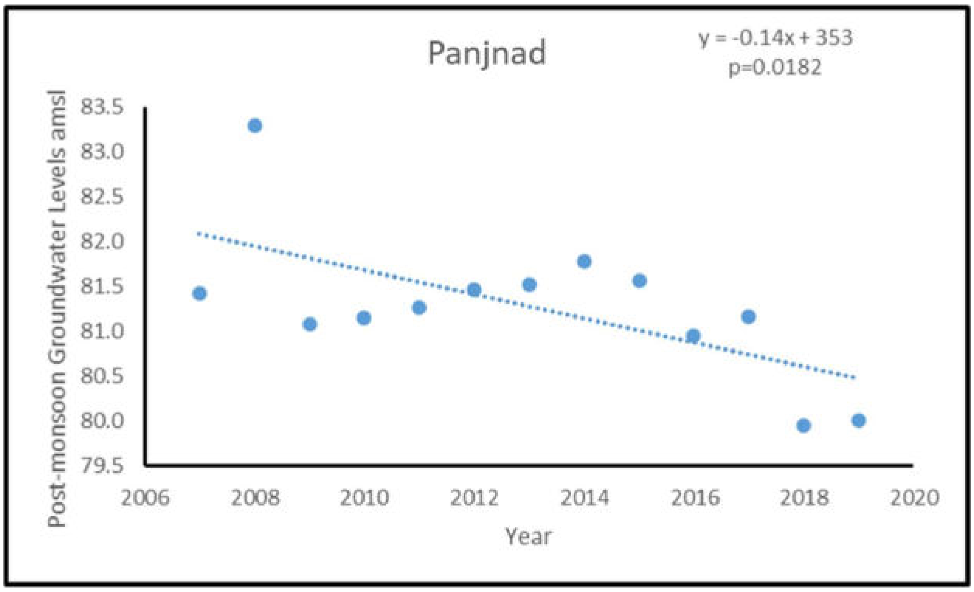

Figure 49: Trendline of changes to post monsoon groundwater levels – Panjnad

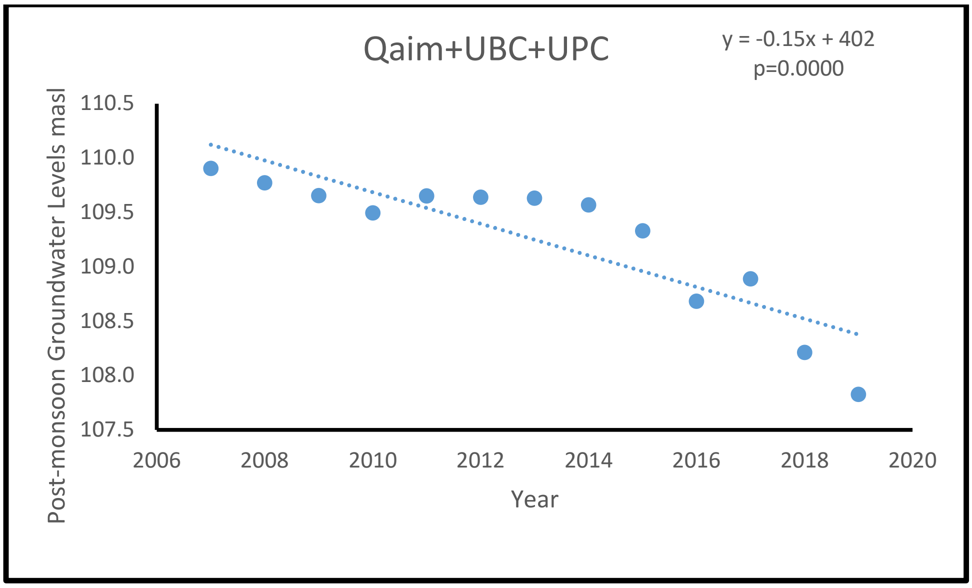

Figure 50: Trendline of changes to post monsoon groundwater levels – Qaim+UBC+UPC

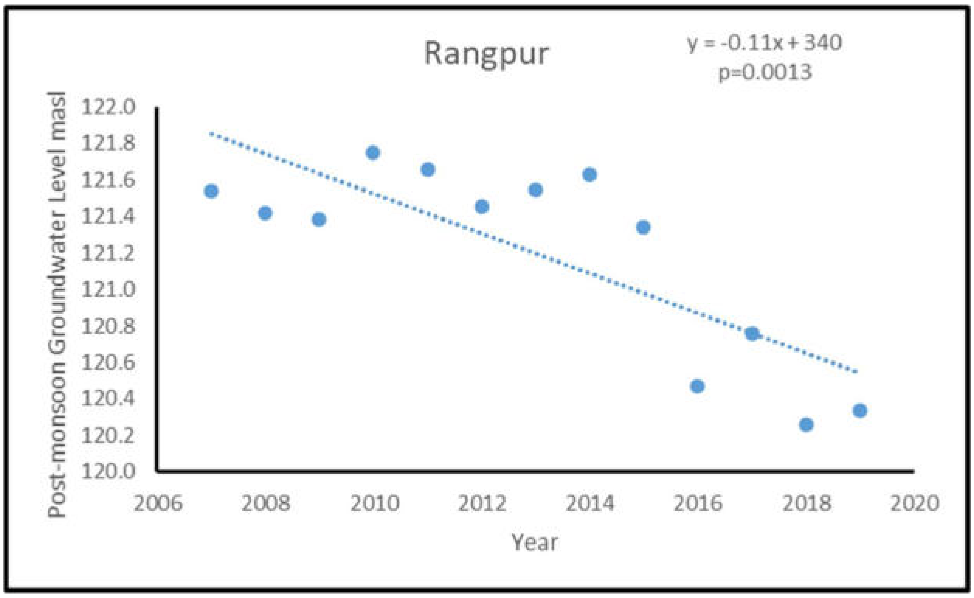

Figure 51: Trendline of changes to post monsoon groundwater levels – Rangpur

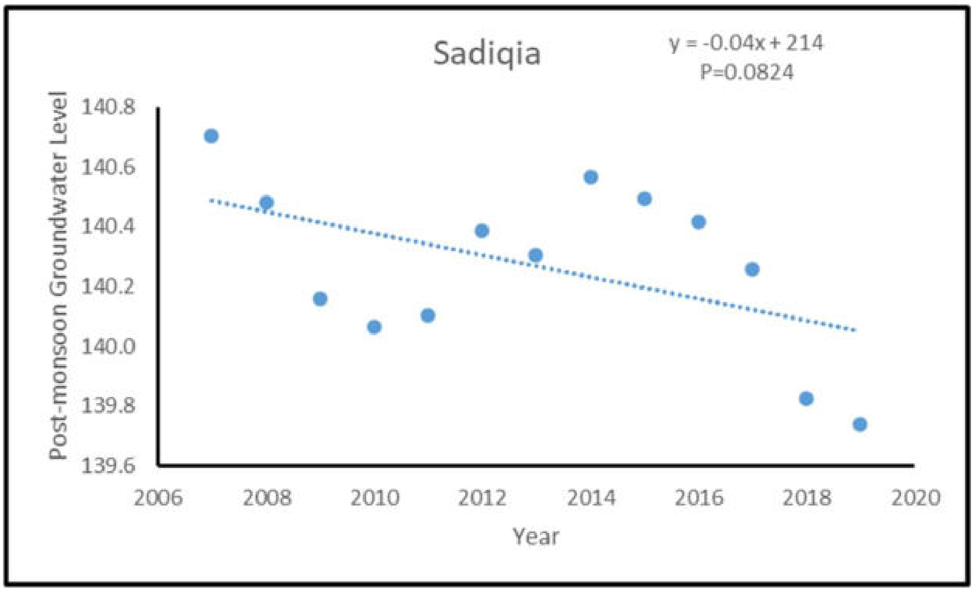

Figure 52: Trendline of changes to post monsoon groundwater levels – Sadiqia

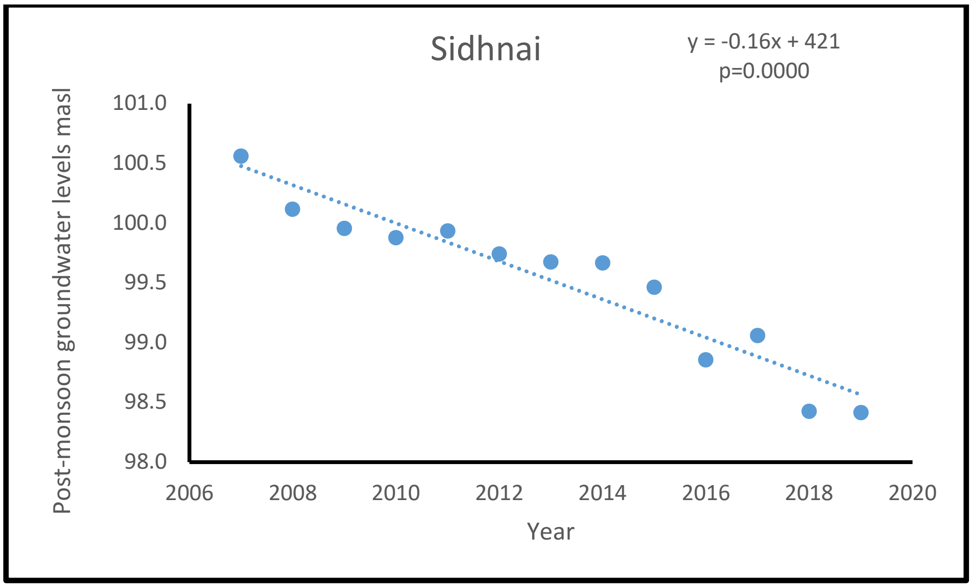

Figure 53: Trendline of changes to post monsoon groundwater levels – Sidhnai

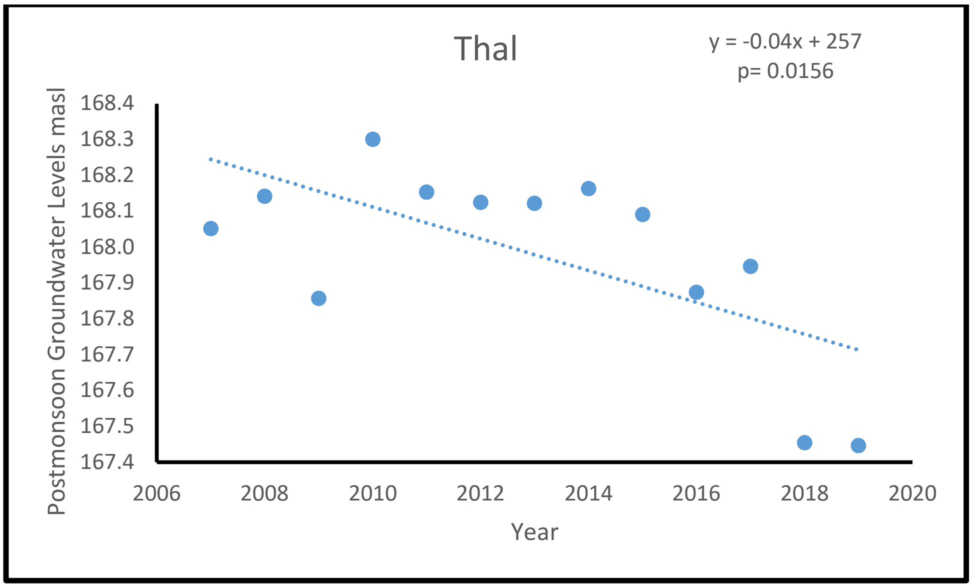

Figure 54: Trendline of changes to post monsoon groundwater levels - Thal

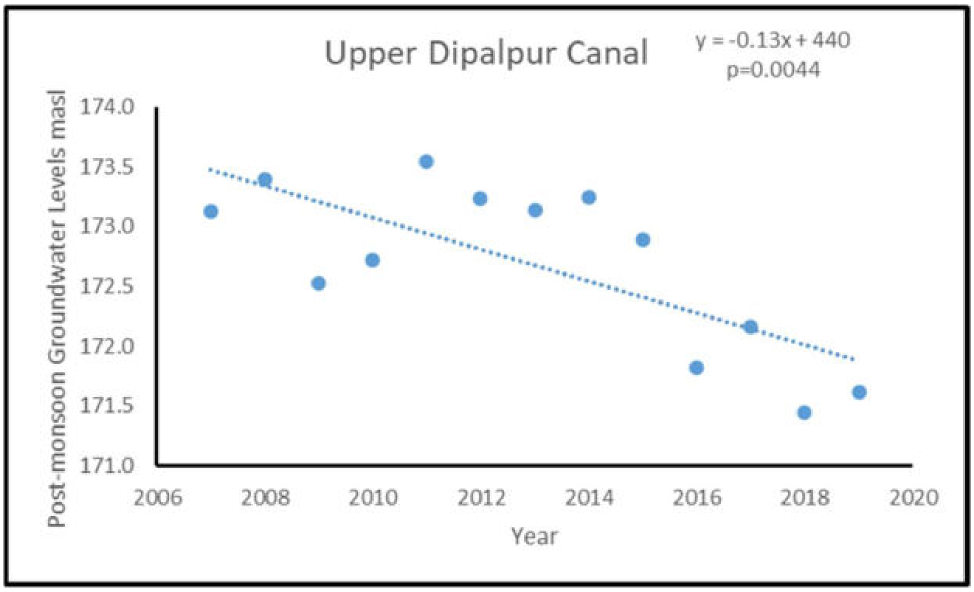

Figure 55: Trendline of changes to post monsoon groundwater levels – UDC Multan

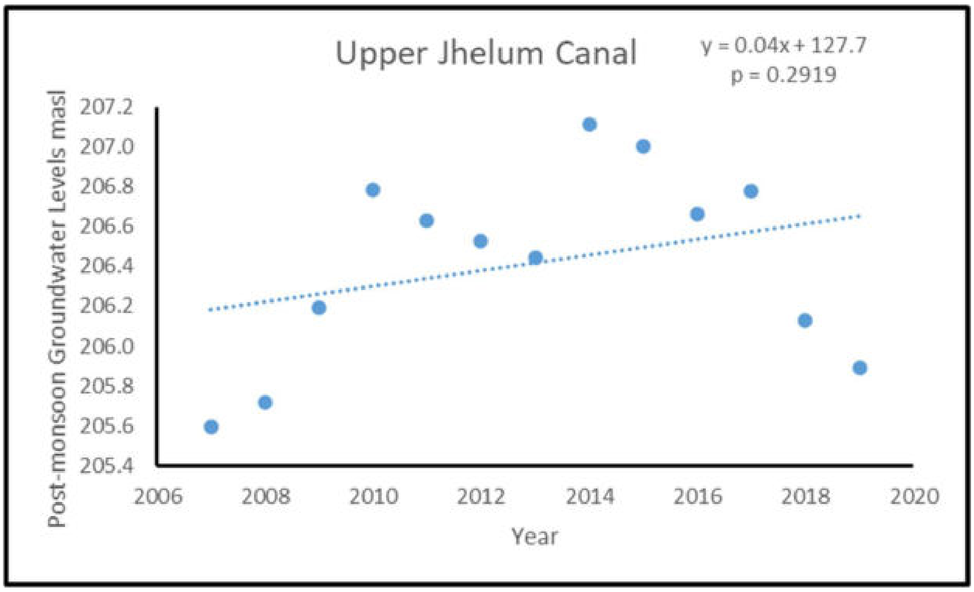

Figure 56: Trendline of changes to post monsoon groundwater levels – UJC Sargodha

