ANALYSIS OF GROUNDWATER DEPTH AND MAPPING FOR BARI DOAB

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List of Abbreviations

AF	Acre Feet
Amsl	Average mean sea level
ARIMA	Auto-Regressive Integrated Moving Average
Avg.	Average
bgl	Below Ground Level
BLUPs	Best Linear Unbiased Predictors
CFS	Cubic Feet Per Second
cm	Centimeter
csv	Comma-separated value
DEM	Digital Elevation Model
DLR	Directorate of Land Reclamation
DSMW	Digital Soil Map of the World
DTW	Depth to groundwater
FAO	Food and Agriculture Organization
GCA	Gross Command Area
GIS	Geographic Information System
GW	Groundwater
HUA	Hanoi's Holocene Unconfined Aquifer
IBIS	Indus Basin Irrigation System

IWASRI	International Waterlogging and Salinity Research Institute
IWRM	Integrated Water Resources Management
Km	Kilometer
LULC	Land use & Land cover
MATLAB	Matrix Laboratory
MAF	Million Acre Feet
MAKESENS	Mann-Kendall test for trend and Sen's slope estimator
MHa	Million Hectare
MK	Mann-Kendall
NSL	Natural Surface Level
O&M	Operation and Maintenance
PBS	Pakistan Bureau of Statistics
PID	Punjab Irrigation Department
PIDA	Punjab Irrigation & Drainage Authority
SCARP	Salinity Control and Reclamation Project
SMO	SCARPs Monitoring Organization
USGS	US Geological Survey
WAPDA	Water and Power Development Authority
WASID	Water and Soils Investigation Division

ABSTRACT

Groundwater is the most vital and reliable source of fresh water in all parts of the world. This study examined the variability in depth to water level below ground level in agriculture-dominated Bari Doab in Pakistan. GIS tools and surfer software were used to map the Spatio-temporal distribution of groundwater depth. Change in the depth of the ground water table was observed by preparing maps for both pre-monsoon and post-monsoon seasons by five-year difference intervals from 2005-2020. The trend of the groundwater table was analyzed by non-parametric methods i.e., Mann-Kendall (MMK) and Sen's slope estimator in all districts. The trend analysis was performed at a significance level of 5 percent. The fluctuation of the water table in the study area showed a progressive decline in water level over 15 years in all districts except Pattoki and Kot Radha Kishan tehsil of Kasur where a minor increase is observed. The seasonal fluctuation based on pre-monsoon and post-monsoon seasons during the 15 years (2005-2020) showed that of 26 Tehsils, the average depth to water table increased in 12 tehsils in the post-monsoon season while in 11 tehsils it decreased and in 3 tehsils there was no change. Observation points of groundwater table depth with a 5% significance level were used to project future water table depths in the region that depicts further depleting trend in Bari Doab for both the pre-monsoon and post-monsoon seasons indicating alarming trends in some regions of the Bari Doab.

Keywords: Groundwater, Bari Doab, Spatio-temporal DTW, GIS, Surfer, Mann-Kendall (MK), Sen's slope estimator, Trend analysis, MATLAB

CHAPTER 1

1 INTRODUCTION

1.1 Overview

Previously, supply-side management based on a fragmented strategy, i.e., without the integration of other crucial factors, was preferred. Water resource management primarily focused on directing water from river courses to where and when it was most required. Today, the possibilities for diverting additional river flows are limited, and there are indications that the availability of surface water resources is declining. This is a result of declining storage capacity, an increase in population, and rising water use by increasing population over time. A few decades ago, in parallel to surface water consumption, rising groundwater use was a major contributor to satisfying extra water needs. Pakistan's agriculture industry has gained various benefits both economically and environmentally from the private farmers' use of groundwater. Nearly fifty percent of agricultural water needs in an irrigated region are now satisfied by groundwater. Even though there is obvious evidence of groundwater overexploitation, as seen by dropping water tables, hundreds of new wells are being drilled annually without knowledge of the aquifer's capacity to fulfill this increased demand. This situation has gotten increasingly severe in recent years as a result of the country's continuous and prolonged drought during the previous decade. However, uncontrolled and unequally withdrawal on a large scale in the Bari Doab region is resulting in unbalanced dispersal of water table depth (DTW).

This scenario has a variety of negative impacts, such as an abnormally low water table, a rise in energy costs for pumping deeper groundwater, and the possibility of lateral flow of salty water into fresh water zones, causing groundwater drinking issues. There is an urgent requirement for the study to increase scientific understanding of the linkages between climate trends, land use changes, and hydrology of the system, especially groundwater. This will drive system operators and irrigation administrators to reevaluate present operational concepts.

As witnessed in Pakistan and India, licensing is not the most effective solution due to the increasing number of water wells in the region by local farmers (Qureshi, McCornick, et al., 2010). The encouragement of farmers to use the water resources conjunctively is a good option for groundwater conservation.

According to (Foster & Steenbergen, 2011), in many alluvial regions, surface water-oriented organizations manage water resources due to irrigated agriculture, from impounding reservoirs or river intakes and major irrigation canals. Conjunctive use of groundwater and surface water can enhance water supply reliability in irrigated agriculture and urban water distribution in the area, chiefly on alluvial plains, which are population and economic centers. Conjunctive consumption is however challenging to handle than surface or groundwater alone.

1.2 Groundwater Resources of Pakistan

The majority of the country's supply of groundwater is located in the irrigated regions of the Indus Basin, while the other is located in places outside the Indus Basin. A century ago, canal irrigation was implemented in the area. Before this system, the groundwater table in the majority of the Basin was 100 feet below the surface. As a result of the establishment of the irrigation system, groundwater is currently located between 5 and 30 feet below the surface of the earth (Amin, 2004). Pakistan uses 4.6% of the world's groundwater for irrigation, accounting for 9% of all groundwater extraction, making it the third largest groundwater consumer in the world (Qureshi, 2020). Groundwater in the nation has been extensively used since the 1960s, Salinity Control and Reclamation Projects are funded by the government through which 16,700 drainage wells having a discharge capacity of 0.80 m^3/sec (SCARPs) were introduced. In 2.6 MHa of irrigated farmland, the SCARP tube wells were put in place to manage problems of water logging and salinity (Siebert et al., 2010). The introduction of the SCARP concept inspired farmers to establish their tube wells, resulting in an explosion in the count of private tube wells from 30,000 in 1960 to more than 1.2 million in 2018. More than ninety percent of them exclusively work in the Province of Punjab. At that time, the area irrigated in Punjab increased (from 8.6 to 16 million hectares) and the proportion of groundwater for irrigation increased from 8% to 75% (Asghar et al., 2018; Qureshi, 2018). Because of the availability at low depths and relatively better quality, groundwater is widely utilized in Punjab.

1.3 Integration of Water Resources

The term "conjunctive water usage" describes the practice of using both groundwater and surface water together to meet the increasing water demand. Most farmers in irrigated regions blend canal supply with groundwater to meet the water requirements effectively. They do it on their own at their farms, independently of any larger scheme or irrigation infrastructure. To enhance production and ensure environmental sustainability, it is necessary to jointly manage surface and groundwater resources at the basin level. This is what "integration of water resources" means in reality. Such a strategy is necessary at the basin and IBIS system levels to boost agricultural water productivity and water for daily consumption by decreasing water wastage in regions with high precipitation and canal water availability. Therefore, conjunctive water management is enhanced when system managers simultaneously regulate surface and groundwater. As a result of the need for institutional change and a reevaluation of agricultural water requirements, it is currently less prevalent at IBIS and almost nonexistent at the basin level. However, conjunctive usage is complicated, but it may prove to be helpful, especially in water-scarce areas and during drought periods (to minimize water shortages) or wet years (to avoid waterlogging and salinity) because not doing so can lead to one or both of these issues.

Humans are confronted with a fundamental problem: how to deal with the continuously increasing demand for water in developing metropolitan cities, the industrial and agricultural sectors, and in-stream water applications for ecological mitigation. Surface water and groundwater have traditionally been regarded as distinct parameters, and have been studied separately for meeting water requirements in any region. In the current scenario odds of further water supply are minimal due to the growing skepticism about the construction of more water reservoirs. As a result, with the likelihood of a rising struggle for available water, water planners have redirected their efforts toward improved management of current resources i.e., the integration of surface water and groundwater. (Todd, 1959) described this as the process of conjunctive usage. (Dennis P. Lettenmaier, 1982) distinguished conjunctive use of groundwater as a short-term usage, whereas cyclic storage, was a long-term basis discharging and recharging process. Other challenges that affect the effectiveness of conjunctive use projects include disparity in groundwater depth across administrative divisions, therefore establishing acceptable and sustainable groundwater supply, as well as surface water distribution and allocation in the region, is the actual problem. Still, as cited by (Karanth, 1987), the favorable impacts of conjunctive water usage in irrigated regions may be summarized:

"The use of groundwater helps to meet peak irrigation needs, reducing the size of canals and, as a result, building costs. Even if rainfall is less or is delayed, supplemental supplies from groundwater sources assure the correct irrigation schedule. Groundwater withdrawals reduce the water table, lowering the danger of waterlogging, soil salinity, and water waste due to soil leaching. Peak runoff is reduced as runoff and subterranean outflows are reduced. When integrated usage is combined with artificial recharge, the requirement for canal lining is minimized since canal seepage recharges the aquifer. Conjunctive usage permits the use of saline or brackish ground or surface water resources, either by mixing them with fresh water or through utilizing alternative water resources for irrigation purposes."

1.4 Demographic Growth Impacts and Water Resources

Population growth resulted in considerable agriculture and industrial expansion, which increased the need for water. In recent decades, there has been a greater realization of the significance of the existence of surface and groundwater along with its distribution spatially and temporally.

Our homeland Pakistan is the 6th most populous country in the world. The population rose from 40 million in 1950 to 173 million in 2012 and is anticipated to reach 237 million by 2025 if the current growth rate is maintained. To meet the food demands of the region's rapidly growing population, it is predicted that the agricultural sector will need to grow by more than 4% per year and water availability by more than 10% (FAO, 2012). Under the normal operation scenario, irrigation water demand will reach 349.2 km^3 by 2025, a 48.3% rise over the present water supply (Seckler et al., 2000). While the requirement for irrigated agriculture continues to rise, the availability is unlikely got to expand; surface water development potential is especially constrained. So, the use of groundwater with surface water became a necessity. The per capita availability of water has reduced from $5260m^3$ in the early 1950's to $1040m^3$ in 2010, representing a 400% decrease. (Archer et al., 2010) projected that per capita water availability will decrease from 725 m^3 in 2025 to 415 m^3 in 2050 if population growth continues at a consistent rate (Watto & Mugera, 2016).

Pakistan is a semiarid to an arid nation with an average annual precipitation of 240 mm. The country's ever-expanding population and economy rely heavily on annual river flows of approximately 180 billion cubic meters (BCM). During hot and dry seasons in arid and semi-arid locations such as Pakistan, the influence of agricultural activities has negative impact water on the amount of water supply and available water resources. The regular canal supply after seepage losses cannot provide the total agricultural water needs. Groundwater resource development began at a rapid pace in response to a scarcity of surface water supplies, prominently during the drought years (1999-2002). Farmers must now rely on groundwater when crop requirements are urgent. Because of the ever-increasing population, irrigation demands have shifted from canal supplies (at the moment of irrigation system development) to canal water supply and groundwater pumping at present. The replenishment of groundwater is also dependent on canal water drainage and precipitation recharge. Consequently, the coordinated use of all water resources, including precipitation, surface, and groundwater, has become crucial for sustaining agricultural growth and productivity at present.

The growing population in the country is putting significant strain on surface and groundwater resources. (Gilani, 2011) the Prime Minister of the Islamic Republic of Pakistan stated at a gathering on the eve of World Population Day that it was essential to devise a plan to balance population growth with the country's resources equitably and efficiently. Pakistan is the sixth most populated nation in the world, with a population growth rate of 2.03% within SAARC countries, resulting in an annual rise of 3.6 million people. It was projected to reach 210.13 million by 2020 and triple during the next 34 years.

The Population growth of the census data from the Pakistan Bureau of Statistics (PBS) with the help of conducted in 1997 and 2017 depicted the increase in population with time. The population growth rate was higher in some districts than the other as shown in Table 1.1. The increase in the rate of population growth put stress on the surface and groundwater resources.

Table 1.1: Demographic data of districts in the Bari Doab region for 1998 and 2017

Districts	**Area**	**Population**	**Population**	**Population Density**	**Population Density**	**Average Annual Growth**
	Sq. Km	**1998**	**2017**	**Sq. Km (1998)**	**Sq. Km (2017)**	**1998-2017**
Lahore	1,772	6,340,114	11,119,985	3577.94	6275.39	3.00
Kasur	3,995	2,354,506	3,454,881	589.36	864.80	2.03
Okara	4,377	2,232,992	3,040,826	510.16	694.73	1.64
Pakpattan	2,724	1,286,680	1,824,228	472.35	669.69	1.85
Sahiwal	3,201	1,843,194	2,513,011	575.82	785.07	1.64
Vehari	4,364	2,090,416	2,902,081	479.01	665.00	1.74
Khanewal	4,349	2,068,490	2,920,233	475.62	671.47	1.83
Lodhran	2,778	1,171,800	1,699,693	421.81	611.84	1.97
Multan	3,720	3,116,851	4,746,166	837.86	1275.85	2.23

Groundwater is presently overdeveloped in many locations, and its quality is diminishing probably as a result of the lateral flow of brackish water to sweet water aquifers, which has the potential to deteriorate the existing sweet water aquifers further and make them unfit. Over the last 40 years, groundwater extraction, largely by private farmers, has resulted in various environmental and economic advantages. During this time, a laissez-faire approach may be suitable. In the present era, almost half of all irrigation needs are met by groundwater. Although there is a significant affirmation of the overexploitation of groundwater in the form of dropping water tables, hundreds of additional tube wells are being built each year. Because of the country's ongoing and prolonged drought, this situation has become increasingly serious in recent years. Farmers in Baluchistan are pumping from hundreds of meters below ground, and depletion is already a reality in many portions of the Indus Basin's sweet water districts. The situation is significantly worse in major cities, where the water table is lowering as a result of extensive groundwater extraction for piped water supplies. The depth of the water table in Lahore has risen to 40 meters in core areas; it was less than 27 meters a few years ago, and it was almost 5 meters deep in 1960 (Basharat, 2012). Furthermore, substantial and rising worries about groundwater quality exist, a situation that is projected to worsen if the current trend of diminishing drawdown continues. As a result, Pakistan has entered a period in which laissez-faire has become an opponent rather than a hope.

If the over-exploitation of water resources, particularly groundwater, is not regulated by preventing over-pumping and wastage by inefficient irrigation methods, the declining groundwater level would undoubtedly worsen the ongoing dispute over water scarcity between provinces as well as the consumers at all local levels. Another risk is the fast groundwater level decline, which will result in the lateral migration of salty water to the fresh aquifers. To maintain a balance between the rate of agricultural expansion equivalent to population increase, more land must be put under cultivation. Since no new water is predicted, it is preferable to alleviate the efficiency of current water resources systems and land capacities, lest the country face a severe scarcity of food, fiber, and edible oil soon. The lack of a groundwater management system in Pakistan might be a serious concern in the coming years, resulting in fast-declining groundwater levels and contamination of both surface and groundwater. All of these concerns affect agricultural productivity, food security, and the nation's overall potential to enhance the economic growth of the irrigated area. According to (Perry, 2001), the obvious overuse and wastage of irrigation water, particularly in the setting of cheap and subsidized irrigation water, water prices, and the degradation of irrigation systems recommend that charges be raised to pay the expenses of system operation and that pricing mechanisms play an important role in promoting more effective resource use. He goes on to say that water is a difficult economic and political resource, with varying values over time, geography, and usage. In his perspective, volumetric water allocation would better serve the goal of greater water usage efficiency than expecting markets to achieve the appropriate balance among conflicting objectives in productivity, environment, and social equality.

The decline in aquifer level will result in increased pumping costs for farmers and, in certain regions, may need to update the pumping equipment to handle larger lifts. Poor farmers may be unable to access groundwater. According to (Steenbergen & Oliemans, 1997), Pakistan's policy landscape has altered due to a major rise in the magnitude of groundwater extraction over the previous three decades, i.e., "the key policy challenges now pertain to environmental sustainability and welfare." They emphasized the need to "avoid dropping groundwater tables and worsening groundwater quality in fresh groundwater areas," as well as "ensuring fair access to an increasingly vital natural resource." According to (Rafiq et al., 2011), "maintaining the large welfare advantages that groundwater development has brought without depleting the supply is a critical water dilemma confronting the globe today." As a result, there is a dire need to devise practical approaches and techniques for bringing about change. Groundwater withdrawals must be balanced with recharge, a tough process that will need action by the government as well as knowledgeable and organized consumers. Because irrigation is responsible for much of the groundwater recharge in the Indus Basin, an integrated strategy for surface and groundwater management is required.

1.5 Problem Statement

In many regions of the world, economic activities and population increase have caused a substantial decline in per capita water supply, as well as a decline in groundwater level and surface run-off. The country is transitioning to a water-scarce zone from a water-stressed zone, and its water resources continue to approach their minimum levels. As predicted by (John Briscoe, 2005), the current per capita water supply has reached 1000 m^3 per year because of an increment in the population of 2.03% per year. In comparison to other nations, water productivity is also low; food yields per unit of irrigated land are less. All of the above realities necessitate novel approaches to effectively manage limited water supplies.

Together with surface water, groundwater is utilized for agricultural operations. Due to a rise in population, agricultural activities and daily water usage in the region have grown, necessitating an increase in water pumping from subsurface reservoirs to satisfy demand. Due to repeated groundwater mining, centrifugal pumps face suction limitations, restricting access only to those who can deploy turbine pumps propelled by electricity at extremely high costs. Precipitation is frequently the most influential factor influencing irrigation demand. Precipitation averages over 100 millimeters per year in some portions of the Lower Indus Plain and well over a thousand millimeters per year in the Upper Indus Plain, especially close to the foothills. The recharge is not sufficient to replenish the water table. This may result in the depletion of the underground water table in the future to a level that can be of great concern for meeting the demand for underground water for future generations. To meet this problem, a new pragmatic approach based on the integrated and conjunctive utilization of canal and groundwater resources that takes climate, economic, and environmental aspects into account is required.

1.6 Objectives

The main goal of this research is to assess spatial and temporal groundwater variability and its trend in the Bari Doab region. The notion is that anomalous groundwater depletion in the region is cause for concern and at the Doab level steps must be implemented to adopt conjunctive water usage and integrated water resource management (IWRM). The particular objectives are

- To assess the spatiotemporal variability of the groundwater table in different zones of the Bari Doab region
- To detect the trend of water table fluctuation by non-parametric tests
- Extrapolate and project the water table variation trends for pre-monsoon and the post-monsoon season

1.7 Scope and Limitations of the Study

The study comprises the area included in Bari Doab. The examination of groundwater depths in the region gave an idea about the situation of the groundwater table. The study will provide a foundation for conjunctive usage of surface and groundwater in the future based on the depths of the groundwater in the region and its future projected trend. (Halcrow, 2006a) identified that the overall recharge in the Bari area is less than the overall abstractions in the area. By the identification of areas vulnerable to groundwater depletion decisions and remedial measures like groundwater recharge practices on the national level can be taken for the management and sustainability of groundwater in the Bari Doab region.

There is a lack of thorough data about aquifer features, groundwater availability, and farmer consumption in such a large area except for a poor estimate of yearly groundwater depth and quality through the Punjab Irrigation & Drainage Authority (PIDA) and International Water Logging and Research Institute (IWASRI). Moreover, the available data in the region was not monitored on a regular grid during the repeated surveys.

1.8 THESIS LAYOUT

- **Chapter 1: Introduction:** Overview, Introduction, and holistic picture of water resources in the basin, objectives, and significance of the study.
- **Chapter 2: Literature Review:** A literature review consists of background, studies on groundwater in the basin, and global studies carried out on spatio-temporal groundwater trends.
- **Chapter 3: Research Methodology:** Description of the study area and the tools, techniques, and methodology applied for this study.
- **Chapter 4: Result and Discussion:** The results and findings of the study area are presented and discussed in this chapter with the help of spatio-temporal maps and a table.
- **Chapter 5: Conclusion & Recommendation:** Overview of the findings of this study and the recommendations for the future.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Background

Water scarcity is caused not just by a physical lack of water, but also by inadequate management; or, in the words of the World Water Council, "Today's water issue is not about having insufficient water to meet our requirements." It is a water management disaster that is wreaking havoc on billions of individuals and the environment (William J. Cosgrove, 2000). The above remark is also entirely correct for Pakistan. Surface water resource planning and management are just as vital today as it was in the past. However, given that groundwater accounts for 50 percent of agricultural activities, there is a dire need to manage groundwater effectively for the productivity of an area. Groundwater can be of substantial importance in drought seasons and act as a buffer to meet requirements along with surface water. Poor management of this buffering mechanism, on the other hand, "may have major consequences for the ecology and, ultimately, food security" (Ahmad, 2002). According to (Shah et al., 2000), sustainable groundwater management is a more significant concern than development. However, this problem is complicated, and its resolution is not simple. In nations such as Pakistan, the lack of a solid knowledge foundation is a fundamental impediment to good management. Universally, it is widely believed that integrated surface and groundwater management will deliver more water at lower costs than independently managed ground and surface water resources.