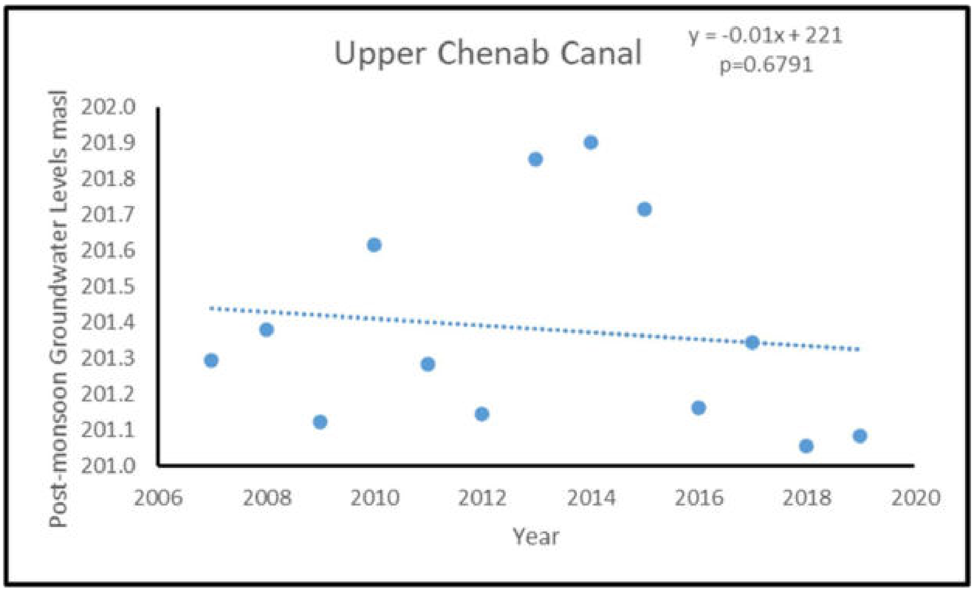

Figure 57: Trendline of changes to post monsoon groundwater levels – Upper Chenab