In 1997, the Government of Punjab established the PIDA Act with the following objectives: a) to replace the current administrative structure and procedures with more timely, productive, and efficient alternatives; b) to achieve economical, sustainable, and effective O&M of the irrigation and drainage network for long-term. However, the results were not as expected since the inherent objectives differed from those stated previously. Conjunctive groundwater and surface water system must be managed by a single institution with a long-term perspective to manage effectively through the involvement of beneficiaries. Effective conjunctive management can be achieved by a strategy that combines groundwater and surface water into a unified institutional framework that manages it jointly. Current institutions and their policies are not suitable for conjunctive water resource management.

Soon after the commencement of the irrigation system, the unequal distribution of canal water has been one of the major unaddressed difficulties in the Indus basin irrigation system (IBIS). According to (Jehangir et al., 2002), the second issue for farmers is the unavailability of irrigation water at the correct time, which leads farmers to leave portions of their farmland fallow and reduce production. According to (Jehangir et al., 2002), the supply of surface water poses technical challenges for farmers in the Rachna Doab. For the Bari Doab area, (Shakir, A.S.; Rehman, H.U.; Khan, N.M.; Qazi, 2011) suggested "exploring the viability of a water distribution model with changeable water allocations in sub-components of a canal command region based on canal water and groundwater availability." According to (Raza A., Khanzada S.D., 2012), the water division between the farmers in a province is not regular and does not adhere to a predetermined plan. Farmers along existing canals and key water distribution locations typically pump the majority of irrigation water without permission.

2.2 Outdated Groundwater Management Practices

On more than 70 percent of irrigated IBIS land, conjunctive usage is employed (Qureshi, Gill, et al., 2010). Unfortunately, this conjunctive usage is performed primarily by individual farmers at the farm level; there is no collective or organized management at the canal command or basin level. Pakistan has explored a variety of direct and indirect groundwater management measures over the past three decades, particularly for managing waterlogging and salinity. At the public level, SCARP procedures were implemented, while at the farm level, private tube well construction was supported. Nonetheless, the success has been modest. Prior efforts to enhance groundwater management were project-based and scattered. Monitoring the quantity and quality of groundwater is the only regular groundwater management duty that currently exists.

According to (Qureshi, McCornick, et al., 2010), frameworks and management tools tailored to Pakistani demands must be developed. Pakistan should practice both supply and demand management. Adoption of water conservation technology, revision of current farming patterns, and discovery of other water sources should be promoted for demand control. Priority should be given to the implementation of groundwater regulatory frameworks under Provincial Irrigation and Drainage Authorities (PIDAs) and the development of institutional changes to improve cooperation between multiple institutions tasked with the management of groundwater resources. (Qureshi, McCornick, et al., 2010) suggest further that farmers should use enhanced irrigation approaches for demand control. Current land use patterns should be revised with water-efficient alternatives. In addition, cooperation between agencies responsible for managing groundwater resources must be improved. As witnessed in Pakistan and India, licensing is not the most effective solution due to the large number of wells constructed by small farmers (Qureshi, McCornick, et al., 2010). According to (Laghari et al., 2012), the uncontrolled pumping of groundwater at the head ends of the canals leads the water table to rise, while salt concerns are rising at the tail ends. According to them, this condition may be remedied by properly managing groundwater.

2.3 Documented issues of Groundwater in IBIS

Increasing demands by cities and the environment, increasing uses by locals in upper catchments, and the severe drought in the early 2000s all reduce irrigation diversions. In Pakistan, reservoir siltation reduces online storage and as a result, decreased Rabi production. An effective irrigation system must generate more with less water. Since no additional supply or storage is predicted, the situation in Pakistan will worsen. The nation may soon confront food, edible oil, and fiber shortages if water and land resources are not improved. In the future, Pakistan's greatest difficulty will be the lack of a groundwater management system, resulting in significantly dropping groundwater levels, surface and groundwater contamination, and areas of deficient and saline groundwater. These factors affect agricultural output, food security for the poor, and the nation's ability to improve irrigated agriculture's economic performance.

Irrigated agriculture in Pakistan relies largely on groundwater for productivity. It gives flexibility in water usage that the surface water system does not, making it a key production resource. A variety of potentially major groundwater management issues must be considered to maximize possible advantages. There are no effective and practical measures in place to manage groundwater. Pakistan confronts a future of mismanagement in a water-scarce environment, and the present water institutions are not equipped to meet the problems, as described below.

- Groundwater extraction exceeds annual recharge, causing a groundwater imbalance.;
- Lowering the water table reduces well yield and raises pumping costs.;
- No province manages groundwater comprehensively.;
- Despite the alarming condition, there is no water management plan for keeping the water table level in a suitable range; and
- Due to the lack of equitable distribution of surface irrigation supplies, groundwater extraction in the lower parts of the Doab increased.

As this is discussed until 1950 the ground and surface water were handled independently. The negative impacts of this above strategy have been apparent for decades, since the last few decades the concurrent use of ground and surface water has been recognized as an essential management technique. In the recent decade, water quantity and quality challenges have become the most pressing worldwide water management concerns, and this trend is anticipated to increase in the future decades. Countries are developing strategies for coping with the depletion of water supplies. Research has always responded on time to solve the challenges of the moment. However, due to the continuously changing economic and environmental factors, particularly in the water field, the research demands vary by field and continue to develop globally.

Globally alarming population growth rates and industrial and agricultural activities, especially in emerging nations, are putting pressure on underground water resources, but the extent of both groundwater extraction and groundwater contamination is uncertain. The sustainability of groundwater and maintaining its benefits for future generations is a significant water problem on which the current research community, endowed with contemporary knowledge and computational capability, must concentrate.

2.4 Spatio-temporal Groundwater Studies in the Indus basin

The groundwater potential of a place is the amount of groundwater that may be extracted by pumping without affecting long-term resource depletion. WAPDA (1965) undertook a basin-level study that described the characteristics of the basin's aquifers. The Indus plain lithology over 300 m depth compromises the layer of unconsolidated, highly permeable alluvium composed mostly of fine to medium sand, silt, and clay, according to the research. Sands that are 65 to 75 percent alluvium, function as a cohesive, highly transmissive aquifer since fine-grained deposits with poor permeability are typically discontinuous. Depending on usage, the groundwater inside the basin varies geographically in terms of its water table. The groundwater table ranged between 20 and 30 meters before the irrigation system came into practice. In several regions, the water table rose significantly due to recharge from clay canals and irrigated regions. This severe lack of irrigation water compelled farmers to tap into groundwater reserves. In Pakistan, the number of tube wells climbed from 374,099 in 1992-93 to 107,0375 in 2009-10 (Agricultural Statistics of Pakistan, 2011) causing the water table to drop in other places. The depth to water table wildly varies across the IBIS as shown in Figure 2.1 because of autonomy people have to drill tubewells and take as much groundwater as possible.

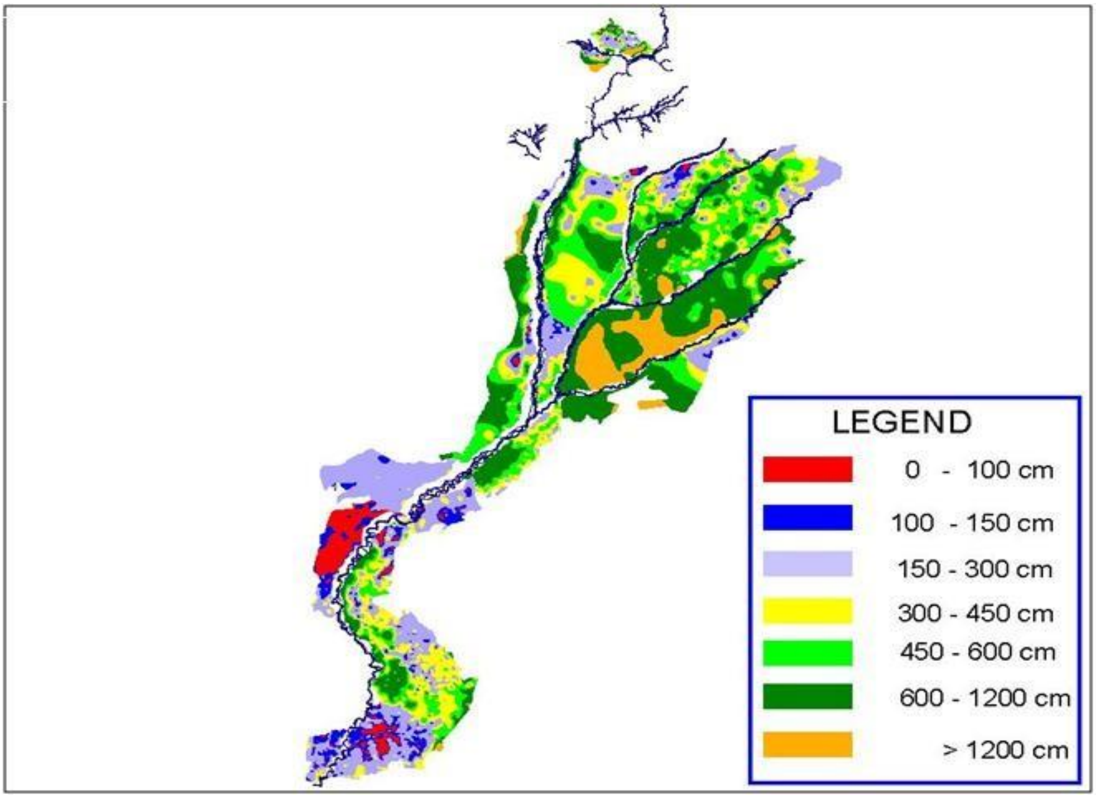


Figure 2.1: Areas under different depths to water table (October 2002) in IBIS

Lower portions of Bari Doab are losing water at a rate of around 0.15-0.55 meters per year (Basharat & Tariq, 2014). Therefore, the negative groundwater potential is observed in lower parts of Bari Doab mainly due to less recharge than the long-term water abstraction. In contrast, in some regions with shallow groundwater depths, groundwater potential is present, but its usage is not feasible because of the small shortfall in agricultural water demand and supply from canals and rains in these regions. In general, a persistent pattern of water table loss is noted, particularly in the province of Punjab, which indicates a severe disproportion between withdrawals and recharge. The regional variation in groundwater supply and agricultural water demand makes it difficult to quantify abstractions. In the Indus Basin, land use, climate, surface water supply, soil types, and irrigation techniques are very variable, but there is no legislation in place to quantify groundwater abstraction. (Basharat & Tariq, 2013) suggested reallocating surface water supply proportionally to the irrigation water demand index and agricultural intensities to manage waterlogging and groundwater depletion in different regions.

In regions where the problem of water logging exists farmers utilize many boreholes to skim the water for irrigation water. The government is providing loans and subsidies to farmers to employ different irrigation schemes and line water courses in water-logged areas. These activities like skimming wells, improved field channel layout, and operation of the watercourse, as well as the application of conjunctive use strategies, mainly in saline groundwater areas, are useful for the rehabilitation and improvement of the irrigation system (Government of Punjab, 2006).

Throughout the Indus basin from 2003 to 2016, the shifts in groundwater storage were studied. About 1.12 million square kilometers are included in IRB's coverage area. Pakistan (47%), India (39%), China (8%), Afghanistan (6%), and Afghanistan (4%) all have a share of it. The basin is located between a longitude of 66.3 and 82.47 degrees East and a latitude of 24.63 and 37.05 degrees North (FAO, 2011). The Indus River, which is around 3000 km long, begins at Mount Kailash (5,500 m) on the Tibetan Plateau and flows southward into the Arabian Sea. (Archer et al., 2010). The Indus, Jhelum, Chenab, Ravi, Sutlej, and Bias rivers all feed into IRB. The Chitral River is the eastern tributary, and it begins in Pakistan, runs through Afghanistan, and then discharges into Pakistan's Indus River. The groundwater level dropped during the studied interval from 2003-2016. The decline rate is higher between 2003–2009 than in 2010–2016. Respectively, 24%, 14%, and 2% of the upper, middle, and lower sections of the IRB experienced a 'severe groundwater decrease' for the whole period (2003–2016). The in-situ and GRACE-based satellite data of groundwater for Bari Doab region depicted a correlation of 0.77 (Mehmood et al., 2022). Another study conducted using Grace-satellite data in the Indus basin manifests an analogous increase in depth to water table (DTW) (Akhter et al., 2021).

2.5 Increasing Role of Groundwater in IBIS

The use of groundwater is a prime factor in Pakistan's agricultural expansion during the past thirty to fifty years.70% percent of Pakistan's population is dependent on groundwater. In addition, several companies utilize groundwater for meeting their needs. Previous studies in the nation have been primarily concerned with quantifying the magnitude of the problem, rather than making concentrated efforts to address the depletion and degradation of groundwater in barani and irrigated regions. 1990 research indicates that the volume of groundwater withdrawn in Punjab is more than the volume returned. The research estimates it to be about 27% for the province of Punjab (NESPAK/SGI, 1991), however, this overuse is intense in a few locations with fresh groundwater. By the findings of (Steenbergen & Oliemans, 1997), the proportion of groundwater used for agriculture increased from 8% to 40% over 25 years from 1960 to 1985. Additionally, (Halcrow, 2006b) pointed "groundwater consumption by farmers has expanded from 8% in 1960 to 60% at the beginning of the 21st century - constituting the single most important contributor to agricultural growth in Pakistan over the past three decades." Still, the role of groundwater in achieving irrigation needs is largely unclear in Pakistan since it is mismanaged and assessed inconsistently. Despite grave concerns for the national water resource, economy, and possibly national safety if this intensive extraction continues.

Groundwater recharge in the IBIS derives from seepage from surface irrigation networks, river beds, and precipitation. The contributions of river flows and precipitation to groundwater recharging are highly varied. Generally, in Punjab major canals travel north to south, corresponding to the natural surface slope. This is also the direction of decreasing precipitation in the region; the difference in annual average precipitation is especially pronounced between the higher and central regions of the Punjab province. Therefore, the recharging of groundwater from precipitation decreases from head to tail of the canal commands region, leading to an increase in water table depth in the lower reach of Punjab. This generates unfairness in the supply of water to farmers, notably from rainfall and groundwater, which accounts for around 60% of agricultural water requirements. However, current surface water allocations were determined without taking into account rainfall and groundwater variations. As a result, the overall cost and quantity of irrigation water delivered to crops vary for different farmers due to a lack of equity in the distribution of surface water supplies.

2.6 Global Studies on Groundwater Spatio-Temporal Trend Analysis

Geographic information systems (GIS) are increasingly being used across all sectors for processing and analyzing spatial data (Yangbo Chen, Kaoru Takara, Ian D. Cluckie, 2004). The coordinated use of geostatistics and GIS is proving to be an efficient research approach for the examination of various spatiotemporal hydrogeological data. The groundwater resource studies frequently involve GIS technology for groundwater table mapping and flow patterns in the underlain aquifers. The water level or water table is the free water surface of the unconfined aquifer and for the confined aquifer, it is the static water level in the well penetrated into the aquifer. Water table rise is observed if the recharge is higher and a decline in the water table is observed if withdrawal is more than the recharge. The water level changes due to climatic and anthropogenic activities (Abbas Alipour, Seyedmostafa Hashemi, 2018; Abiye et al., 2018; Arshad & Umar, 2020; Zakwan, 2021). Natural factors include changes in the frequency and pattern of precipitation and temperature, whereas anthropogenic causes include alterations in land use and land cover situation of the area, method of irrigation practices, groundwater abstractions, and groundwater recharge (AC et al., 2018; Ara & Zakwan, 2018; Marghade et al., 2021).

Groundwater monitoring and observation are tedious and expensive tasks various interpolation techniques are used to generate continuous contour water table maps from limited observation wells point data and unmonitored zones are predicted (Bergh, J., & Löfström, 2012; Pedersen, 2018; Shahmohammadi-Kalalagh & Taran, 2021). The kriging interpolation technique was used to comprehend the groundwater distribution in the area of Hyderabad, A.P., India (Prakash & Singh, 2000). The study analyzed the groundwater scenario in the region and estimated the optimal number of observation wells that can be added to the existing network. Analyzing groundwater trends and fluctuations can be done using a number of different statistical methods i.e., simple linear regression to advanced parametric and non-parametric techniques. Sustainably developing and utilizing groundwater resources calls for the analysis of time series data on groundwater levels and the forecasting of future trends. The time series analysis helps in detecting the trend, its behavior and possible effects can be predicted (Patle et al., 2015).

With regards to hydrological and climatic parameters such as groundwater level change, long-term climatic characteristics, etc., the Mann-Kendall test is the most widely used method of analyzing time series data (Abdul Aziz & Burn, 2006; Kampata et al., 2008; Kendall, 1955; Mann, 1945; Mondal et al., 2012; Robert M. Hirsch, 1984; A. B. A. B. N. S. R. and R. Singh, 2009). Although linear regression is commonly employed to identify trends, it cannot be relied upon to accurately evaluate non-linear changes in borehole groundwater levels. (Kawamura et al., 2011) by employing the non-parametric Mann-Kendall trend test and Sen's slope estimator analyzed the groundwater level trends in Hanoi's Holocene Unconfined Aquifer (HUA). They found that the non-parametric method gives better results in the case of hydrological series in general and groundwater level series in particular.

(Tabari et al., 2012) examined seasonal, annual, and monthly variations in groundwater levels in Iran's Mazandaran province using the statistical methods of the Mann-Kendall test and Sen's slope estimator. Groundwater levels in Gujarat, western India, were analyzed for trends by (Panda et al., 2012) who used the nonparametric Kendall slope to determine the magnitude of the trend. Fifty-eight percent of the 555 wells they were monitoring showed signs of decline and thirty-nine percent showed a rising trend. Groundwater levels in the area declined at a rate of 0.11m/yr. in pre-monsoon season. (Patle et al., 2015) conducted a study using Mann-Kendall and Sen's slope and time series modeling to forecast groundwater levels in the Karnal district of Haryana before and after the monsoon. (Thakur & Thomas, 2011) analyzed trends in seasonal groundwater levels in the Sagar district of MP, India using a combination of nonparametric and parametric tests. For groundwater to be used wisely and to sustain the resource, it is necessary to analyze groundwater level data as a time series and predict future trends. (Satish Kumar & Venkata Rathnam, 2019) utilized four variations of Mann-Kendal and Auto-Regressive Integrated Moving Average (ARIMA) for prediction and trend analysis of 40 observational wells in the Warangal district, India. According to this study, three wells showed a positive trend and 37 wells showed a negative trend. Positive groundwater level trends are a serious concern that must be monitored at an early stage. A positive trend indicates a decrease in groundwater level below the surface level, which can be attributed to poor recharge caused by changes in land use and land cover in a specific region. Groundwater trend analysis studies on the Ardabil plain of Iran depict a significant decreasing trend in the groundwater levels in that region (Daneshvar Vousoughi et al., 2013). The Kendall approach was used to examine groundwater levels and annual decline rates in Beijing, Tianjin, and Hebei. This study found a continual regional decline in groundwater levels (Fang et al., 2019). A downward water table trend of 4.51 m to 4.73 m on average was found between the years 1991 and 2010 in a trend analysis study carried out in Bangladesh, and it was expected that the reduction of groundwater will be 1.16–1.8 times greater over the period between 2020 and 2050 (Rahman et al., 2017). The Parametric (linear regression test) and non-parametric test (Mann-Kendall test and Sen’s slope) both were applied to detect the notable declining groundwater level trend in Haryana, India (O. Singh et al., 2020). (Anand et al., 2020) used the GIS and trend analysis technique to observe the fluctuating trend in the groundwater table in India. Spatio-temporal groundwater depth trends from the period (1996-2017) were observed in the upper Ganges plain (between the Ganges and the Yamuna) showing that the groundwater level falls by 12.47 m in this study period (G. P. Kumar et al., 2022).