17 Appendix C: Probability distribution of deviation from mean depth in canal commands.

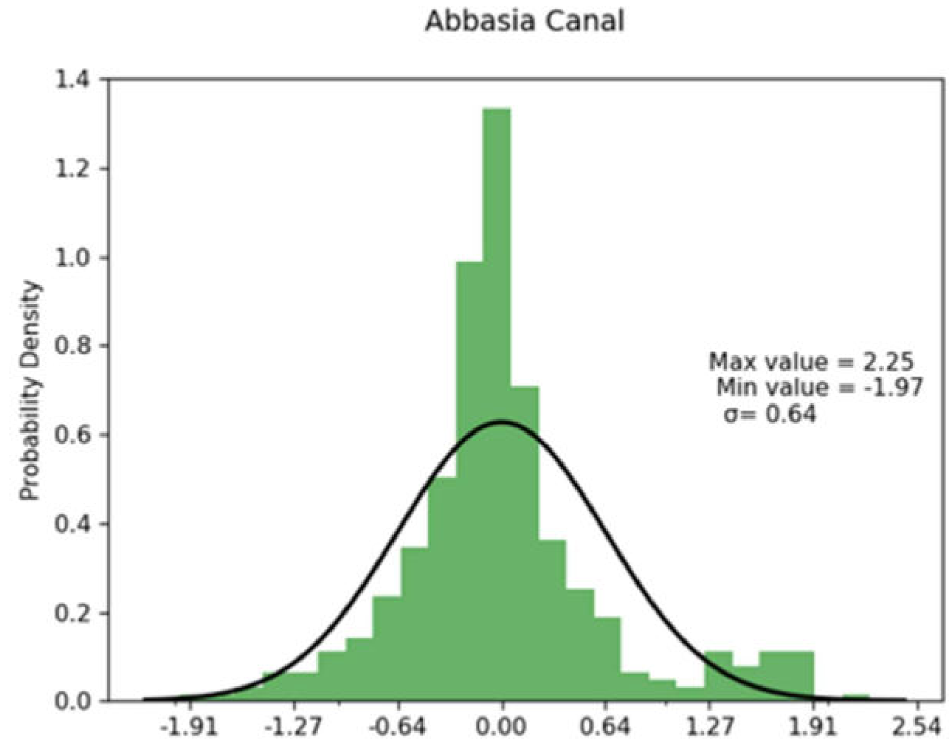

Figure 58: PDF of deviations from Mean - Abbasia Canal

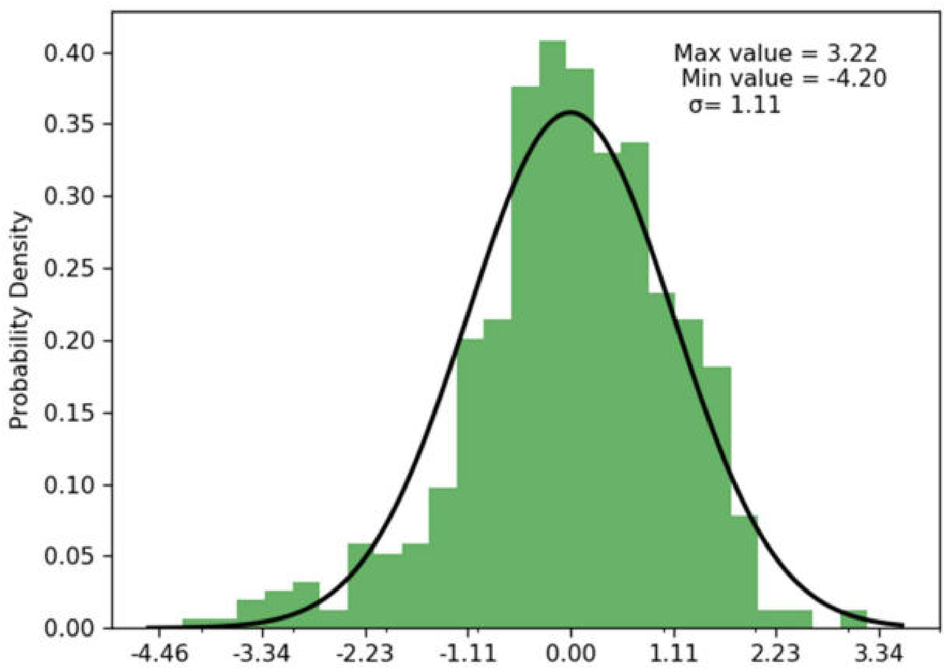

Figure 59: PDF of deviations from Mean - Lower Bahawal Canal

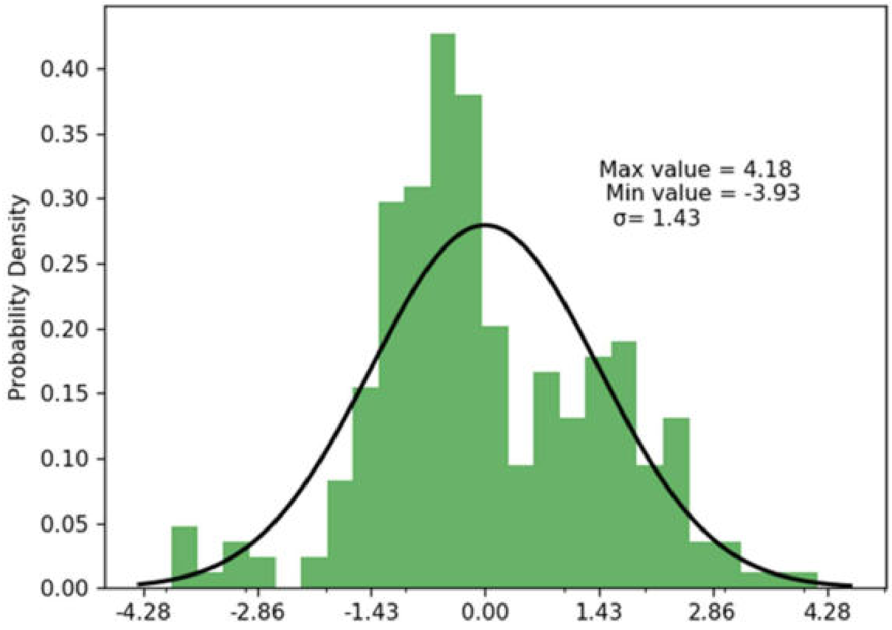

Figure 60: PDF of deviations from Mean - CBDC Canal

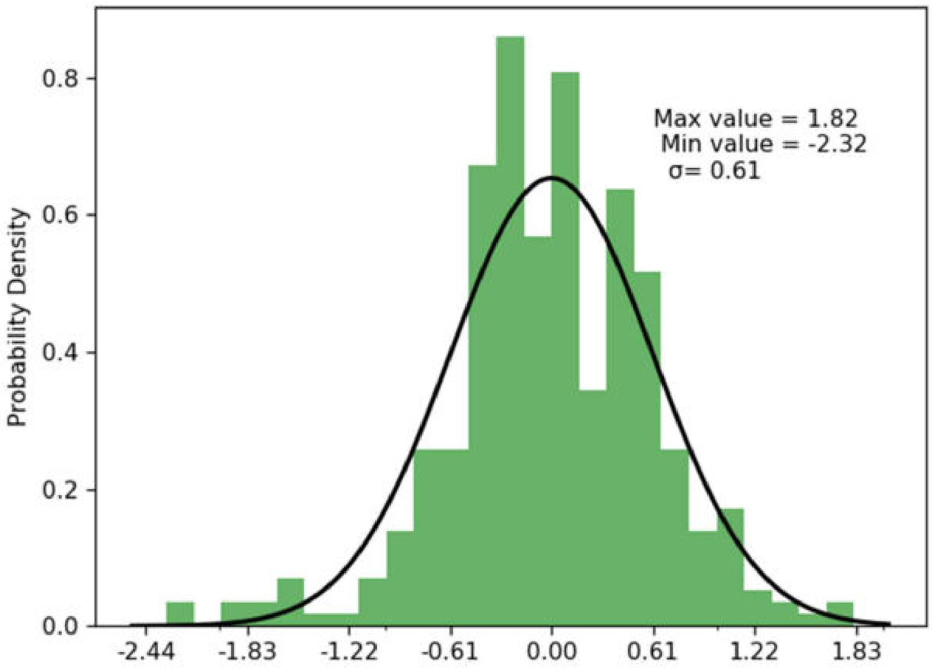

Figure 61: PDF of deviations from Mean - CRBC Canal

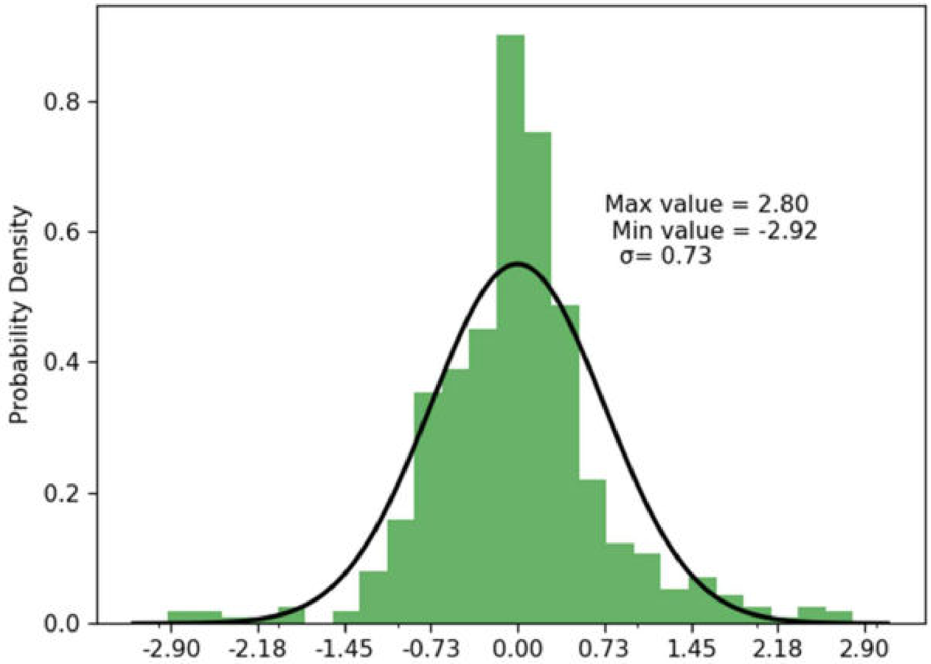

Figure 62: PDF of deviations from Mean – DG Khan

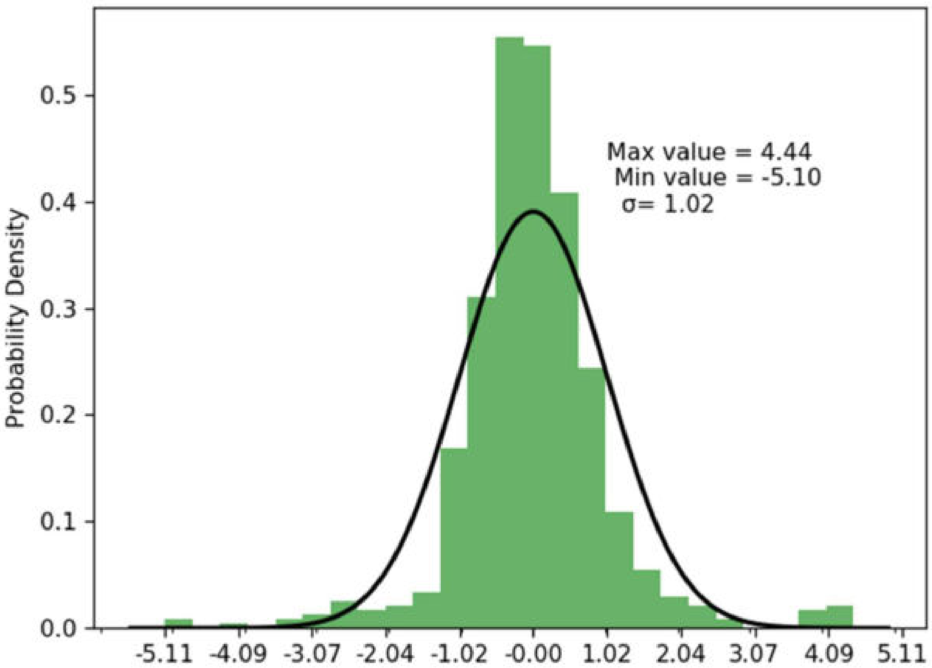

Figure 63: PDF of deviations from Mean – Fordwah

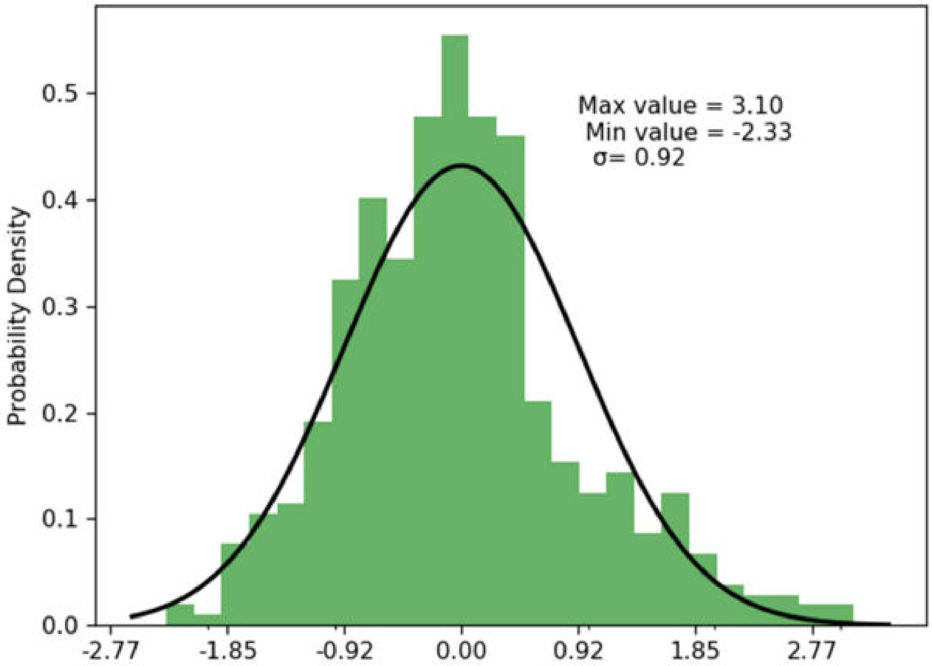

Figure 64: PDF of deviations from Mean – Haveli

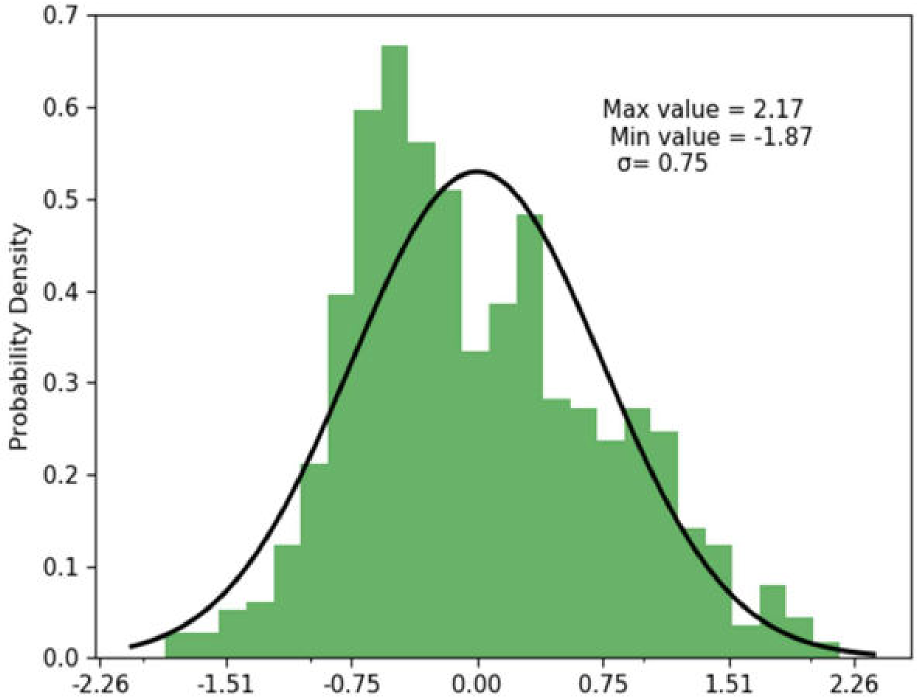

Figure 65: PDF of deviations from Mean – LBDC Multan

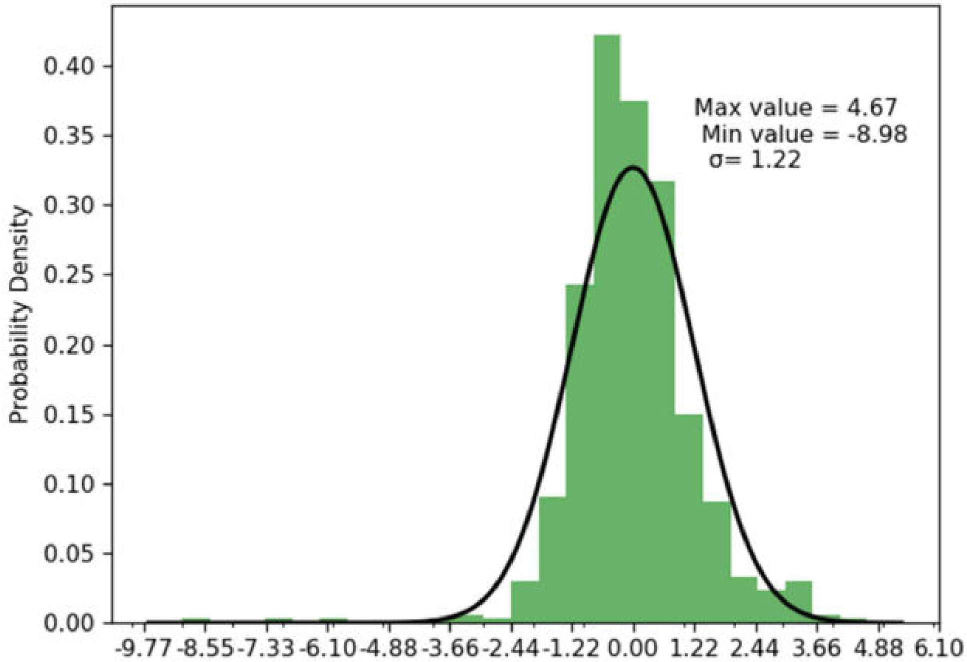

Figure 66: PDF of deviations from Mean – LCC Faisalabad

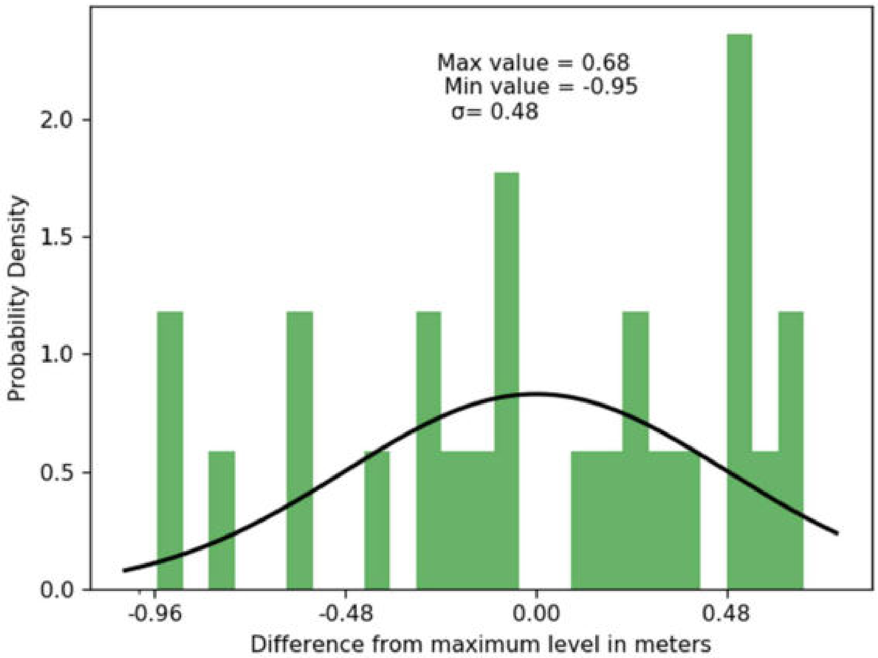