Statistical analysis and GIS technology were used to investigate the groundwater level trend in the Jakham River Basin catchment region. The role of precipitation in the upwards and downward shifts in groundwater levels from 2009 to 2019 was also investigated. The resulting Thiessen polygons were used to examine the impact of each well on groundwater levels during periods of replenishment and extraction. Seventy-five wells in the Jakham River basin have been selected for statistical analysis of water level trends using the Mann-Kendall test. Pre-monsoon season sees a fall in water levels at 15% of wells, whereas post-monsoon sees a decline at a far smaller percentage of wells (Gautam et al., 2022). Statistical and graphical approaches have been used to examine the spatial-temporal fluctuation of groundwater level (GWL) in the city of Raipur, India. The Mann-Kendall test and Sen's slope estimator have been used to examine GWL's monthly trend. Thirty observation wells (dug wells) in the city provided monthly GWL data for the years 2010 to 2014, which were utilized to compile the study's findings. The contour map reveals that the average GWL fluctuates from 1.74 to 13.80 m bgl before the monsoon and from 1.64 to 6.75 m bgl post-monsoon. Groundwater flow is shown to be mostly north-westerly on contour maps. Trend analysis shows that, with a few exceptions, no significant trends can be observed even at the 5% significance level (S. Kumar et al., 2018). Ropar district of Punjab state was analyzed for groundwater trends by utilizing XLSTAT's non-parametric techniques (Mann-trend Kendall's test, Sen's slope test, Pettitt's test, and the Standard Normal Homogeneity Test). All four tests showed the existence of a rising trend and change-point in groundwater level in the Ropar district during both pre- and post-monsoon seasons. The pre-monsoon and post-monsoon water depths in the region are 2.7-10.3 m and 2.1-11.6 m, respectively, with a decadal decline of -0.015-1.05 m yr^{-1} representing that groundwater decline is a concern in the district (T. Kumar et al., 2022). A similar study on a spatial and temporal examination of groundwater level variations in Bhopal district, Madhya Pradesh, India was carried out. Approximately 350 monitoring stations point measurements in the Huzur Tehsil in the Bhopal district were collected. In addition, the GWL (groundwater level) trend analysis was performed by employing spatial analysis capabilities provided by ArcGIS10.5. This allowed for the identification of distinct shifts in groundwater levels across the study period of 1996–2015. By using trend analysis of groundwater levels from 1996 to 2015, as well as projecting it by MATLAB modeling groundwater levels in the future were predicted (2016–2050) (Sarup, 2020).

CHAPTER 3

3 RESEARCH METHODOLOGY

This chapter describes the methods and steps for achieving the objectives outlined in chapter 1. The research framework and the tools used for achieving the study objectives are discussed.

3.1 Study Area

The present study was conducted on Bari Doab which lies on the North-Eastern border of Pakistan. Bari Doab, between two major rivers Ravi and Beas upstream, and Ravi and Sutlej located downstream as shown in Figure 3.1. The slope of the study area is flat (one foot per mile regional slope). The study region is located in the upper portion of the broad stretch of Bari Doab's source watershed. After partition, the uppermost half of the upper Bari Doab became Indian Territory, but being an innate element of the Lower and Central Bari Doab, it supplies the natural path of groundwater flow in the Bari Doab region. The geographical area of the Bari Doab study area is 29,000 km^2 (Basharat & Tariq, 2015).

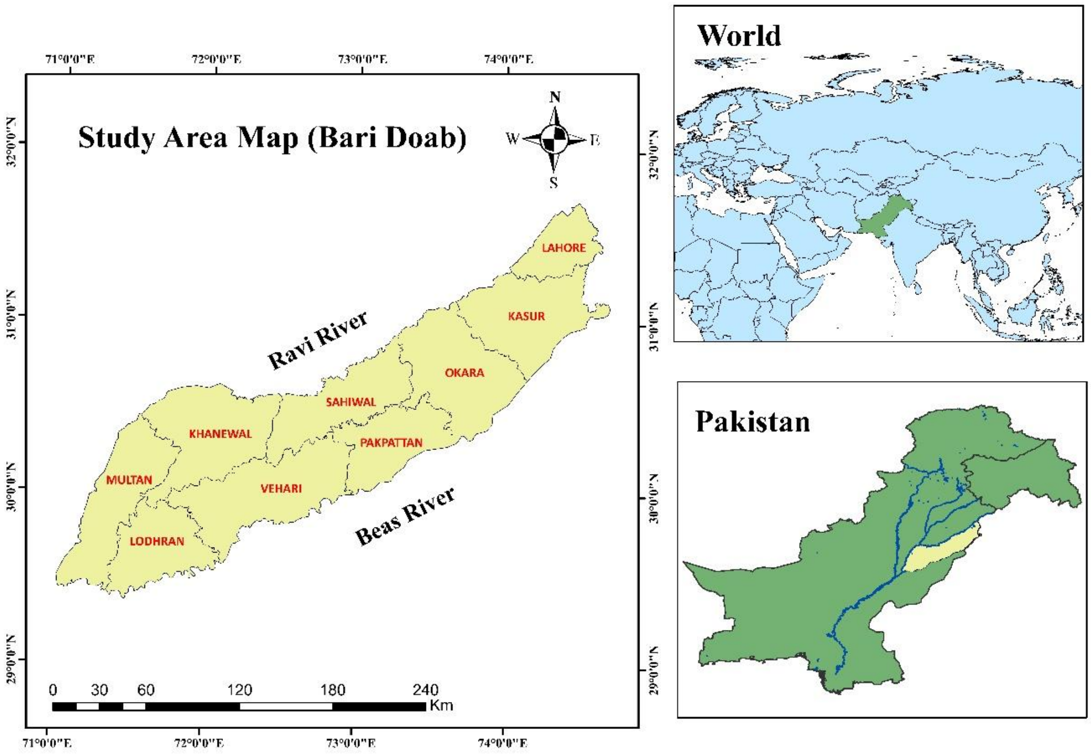


Figure 3.1: Study area map of Bari Doab

3.2 Digital Elevation Model of the study area

DEMs (digital elevation models) are digital representations of topography or terrain on Earth's surface. DEM is a raster data set and the accuracy of DEM depends on the resolution of the dataset. The resolution is the distance between the sampling points. For this study, the DEM (Digital Elevation Model) of resolution 12.5m was obtained from ALOS PALSAR. Figure 3.2 shows the elevation of different regions in the Bari Doab region. The upper portion of the map has high values than the lower portion of the map. The values of elevation from the natural surface level (NSL) range from 239 m to 97 m in the Bari Doab region.

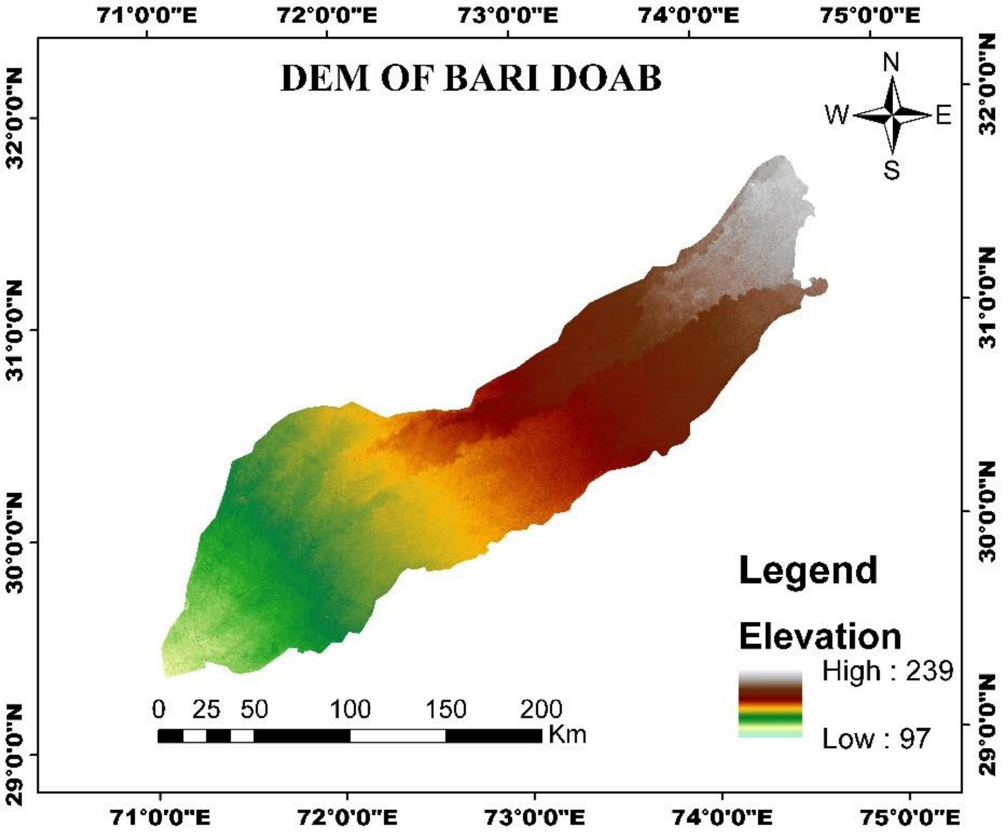


Figure 3.2: Digital Elevation Model of Bari Doab

3.3 Regional Geography

According to Water and Soils Investigation Division (WASID) examinations conducted in 1961-62, the area is underlain by a substantial thickness of alluvial deposits up to 300 m in depth (*Hydrologic Evaluation of Salinity Control and Reclamation Projects in the Indus Plain, Pakistan: A Summary*, 1976).

These alluvial sediments are highly heterogeneous both laterally and vertically. Despite this, the aquifer is widely assumed to function as a single homogeneous, unconfined aquifer. According to the lithological logs of test holes (180-300 m depth) and test tube wells (30-110 m depth), Bari Doab is composed of cemented sand, silt, and silty clay, with varying proportions of kankers (Basharat, 2014). The sands are primarily grey to greyish-brown in colour, fine-to-medium-grained, and sub-angular to sub-rounded in shape. The fine-grained deposits consist mainly of sandy silt, silt, and silty clay with significant amounts of kankers and other concretionary material.

3.4 Climate

Pakistan is mostly dry. The northern region is humid. Sind, most of Baluchistan, most of Punjab, and core Northern Areas have less than 250 mm of annual rainfall. After 750 mm in the lowlands and 625 mm in the highlands, humid conditions appear. Southwest is drier due to less rainfall and higher temperatures near the equator (Basharat, 2014).

3.5 Soils and Geology

The study area is part of the Indo-Gangetic plain, a flat alluvial plain that reaches the north to the foothills of the outer Himalayas. It is known as the Indus Plain in Pakistan, and it stretches from the foothills of the outer Himalayas and the Western mountains to the Arabian Sea. It borders India in the east. This flat alluvial Indus Plain was formed by the Indus and its eastern tributaries, particularly the Jhelum, Chenab, Ravi, Beas, and Sutlej.

(D. W. GREENMAN, W. V. SWARZENSKI, 1970) reported on the findings of a comprehensive groundwater and soil investigation effort that began in 1954. The research's main goals were to analyze Punjab's water and soil resources, namely the linkages between hydrology, irrigation operations, and the problem of subsurface drainage. Waterlogging was a severe issue over much of Punjab, although it was not a major concern in the Lahore area of the Upper Bari Doab. The area's soils are made up of alluvial material brought from the Himalayan peaks by rivers of the huge Indus River system. Frequent fluctuations in stream flow, recurring floods, and ponding of sediment-laden water have resulted in a variable and mixed soil pattern throughout the area. The soils are of recent origin, and they have a high degree of uniformity throughout the area. They are reddish-brown to greyish-brown soils with a relatively coarse to medium texture with a high percentage of fine to very fine sand and silt. The clay portion is mostly made up of non-swelling minerals, which are assumed to be responsible for the soil's high permeability. In general, the land is fertile and productive. The study area geology is alluvium material of quaternary origin.

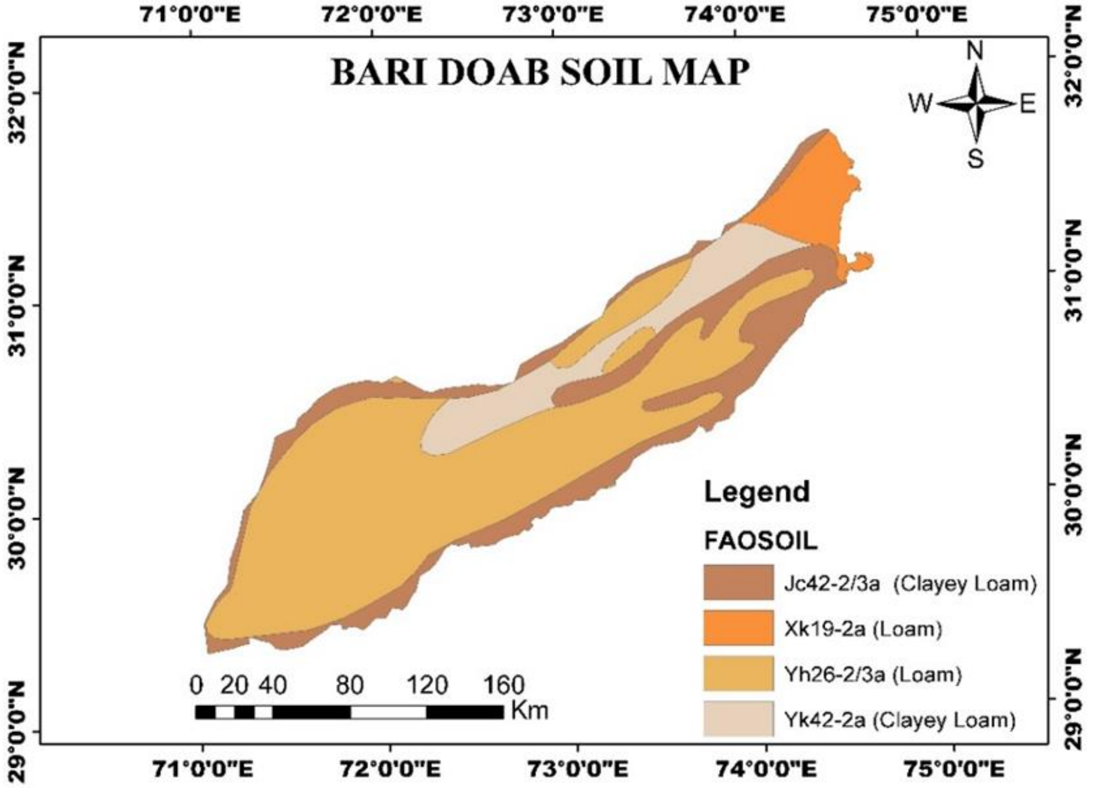


Figure 3.3: Soil map of Bari Doab

Digital Soil Map of the World (DSMW) 1:5,000,000 (30 Arc-Second) was obtained from the Food and Agriculture Organization (FAO) of the United Nations. From the global soil map required study area was extracted by GIS. According to the criteria established by FAO, the soil in Bari Doab may be divided into four distinct zones. Soil classification is shown in Figure 3.3. The primary distinction is between loamy soil and clayey soil. Loam is a type of soil that is composed of sand, silt, and clay in proportions that are all equal. Clay is present in greater quantities than any of the other components that make up clayey loam. Quaternary sediments are the sediments in earth's geological history that were deposited the most recently. The majority of the sediments are unconsolidated, which indicates that the strata have not been enough consolidated to be considered rocks.

3.6 Land Cover and Land Use

The replenishment of groundwater in any area depends heavily on land use and land cover (Halder et al., 2020). Due to urbanization and human construction activities, the soil surface is replaced by settlements leading to less infiltration in the area. The recharge is reduced resulting in more run-off in the region. Land use and land cover classes are analyzed using supervised classification in GIS (Figure 3.4).

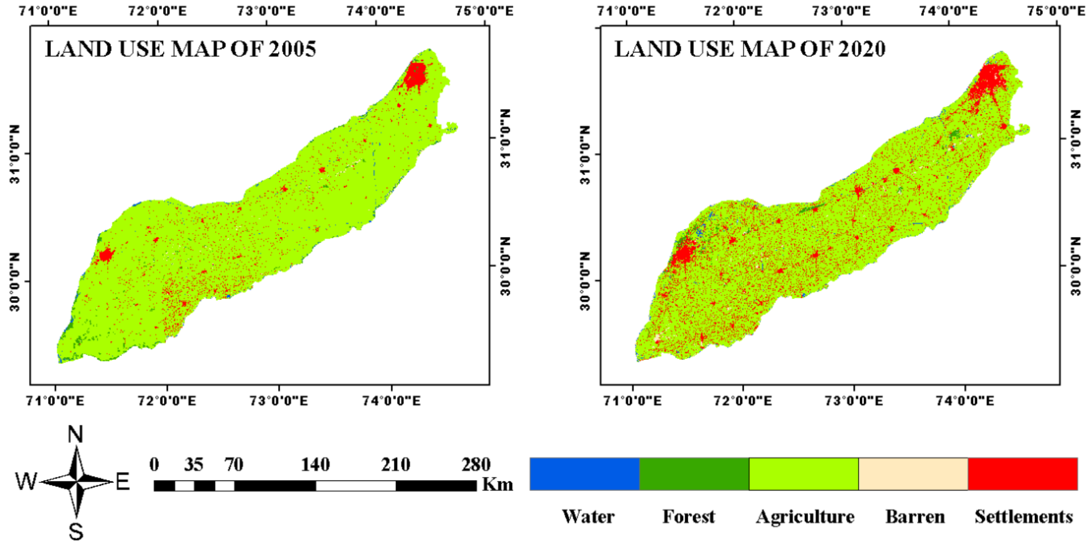


Figure 3.4: Land use and land cover maps of Bari Doab

Table 3.1: Different land use classes w.r.t Area estimation based on 2005 and 2020

Class	**Land Use 2005**		**Land Use 2020**		**% Change**
	Area (Km^2)	**%**	**Area (Km^2)**	**%**	
Water	280.62	0.90	280.82	0.90	0.07
Forest	480.11	1.54	367.30	1.18	-30.71
Agriculture	28130.96	90.30	25516.95	82.08	-10.24
Barren Land	736.23	2.36	412.19	1.33	-78.62
Settlements	1525.25	4.90	4509.28	14.51	66.18

Land use and land cover of 2005 and 2020 have been classified into five classes i.e., water, forest, agriculture, barren land, and settlements. From Table 3.1, it can be seen that the area under different classes has undergone a drastic change in 15 years. The dominant class in the area is agriculture which covered around 90% of the area in 2005 and is now reduced to around 82% observing a 10% decrease in area. Most of the agricultural land is transformed into settlements that raised about 66% in the area in the last 15 years. The increase in settlement area from about 5% to 14.5% has led to a decrease in infiltration in the area reducing recharge at these locations significantly.

3.7 Data Collection and Analysis

For the study area, the water table depth is acquired in all the wells scattered in different regions in the area. Groundwater level data is monitored by the international water logging and salinity research institute (IWASRI) of WAPDA and the directorate of land reclamation (DLR) of the irrigation department The data is taken from the year 2005-2020. The depth to groundwater readings is taken twice a year i.e., during pre-monsoon and post-monsoon season. The well locations that are marked by DLR and IWASRI are plotted in GIS and surfer software.

3.8 Methodology

For the study area, the methodological framework is represented in Figure 3.5. After marking the wells in GIS software, spatiotemporal analysis of groundwater depth is carried out for both pre-monsoon and post-monsoon seasons with surfer and GIS software through the kriging method. Spatio-temporal maps are obtained. Trend analysis is also performed on the same data for both seasons. Groundwater level trends for all observation points were analyzed using the Mann-Kendall test in XLSTAT for the years 2005 through 2020 to determine whether or not a data set exhibits a declining, growing, or non-significant trend. The observation points of both seasons showing significant trends are extrapolated in MATLAB software for predicting future spatio-temporal scenarios in the region.