Figure 67: PDF of deviations from Mean – LDC Lahore

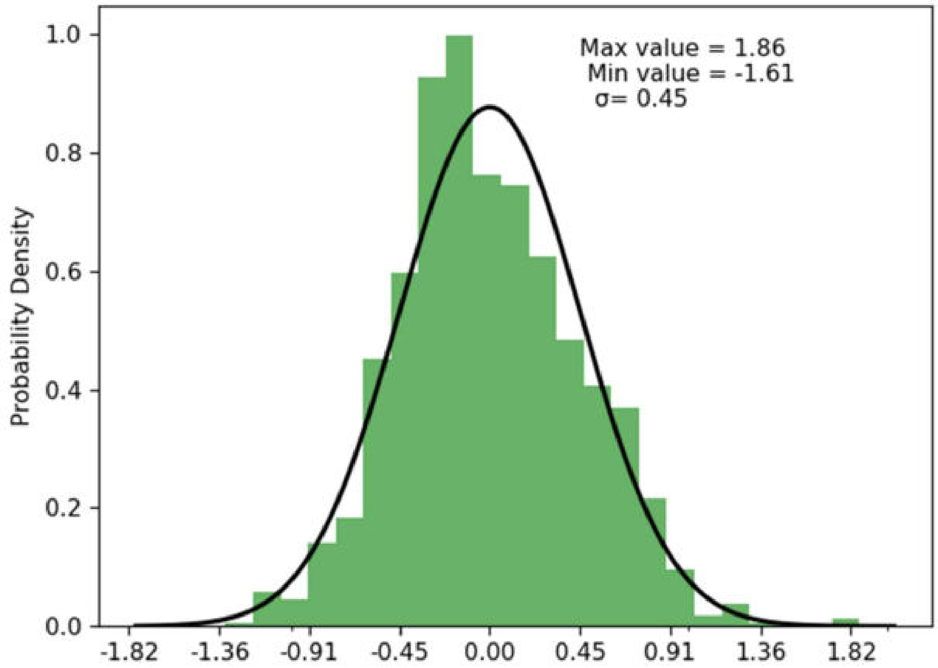

Figure 68: PDF of deviations from Mean – LJC Sargodha

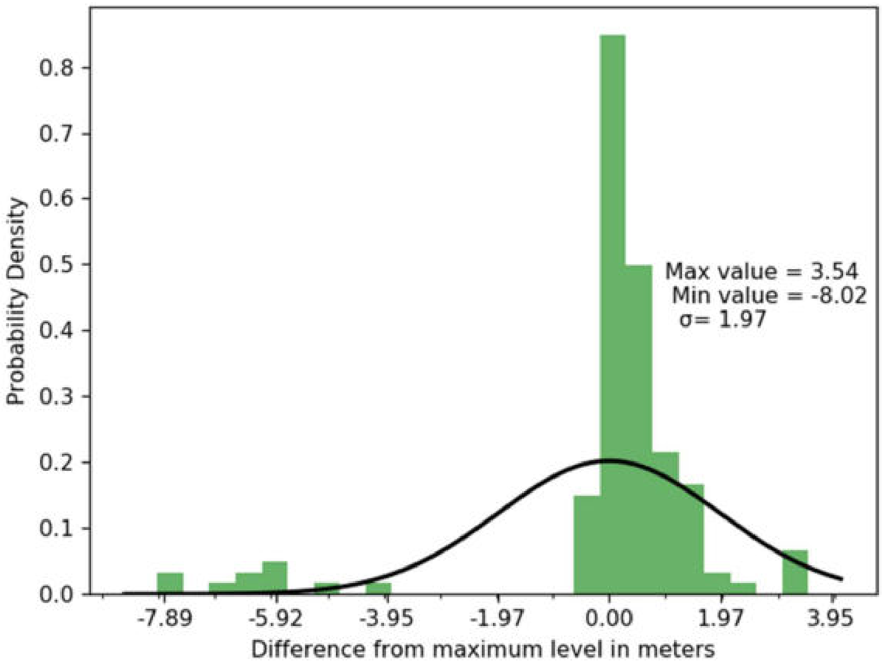

Figure 69: PDF of deviations from Mean – LPC Multan

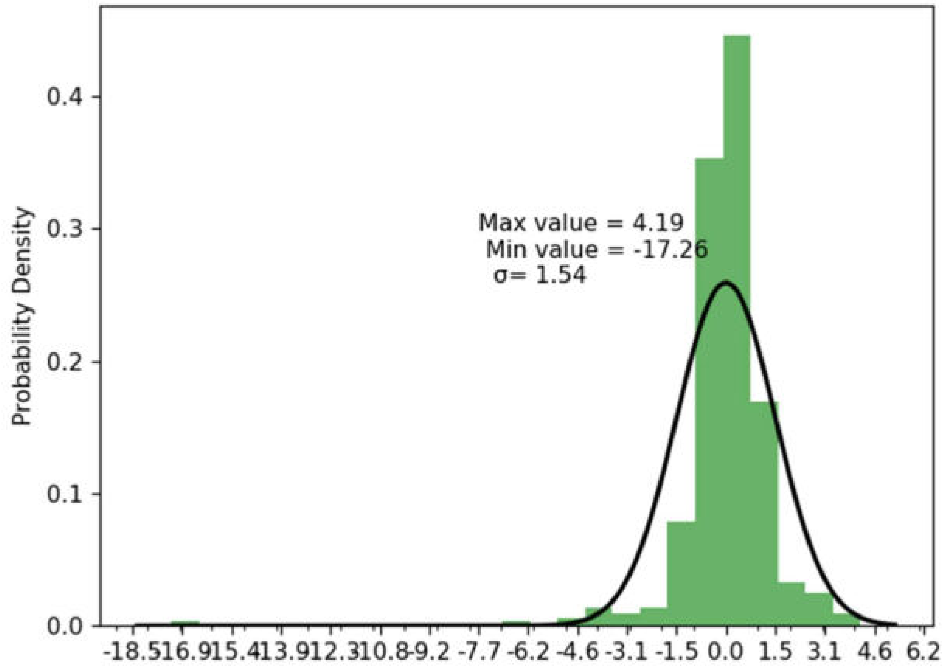

Figure 70: PDF of deviations from Mean – Mailsi

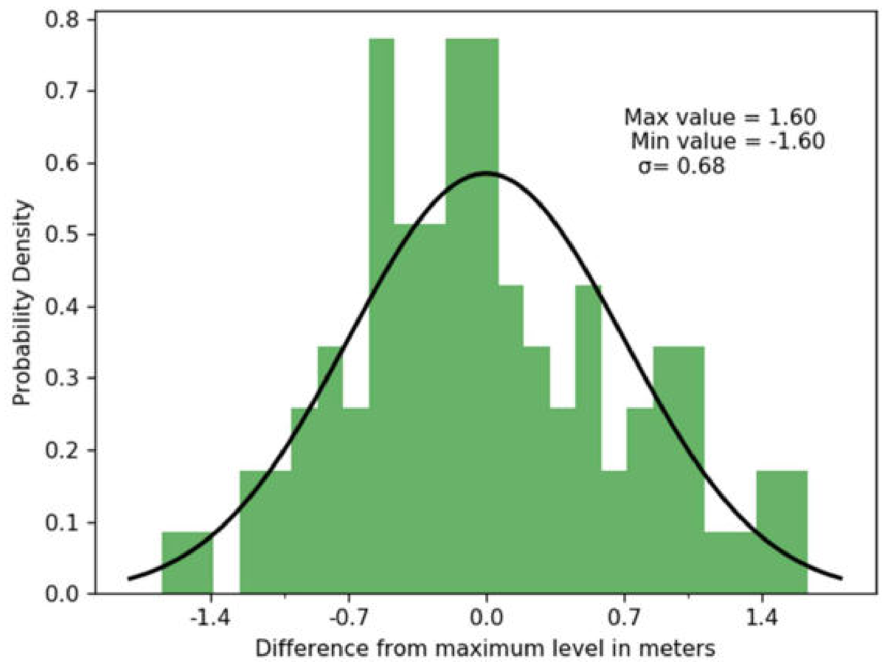

Figure 71: PDF of deviations from Mean – Marala Ravi

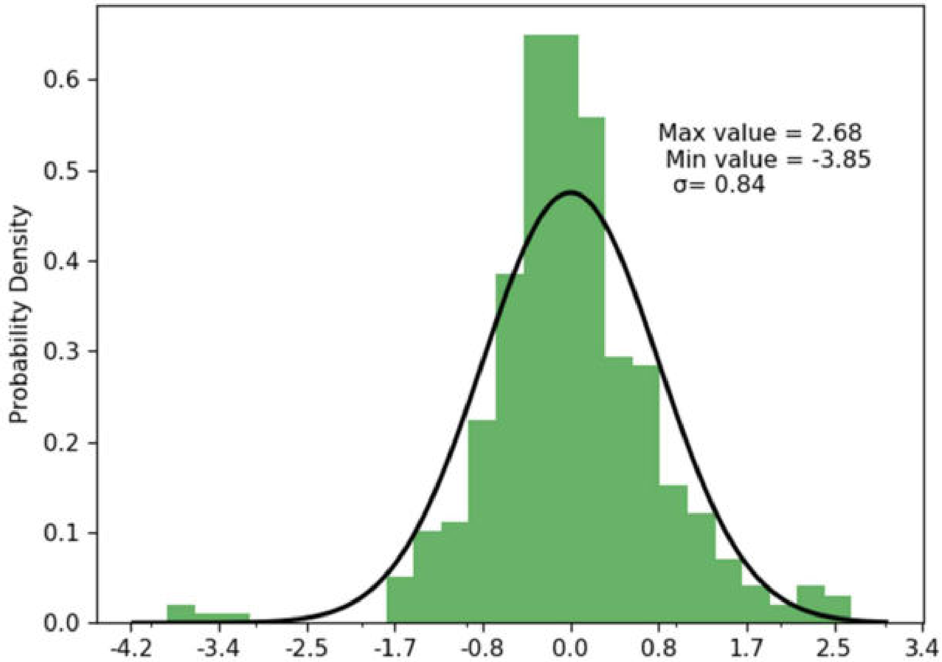

Figure 72: PDF of deviations from Mean – Muzaffargarh

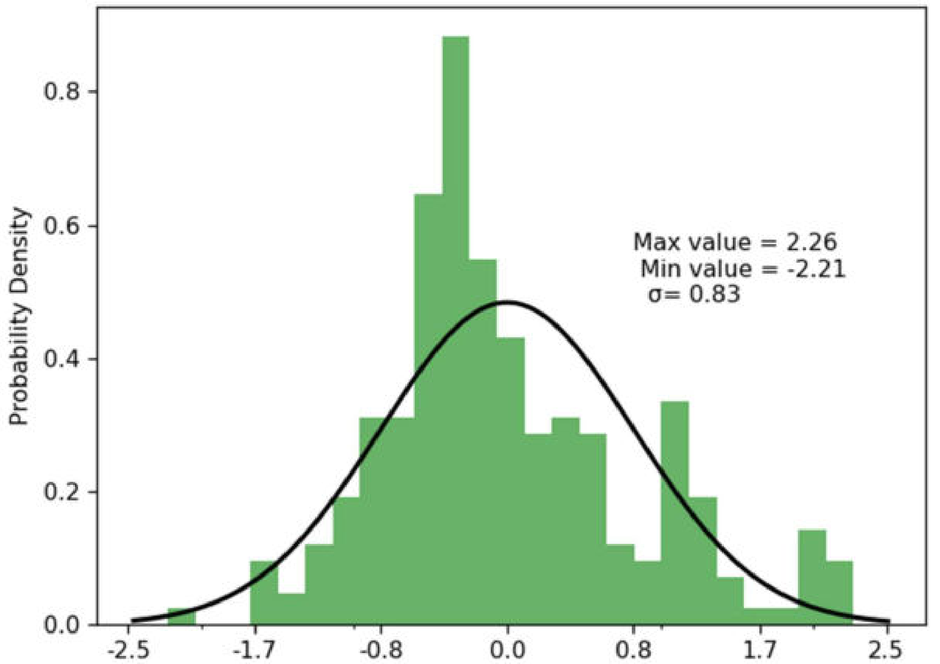

Figure 73: PDF of deviations from Mean – Panjnad

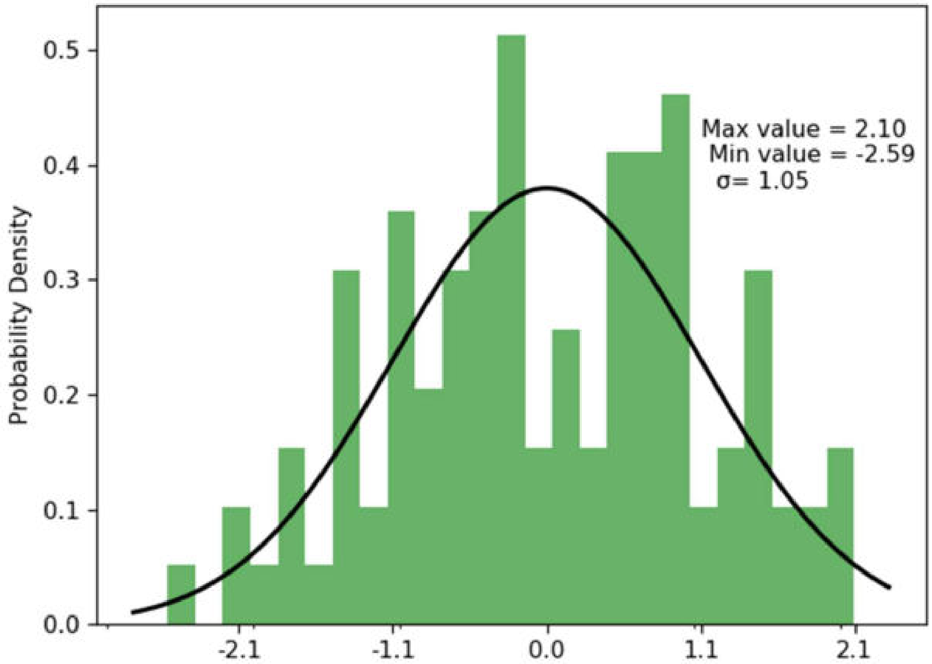

Figure 74: PDF of deviations from Mean – Qaim

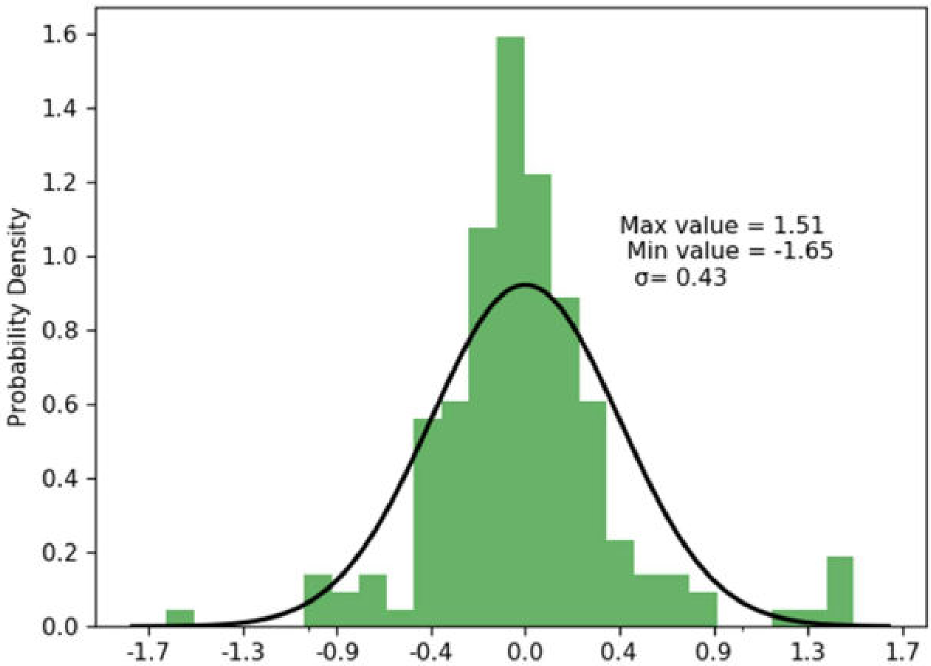

Figure 75: PDF of deviations from Mean – Rangpur

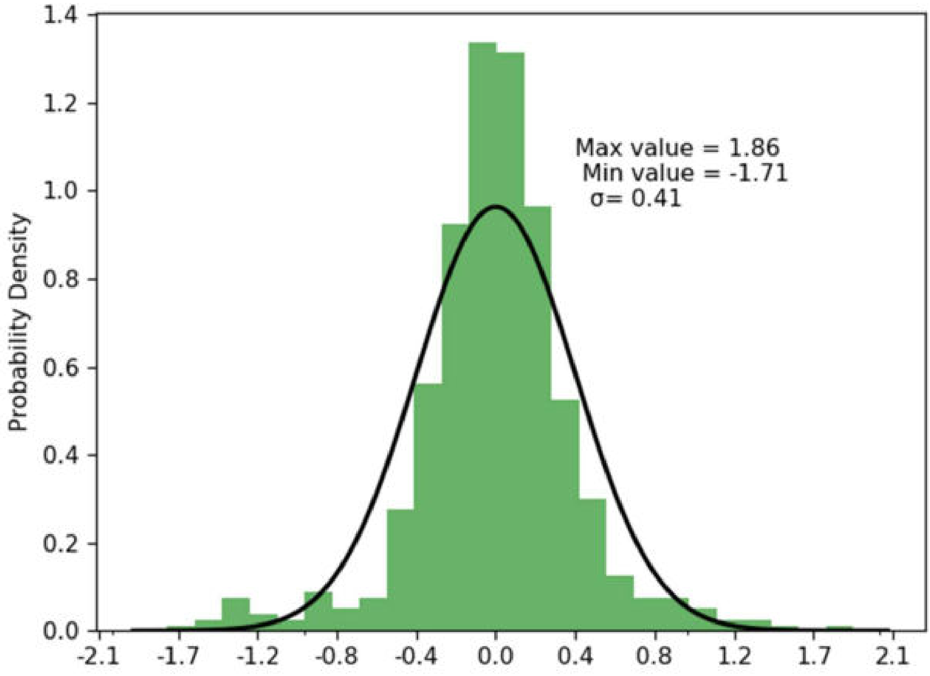

Figure 76: PDF of deviations from Mean – Sadiqia

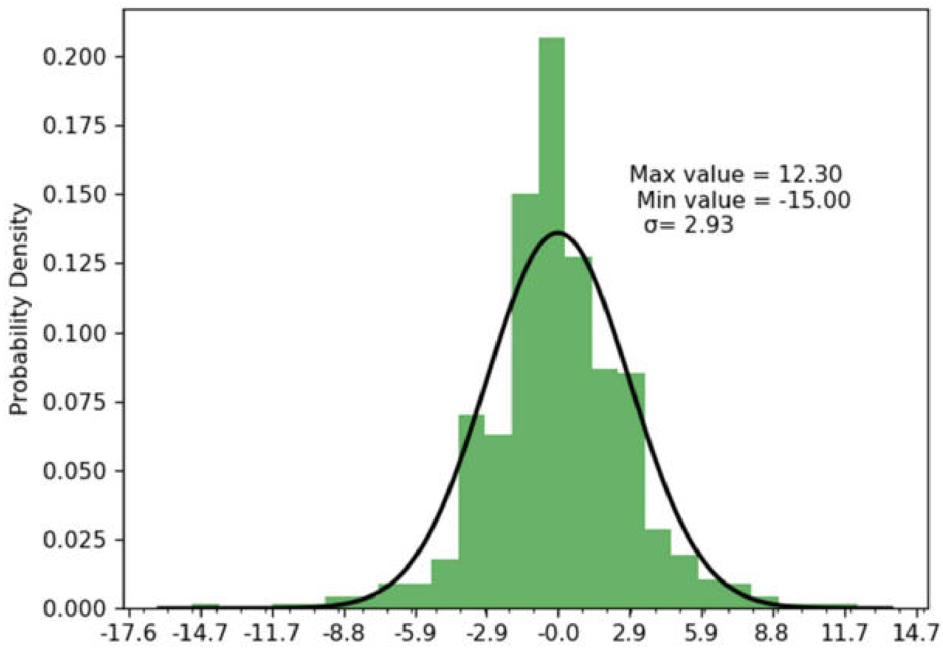

Figure 77: PDF of deviations from Mean – Sidhnai

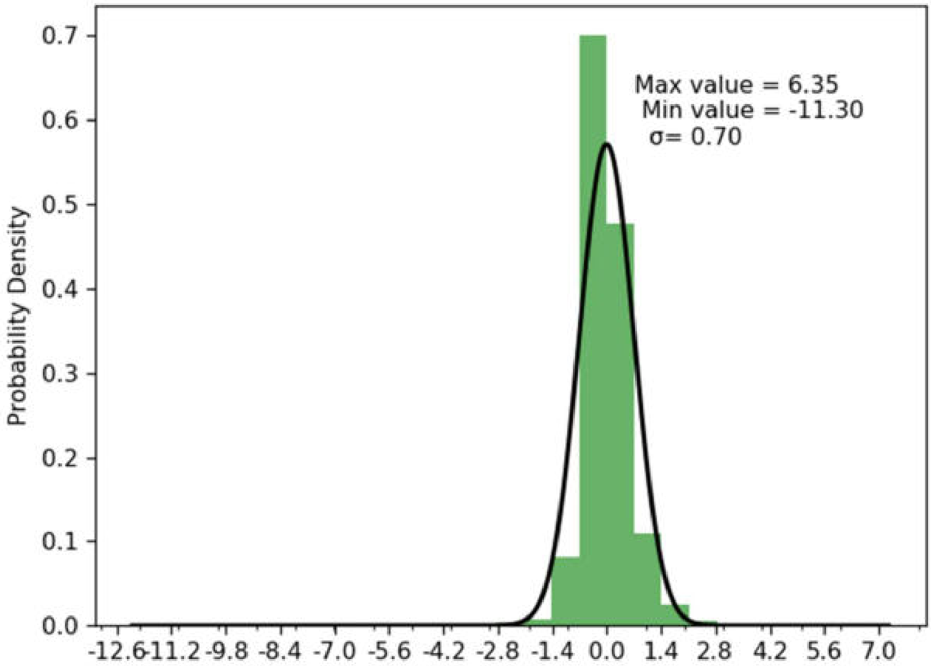

Figure 78: PDF of deviations from Mean – Thal

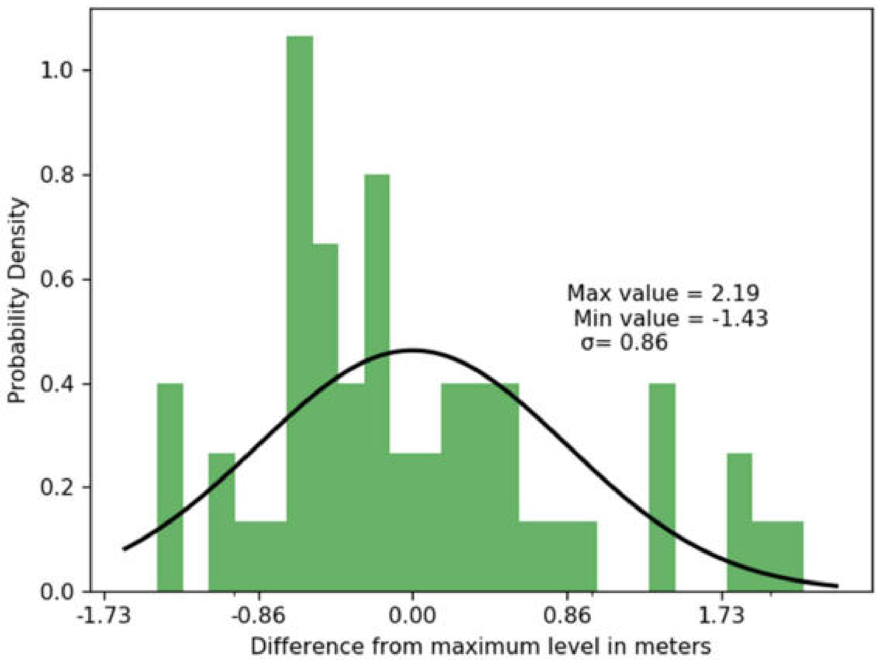

Figure 79: PDF of deviations from Mean – UDC Multan

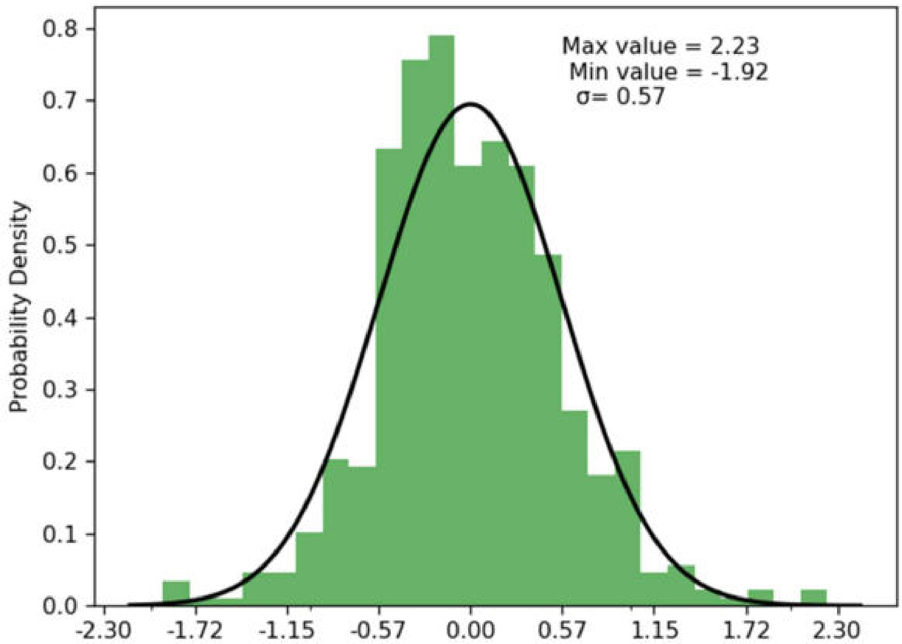

Figure 80: PDF of deviations from Mean – UJC Sargodha

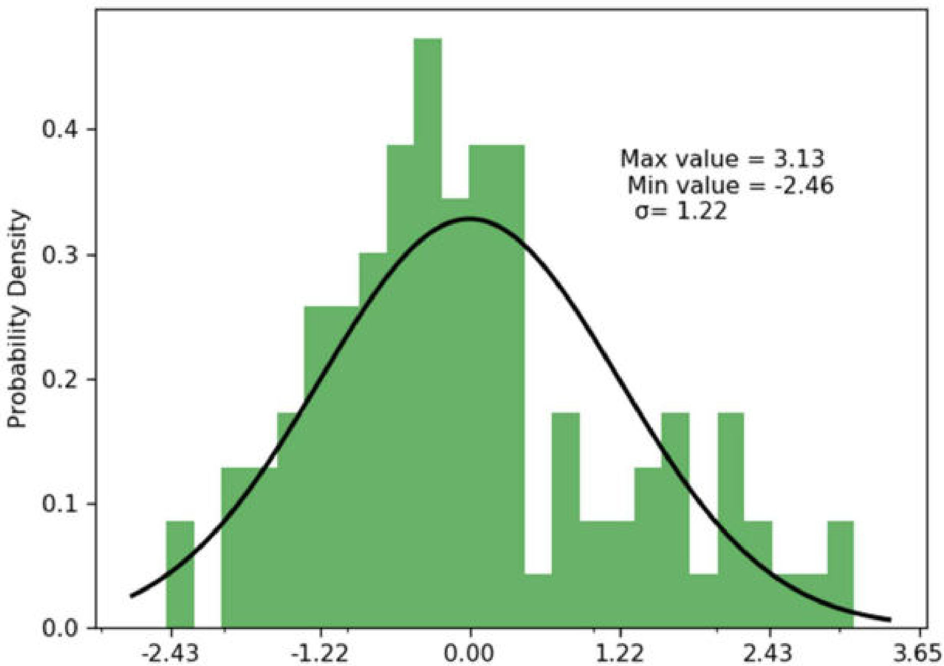

Figure 81: PDF of deviations from Mean – UPC Multan

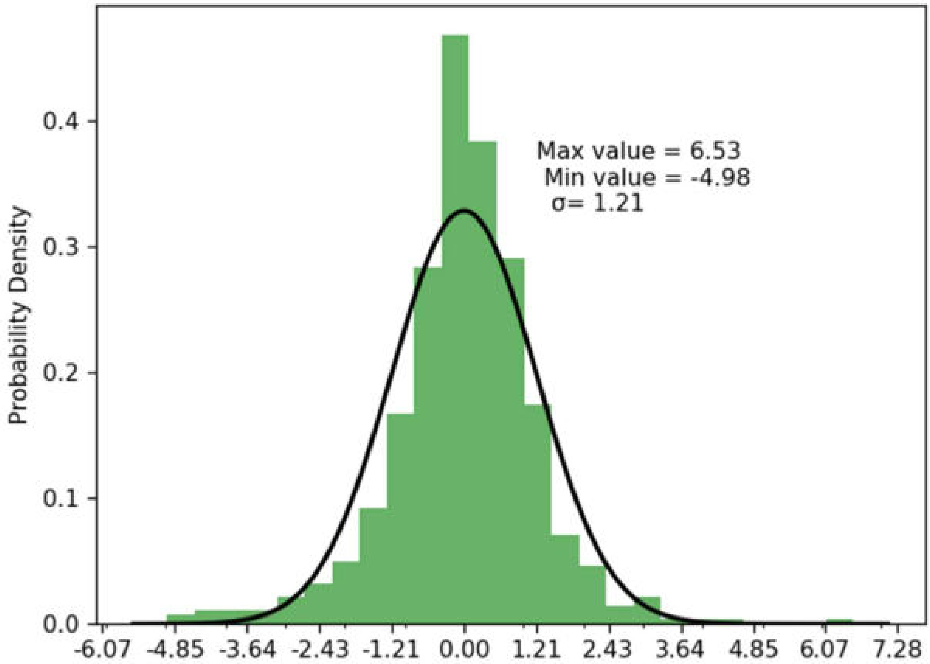

Figure 82: PDF of deviations from Mean – Upper Chenab

18 Appendix D: Cumulative Probability Distribution of deviations from mean depth

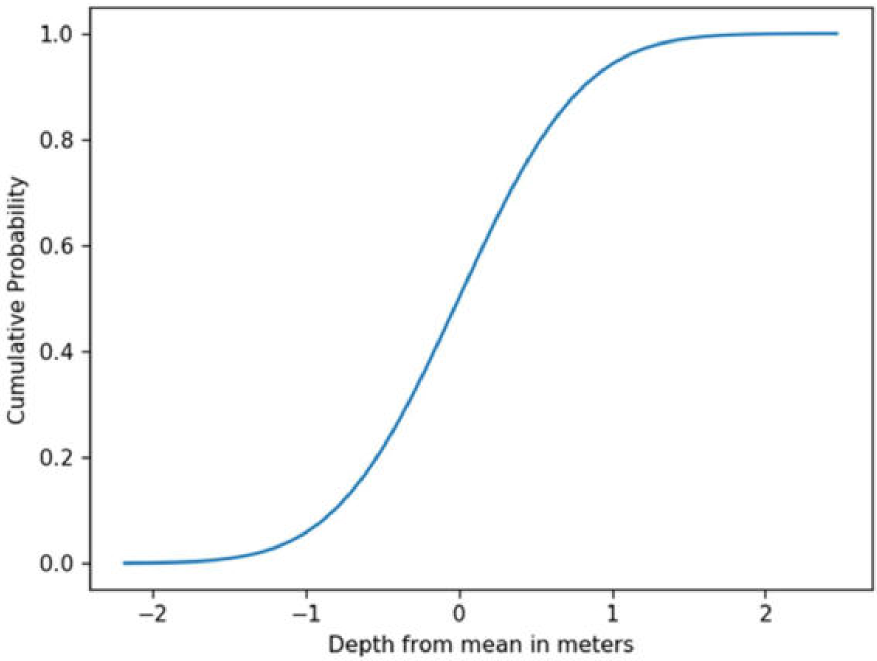

Figure 83: Cumulative Probability of Deviation from Mean depth to water table-Abbasia

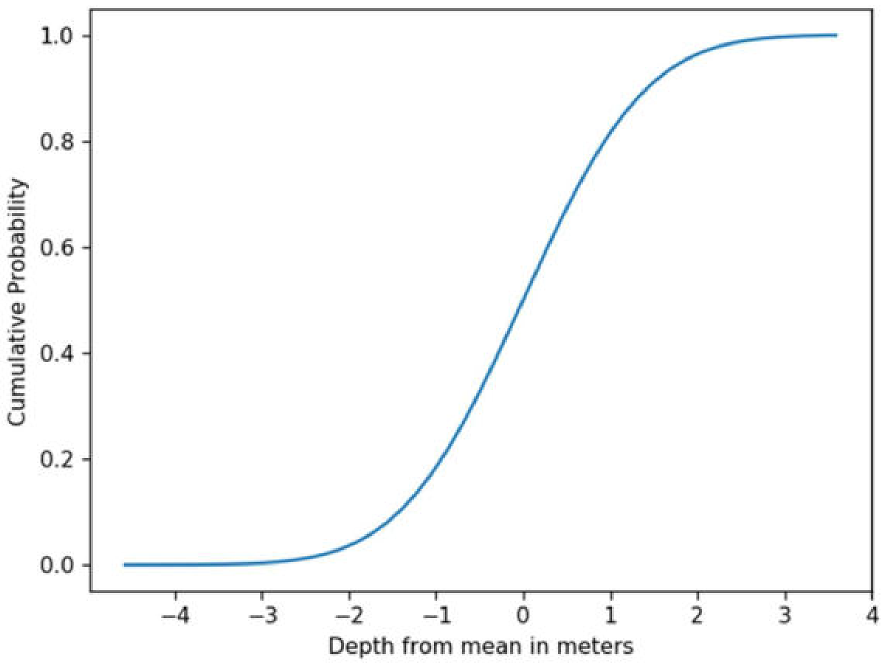

Figure 84: Cumulative Probability of Deviation from Mean depth to water table- Lower Bahawal

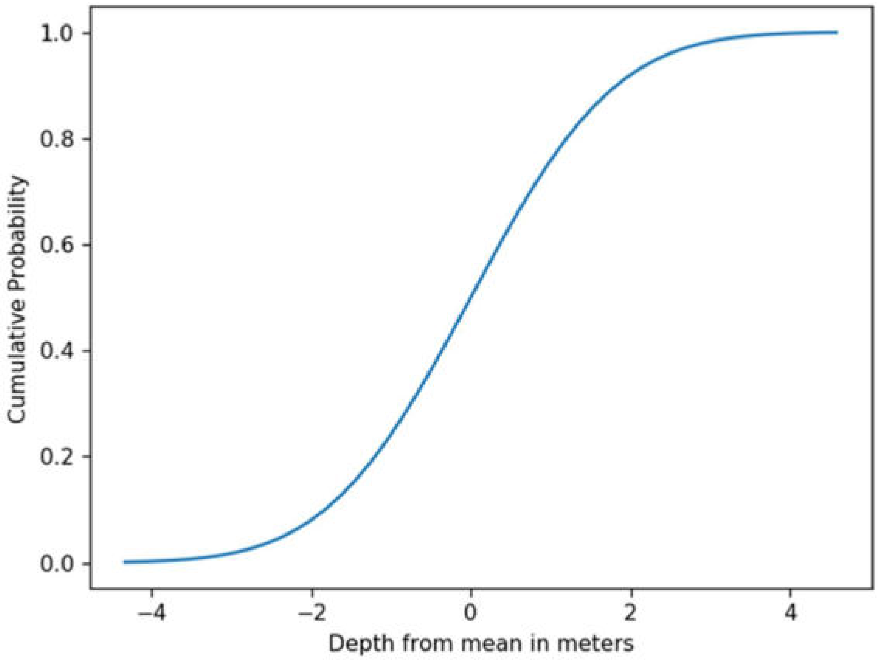

Figure 85: Cumulative Probability of Deviation from Mean depth to water table- CBDC