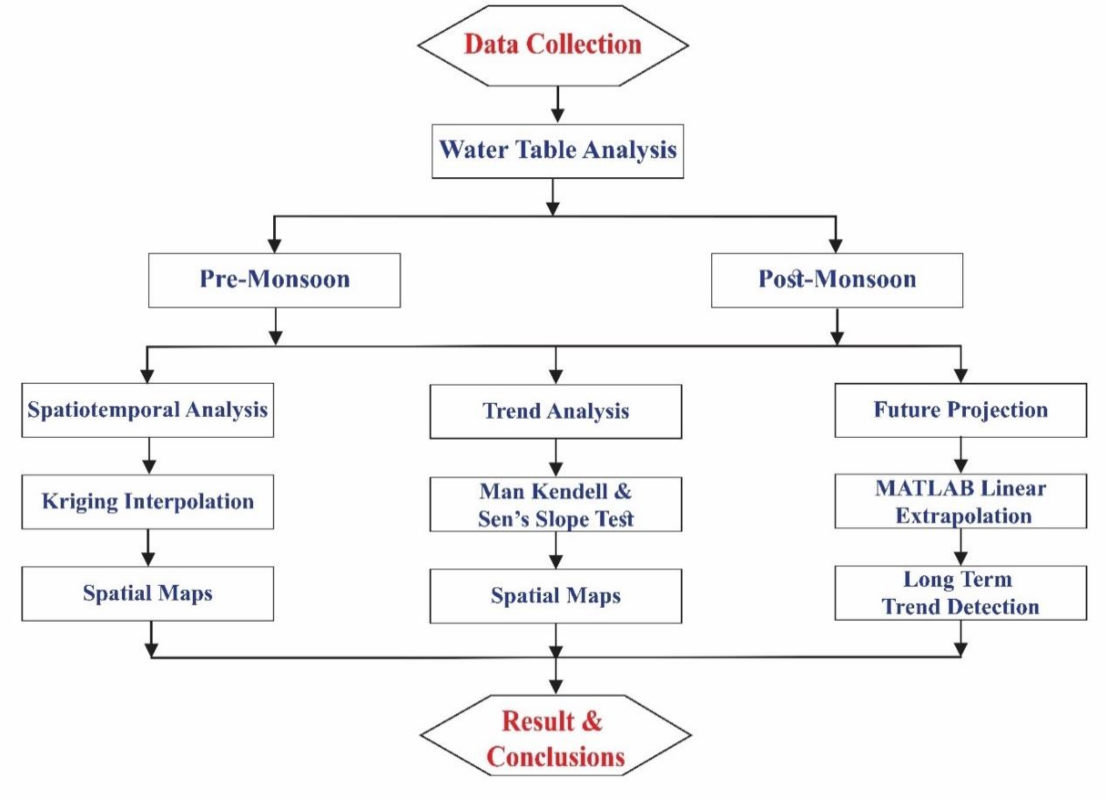


Figure 3.5: Flow chart of research methodology

3.9 Surfer Software

Surfer is a grid-based mapping application that interpolates unevenly spaced XYZ data into a regular grid. Other sources, such as the US Geological Survey (USGS) grids can also be imported. The grid is used to create various maps such as contour, vector, image, shaded relief, 3D surfaces, and 3D wireframe maps. For representing data according to specifications Surfer has a comprehensive set of gridding and mapping methods. The range of ways offered provides varied interpretations of our data and allows us to select the best method for our purposes. The maps are viewed and enhanced in Surfer. Creating publication-quality maps is as simple as adding several map layers, tweaking the map presentation, and annotating with text. It supports the creation, modification, and display of a variety of map types i.e., Contour, base, post, classified post, image, shaded relief, 1-grid vector 3D surface, and 3D wireframe maps are among the map formats created in Surfer.

3.9.1 Contour Maps

A contour map represents three-dimensional data in two dimensions. The contour lines on a map are the lines that have the same Z value. The contour maps show the shape of the surface in the area by contour lines. Different contour intervals and the pattern of contours help in the identification and examination of the area

3.9.2 Post Maps

Post maps and classified post maps depict data points on a map. Individual post-label placements and post symbols can be adjusted.

3.9.3 3D Surfaces

3D Surfaces are three-dimensional, coloured representations of a grid data set. A 3D surface allows for a better representation of layers and visualization of a map.

3.10 GIS Software

GIS software can also be used for contouring. In the spatial analysis tool of GIS different options for preparing groundwater contour maps are given. The most commonly used method is the kriging interpolation technique. The accuracy of Surfer is more than GIS in plotting groundwater contours hence the contours are plotted in Surfer and exported to GIS format.

3.11 Ordinary Kriging

The spatial interpolation method known as Kriging was devised by South African mining engineer Danie Krige and is used in the field of mining geology.

Kriging is one of the various strategies for calculating the value of a parameter over a continuous spatial field using a small number of sample points. It differs from simpler techniques such as Gaussian decays, linear regression, and inverse distance weighted interpolation as it interpolates spatial field values based on the spatial correlation between sampled locations rather than a presumed model of spatial distribution. Kriging is also used to quantify the uncertainty in each interpolated estimate.

When calculating kriging weights, points closer to the interest location have more weight. Consider the cluster of places. Clusters of stations are weighted less to reduce bias. The kriging predictor determines each interpolated quantity to reduce estimation error for that location. At this stage, the kriging value is comparable to the measured data for each sampled point, and all interpolated values become Best Linear Unbiased Predictors (BLUPs).

Kriging is a two-step process: first, the spatial covariance component of the measurement points is defined by matching a variogram, and then weights are used to interpolate values for unsampled points over the geographical area.

Variograms (sometimes known as “semi-variograms”) are graphical representations of data covariance. The gamma-value or “semi-variance” for each sample point pair is charted versus their spacing, or “lag”. The “theoretical” or “model” variogram best fits the data, while the “experimental” variogram shows measured values. Variograms are derived from linear, exponential, power, and spherical models (Figure 3.6).

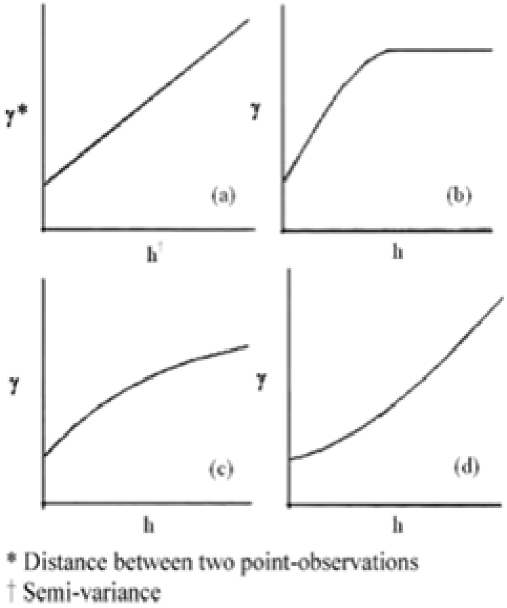


Figure 3.6: a) Linear semi-variogram, b) Spherical semi-variogram, c) Exponential semi-variogram and d) Power semi-variogram

Using the spatial structure of each interpolated position, weights are assigned to all measurement points. After extracting the variogram, the weights are adjusted depending on the data's spatial structure.

Ordinary kriging is one of the most widely used techniques for spatial interpolation. The spatial estimate of the unmeasured location yo is obtained by projecting a value that is equivalent to the line sum of the previously measured values (i.e., observed values). The formula given by (Cressie, 2015; Hohn, 1991; Pham et al., 2019) provides a simple representation of kriging:

$$\boldsymbol{X}^{*}(\boldsymbol{y_o}) = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{\alpha_i X(y_i)} \qquad \textbf{3.1}$$

Where X * (yo), X (yi), αi, and n represents the predicted value at the unmeasured point yo, the measured value at point yi, the weighting coefficient from the measured position to yo, the number of points in the neighborhood search respectively (Hengl & European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2007).

3.12 MAKESENS

Mann-Kendall test for trend and Sen's slope estimations (MAKESENS) is devised to identify and measure the trend in time series. The Mann-Kendall Trend Test (also known as the M-K test) is applied for detecting monotonically increasing or decreasing trends in time series of hydrologic parameters over time and for finding the slope of the linear trend Sen’s slope method is applied (Gilbert, 1987). The test being non-parametric applies to all types of distributions. The data does not have to be a bell-shaped curve or normally distributed. However, the data should not have any serial correlation (sampling data is independent) or any seasonal cycles in the measured observations. The linear regression method is applied for normally distributed data. With four values of time series, the method can be used to find the trend in the data. With more data points the test results become more efficient. Hence at least 8 to 10 values are recommended for better results and trend detection in the time series.

A time series is formed when a sequence of readings is arranged in a regular order corresponding to their occurrences. A trend is defined as a consistent increase or decrease in the time series attributes (Patra, 2001).

The test relies on two hypotheses

- The null hypothesis for the test is that there is no trend in the time series
- The alternate hypothesis for the test is whether there is an increasing or decreasing trend in time series

The Mann-Kendall test is applied to statistically check if there is a monotonic trend present (Kendall, 1975). An increasing monotonic trend means the variable increases or decreases continuously with time. The trend may not be linear but it should be consistent. According to (Hirsch et al., 1982), the MK test is most useful when viewed as a data exploration and is applied to find stations where changes are large in magnitude and can be measured.

For finding the slope of the trend a linear model is used in the method. The variability of the residuals should be constant over time. There can be missing values present in the data as well. Sen’s slope is unaffected by outliers or measurement errors in the data. However, the performance efficiency of the test will suffer. To calculate the statistical test, MAKESENS makes use of both the normal approximation (Z statistics) and the S statistics provided by Gilbert (1987). If the number of observations is less than 10 S test is used and for more than 10 normal approximation (Z-test) is applied. The number of years present in the data set is given by n. Because missing data is tolerated, n does not have to be equal to the number of years in the time series under consideration. The test is employed at the 0.1, 0.05, 0.01, and 0.001 levels of significance (α) in MAKESENS. If the value of S absolute is greater than or equal to S $\alpha/2$, where S $\alpha/2$ is the smallest S with a probability less than $\alpha_{/2}$ to occur in absence of a trend, then H_0 is declined in support of H_1 at a given probability threshold. If S is increasing (decreasing), then the trend is moving upwards (downwards, respectively).

The 0.001 significance level indicates a 0.1% chance that the time series data come from a random distribution and by that percent we are making an error while rejecting the null hypothesis which is based on no trend in the data (H0). So, it can be concluded that with a significance level of 0.001, the presence of a monotonic trend is extremely likely. The significance level of 0.1 indicates that the chance of error when rejecting the null hypothesis (H_0) is 10%.

As Normal approximation is used for n equal to or greater than 10. However, if the data contains many linked values (i.e., equal values), the authenticity of the normal approximation may be reduced when the amount of data points approaches 10. The Z value is used to determine whether or not a statistically significant trend is present. A positive Z value indicates an increasing trend and vice-versa (Adhikari et al., 2018). The value of Z is described by the normal distribution. For checking the upward or downward monotonic trend, If the absolute value of Z is larger than Z1- α /2 H0 is rejected, where the value of Z1- α /2 is calculated using the standard normal cumulative distribution tables. In MAKESENS, the significance thresholds that have been used are 0.001, 0.01, 0.05, and 0.01.

The Mann-Kendall Trend Test compares the signs of previous and subsequent data points. If the trend exists, the values in the time series will generally increase or decrease continuously. Each value in the time series is compared to every value before it, giving a sum of n (n - 1) / 2 data pairs, where "n" is the total observations. The Mann-Kendall statistic S initial value is supposed to be 0 (e.g., no trend). S is incremented by 1 if later data is higher than earlier data. If later data is lower, S is decremented by 1. All increments and decrements add up to S.

$$\boldsymbol{s} = \sum_{i=1}^{n-1} \sum_{j=k+1}^{n} \boldsymbol{sign}(\boldsymbol{x}_j - \boldsymbol{x}_i) \qquad \textbf{3.2}$$

For more than 10 values following the normal approximation (Z) is used

$$\boldsymbol{Var}(\boldsymbol{S}) = \mathbf{1/18}[(\boldsymbol{n}(\boldsymbol{n}-\mathbf{1})(\mathbf{2}\boldsymbol{n}+\mathbf{5}) - \sum_{p-1}^{g} \boldsymbol{t_p}(\boldsymbol{t_p}-\mathbf{1})(\mathbf{2}\boldsymbol{t_p}+\mathbf{5})] \qquad \textbf{3.3}$$

Number of data points represented by n, number of tied groups denoted by g (set of data samples having the same value), and t_p denote the data point number in the p^{th} group.

$$\boldsymbol{Z} = (\boldsymbol{S}-\mathbf{1})/[\boldsymbol{Var}(\boldsymbol{S})]^{\mathbf{1/2}}\ \boldsymbol{if\ S>0} \qquad \textbf{3.4}$$

Z =0 if S=0

$$\boldsymbol{Z} = (\boldsymbol{S}+\mathbf{1})/[\boldsymbol{Var}(\boldsymbol{S})]^{\mathbf{1/2}} \boldsymbol{if\ S<0} \qquad \textbf{3.5}$$

3.13 MATLAB

MATLAB is a programming language and interactive environment for doing numerical calculations and visualization of results. To create a contour plot, first prepare a file that will import easily into MATLAB, then resample the data to a uniform grid and create the contour map.

3.13.1 Generating the Input File

After creating an Excel file with columns for latitude and longitude and the data you want to contour, such as groundwater level contours. First, remove any text columns as MATLAB would not import columns as vectors if there is text in columns. Rows or columns with blank values should ideally be removed or filled in. At the top of the file leave a set of labels (though remove spaces from these also to avoid trouble later on; these will become your variable names). Export the data as a comma-separated value (csv) or tab-delimited text file.

3.13.2 Importing and Gridding Data in MATLAB

The file to be imported must be in csv format. After launching MATLAB, choose Import data from the file menu. Correct it if MATLAB does not figure out the number of text lines at the beginning and the delimiter (comma or tab), If everything is correct, the preview should show data, text data, and colheaders. In gridding, it is required to have a grid that is uniformly spaced in X and Y. Thus, it is preferable to have imported data with a Northing and Easting of some kind rather than Latitude and Longitude. It is assumed that the data vector with a distance east called Easting, a vector with a distance north called Northing, and a vector of data to contour i.e. groundwater table data. Set the 0.1 value to the spacing between grid points. In the case of using latitude and longitude, different spacing should be used for X and Y as a degree of latitude is longer than one of longitude, otherwise, the grid will be somewhat distorted.

By making two vectors that contain the X and Y positions of each line of nodes. The vector X starts below the lowest value in Easting (floor (min (Easting))) and goes above the highest value (ceil (max (Easting)) with a 0.1 interval. The colons create an evenly spaced vector between the end values and the middle value. The semicolon means we don't want the result displayed. Now build a pair of big rectangular matrices that have the X and Y values of each grid point (as opposed to just listing them all).

Now will generate a grid from the data. The new matrix grid has values interpolated to each grid point from the irregular collection of points defined at Easting, Northing, and Groundwater level data for all the points in the original vectors. Grid data has several options for gridding (you can use linear or cubic interpolation, nearest neighbor, or a special MATLAB interpolation 'v4'; linear interpolation is the default. Then contour plot is generated by the following command.

```
[C,h]=contour(X,Y,Griddata);
```

Labels can be added interactively by giving the command clabel (C,h, 'manual'). It will allow to pick the spots where contours were to be labeled and also the contour interval can be specified by using the commands in MATLAB.

CHAPTER 4

4 RESULTS AND DISCUSSIONS

This chapter encompasses the outputs from the analysis carried out on the study area.

4.1 Spatio-Temporal Variation of Ground Water Depth

The spatio-temporal water table map represents the water table depth in the region measured from the natural surface level (NSL). Kriging Interpolation in surfer software is used to plot the maps from the water table readings of the piezo metric wells installed in the area. The water table maps were plotted at a successive interval of 5 years from 2005-2020 to show the variability in groundwater table depths (Figure 4.1 to 4.4). The comparison of maps showed a decline in the water table. However, the decline is non-uniform both spatially and temporally. The water table depths of the post-monsoon season have much low depth to groundwater (DTW) readings in some regions compared to the pre-monsoon season of the same year.

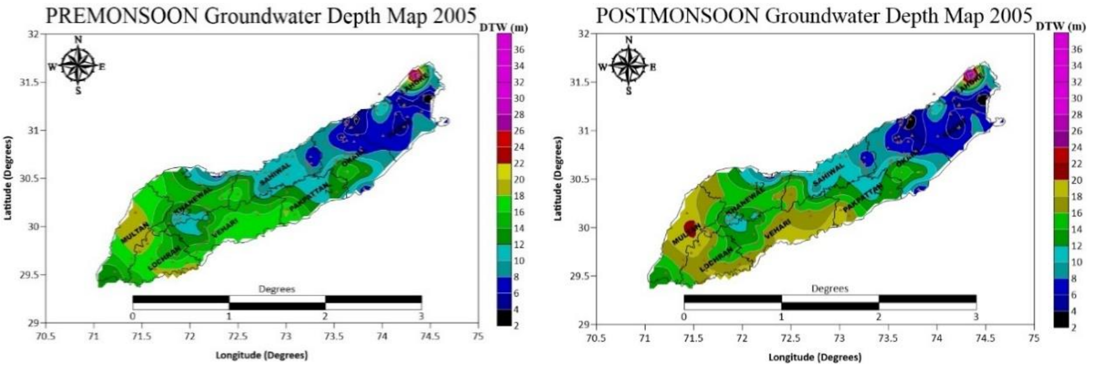


Figure 4.1: Depth to groundwater map 2005

The spatial and temporal variation of depth to water table over 5 years shows that DTW values are increasing over the years. The fluctuation in water table values from the natural surface level is much more prominent from 2005-2010.

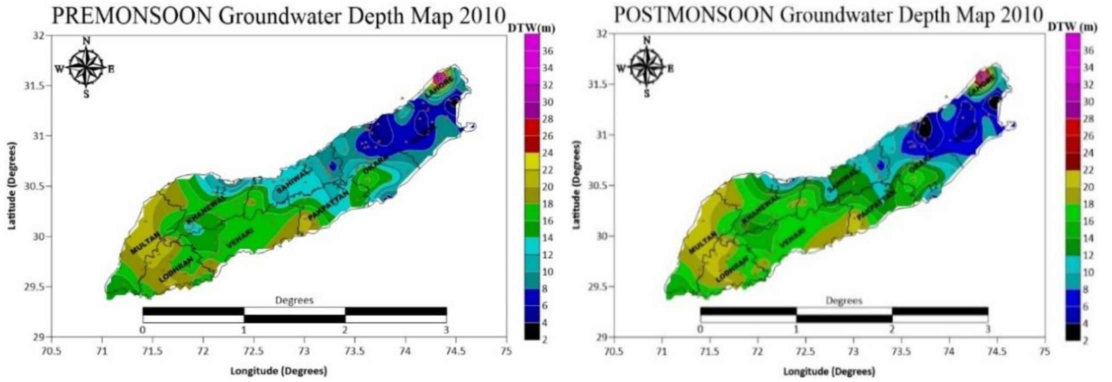


Figure 4.2: Depth to groundwater map 2010

From 2010-2015 there is overall an increasing trend in depth to the groundwater table. The fluctuation in DTW values is however not much prominent as in the case of the time period from 2005-2010 when the fluctuation is prominent.

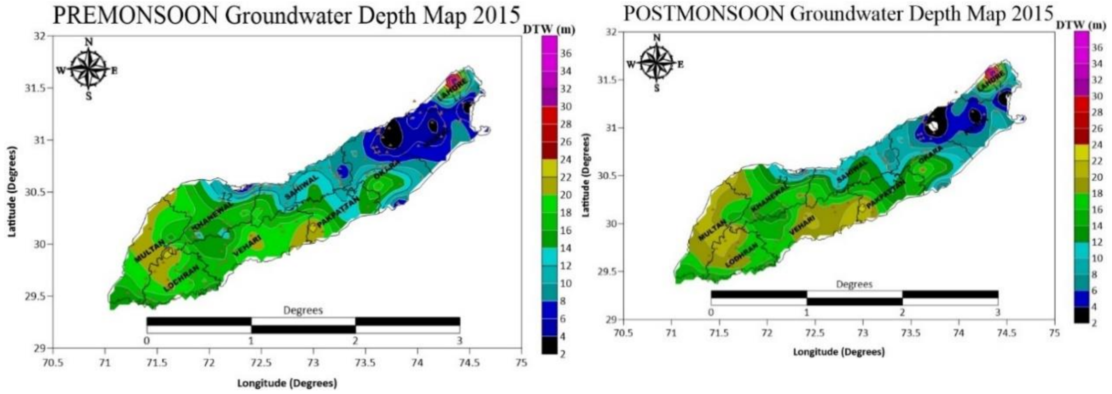


Figure 4.3: Depth to groundwater map 2015

The fluctuation in the water table is prominent from 2015-2020 as observed from 2005-2010. The fluctuation of the water table in the study area depicted that the water level declined over 15 years in all districts except Pattoki and Kot Radha Kishan tehsil of Kasur and Multan Saddar tehsil of Multan district where a minor increase is observed. The water level depth was observed maximum in some regions of Lahore Cantt tehsil. The average depth to water level values in the piezo metric wells installed in Multan, Lodhran, Vehari, and Khanewal districts was found to be high. The annual decline was found to be maximum in Vehari followed by Pakpattan, Lahore, and Khanewal districts. The seasonal fluctuation based on the difference between pre-monsoon and post-monsoon seasons during the 15 years (2005-2020) showed that of 26 Tehsils the average depth to water table increased in 12 tehsils in the post-monsoon season while in 11 tehsils the average depth to the water table is decreased and no change is observed in 3 tehsils of the 9 districts in the study area (Table 4.1 & 4.2).