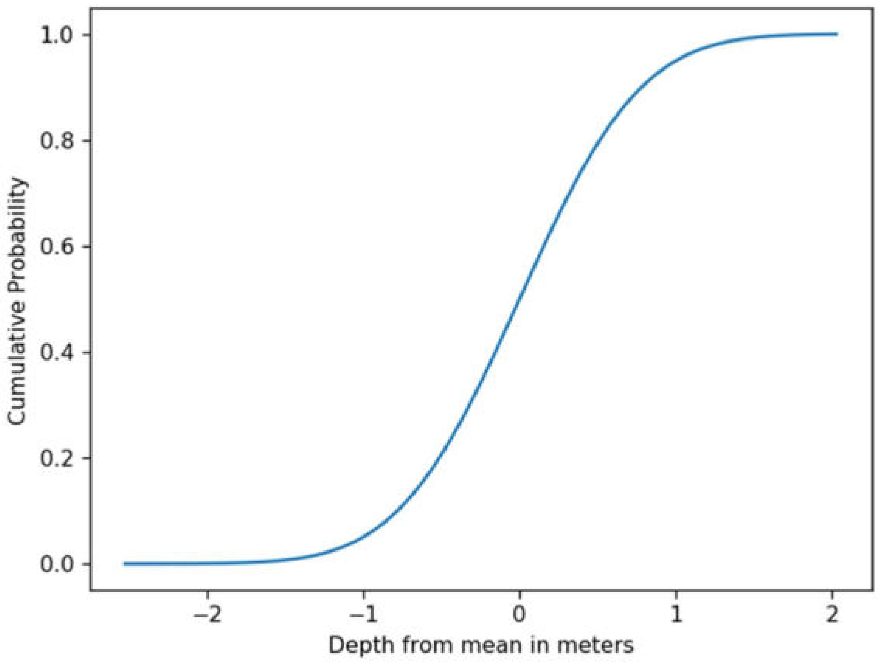

Figure 86: Cumulative Probability of Deviation from Mean depth to water table- CRBC

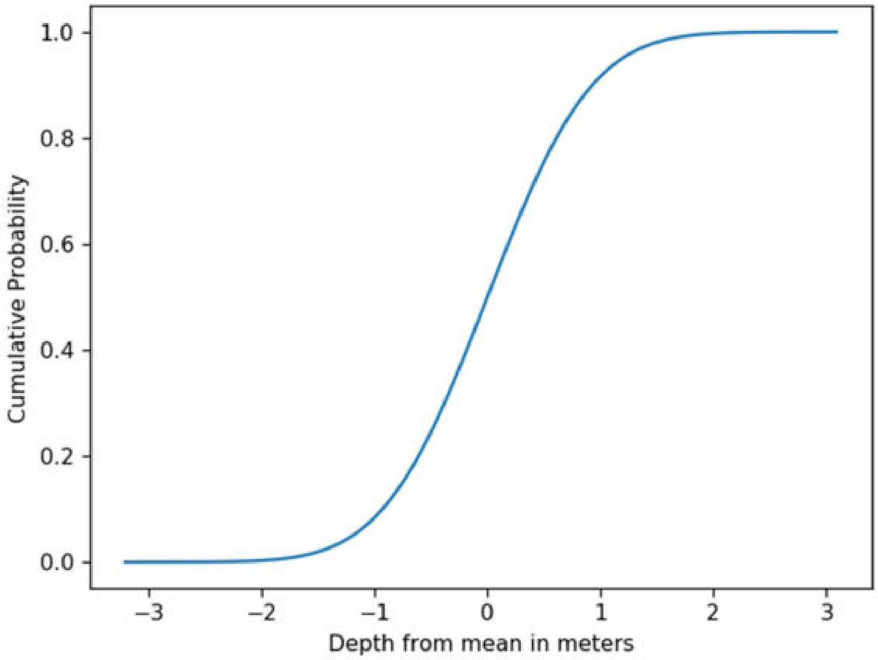

Figure 87: Cumulative Probability of Deviation from Mean depth to water table – DG Khan

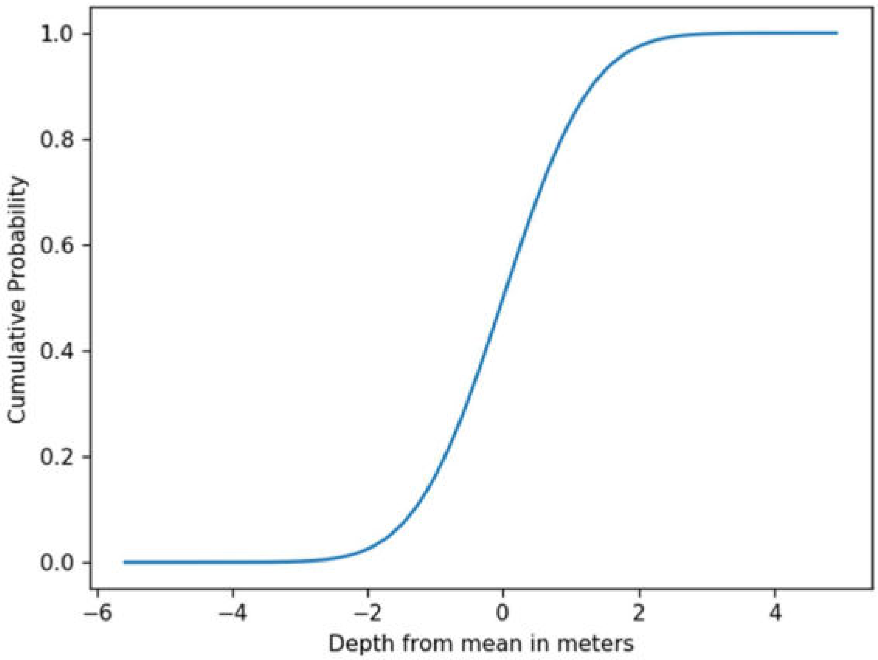

Figure 88: Cumulative Probability of Deviation from Mean depth to water table – Fordwah

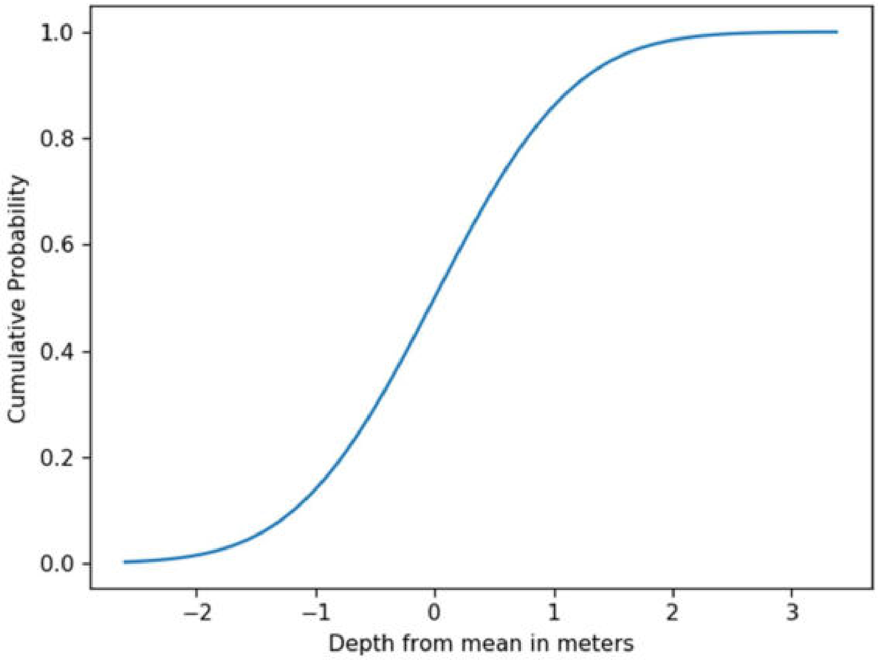

Figure 89: Cumulative Probability of Deviation from Mean depth to water table – Haveli

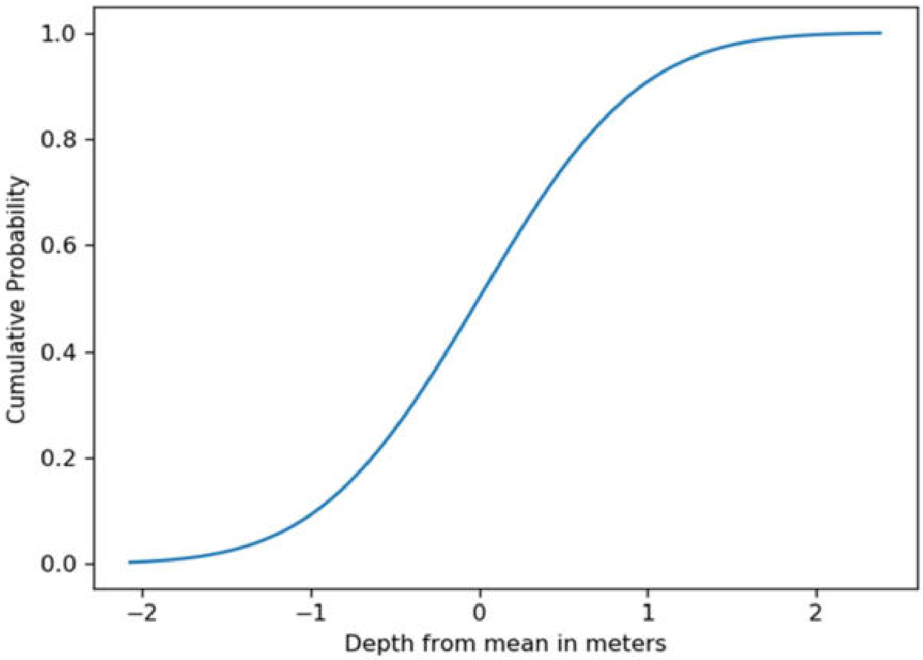

Figure 90: Cumulative Probability of Deviation from Mean depth to water table – LBDC Multan

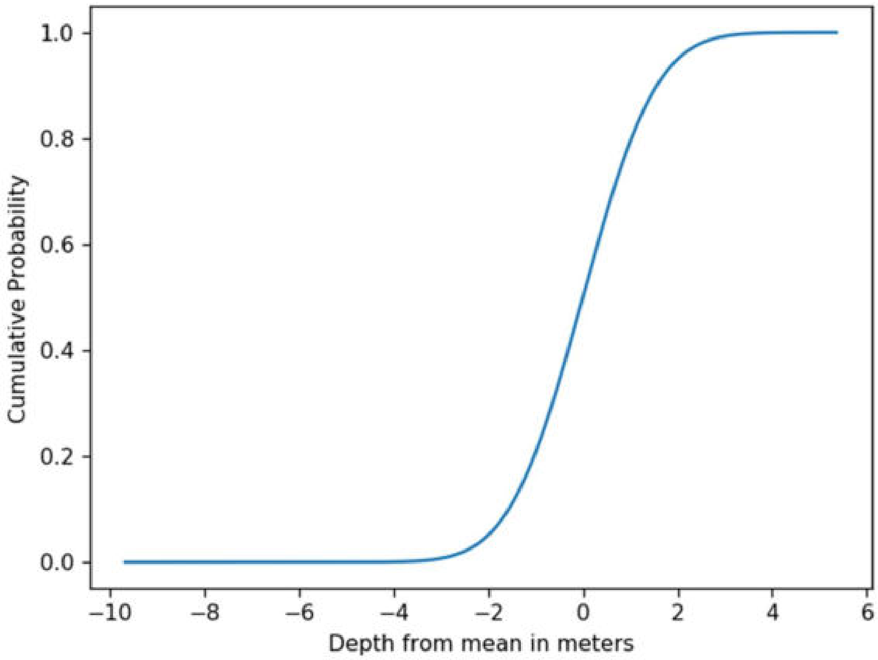

Figure 91: Cumulative Probability of Deviation from Mean depth to water table – LCC Faisalabad

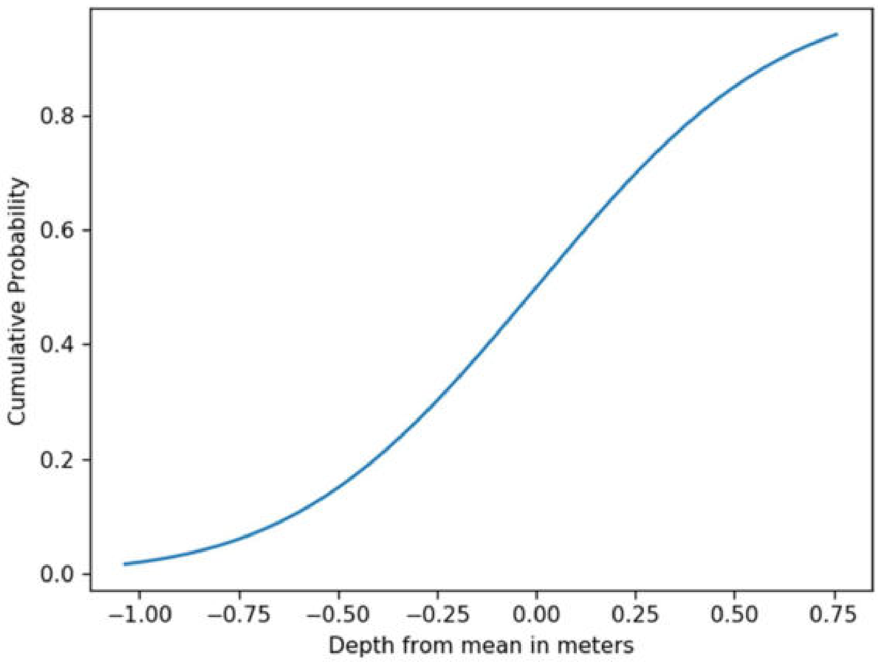

Figure 92: Cumulative Probability of Deviation from Mean depth to water table – LDC Lahore