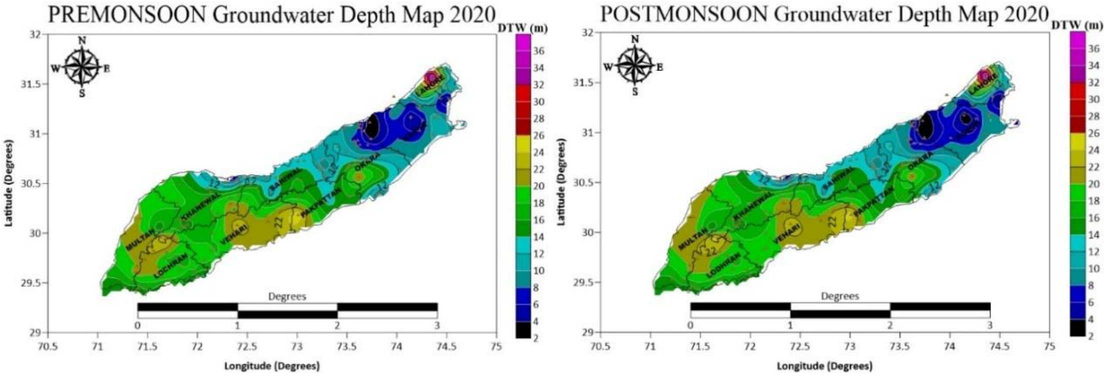


Figure 4.4: Depth to groundwater map 2020

Table 4.1: Pre-monsoon average depth to water level and groundwater fluctuation

Districts	Tehsils	Average Depth from NSL Pre-monsoon (m)				Decline or Rise in successive five years (m)			Decline or Rise (m)	Annual Decline or Rise (m/year)
		2005	2010	2015	2020	05-10	10-15	15-20	2005-2020	2005-2020
Lahore	Lahore Cantt	12.42	13.53	13.74	15.75	1.11	0.21	2.00	3.33	0.22
	Lahore City	7.53	9.17	9.31	11.56	1.64	0.14	2.24	4.03	0.27
Kasur	Kasur	6.45	7.03	6.49	8.67	0.57	-0.54	2.18	2.21	0.15
	Chunian	7.26	7.24	6.63	8.08	-0.03	-0.61	1.45	0.81	0.05
	Pattoki	8.08	8.22	5.80	6.81	0.15	-2.42	1.00	-1.27	-0.08
	Kot Radha Kishan	6.43	6.00	5.24	6.32	-0.43	-0.77	1.09	-0.11	-0.01
Okara	Depalpur	10.32	11.65	11.58	13.49	1.33	-0.07	1.91	3.16	0.21
	Okara	9.21	10.55	10.09	12.39	1.34	-0.46	2.30	3.18	0.21
	Renala Khurd	6.55	7.02	5.34	7.07	0.46	-1.67	1.73	0.52	0.03
Pakpattan	Arif Wala	16.05	18.37	19.52	21.61	2.32	1.15	2.09	5.57	0.37
	Pakpattan	13.88	15.84	16.07	16.81	1.96	0.23	0.75	2.93	0.20
Sahiwal	Sahiwal	8.75	9.57	9.42	11.34	0.82	-0.15	1.91	2.58	0.17
	Chichawatni	12.07	13.41	12.24	13.53	1.34	-1.17	1.29	1.46	0.10
Vehari	Burewala	15.26	16.81	18.12	20.30	1.55	1.30	2.18	5.03	0.34
	Mailsi	13.26	16.04	16.15	17.98	2.78	0.11	1.83	4.72	0.31

Khanewal	Mian Channu	12.63	13.97	13.42	15.18	1.34	-0.55	1.76	2.55	0.17
	Khanewal	13.58	15.25	15.23	16.85	1.67	-0.02	1.62	3.26	0.22
	Kabirwala	15.70	18.65	19.04	18.56	2.95	0.39	0.48	2.86	0.19
	Jahanian	12.64	15.29	16.23	17.76	2.65	0.94	1.53	5.12	0.34
Lodhran	Lodhran	16.94	18.94	18.24	17.91	2.00	-0.71	0.33	0.97	0.06
	Kahror Pakka	16.71	17.08	16.63	16.93	0.36	-0.44	0.30	0.22	0.01
	Dunyapur	16.18	18.49	19.30	19.71	2.31	0.81	0.42	3.54	0.24
Multan	Multan City	18.44	21.05	20.73	20.42	2.62	-0.33	0.30	1.98	0.13
	Multan Saddar	14.89	15.04	14.42	13.84	0.15	-0.61	0.59	-1.05	-0.07
	Shujjabad	17.65	18.97	19.15	19.75	1.33	0.17	0.60	2.10	0.14
	Jalapur Pirwala	14.92	16.85	17.32	18.47	1.93	0.46	1.16	3.55	0.24

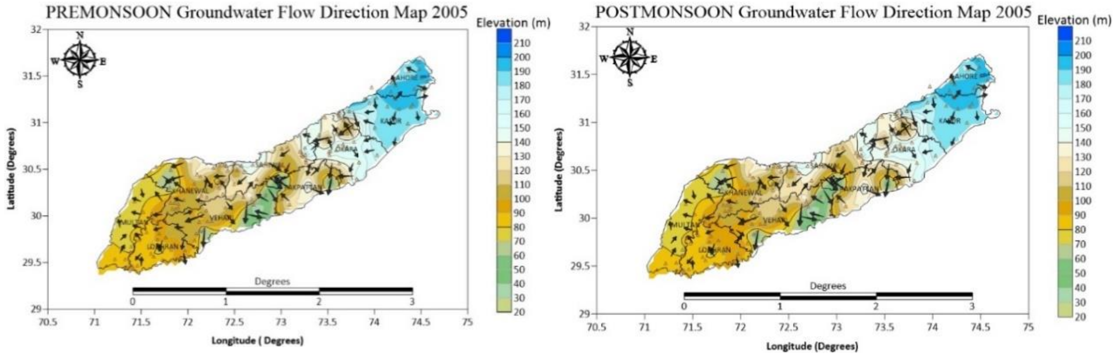
Table 4.2: post-monsoon average depth to water level and groundwater fluctuation

Districts	**Tehsils**	**Average Depth from NSL Post-monsoon (m)**				**Decline or Rise in successive five years (m)**			**Decline or Rise (m)**	**Annual Decline or Rise (m/year)**
		2005	**2010**	**2015**	**2020**	**05-10**	**10-15**	**15-20**	**2005-2020**	**2005-2020**
Lahore	Lahore Cantt	12.23	13.09	13.56	15.37	0.86	0.47	1.81	3.14	0.21
	Lahore City	7.47	8.42	8.97	11.46	0.95	0.54	2.49	3.98	0.27
Kasur	Kasur	5.88	5.97	6.10	7.50	0.09	0.13	1.40	1.62	0.11
	Chunian	7.16	6.78	6.37	7.77	-0.38	-0.41	1.40	0.61	0.04
	Pattoki	7.69	7.04	5.20	6.70	-0.65	-1.84	1.50	-1.00	-0.07
	Kot Radha Kishan	6.16	5.15	4.61	5.25	-1.00	-0.54	0.63	-0.91	-0.06
Okara	Depalpur	9.89	11.48	11.22	13.12	1.59	-0.26	1.90	3.23	0.22
	Okara	9.18	10.38	9.72	12.28	1.19	-0.65	2.55	3.09	0.21
	Renala Khurd	6.20	6.49	4.95	6.79	0.29	-1.54	1.84	0.60	0.04
Pakpattan	Arif Wala	16.80	18.70	19.37	21.21	1.90	0.67	1.84	4.40	0.29
	Pakpattan	14.30	15.95	15.90	17.53	1.65	-0.05	1.63	3.22	0.21
Sahiwal	Sahiwal	9.15	9.98	9.79	11.88	0.82	-0.19	2.10	2.73	0.18
	Chichawatni	12.26	13.20	11.71	13.75	0.94	-1.50	2.05	1.49	0.10

Vehari	Burewala	15.95	17.07	18.51	20.31	1.12	1.44	1.80	4.36	0.29
	Mailsi	14.09	15.95	15.92	19.05	1.86	-0.04	3.13	4.96	0.33
Khanewal	Mian Channu	12.58	13.84	13.17	15.44	1.26	-0.67	2.27	2.86	0.19
	Khanewal	13.84	15.29	15.10	17.14	1.45	-0.20	2.04	3.30	0.22
	Kabirwala	16.26	18.82	18.81	18.75	2.56	0.00	-0.06	2.49	0.17
	Jahanian	13.05	15.37	16.05	17.84	2.33	0.68	1.78	4.79	0.32
Lodhran	Lodhran	16.94	18.76	17.67	17.73	1.82	-1.09	0.06	0.79	0.05
	Kahror Pakka	16.56	16.73	16.08	17.37	0.17	-0.65	1.29	0.82	0.05
	Dunyapur	16.45	18.57	19.02	20.12	2.13	0.45	1.09	3.67	0.24
Multan	Multan City	18.90	21.28	20.62	22.07	2.38	-0.66	1.45	3.17	0.21
	Multan Saddar	17.91	17.68	15.96	15.78	-0.23	-1.71	-0.19	-2.13	-0.14
	Shujjabad	17.36	18.90	19.08	19.88	1.53	0.18	0.80	2.52	0.17
	Jalapur Pirwala	15.03	16.90	17.55	18.01	1.87	0.65	0.46	2.98	0.20

4.2 Flow Direction of Ground Water

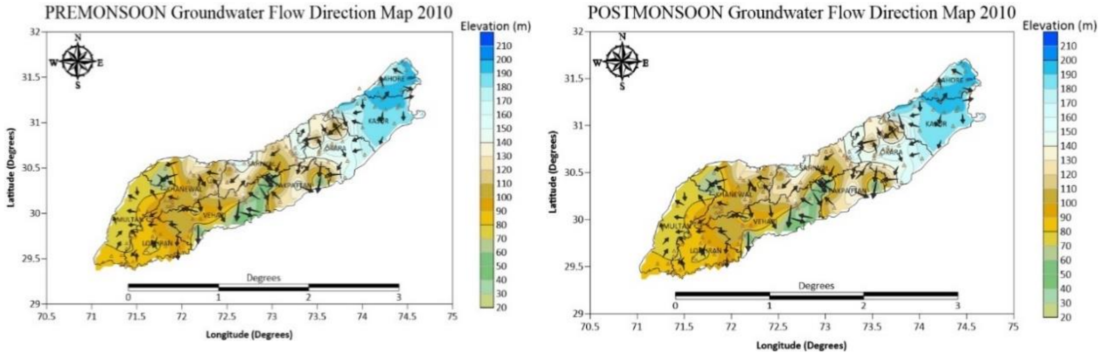
Groundwater horizontal flow direction beneath the natural surface level was determined by plotting water table maps of the catchment. The 2 D and three-dimensional contour maps of the watershed revealed the pattern of flow in the region. To determine flow direction average mean surface level was taken as a reference. From DEM 12.5 m*12.5 m of the study area, the ground elevations were obtained, and by subtracting the values of ground elevations from DTW values contour maps were generated to get the direction of groundwater flow. The direction of groundwater flow is perpendicular to the contour line, from the highest contour elevation to the contour having the lowest elevation (R. W. Buddemeier, 2000). The contour map of the area showed that groundwater is flowing from the upper districts of Lahore and Kasur towards the lower districts reinforcing the statement that water flows from the high hydraulic head towards the low hydraulic head (Figure 4.5 to 4.8).



PREMONSOON Groundwater Flow Direction Map 2005

POSTMONSOON Groundwater Flow Direction Map 2005

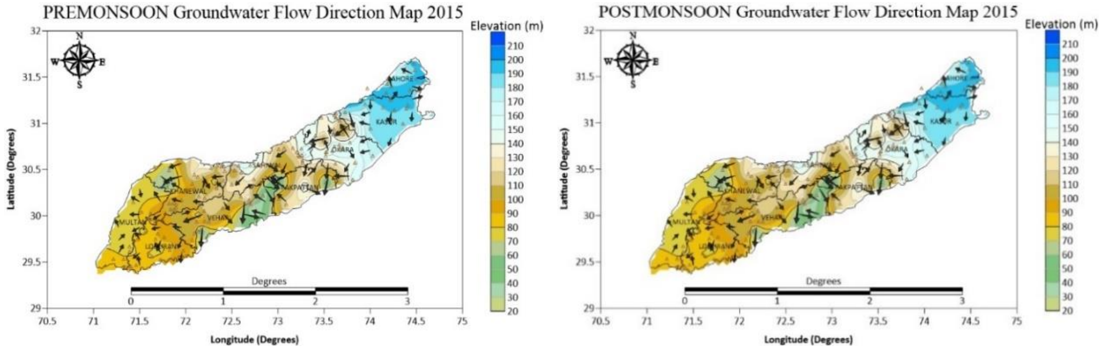
Figure 4.5Groundwater flow direction map 2005



PREMONSOON Groundwater Flow Direction Map 2010

POSTMONSOON Groundwater Flow Direction Map 2010

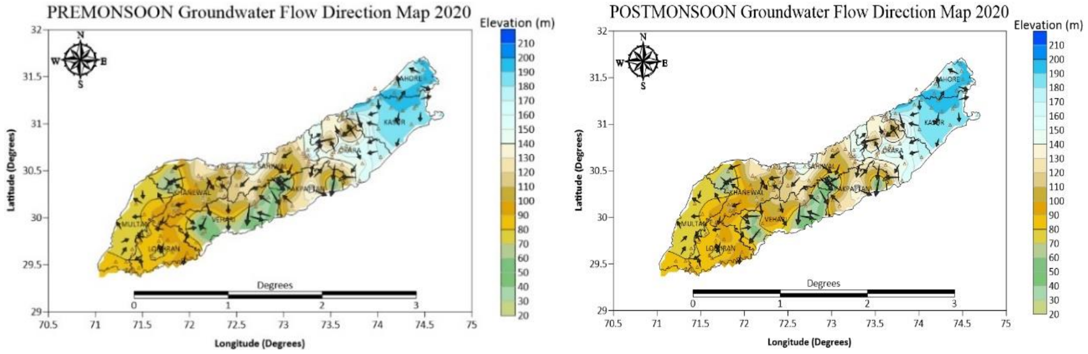
Figure 4.6: Groundwater flow direction map 2010



PREMONSOON Groundwater Flow Direction Map 2015

POSTMONSOON Groundwater Flow Direction Map 2015

Figure 4.7: Groundwater flow direction map 2015



PREMONSOON Groundwater Flow Direction Map 2020

POSTMONSOON Groundwater Flow Direction Map 2020

Figure 4.8: Groundwater flow direction map 2020

The 3D water table elevation map taking the average mean sea level (Amsl) as a reference shows the flow direction of groundwater (Figure 4.9). Sharp reversals in flow direction can be seen at points of convergence and divergence in a two-dimensional groundwater contour map. However, the three-dimensional map shows a clear picture and reveals the regulating factors like topography that influence the flow pattern.

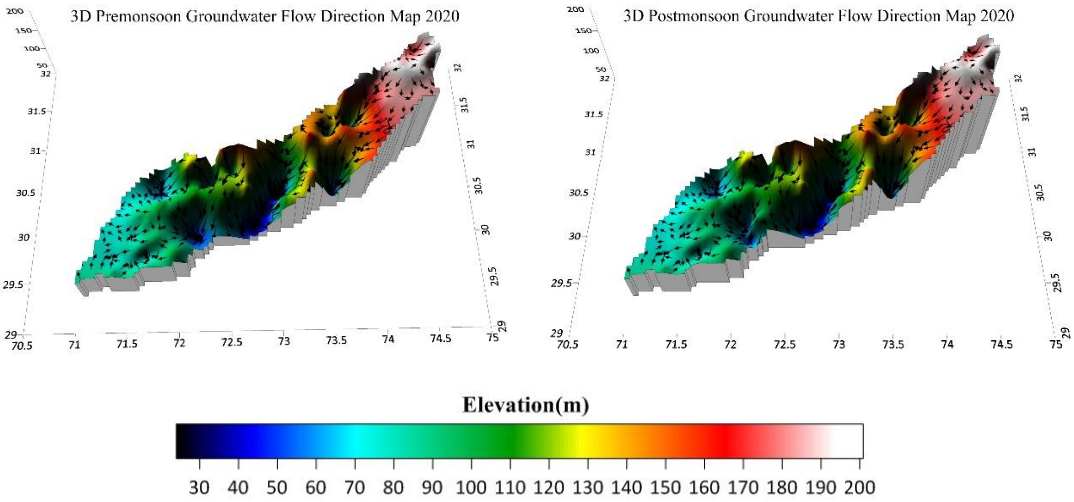


Figure 4.9: 3D Groundwater flow direction map 2020

4.3 Recharging and Discharging Zones Identification

The assessment of the groundwater flow system relating to recharge and discharge areas is crucial for the development of a beneficial land-use planning and management strategy (Messene, 2017). Using Surfer 8, Arc GIS 10.5, and an integrated thematic catchment map, we were able to pinpoint the Doab recharging and discharging zones. Using the Surfer 8 software, we created a contour map of the groundwater table depth in the Doab. The catchment's convergence and divergence zone were identified on the basis of the flow direction of groundwater shown by arrows in a contour map. The groundwater contour map shows the flow nets along with recharging and discharging zones. In a flow net, the flow line will typically curve away from the sources of recharge and in toward the sink (C.W. FETTER, 2001). By using indicators like topography, groundwater flow pattern, and static groundwater levels the map of the catchment's groundwater recharge, discharge, and intermediate zones is prepared (Desalegn, 2011). Those indicators have assisted in the demarcation of the boundaries between the recharging, transitional, and discharging regions. The topographic elevation is the simplest of these indicators (Freeze, R.A. and Cherry, 1979).

In order to delineate the recharge and discharge zones, the topography is the main factor to take into account. Recharge areas are typically indicated by areas of high elevation. Recharge and discharge regions can be identified by the direction in which vector flow lines point i.e., diverge in case of recharging and converge in discharging zone. Groundwater recharge and discharge areas were mapped using water table contours as shown in Figure 4.10 (C.W. FETTER, 2001).

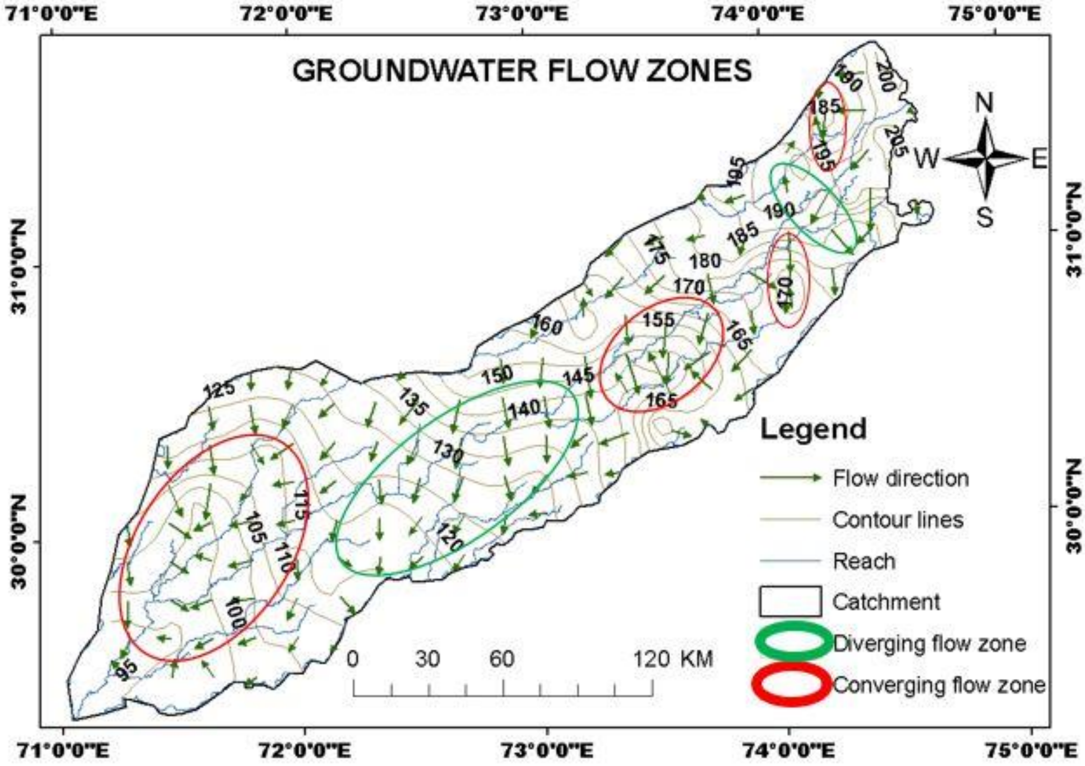


Figure 4.10: Groundwater Flow zones map of 2020

4.4 Mann-Kendall and Sen’s Slope Estimators

4.4.1 Significance Level (P-value)

For trend detection, a non-parametric Man-Kendall test at a significance level α=0.05 is applied for all the wells in the study area. For statistical significance, a p-value of less than 0.05 (typically 0.05) is used. As there is less than a 5% chance that the null hypothesis is right, this is very convincing evidence against it. As a result, we choose to believe the alternative hypothesis rather than the null. For each well, the exact p-value computation is not possible but an approximated p-value is computed and the rejection of the null hypothesis is possible if the computed p-value for each piezo metric well in the study area is less than your significance threshold p-value (typically 0.05).

This does not equate to a 95% certainty that the alternative hypothesis is correct. While the p-value is dependent on the truth or falsity of the null hypothesis, it has nothing to do with the veracity of the alternative hypothesis. A 5% significance level corresponds to a 95% confidence interval. The results showed that there is a trend at a 5% significance level in some portions of the Lahore, Sahiwal, and Okara districts. While the absence of a trend is seen in the Kasur district at a 5% significance level. The green region in Figure 4.11 having a p-value less than 0.05 shows a significant trend while the red region shows a non-significant trend at a 5% percent significance level.

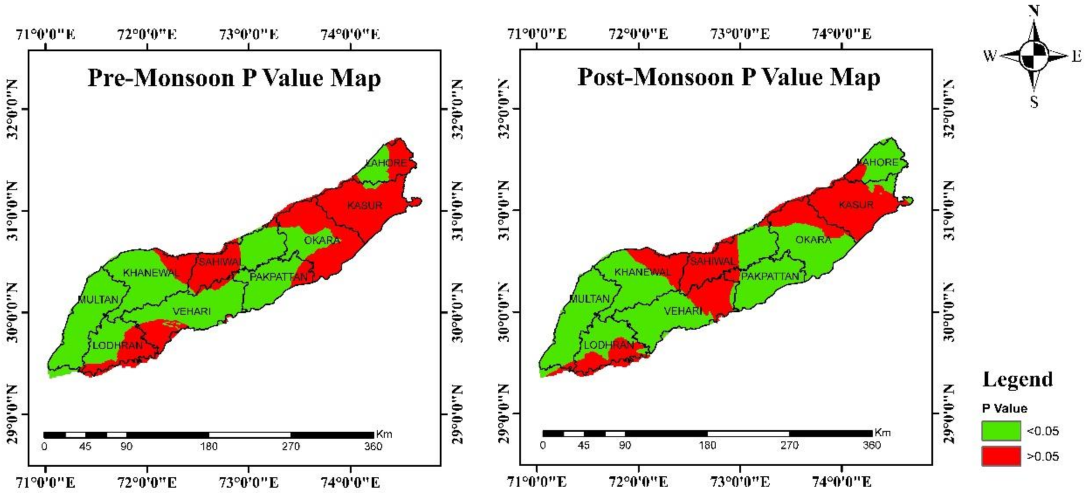


Figure 4.11: significance level (p-value)

4.4.2 Significance Level of Water Table Fluctuation Trend

The pre-monsoon and post-monsoon significance level or confidence interval maps represent the districts and the significance of the trend in these districts. The Mann-Kendall trend analysis is performed by XLSTAT and the trend is usually observed at a 5 percent level of significance i.e., 95% confidence interval as exhibited in Figure 4.12. The 5 percent significance level depicts that there is only a 5 % chance that the null hypothesis is true i.e., there is no trend in the time series. In other words, the null hypothesis does not lie in the 95% confidence interval.

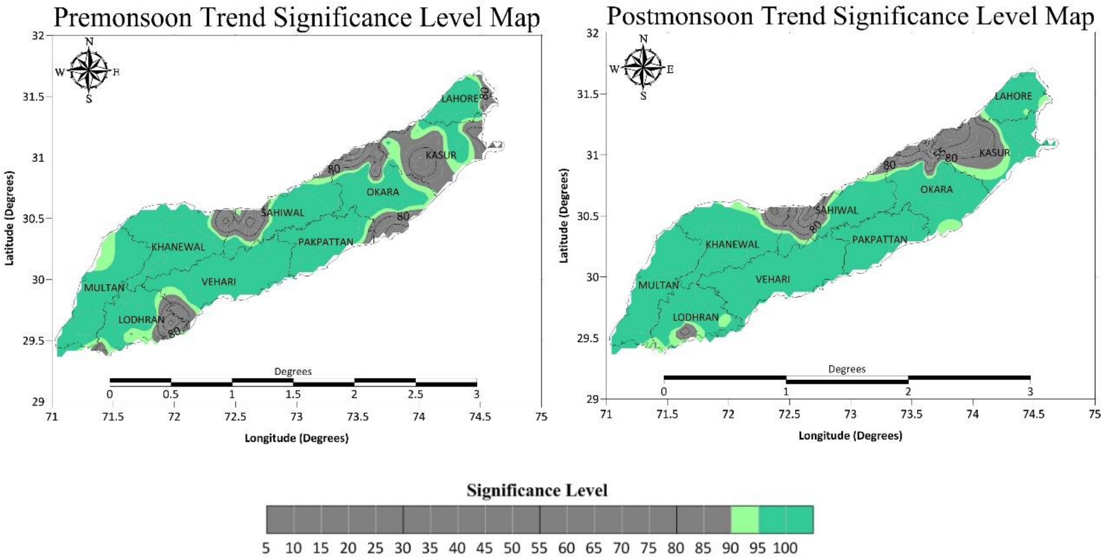


Figure 4.12: Significance level/confidence interval

4.4.3 Mann-Kendall Tau Value

Kendall's tau, which is a measure of correlation and thus measures the strength of the relationship between the two variables, is one of the statistics obtained after running the Mann-Kendall test. Kendall's tau, like Spearman's rank correlation, is applied to data ranks. That is, for each variable, the values are sorted and numbered, with 1 representing the lowest value, 2 representing the next lowest, and so on. Like other measures of correlation, Kendall's tau, takes values between 1 and +1, with a positive correlation indicating that the ranks of both variables increase together, and a negative correlation indicating that as the rank of one variable increases, the rank of the other decreases. Mann–Kendall test statistics (Z) with positive values show increasing trends and vice-versa. The trend of groundwater level in some regions of Kasur District is increasing while all other regions are showing a decreasing trend in groundwater level as shown in Figure 4.13.

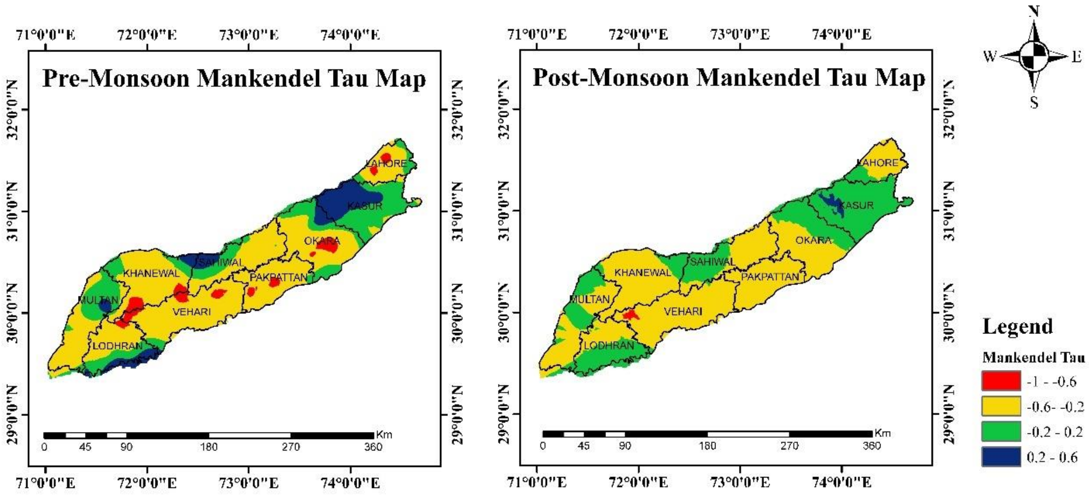


Figure 4.13: Mann-Kendall Tau Map (2005-2020)

4.4.4 Sen’s Slope Estimator

The p-value indicates about the significance of the trend at a particular significance level while the magnitude of the trend was estimated by Sen’s slope. Sen's Slope was used to find the slope of the trend line for each well in this study area based on the rate of water level drop or rise (m per year). The positive slope variable showed that the groundwater level was going up and that the trend was in the increasing water level scenario, while the negative slope variable showed that the trend was going down depicting that the water table was falling in the area. The slope in most of the region was negative indicating that the water level was decreasing in the area as depicted in Figure 4.14. The maximum decrease in pre-monsoon season was observed in Multan, Vehari, and Lahore districts of about 0.3 m/year. While in the post-monsoon season Vehari and Lahore district a sharp decline of 0.3 m/year was observed. In some portions of Kasur district in both pre-monsoon and post-monsoon seasons, a rise of the water table was observed in the range of 0-1 m/year. However, according to the p-value, the trend of decrease in the water table according to time series data in the Kasur district was not significant at a 5 percent level of significance.

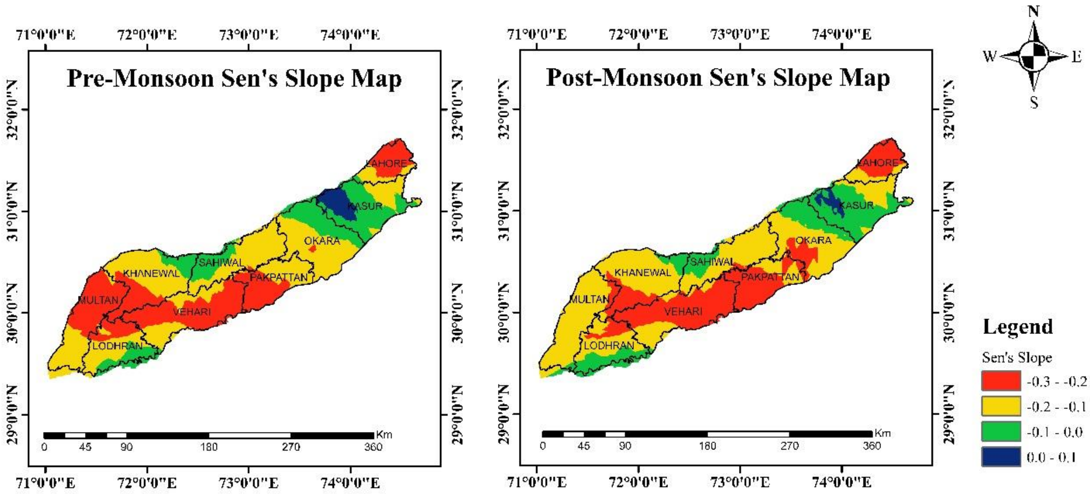


Figure 4.14: Sen's Slope Map (2005-2020)

4.5 Future Projection of Water Table depth using MATLAB and Surfer

The observation points of the groundwater table depth where a significant trend was observed at a 5% level of significance were used for future projections of water table depths in the region. The trend was extrapolated with a linear graph with the least squared error with the observation points shown by white dots in the figure that have a significant trend at a 95% confidence interval in the depth to groundwater table data. These new observation points obtained by extrapolation were then used as the mean and the difference between the maximum and minimum of previous data was used as the deviation. With this using Gaussian distribution, new points were generated which follow the trend (increasing or decreasing) of previous data monotonically.

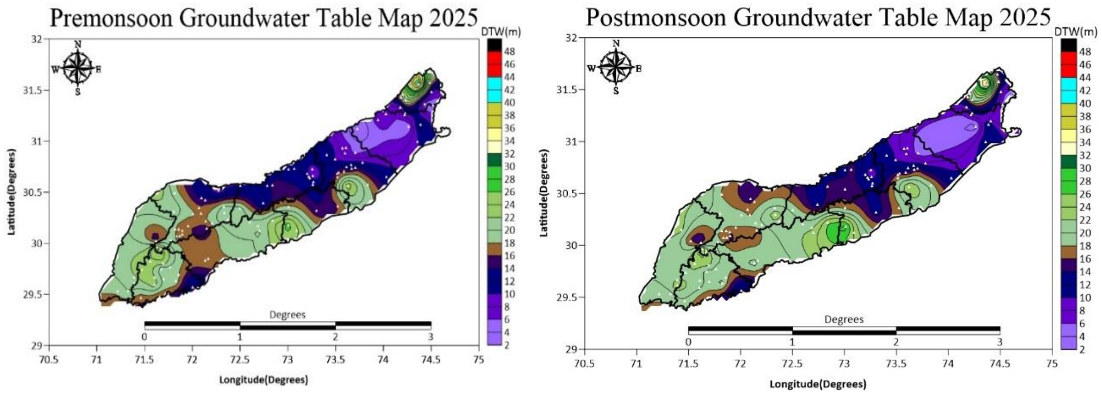


Figure 4.15: Depth to groundwater map 2025

In the future, the projection of groundwater table depth fluctuation also showed a depleting trend in Bari Doab for both the pre-monsoon and post-monsoon seasons as shown in Figure 4.15. Some part of the Lahore district was severely depleting and that depletion would reach approximately 50m by the end of this decade in 2030 according to the observed trend as shown in Figure 4.16. According to the trend, in the Kasur and Okara districts, low values of DTW were observed showing recharge in some areas of these districts in the future. The districts towards the tail of Bari Doab i.e., Khanewal, Vehari, Lodhran, Multan, Pakpattan, and Sahiwal showed higher DTW values in the future by following the trend. Although there were very few portions in Multan, Lodhran, and Sahiwal districts where the values of DTW were expected to fall in the future according to the trend as represented in the maps.

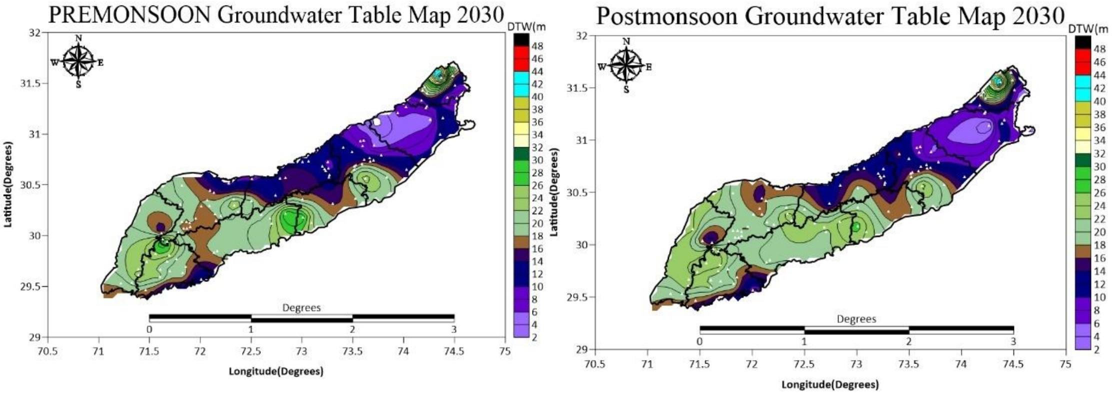


Figure 4.16: Depth to groundwater map 2030

CHAPTER 5

5 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the discussion given in the dissertation and lists the limitations while conducting this study. Additionally, it includes recommendations for groundwater sustainability and suggestions for future research.

5.1 Conclusions

The present study on the groundwater table represents the pattern of spatio-temporal variation in the groundwater table. The region is an agricultural region that uses groundwater particularly more in the Kharif season. The season being the hottest causes more surface water evapotranspiration resulting in more groundwater usage to meet agricultural needs. Statistical tests of Mann Kendall and Sen’s slope are applied to the groundwater table data and the trend is observed at a 5% significance level. Both the spatio-temporal analysis and the statistical test represents a declining trend in the groundwater table along the time series. The observations points where the trend is observed at a 5% level of significance are extrapolated using MATLAB software and a further declining trend in the water table is observed in the future if the trend continues.

5.2 Limitations

First and foremost, the groundwater table data has many limitations. Although there are many piezo metric wells in the area, the lack of reliable groundwater level data is a major obstacle to this study. Numerous groundwater wells with missing values or erroneous readings of piezo metric wells in the data time-series data were dismissed because most statistical methods necessitate a continuous data set with no missing values. Having to make spatial interpolation of groundwater depth by kriging or any other method with less data points increases the risk of making incorrect measurements reducing the reliability of the results. Also, the data points are not uniformly distributed in the region causing biased spatio-temporal kriging interpolation. The groundwater pumping in the region is not properly monitored. The government has no record of private tube wells and other pumping wells operating in the region. Hence, the discharge from the Bari Doab region cannot be calculated accurately hindering the calculation of net recharge or discharge of groundwater occurring in Bari Doab in different seasons.

5.3 Recommendations

The Framework should include various methods and technologies to recharge the depleting water level in the Bari Doab. Methods like rainwater harvesting and artificial recharge are employed to maintain or recharge the depleting water level in areas prone to depletion. Also, proper and regular monitoring of groundwater pumping wells should be carried out on the local and watershed scales. This will give a rough estimate of withdrawal and recharge along with the depth to groundwater table values in the region. Consequently, the water budget of the Bari Doab can be calculated by measuring some other parameters i.e., precipitation, evapotranspiration, and runoff. The piezo metric wells should be checked regularly and should be replaced by new ones in case they became functionless to monitor the water table on regular basis to take precautionary measures where groundwater depth vulnerability is becoming a cause of concern. New piezo metric wells should be installed at regular intervals in areas where there are fewer piezometers already installed. Along with the depth, the parameters related to the quality of groundwater in the Doab can also be mapped and spatio-temporal groundwater quality trends in the region can be observed. Conjunctive use, management, and distribution of water resources as per requirements will help in building an approach towards sustainable management and conservation of groundwater table for the future.

References

Abbas Alipour, Seyedmostafa Hashemi, S. B. S. S. and M. M. (2018). *Spatio-temporal analysis of groundwater level in an arid area*.

Abdul Aziz, O. I., & Burn, D. H. (2006). Trends and variability in the hydrological regime of the Mackenzie River Basin. *Journal of Hydrology*, *319*(1–4), 282–294. https://doi.org/10.1016/j.jhydrol.2005.06.039

Abiye, T., Masindi, K., Mengistu, H., & Demlie, M. (2018). Understanding the groundwater-level fluctuations for better management of groundwater resource: A case in the Johannesburg region. *Groundwater for Sustainable Development*, *7*(October 2017), 1–7. https://doi.org/10.1016/j.gsd.2018.02.004

AC, A., JM, N., RW, S., & AK, M. (2018). Groundwater remediation optimization using Solving Constraint Integer Program (SCIP). *Groundwater for Sustainable Development*, *7*(May), 176–184. https://doi.org/10.1016/j.gsd.2018.05.001

Adhikari, S., Caron, L., Steinberger, B., Reager, J. T., Kjeldsen, K. K., Marzeion, B., Larour, E., & Ivins, E. R. (2018). Methods 1. *Earth and Planetary Science Letters*, *502*(1), suppl.

Agricultural Statistics of Pakistan. (2011).

Ahmad, M. (2002). *Estimation of net groundwater use in irrigated river basins using geo-information techniques: a case study in Rechna Doab, Pakistan.* http://www.cabdirect.org/abstracts/20046798467.html

Akhter, G., Ge, Y., Iqbal, N., Shang, Y., & Hasan, M. (2021). Appraisal of remote sensing technology for groundwater resource management perspective in indus basin. *Sustainability (Switzerland)*, *13*(17), 1–12. https://doi.org/10.3390/su13179686

Amin, M. (2004). *Pakistan's Groundwater Reservoir and Its Sustainability*. 1–7.

Anand, B., Karunanidhi, D., Subramani, T., Srinivasamoorthy, K., & Suresh, M. (2020). Long-term trend detection and spatiotemporal analysis of groundwater levels using GIS techniques in Lower Bhavani River basin, Tamil Nadu, India. *Environment, Development and Sustainability*, *22*(4), 2779–2800. https://doi.org/10.1007/s10668-019-00318-3

Ara, Z., & Zakwan, M. (2018). Estimating Runoff Using SCS Curve Number Method. *International Journal of Emerging Technology and Advanced Engineering*, *8*(5), 195–200.

Archer, D. R., Forsythe, N., Fowler, H. J., & Shah, S. M. (2010). Sustainability of water resources management in the Indus Basin under changing climatic and socio economic conditions. *Hydrology and Earth System Sciences*, *14*(8), 1669–1680. https://doi.org/10.5194/hess-14-1669-2010

Arshad, I., & Umar, R. (2020). Status of urban hydrogeology research with emphasis on India. *Hydrogeology Journal*, *28*(2), 477–490. https://doi.org/10.1007/s10040-019-02091-z

Asghar, S., Sasaki, N., Jourdain, D., & Tsusaka, T. W. (2018). Levels of technical, allocative, and groundwater use efficiency and the factors affecting the allocative efficiency of wheat farmers in Pakistan. *Sustainability (Switzerland)*, *10*(5). https://doi.org/10.3390/su10051619

Basharat, M. (2012). *Integration of Canal and Groundwater To Improve*.

Basharat, M. (2014). *Groundwater Environment and Evaluation of Long-Term Sustainability of the Aquifer under Lahore , Punjab , Pakistan Under the Project " Enhancing the groundwater management capacity in Asian cities through the development and application of groundwater sus*.