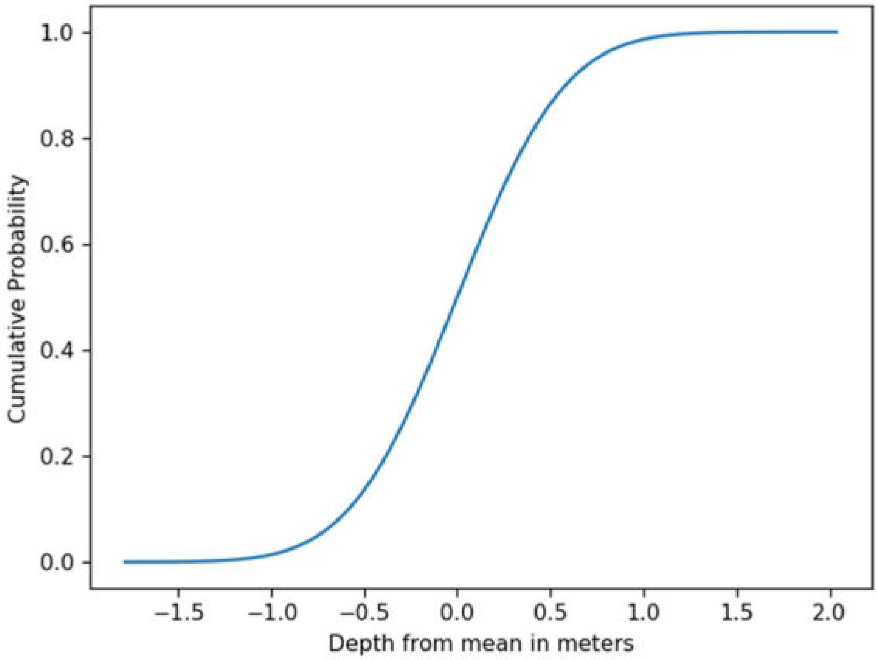

Figure 93: Cumulative Probability of Deviation from Mean depth to water table – LJC Sargodha

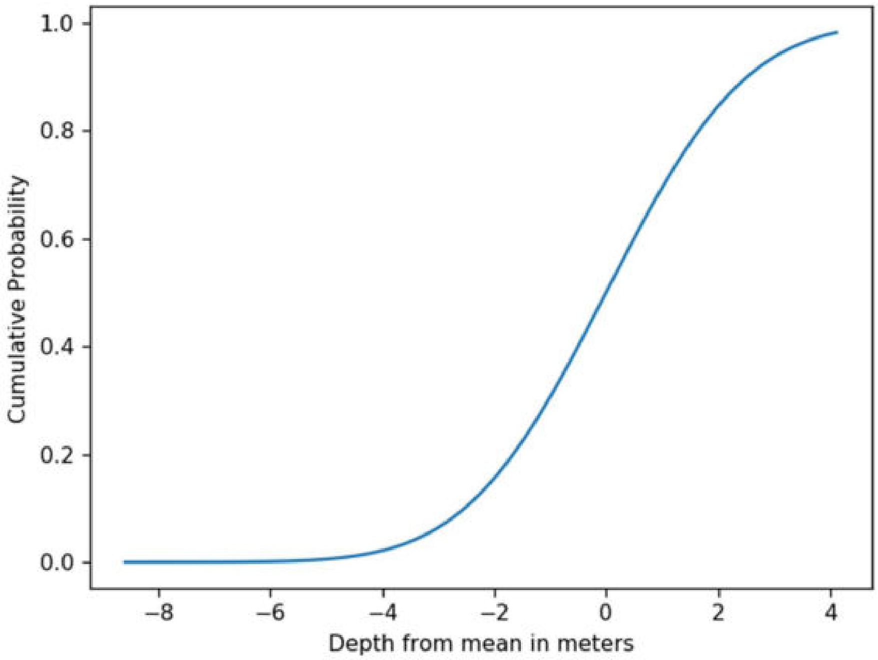

Figure 94: Cumulative Probability of Deviation from Mean depth to water table – LPC Multan

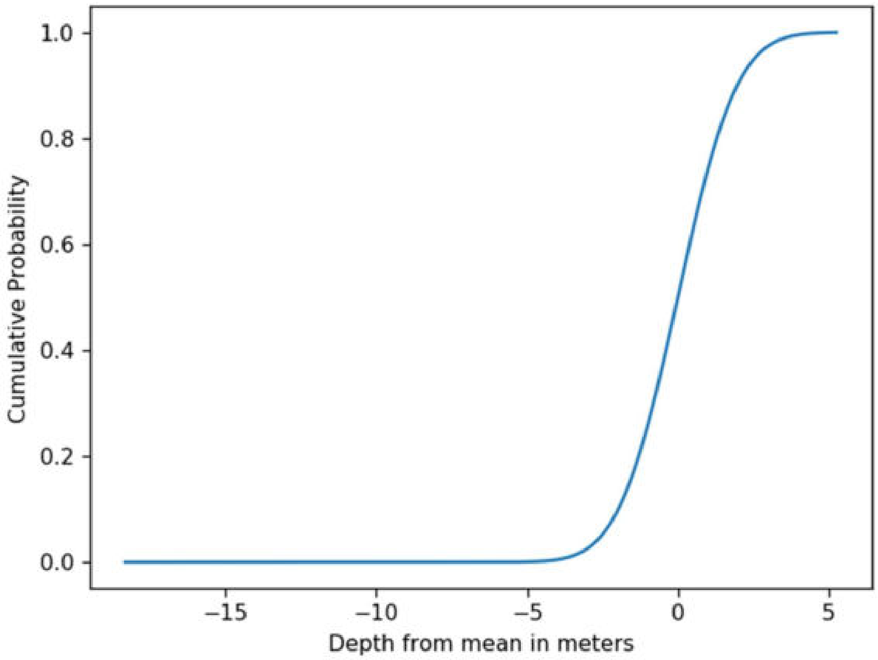

Figure 95: Cumulative Probability of Deviation from Mean depth to water table – Mailsi

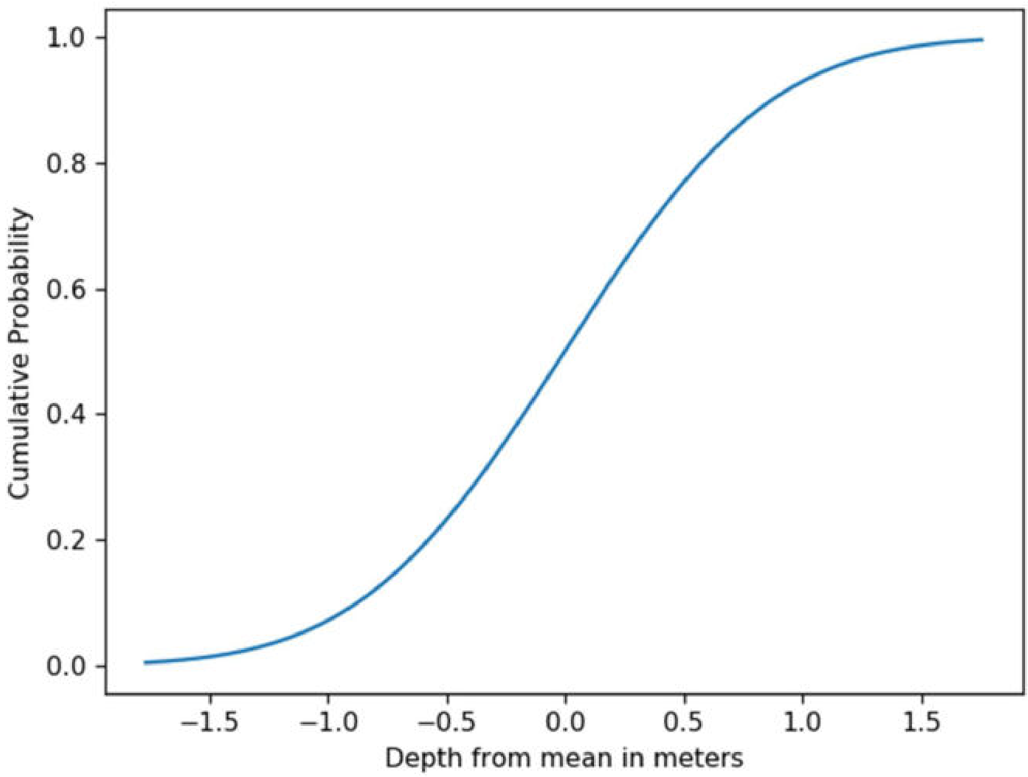

Figure 96: Cumulative Probability of Deviation from Mean depth to water table – Marala Ravi

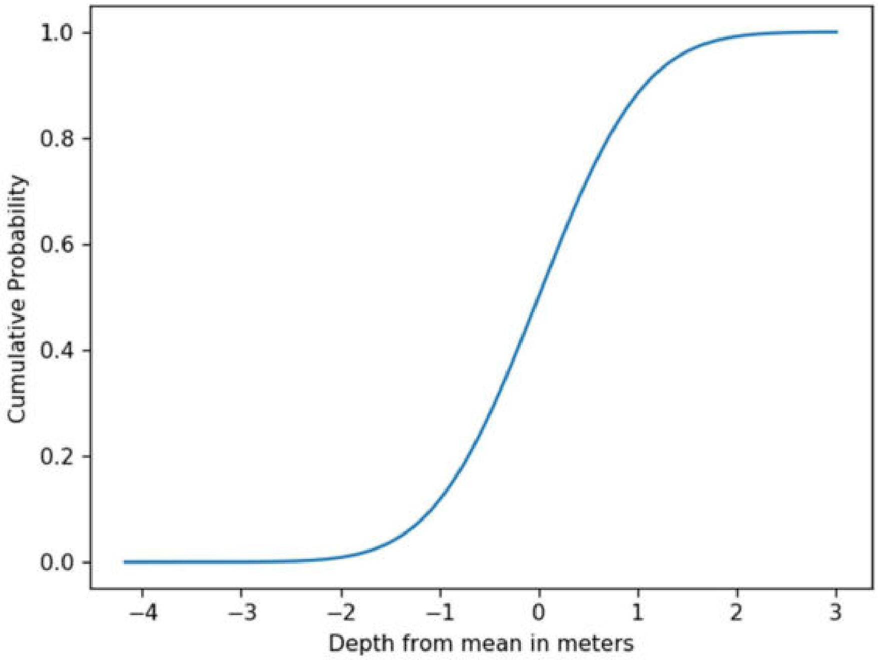

Figure 97: Cumulative Probability of Deviation from Mean depth to water table – Muzaffargarh

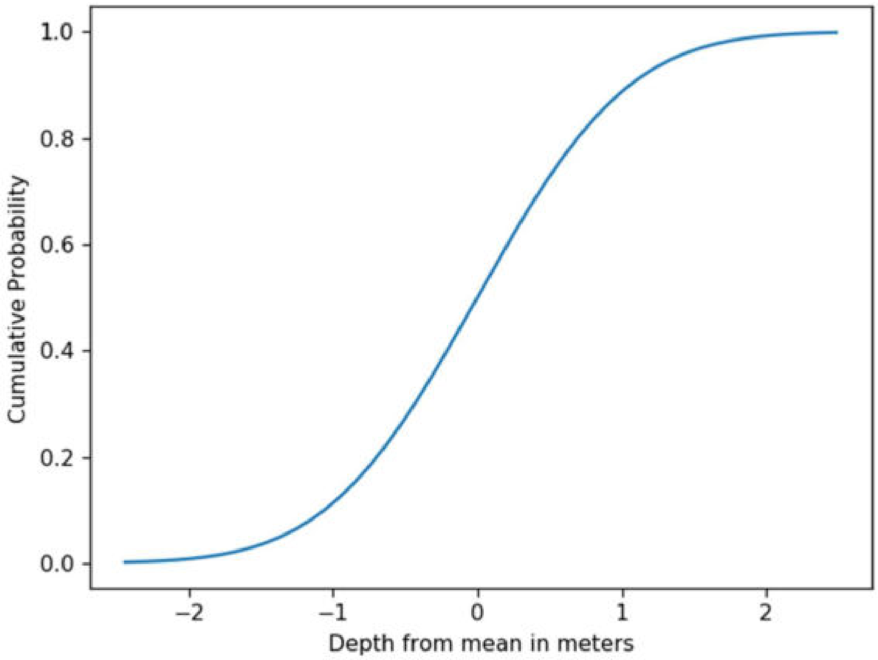

Figure 98: Cumulative Probability of Deviation from Mean depth to water table – Panjnad

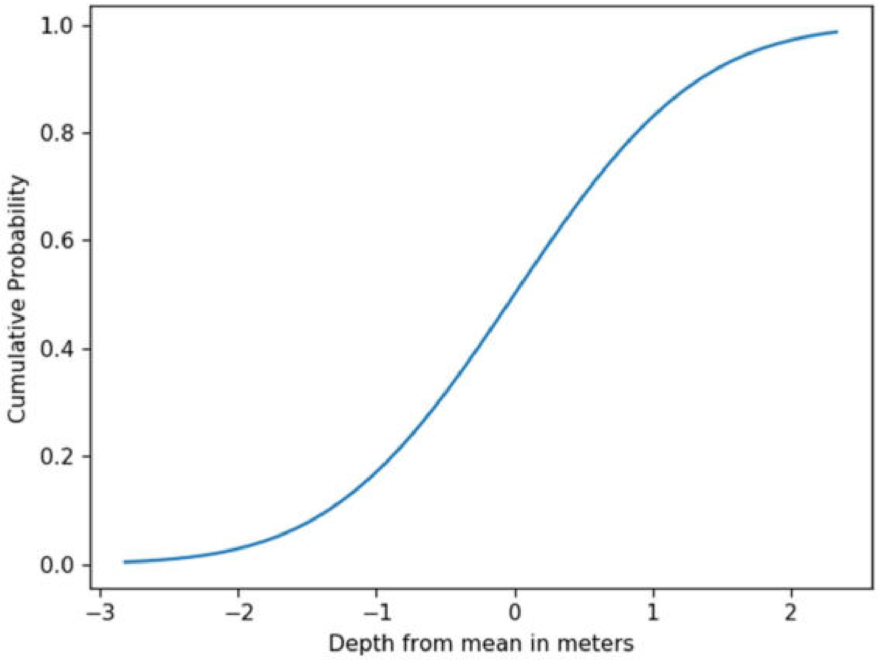

Figure 99: Cumulative Probability of Deviation from Mean depth to water table – Qaim

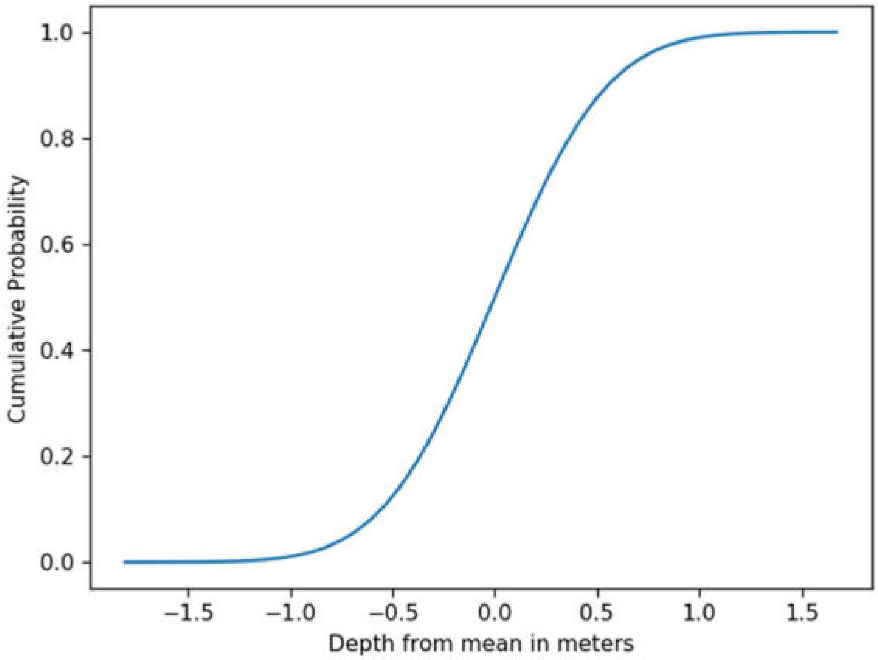

Figure 100: Cumulative Probability of Deviation from Mean depth to water table – Rangpur

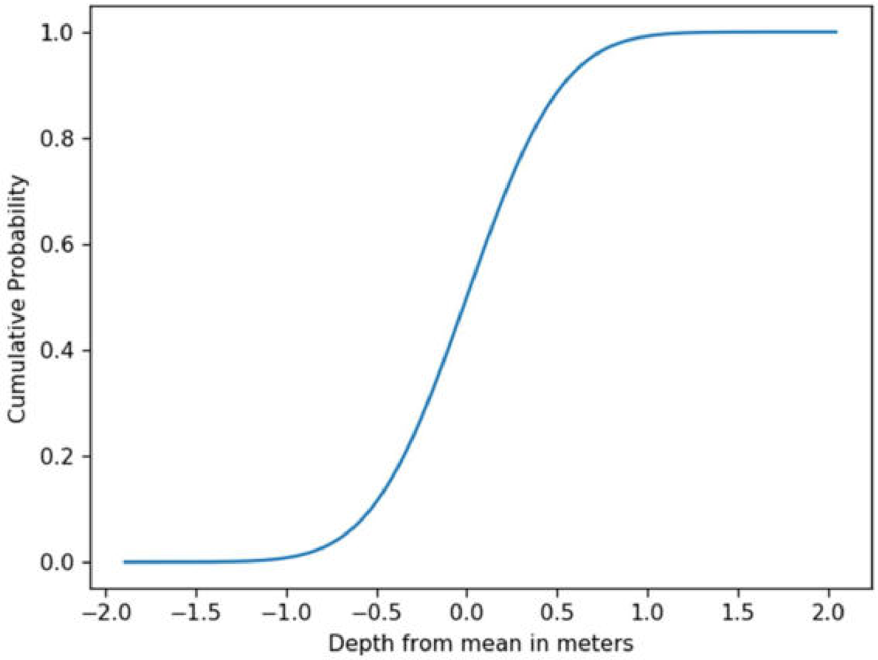

Figure 101: Cumulative Probability of Deviation from Mean depth to water table –Sadiqia

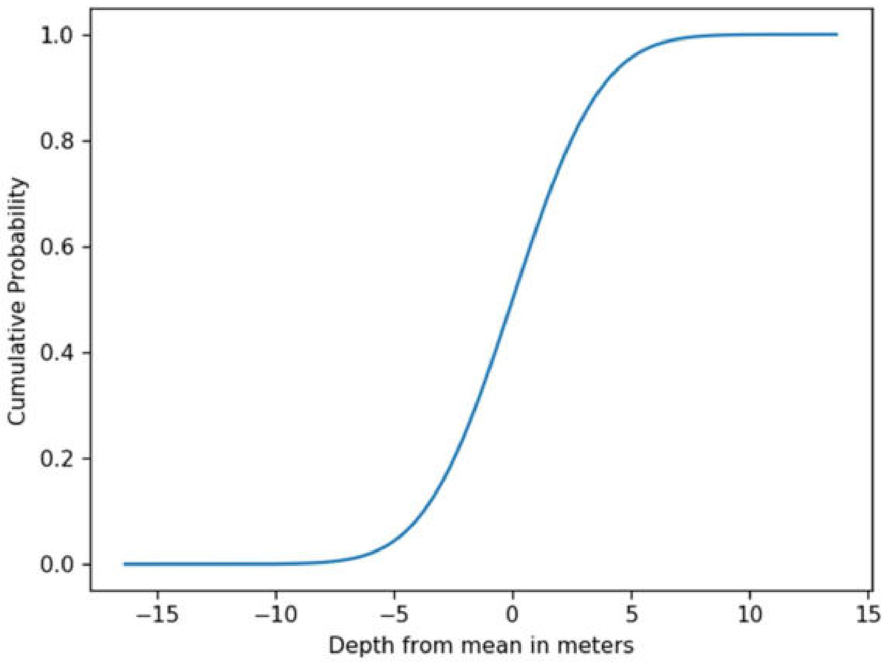

Figure 102: Cumulative Probability of Deviation from Mean depth to water table –Sidhnai

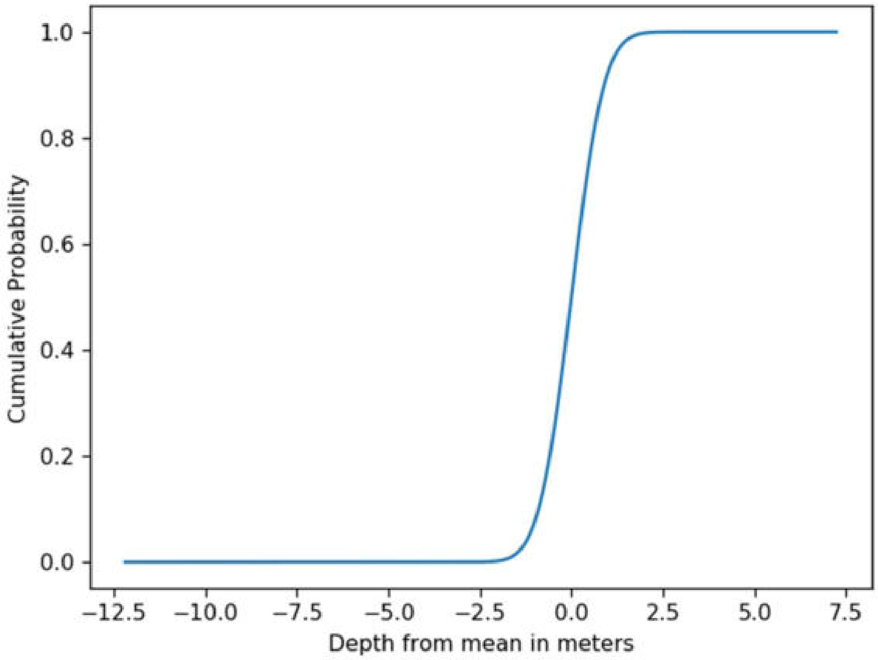

Figure 103: Cumulative Probability of Deviation from Mean depth to water table – Thal

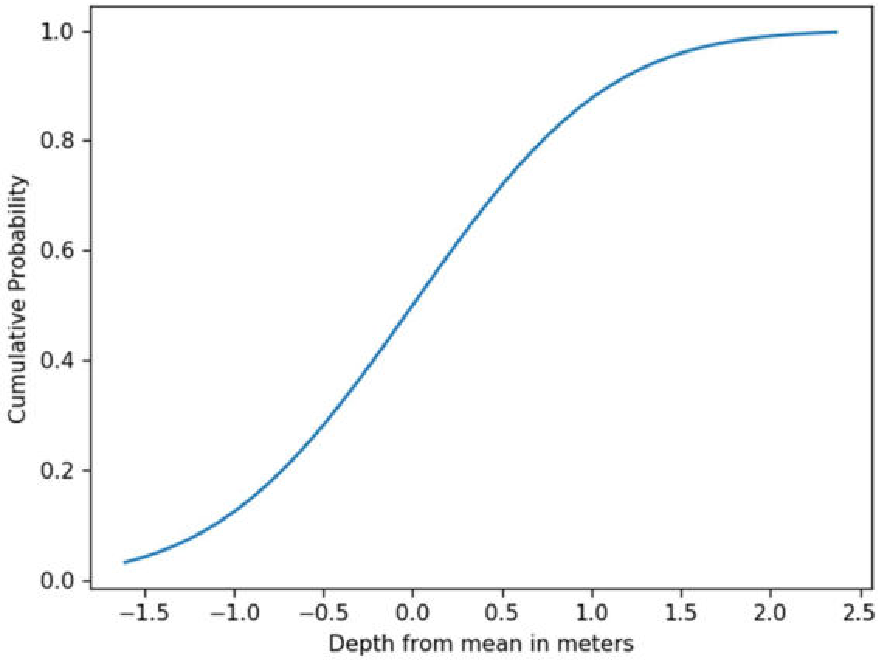

Figure 104: Cumulative Probability of Deviation from Mean depth to water table – UDC Multan

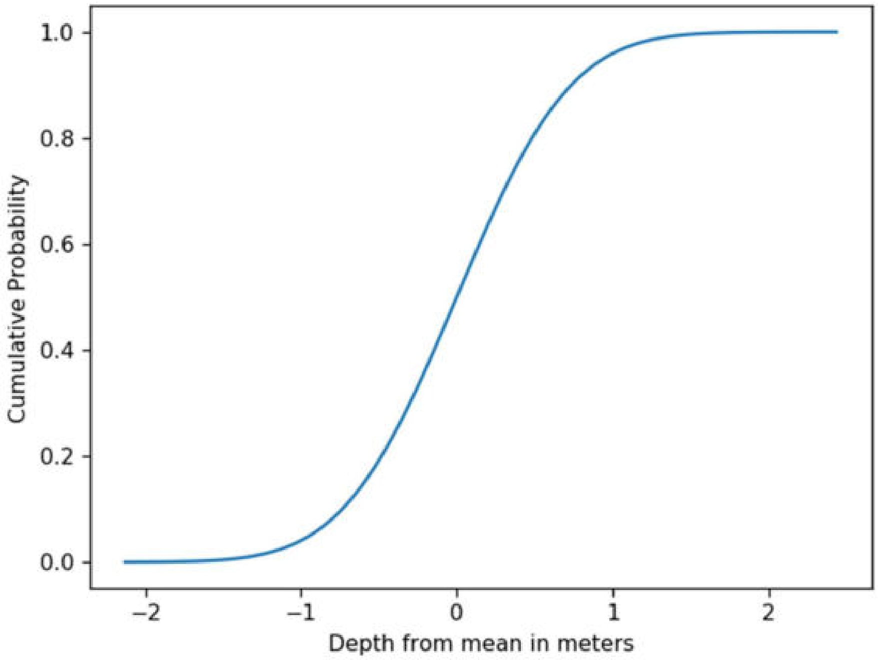

Figure 105: Cumulative Probability of Deviation from Mean depth to water table – UJC Sargodha

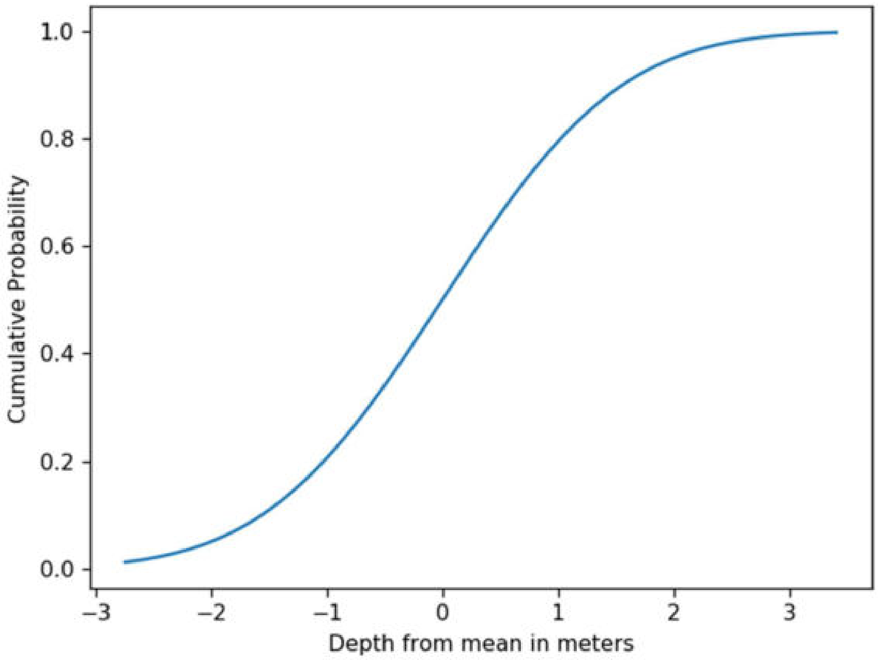

Figure 106: Cumulative Probability of Deviation from Mean depth to water table – UPC Multan

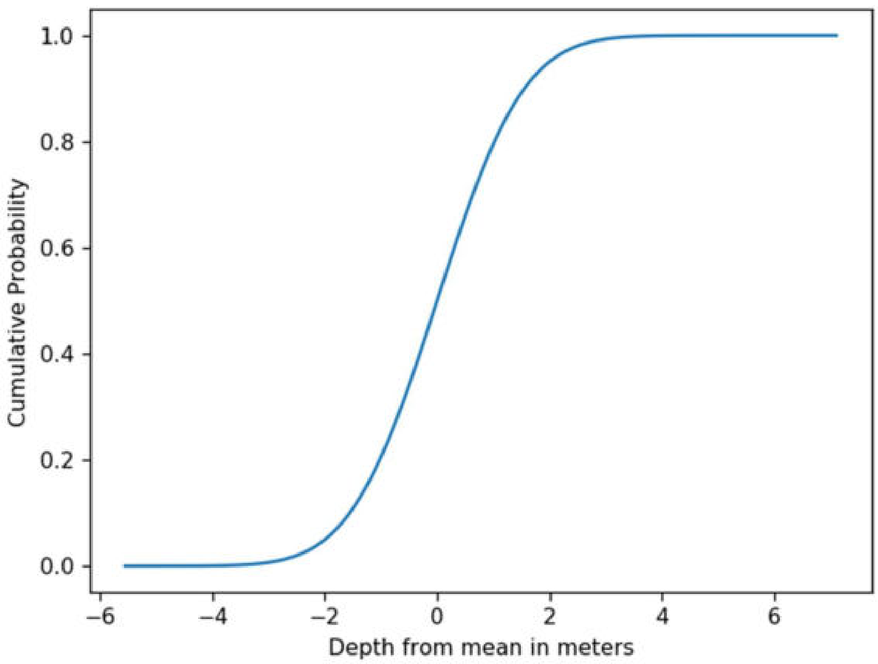

Figure 107: Cumulative Probability of Deviation from Mean depth to water table – Upper Chenab