Basharat, M., & Tariq, A. U. R. (2014). Command-scale integrated water management in response to spatial climate variability in Lower Bari Doab Canal irrigation system. *Water Policy*, *16*(2), 374–396. https://doi.org/10.2166/wp.2013.221

Basharat, M., & Tariq, A. ur R. (2013). Spatial Climate Variability and Its Impact on Irrigated Hydrology in a Canal Command. *Arabian Journal for Science and Engineering*, *38*(3), 507–522. https://doi.org/10.1007/s13369-012-0336-9

Basharat, M., & Tariq, A. ur R. (2015). Groundwater modelling for need assessment of command scale conjunctive water use for addressing the exacerbating irrigation cost inequities in LBDC irrigation system, Punjab, Pakistan. *Sustainable Water Resources Management*, *1*(1), 41–55. https://doi.org/10.1007/s40899-015-0002-y

Bergh, J., & Löfström, J. (2012). *Interpolation spaces: an introduction (Vol. 223). Springer Science & Business Media.*

C.W. FETTER. (2001). *Applied Hydrogeology* (Fourth Edi). https://arjzaidi.files.wordpress.com/2015/09/unimasr-com_e7ce669a880a8c4c70b4214641f93a02.pdf

Cressie, N. A. C. (2015). Statistics for spatial data revised edition. *Statistics for Spatial Data*, 1–900. https://doi.org/10.1002/9781119115151

D. W. GREENMAN, W. V. SWARZENSKI, and G. D. B. (1970). Ground-water hydrology of the punjab, west Pakistan, with emphasis on problems created by canal irrigation. *Journal of Hydrology*, *10*(3), 312. https://doi.org/10.1016/0022-1694(70)90289-1

Daneshvar Vousoughi, F., Dinpashoh, Y., Aalami, M. T., & Jhajharia, D. (2013). Trend analysis of groundwater using non-parametric methods (case study: Ardabil plain). *Stochastic Environmental Research and Risk Assessment*, *27*(2), 547–559. https://doi.org/10.1007/s00477-012-0599-4

Dennis P. Lettenmaier, S. J. B. (1982). *Cyclic Storage: A Preliminary Assessment*. https://doi.org/https://doi.org/10.1111/j.1745-6584.1982.tb01348.x

Desalegn, A. (2011). *Groundwater Potential Evaluation and Flow Dynamics of Hormat-Golina River Catchment, Kobo Valley, Northern Ethiopia*. http://thesisbank.jhia.ac.ke/id/eprint/4527

Fang, C., Sun, S., Jia, S., & Li, Y. (2019). Groundwater Level Analysis Using Regional Kendall Test for Trend with Spatial Autocorrelation. *Groundwater*, *57*(2), 320–328. https://doi.org/10.1111/gwat.12800

FAO. (2011). Irrigation in Southern and Eastern Asia in Figures. AQUASTAT Survey – 2011. In *Food and Agriculture Organization*. http://www.fao.org/nr/water/aquastat/data /query /results .html.

FAO. (2012). *Crop evapotranspiration, guidelines for computing crop water requirements, FAO Paper No. 56, Rome.*

Foster, S., & Steenbergen, F. Van. (2011). *Conjunctive groundwater use : a ' lost opportunity ' for water management in the developing world ? August*. https://doi.org/10.1007/s10040-011-0734-1

Freeze, R.A. and Cherry, J. A. (1979). *Groundwater*. Prentice-Hall.

Gautam, V. K., Kothari, M., Singh, P. K., Bhakar, S. R., & Yadav, K. K. (2022). *Analysis of groundwater level trend in Jakham River Basin of Southern Rajasthan*. *10*(1), 1–9. https://doi.org/10.19637/j.cnki.2305-7068.2022.01.001

Gilani, S. Y. R. (2011). No Title. *World Population Day*.

Gilbert, R. O. (1987). *Statistical Methods for Environmental Pollution Monitoring*.

Government of Punjab. (2006).

Halcrow. (2006a). *Islamic Republic of Pakistan: Preparing the Punjab Irrigated Agriculture Development Sector Project (Cofinanced by the Japan Special Fund, the Government of the Netherlands, and the Cooperation Fund for the Water Sector).*

Halcrow, G. L. (2006b). Punjab Irrigated Agriculture Development Sector Project. *Final Report, Asian Development Bank, TA-4642-Pakistan, August*.

Halder, S., Roy, M. B., & Roy, P. K. (2020). Analysis of groundwater level trend and groundwater drought using Standard Groundwater Level Index: a case study of an eastern river basin of West Bengal, India. *SN Applied Sciences*, *2*(3), 1–24. https://doi.org/10.1007/s42452-020-2302-6

Hengl, T., & European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2007). *A practical guide to geostatistical mapping of environmental variables*. Publications Office.

Hirsch, R. M., Slack, J. R., & Smith, R. A. (1982). Techniques of trend detection for monthly water quality data. *Water Resources Research*, *18*(1), 107–121.

Hohn, M. E. (1991). An Introduction to Applied Geostatistics: by Edward H. Isaaks and R. Mohan Srivastava, 1989, Oxford University Press, New York, 561 p., ISBN 0-19-505012-6, ISBN 0-19-505013-4 (paperback), $55.00 cloth, $35.00 paper (US). *Computers & Geosciences*, *17*(3), 471–473. https://doi.org/10.1016/0098-3004(91)90055-I

Hydrologic Evaluation of Salinity Control and Reclamation Projects in the Indus Plain, Pakistan: A Summary. (1976). 59.

Jehangir, W. A., Qureshi, A. S., Ali, N., & International Water Management Institute. (2002). *Conjunctive water management in the Rechna Doab : an overview of resources and issues* (Issue January).

John Briscoe, U. Q. (2005). *Pakistan's Water Economy Running Dry*.

Kampata, J. M., Parida, B. P., & Moalafhi, D. (2008). Trend analysis of rainfall in the headstreams of the Zambezi River Basin in Zambia. *Physics and Chemistry of the Earth, Parts A/B/C, 33*, 621–625. https://doi.org/10.1016/j.pce.2008.06.012

Karanth, K. R. (1987). *Groundwater Assessment, Development and Management. Tata McGraw Hill, New Delhi*.

Kawamura, A., Bui, D. D., Tong, T. N., Amaguchi, H., & Nakagawa, N. (2011). Trend detection in groundwater levels of holocene unconfined aquifer in Hanoi, Vietnam by non-parametric approaches. *World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability - Proceedings of the 2011 World Environmental and Water Resources Congress*, *41173*(July 2016), 914–923. https://doi.org/10.1061/41173(414)94

Kendall, M. G. (1955). *Rank Correlation Methods. Charles Griffin, London.*

Kendall, M. G. (1975). *Trend Analysis in Standardized Precipitation Index and Standardized Anomaly Index in the Context of Climate Change in Southern Togo*.

Kumar, G. P., Sen, S. D., Dhirendra, K., Kumar, S. A., & Balkrishan, V. (2022). Assessment of morphometric characteristics and decadal fluctuation of groundwater level of Kali River basin and its link with climate change, West Uttar Pradesh, India Using Geographical Information System. *Disaster Advances*, *15*(5), 26–38.

Kumar, S., Singh, S., Kale, R. V, Ghosh, N. C., Sonkusare, M. M., & Chandniha, S. K. (2018). *Spatio-Temporal Variation and Trend Analysis of Groundwater Level in Raipur City , Chhattisgarh*.

Kumar, T., Singh, M. C., & Singh, J. P. (2022). *Trend Analysis of Groundwater Level , Rainfall and Area under Groundwater Irrigation in Ropar District of Punjab*. *14*(1), 108–116.

Laghari, A. N., Vanham, D., & Rauch, W. (2012). The Indus basin in the framework of current and future water resources management. *Hydrology and Earth System Sciences*, *16*(4), 1063–1083. https://doi.org/10.5194/hess-16-1063-2012

Mann, H. B. (1945). *Non-Parametric Test against Trend. Econometrica, 13, 245-259.* https://doi.org/http://dx.doi.org/10.2307/1907187

Marghade, D., Malpe, D. B., Duraisamy, K., Patil, P. D., & Li, P. (2021). Hydrogeochemical evaluation, suitability, and health risk assessment of groundwater in the watershed of Godavari basin, Maharashtra, Central India. *Environmental Science and Pollution Research*, *28*(15), 18471–18494. https://doi.org/10.1007/s11356-020-10032-7

Mehmood, K., Tischbein, B., Flörke, M., & Usman, M. (2022). Spatiotemporal Analysis of Groundwater Storage Changes, Controlling Factors, and Management Options over the Transboundary Indus Basin. *Water (Switzerland)*, *14*(20). https://doi.org/10.3390/w14203254

Messene, G. M. (2017). Groundwater Flow Direction , Recharge and Discharge Zones Identification in Lower Gidabo Catchment , Rift Valley Basin ,. *Journal of*

Environment and Earth Science, *7*(2), 32–39.

Mondal, A., Kundu, S., & Mukhopadhyay, A. (2012). *Case Study RAINFALL TREND ANALYSIS BY MANN-KENDALL TEST : A CASE STUDY OF NORTH-EASTERN PART OF CUTTACK DISTRICT , ORISSA School of Oceanographic Studies , Jadavpur University , Kolkata-700032 * Author for Correspondence Case Study Trend Analysis*. *2*(1), 70–78.

NESPAK/SGI. (1991). *Contribution of private tubewells in the development of water potential. National Engineering Services of Pakistan and Special Group Inc., Lahore, prepared for Planning and Development Division, Ministry of Planning and Development, Islamabad.*

Panda, D. K., Mishra, A., & Kumar, A. (2012). Quantification des tendances du niveau des eaux souterraines du Gujerat (Inde occidentale). *Hydrological Sciences Journal*, *57*(7), 1325–1336. https://doi.org/10.1080/02626667.2012.705845

Patle, G. T., Singh, D. K., Sarangi, A., Rai, A., Khanna, M., & Sahoo, R. N. (2015). Time series analysis of groundwater levels and projection of future trend. *Journal of the Geological Society of India*, *85*(2), 232–242. https://doi.org/10.1007/s12594-015-0209-4

Patra, K. C. (2001). *Hydrology and water resources engineering*. Boca Raton, Fla. : CRC Press ; New Delhi : Narosa Pub. House.

Pedersen, M. (2018). Interpolation Spaces. In *Functional Analysis in Applied Mathematics and Engineering*. https://doi.org/10.1201/9780203755426-10

Perry. (2001). *Charging for irrigation water. the issue and options with a case study from Iran*. *April*. http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub052/Report52.pdf %5CnY:%5CLiteratur%5CSuWaRest%5CEconomic%5Cwater

Pham, T. G., Kappas, M., Huynh, C. Van, & Nguyen, L. H. K. (2019). Application of ordinary kriging and regression kriging method for soil properties mapping in hilly region of central Vietnam. *ISPRS International Journal of Geo-Information*, *8*(3). https://doi.org/10.3390/ijgi8030147

Prakash, M. R., & Singh, V. S. (2000). Network design for groundwater monitoring - A case study. *Environmental Geology*, *39*(6), 628–632. https://doi.org/10.1007/s002540050474

Qureshi, A. S. (2018). *Challenges and Opportunities of Groundwater Management in Pakistan*. *June*, 735–757. https://doi.org/10.1007/978-981-10-3889-1_43

Qureshi, A. S. (2020). Groundwater governance in pakistan: From colossal development to neglected management. *Water (Switzerland)*, *12*(11), 1–20. https://doi.org/10.3390/w12113017

Qureshi, A. S., Gill, M. A., & Sarwar, A. (2010). Sustainable groundwater management in Pakistan: Challenges and pportunities. *Irrigation and Drainage*, *59*(2), 107–116. https://doi.org/10.1002/ird.455

Qureshi, A. S., McCornick, P. G., Sarwar, A., & Sharma, B. R. (2010). Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan.

Water Resources Management, *24*(8), 1551–1569. https://doi.org/10.1007/s11269-009-9513-3

R. W. Buddemeier, J. A. S. (2000). *Groundwater Storage and Flow*. https://www.kgs.ku.edu/HighPlains/atlas/apgengw.htm

Rafiq, M., Ahmed, M. O., Ahmed, S., Siddique, R., & Pervaiz, A. (2011). *Some Finite Difference Methods for One Dimensional Burger ' s Equation for Irrotational Incompressible Flow Problem*. *9*, 13–16.

Rahman, A. T. M. S., Jahan, C. S., Mazumder, Q. H., Kamruzzaman, M., & Hosono, T. (2017). Drought analysis and its implication in sustainable water resource management in Barind area, Bangladesh. *Journal of the Geological Society of India*, *89*(1), 47–56. https://doi.org/10.1007/s12594-017-0557-3

Raza A., Khanzada S.D., A. S. and A. M. (2012). *Improving water use efficiency for wheat production in Pakistan*.

Robert M. Hirsch, J. R. S. (1984). *A Nonparametric Trend Test for Seasonal Data With Serial Dependence*.

Sarup, J. (2020). *Future Projected Groundwater Level Trend Analysis using GIS Techniques*. *3075*(4), 1286–1294. https://doi.org/10.35940/ijitee.D1415.029420

Satish Kumar, K., & Venkata Rathnam, E. (2019). Analysis and Prediction of Groundwater Level Trends Using Four Variations of Mann Kendall Tests and ARIMA Modelling. *Journal of the Geological Society of India*, *94*(3), 281–289. https://doi.org/10.1007/s12594-019-1308-4

Seckler, D., Amarasinghe, U., & others. (2000). Water supply and demand, 1995 to 2025. *IWMI, Annual Report 1999--2000, January*, 9–17.

Shah, T., Molden, D., Sakthivadivel, R., & Seckler, D. (2000). The global groundwater situation: overview of opportunities and challenges. *The Global Groundwater Situation: Overview of Opportunities and Challenges*. https://doi.org/10.5337/2011.0051

Shahmohammadi-Kalalagh, S., & Taran, F. (2021). Evaluation of the classical statistical, deterministic and geostatistical interpolation methods for estimating the groundwater level. *International Journal of Energy and Water Resources*, *5*(1), 33–42. https://doi.org/10.1007/s42108-020-00094-1

Shakir, A.S.; Rehman, H.U.; Khan, N.M.; Qazi, A. U. (2011). *Impact of canal water shortages on groundwater in the Lower Bari Doab Canal system in Pakistan*.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation - A global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880. https://doi.org/10.5194/hess-14-1863-2010

Singh, A. B. A. B. N. S. R. and R. (2009). *Temporal Trends in Estimates of Reference Evapotranspiration over India*.

Singh, O., Kasana, A., Singh, K. P., & Sarangi, A. (2020). Analysis of Drivers of Trends in Groundwater Levels Under Rice–Wheat Ecosystem in Haryana, India. *Natural Resources Research*, *29*(2), 1101–1126. https://doi.org/10.1007/s11053-019-

09477-6

Steenbergen, F. V., & Oliemans, W. (1997). ILRl Workshop: Groundwater management sharing responsibility for an open access resource. *Proceeding of the Wageningen Water Workshop, December*, 93–109. http://library.wur.nl/WebQuery/titel/1015204

Tabari, H., Nikbakht, J., & Shifteh Some'e, B. (2012). Investigation of groundwater level fluctuations in the north of Iran. *Environmental Earth Sciences*, *66*(1), 231–243. https://doi.org/10.1007/s12665-011-1229-z

Thakur, G. S., & Thomas, T. (2011). Analysis of groundwater levels for detection of trend in Sagar district, Madhya Pradesh. *Journal of the Geological Society of India*, *77*(4), 303–308. https://doi.org/10.1007/s12594-011-0038-z

Todd, D. K. (1959). *Groundwater hydrology. Wiley, New York*.

Watto, M. A., & Mugera, A. W. (2016). Groundwater depletion in the Indus Plains of Pakistan: imperatives, repercussions and management issues. *International Journal of River Basin Management*, *14*(4), 447–458. https://doi.org/10.1080/15715124.2016.1204154

William J. Cosgrove, F. R. R. (2000). *World Water Vision Making Water Everybody's Business*.

Yangbo Chen, Kaoru Takara, Ian D. Cluckie, F. H. D. S. (2004). *GIS and Remote Sensing in Hydrology, Water Resources and Environment (IAHS Proceedings & Reports)*.

Zakwan, M. (2021). Groundwater Resources Development and Planning in the Semi-Arid Region. *Groundwater Resources Development and Planning in the Semi-Arid Region*, *May*. https://doi.org/10.1007/978-3-030-68124-1

APPENDIX

Table A1: Pre-monsoon trend analysis

Districts	Tehsils	Sen slope	Kendall's Tau	S	Var(S)	p-value	alpha	Trend at alpha
						(Two-tailed)		(5% level of significance)
Lahore	Lahore Cantt	-0.1210	-0.828	-99	492.3	0.000	0.05	Decreasing
Lahore	Lahore Cantt	-0.5056	-0.983	-118	0.0	0.000	0.05	Decreasing
Lahore	Lahore Cantt	-0.0498	-0.322	-38	488.7	0.094	0.05	No Trend
Lahore	Lahore Cantt	-0.3372	-0.795	-95	492.3	0.000	0.05	Decreasing
Lahore	Lahore Cantt	0.0246	0.067	8	0.0	0.757	0.05	No Trend
Lahore	Lahore Cantt	-0.0762	-0.515	-61	490.3	0.007	0.05	Decreasing
Lahore	Lahore City	-0.0587	-0.41	-49	492.3	0.031	0.05	Decreasing
Lahore	Lahore City	-0.1707	-0.767	-92	0.0	0.000	0.05	Decreasing
Lahore	Lahore City	-0.2101	-0.778	-93	492.3	0.000	0.05	Decreasing
Lahore	Lahore City	-0.2450	-0.773	-92	491.3	0.000	0.05	Decreasing

Lahore	Lahore City	-0.3302	-0.929	-111	492.3	0.000	0.05	Decreasing
Lahore	Lahore City	-0.5251	-0.979	-117	492.3	0.000	0.05	Decreasing
Kasur	Kasur	-0.1930	-0.661	-79	492.3	0.000	0.05	Decreasing
Kasur	Kasur	-0.0850	-0.35	-42	0.0	0.064	0.05	No Trend
Kasur	Kasur	-0.0872	-0.192	-23	492.3	0.321	0.05	No Trend
Kasur	Kasur	-0.1347	-0.444	-53	492.3	0.019	0.05	Decreasing
Kasur	Kasur	-0.2158	-0.55	-66	0.0	0.002	0.05	Decreasing
Kasur	Chunian	-0.0381	-0.168	-20	491.3	0.391	0.05	No Trend
Kasur	Pattoki	0.0423	0.176	21	492.3	0.367	0.05	No Trend
Kasur	Pattoki	0.1200	0.393	47	492.3	0.038	0.05	**Increasing**
Kasur	Pattoki	0.1440	0.467	56	0.0	0.011	0.05	**Increasing**
Kasur	Pattoki	0.0650	0.611	73	492.3	0.001	0.05	**Increasing**
Kasur	Kot Radha Kishan	-0.2080	-0.711	-85	492.3	0.000	0.05	Decreasing
Kasur	Kot Radha Kishan	0.1084	0.25	30	0.0	0.195	0.05	No Trend
Kasur	Kot Radha Kishan	0.1143	0.644	77	492.3	0.001	0.05	**Increasing**

Okara	Depalpur	-0.2042	-0.895	-107	492.3	0.000	0.05	Decreasing
Okara	Depalpur	-0.1019	-0.633	-76	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.2354	-0.933	-112	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.3552	-0.967	-116	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.1683	-0.84	-100	491.3	0.000	0.05	Decreasing
Okara	Depalpur	-0.1760	-0.817	-98	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.1472	-0.883	-106	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.1725	-0.672	-80	491.3	0.000	0.05	Decreasing
Okara	Depalpur	-0.0192	-0.083	-10	0.0	0.690	0.05	No Trend
Okara	Okara	-0.2780	-0.867	-104	0.0	0.000	0.05	Decreasing
Okara	Okara	-0.1764	-0.65	-78	0.0	0.000	0.05	Decreasing
Okara	Okara	-0.1462	-0.733	-88	0.0	0.000	0.05	Decreasing
Okara	Okara	-0.1798	-0.795	-95	492.3	0.000	0.05	Decreasing
Okara	Okara	-0.1271	-0.7	-84	0.0	0.000	0.05	Decreasing
Okara	Okara	-0.2029	-0.707	-83	487.7	0.000	0.05	Decreasing

Okara	Okara	0.0029	0.017	2	491.3	0.964	0.05	No Trend
Okara	Okara	-0.1698	-0.711	-85	492.3	0.000	0.05	Decreasing
Okara	Renala Khurd	0.0281	0.083	10	0.0	0.690	0.05	No Trend
Okara	Renala Khurd	0.0860	0.447	53	490.3	0.019	0.05	**Increasing**
Okara	Renala Khurd	-0.0445	-0.192	-23	492.3	0.321	0.05	No Trend
Okara	Renala Khurd	-0.0785	-0.35	-42	0.0	0.064	0.05	No Trend
Okara	Renala Khurd	0.0581	0.176	21	492.3	0.367	0.05	No Trend
Okara	Renala Khurd	-0.0497	-0.243	-29	492.3	0.207	0.05	No Trend
Okara	Renala Khurd	-0.1000	-0.46	-55	492.3	0.015	0.05	Decreasing
Okara	Renala Khurd	0.2392	0.605	72	491.3	0.001	0.05	**Increasing**
Okara	Renala Khurd	-0.1018	-0.407	-48	488.7	0.033	0.05	Decreasing
Okara	Renala Khurd	-0.0711	-0.226	-27	492.3	0.241	0.05	No Trend
Pakpattan	Arif Wala	-0.4091	-0.929	-111	492.3	0.000	0.05	Decreasing
Pakpattan	Arif Wala	-0.2720	-0.867	-104	0.0	0.000	0.05	Decreasing
Pakpattan	Arif Wala	-0.2577	-0.867	-104	0.0	0.000	0.05	Decreasing

Sahiwal	Sahiwal	-0.0981	-0.383	-46	0.0	0.041	0.05	Decreasing
Sahiwal	Sahiwal	-0.0866	-0.447	-53	489.7	0.019	0.05	Decreasing
Sahiwal	Sahiwal	-0.0622	-0.445	-52	486.7	0.021	0.05	Decreasing
Sahiwal	Sahiwal	-0.1880	-0.717	-85	490.3	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.0903	-0.628	-75	492.3	0.001	0.05	Decreasing
Sahiwal	Sahiwal	-0.1177	-0.594	-71	492.3	0.002	0.05	Decreasing
Sahiwal	Sahiwal	-0.1442	-0.527	-63	492.3	0.005	0.05	Decreasing
Sahiwal	Sahiwal	-0.1768	-0.633	-76	0.0	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.2164	-0.762	-91	492.3	0.000	0.05	Decreasing
Sahiwal	Chichawatni	-0.1524	-0.45	-54	0.0	0.015	0.05	Decreasing
Sahiwal	Chichawatni	-0.1338	-0.42	-50	491.3	0.027	0.05	Decreasing
Sahiwal	Chichawatni	-0.1349	-0.617	-74	0.0	0.001	0.05	Decreasing
Sahiwal	Chichawatni	0.0742	0.383	46	0.0	0.041	0.05	**Increasing**
Sahiwal	Chichawatni	0.0506	0.183	22	0.0	0.350	0.05	No Trend
Sahiwal	Chichawatni	0.0224	0.084	10	491.3	0.685	0.05	No Trend

Sahiwal	Chichawatni	0.0610	0.259	31	492.3	0.176	0.05	No Trend
Sahiwal	Chichawatni	0.0676	0.36	43	492.3	0.058	0.05	No Trend
Sahiwal	Chichawatni	-0.1049	-0.494	-59	492.3	0.009	0.05	Decreasing
Vehari	Burewala	-0.2528	-0.883	-106	0.0	0.000	0.05	Decreasing
Vehari	Burewala	-0.2737	-0.95	-114	0.0	0.000	0.05	Decreasing
Vehari	Burewala	-0.2189	-0.883	-106	0.0	0.000	0.05	Decreasing
Vehari	Burewala	-0.4774	-0.9	-108	0.0	0.000	0.05	Decreasing
Khanewal	Mian Channu	-0.0432	-0.25	-30	0.0	0.195	0.05	No Trend
Khanewal	Mian Channu	0.0365	0.293	35	492.3	0.125	0.05	No Trend
Khanewal	Mian Channu	-0.0688	-0.417	-50	0.0	0.026	0.05	Decreasing
Khanewal	Mian Channu	-0.3014	-0.967	-116	0.0	0.000	0.05	Decreasing
Khanewal	Mian Channu	-0.2401	-0.883	-106	0.0	0.000	0.05	Decreasing
Khanewal	Mian Channu	-0.1783	-0.867	-104	0.0	0.000	0.05	Decreasing
Khanewal	Mian Channu	0.0190	0.1	12	0.0	0.626	0.05	No Trend
Khanewal	Khanewal	-0.1275	-0.74	-88	491.3	0.000	0.05	Decreasing

Khanewal	Khanewal	-0.2697	-0.857	-102	491.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.1691	-0.617	-74	0.0	0.001	0.05	Decreasing
Khanewal	Khanewal	-0.1855	-0.845	-101	492.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.1579	-0.667	-80	0.0	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.0928	-0.683	-82	0.0	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.0879	-0.575	-67	483.7	0.003	0.05	Decreasing
Khanewal	Khanewal	-0.1034	-0.65	-78	0.0	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.2397	-0.908	-108	491.3	0.000	0.05	Decreasing
Vehari	Mailsi	-0.2515	-0.85	-102	0.0	0.000	0.05	Decreasing
Vehari	Mailsi	-0.2407	-0.667	-80	0.0	0.000	0.05	Decreasing
Lodhran	Karorpacca	-0.2240	-0.75	-90	0.0	0.000	0.05	Decreasing
Lodhran	Karorpacca	-0.1455	-0.617	-74	0.0	0.001	0.05	Decreasing
Lodhran	Karorpacca	0.0053	0.017	2	0.0	0.965	0.05	No Trend
Lodhran	Karorpacca	0.3083	0.7	84	0.0	0.000	0.05	**Increasing**
Khanewal	Kabirwala	-0.1264	-0.383	-46	0.0	0.041	0.05	Decreasing

Khanewal	Kabirwala	-0.1690	-0.561	-67	492.3	0.003	0.05	Decreasing
Khanewal	Kabirwala	-0.1962	-0.527	-63	492.3	0.005	0.05	Decreasing
Multan	Shujjabad	-0.1650	-0.733	-88	0.0	0.000	0.05	Decreasing
Multan	Jalalpur Pirwala	-0.3341	-0.795	-95	492.3	0.000	0.05	Decreasing
Multan	Jalalpur Pirwala	-0.2001	-0.895	-107	492.3	0.000	0.05	Decreasing
Multan	Jalalpur Pirwala	-0.1925	-0.929	-111	492.3	0.000	0.05	Decreasing
Lodhran	Lodhran	-0.1749	-0.577	-69	492.3	0.002	0.05	Decreasing
Lodhran	Lodhran	-0.1647	-0.745	-89	492.3	0.000	0.05	Decreasing
Lodhran	Lodhran	-0.0901	-0.293	-35	492.3	0.125	0.05	No Trend
Lodhran	Lodhran	-0.1758	-0.583	-70	0.0	0.001	0.05	Decreasing
Lodhran	Lodhran	-0.1017	-0.4	-48	0.0	0.033	0.05	Decreasing
Lodhran	Lodhran	0.0643	0.259	31	492.3	0.176	0.05	No Trend
Lodhran	Lodhran	0.1331	0.4	48	0.0	0.033	0.05	**Increasing**
Lodhran	Lodhran	0.0952	0.326	39	492.3	0.087	0.05	No Trend
Lodhran	Dunyapur	-0.2447	-0.824	-98	491.3	0.000	0.05	Decreasing

Lodhran	Dunyapur	-0.1735	-0.812	-97	492.3	0.000	0.05	Decreasing
Lodhran	Dunyapur	-0.1959	-0.51	-61	492.3	0.007	0.05	Decreasing
Lodhran	Dunyapur	-0.2296	-0.783	-94	0.0	0.000	0.05	Decreasing
Multan	Multan City	-0.1270	-0.343	-41	492.3	0.071	0.05	No Trend
Khanewal	Jahanian	-0.2325	-0.946	-113	492.3	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2703	-0.929	-111	492.3	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2719	-0.917	-110	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.3013	-0.95	-114	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2898	-0.912	-109	492.3	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.3392	-0.933	-112	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.3094	-0.9	-108	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.4089	-0.933	-112	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2659	-0.917	-110	0.0	0.000	0.05	Decreasing
Pakpattan	Pakpattan	-0.1460	-0.946	-113	492.3	0.000	0.05	Decreasing
Pakpattan	Pakpattan	-0.1082	-0.5	-60	0.0	0.006	0.05	Decreasing

Pakpattan	Pakpattan	-0.1695	-0.672	-80	491.3	0.000	0.05	Decreasing
Multan	Multan Saddar	0.0663	0.611	73	492.3	0.001	0.05	**Increasing**

Table A2: Post-monsoon trend analysis

Districts	**Tehsils**	**Sen slope**	**Kendall's Tau**	**S**	**Var(S)**	**p-value**	**alpha**	**Trend at alpha**
						(Two-tailed)		**(5% level of significance)**
Lahore	Lahore Cantt	-0.1377	-0.756	-90	491.3	0.000	0.05	Decreasing
Lahore	Lahore Cantt	-0.5212	-0.946	-113	492.3	0.000	0.05	Decreasing
Lahore	Lahore Cantt	-0.0996	-0.712	-84	488.7	0.000	0.05	Decreasing
Lahore	Lahore Cantt	-0.3119	-0.895	-107	492.3	0.000	0.05	Decreasing
Lahore	Lahore Cantt	0.0926	0.336	40	491.3	0.079	0.05	No Trend
Lahore	Lahore Cantt	-0.1140	-0.353	-42	491.3	0.064	0.05	No Trend
Lahore	Lahore City	-0.0973	-0.269	-32	491.3	0.162	0.05	No Trend
Lahore	Lahore City	-0.1471	-0.678	-81	492.3	0.000	0.05	Decreasing
Lahore	Lahore City	-0.2064	-0.633	-75	489.7	0.001	0.05	Decreasing

Lahore	Lahore City	-0.2451	-0.733	-88	0.0	0.000	0.05	Decreasing
Lahore	Lahore City	-0.3800	-0.867	-104	0.0	0.000	0.05	Decreasing
Lahore	Lahore City	-0.5724	-1	-120	0.0	0.000	0.05	Decreasing
Kasur	Kasur	-0.1300	-0.404	-47	483.7	0.036	0.05	Decreasing
Kasur	Kasur	-0.0720	-0.267	-32	0.0	0.165	0.05	No Trend
Kasur	Kasur	-0.1424	-0.403	-48	491.3	0.034	0.05	Decreasing
Kasur	Kasur	-0.1316	-0.628	-75	492.3	0.001	0.05	Decreasing
Kasur	Kasur	-0.2007	-0.695	-83	492.3	0.000	0.05	Decreasing
Kasur	Chunian	-0.0824	-0.276	-33	492.3	0.149	0.05	No Trend
Kasur	Pattoki	0.0184	0.05	6	0.0	0.825	0.05	No Trend
Kasur	Pattoki	0.0407	0.118	14	491.3	0.558	0.05	No Trend
Kasur	Pattoki	0.0645	0.259	31	492.3	0.176	0.05	No Trend
Kasur	Pattoki	0.0104	0.128	15	487.7	0.526	0.05	No Trend
Kasur	Kot Radha Kishan	-0.2240	-0.561	-67	492.3	0.003	0.05	Decreasing
Kasur	Kot Radha Kishan	0.0914	0.202	24	491.3	0.299	0.05	No Trend

Kasur	Kot Radha Kishan	0.1920	0.773	92	491.3	0.000	0.05	**Increasing**
Okara	Depalpur	-0.2509	-0.833	-100	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.0966	-0.567	-68	0.0	0.002	0.05	Decreasing
Okara	Depalpur	-0.2030	-0.817	-98	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.3448	-0.933	-112	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.1780	-0.7	-84	0.0	0.000	0.05	Decreasing
Okara	Depalpur	-0.2202	-0.795	-95	492.3	0.000	0.05	Decreasing
Okara	Depalpur	-0.1546	-0.879	-105	492.3	0.000	0.05	Decreasing
Okara	Depalpur	-0.1839	-0.583	-70	0.0	0.001	0.05	Decreasing
Okara	Depalpur	-0.0662	-0.319	-38	491.3	0.095	0.05	No Trend
Okara	Okara	-0.2811	-0.795	-95	492.3	0.000	0.05	Decreasing
Okara	Okara	-0.1983	-0.672	-80	491.3	0.000	0.05	Decreasing
Okara	Okara	-0.1639	-0.795	-95	492.3	0.000	0.05	Decreasing
Okara	Okara	-0.1993	-0.767	-92	0.0	0.000	0.05	Decreasing
Okara	Okara	-0.1404	-0.527	-63	492.3	0.005	0.05	Decreasing

Okara	Okara	-0.1971	-0.773	-92	491.3	0.000	0.05	Decreasing
Okara	Okara	-0.0023	-0.051	-6	489.3	0.821	0.05	No Trend
Okara	Okara	-0.2488	-0.756	-90	491.3	0.000	0.05	Decreasing
Okara	Renala Khurd	0.0457	0.153	18	488.7	0.442	0.05	No Trend
Okara	Renala Khurd	0.0843	0.444	53	492.3	0.019	0.05	**Increasing**
Okara	Renala Khurd	-0.0640	-0.319	-38	491.3	0.095	0.05	No Trend
Okara	Renala Khurd	-0.0450	-0.142	-17	492.3	0.471	0.05	No Trend
Okara	Renala Khurd	0.0028	0	0	0.0	0.965	0.05	No Trend
Okara	Renala Khurd	-0.0561	-0.35	-42	0.0	0.064	0.05	No Trend
Okara	Renala Khurd	-0.1327	-0.467	-56	0.0	0.011	0.05	Decreasing
Okara	Renala Khurd	0.2152	0.583	70	0.0	0.001	0.05	**Increasing**
Okara	Renala Khurd	-0.1186	-0.527	-63	492.3	0.005	0.05	Decreasing
Okara	Renala Khurd	-0.1057	-0.367	-44	0.0	0.052	0.05	No Trend
Pakpattan	Arifwala	-0.3795	-0.933	-112	0.0	0.000	0.05	Decreasing
Pakpattan	Arifwala	-0.2491	-0.895	-107	492.3	0.000	0.05	Decreasing

Pakpattan	Arifwala	-0.2733	-0.912	-109	492.3	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.1111	-0.387	-46	491.3	0.042	0.05	Decreasing
Sahiwal	Sahiwal	-0.0913	-0.444	-53	492.3	0.019	0.05	Decreasing
Sahiwal	Sahiwal	-0.0819	-0.707	-82	484.0	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.2370	-0.866	-99	475.7	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.1262	-0.494	-59	492.3	0.009	0.05	Decreasing
Sahiwal	Sahiwal	-0.1224	-0.728	-87	492.3	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.1483	-0.51	-61	492.3	0.007	0.05	Decreasing
Sahiwal	Sahiwal	-0.1485	-0.644	-77	492.3	0.001	0.05	Decreasing
Sahiwal	Sahiwal	-0.2480	-0.848	-100	488.7	0.000	0.05	Decreasing
Sahiwal	Sahiwal	-0.2724	-0.874	-104	491.3	0.000	0.05	Decreasing
Sahiwal	Chichawatni	-0.1688	-0.437	-52	491.3	0.021	0.05	Decreasing
Sahiwal	Chichawatni	-0.1145	-0.36	-43	492.3	0.058	0.05	No Trend
Sahiwal	Chichawatni	-0.1301	-0.617	-74	0.0	0.001	0.05	Decreasing
Sahiwal	Chichawatni	0.0598	0.283	34	0.0	0.139	0.05	No Trend

Sahiwal	Chichawatni	-0.0118	-0.033	-4	0.0	0.894	0.05	No Trend
Sahiwal	Chichawatni	-0.0269	-0.05	-6	491.3	0.822	0.05	No Trend
Sahiwal	Chichawatni	0.0485	0.269	32	491.3	0.162	0.05	No Trend
Sahiwal	Chichawatni	0.0530	0.31	37	492.3	0.105	0.05	No Trend
Sahiwal	Chichawatni	-0.1137	-0.655	-78	491.3	0.001	0.05	Decreasing
Vehari	Burewala	-0.2593	-0.967	-116	0.0	0.000	0.05	Decreasing
Vehari	Burewala	-0.2745	-0.983	-118	0.0	0.000	0.05	Decreasing
Vehari	Burewala	-0.2547	-0.85	-102	0.0	0.000	0.05	Decreasing
Vehari	Burewala	-0.4690	-0.867	-104	0.0	0.000	0.05	Decreasing
Khanewal	Mian Channu	-0.0766	-0.326	-39	492.3	0.087	0.05	No Trend
Khanewal	Mian Channu	-0.0198	-0.126	-15	492.3	0.528	0.05	No Trend
Khanewal	Mian Channu	-0.1095	-0.336	-40	491.3	0.079	0.05	No Trend
Khanewal	Mian Channu	-0.3327	-0.95	-114	0.0	0.000	0.05	Decreasing
Khanewal	Mian Channu	-0.2707	-0.879	-105	492.3	0.000	0.05	Decreasing
Khanewal	Mian Channu	-0.1938	-0.862	-103	492.3	0.000	0.05	Decreasing

Khanewal	Mian Channu	-0.0311	-0.142	-17	492.3	0.471	0.05	No Trend
Khanewal	Khanewal	-0.1511	-0.762	-91	492.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.2874	-0.929	-111	492.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.1779	-0.723	-86	491.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.2087	-0.828	-99	492.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.1705	-0.912	-109	492.3	0.000	0.05	Decreasing
Khanewal	Khanewal	-0.0556	-0.532	-63	490.3	0.005	0.05	Decreasing
Khanewal	Khanewal	-0.1053	-0.628	-75	492.3	0.001	0.05	Decreasing
Khanewal	Khanewal	-0.0791	-0.527	-63	492.3	0.005	0.05	Decreasing
Khanewal	Khanewal	-0.2286	-0.95	-114	0.0	0.000	0.05	Decreasing
Vehari	Mailsi	-0.2196	-0.933	-112	0.0	0.000	0.05	Decreasing
Vehari	Mailsi	-0.2524	-0.711	-85	492.3	0.000	0.05	Decreasing
Lodhran	Karorpacca	-0.2131	-0.795	-95	492.3	0.000	0.05	Decreasing
Lodhran	Karorpacca	-0.1435	-0.639	-76	491.3	0.001	0.05	Decreasing
Lodhran	Karorpacca	-0.0440	-0.322	-38	488.7	0.094	0.05	No trend

Lodhran	Karorpacca	0.2229	0.611	73	492.3	0.001	0.05	**Increasing**
Khanewal	Kabirwala	-0.1280	-0.383	-46	0.0	0.041	0.05	Decreasing
Khanewal	Kabirwala	-0.1520	-0.577	-69	492.3	0.002	0.05	Decreasing
Khanewal	Kabirwala	-0.1976	-0.611	-73	492.3	0.001	0.05	Decreasing
Multan	Shujabaad	-0.1874	-0.717	-86	0.0	0.000	0.05	Decreasing
Multan	Jalalpur Pirwala	-0.2022	-0.862	-103	492.3	0.000	0.05	Decreasing
Multan	Jalalpur Pirwala	-0.1787	-0.933	-112	0.0	0.000	0.05	Decreasing
Multan	Jalalpur Pirwala	-0.1688	-0.929	-111	492.3	0.000	0.05	Decreasing
Lodhran	Lodhran	-0.1788	-0.65	-78	0.0	0.000	0.05	Decreasing
Lodhran	Lodhran	-0.1617	-0.583	-70	0.0	0.001	0.05	Decreasing
Lodhran	Lodhran	-0.0541	-0.168	-20	491.3	0.391	0.05	No trend
Lodhran	Lodhran	-0.1183	-0.42	-50	491.3	0.027	0.05	Decreasing
Lodhran	Lodhran	-0.0794	-0.42	-50	491.3	0.027	0.05	Decreasing
Lodhran	Lodhran	0.0690	0.293	35	492.3	0.125	0.05	No trend
Lodhran	Lodhran	0.1639	0.437	52	491.3	0.021	0.05	**Increasing**

Lodhran	Lodhran	0.1113	0.3	36	0.0	0.116	0.05	No trend
Lodhran	Dunyapur	-0.2032	-0.867	-104	0.0	0.000	0.05	Decreasing
Lodhran	Dunyapur	-0.1844	-0.833	-100	0.0	0.000	0.05	Decreasing
Lodhran	Dunyapur	-0.2201	-0.65	-78	0.0	0.000	0.05	Decreasing
Lodhran	Dunyapur	-0.2540	-0.8	-96	0.0	0.000	0.05	Decreasing
Multan	Multan City	-0.1746	-0.521	-62	491.3	0.006	0.05	Decreasing
Khanewal	Jahanian	-0.2420	-0.929	-111	492.3	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2591	-0.95	-114	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2649	-0.933	-112	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2890	-0.95	-114	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2755	-0.9	-108	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.3142	-0.933	-112	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.3167	-0.867	-104	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.3685	-0.967	-116	0.0	0.000	0.05	Decreasing
Khanewal	Jahanian	-0.2645	-0.962	-115	492.3	0.000	0.05	Decreasing

Pakpattan	Pakpattan	-0.1966	-0.862	-103	492.3	0.000	0.05	Decreasing
Pakpattan	Pakpattan	-0.2168	-0.773	-92	491.3	0.000	0.05	Decreasing
Pakpattan	Pakpattan	-0.2099	-0.778	-93	492.3	0.000	0.05	Decreasing
Multan	Multan Saddar	0.0820	0.717	86	0.0	0.000	0.05	**Increasing**
Multan	Multan Saddar	0.2120	0.783	94	0.0	0.000	0.05	**Increasing**