Journal of Groundwater Science and Engineering
ISSN 2305-7068
Indexed by ESCI CABI CSA Scopus GeoRef AJ CNKI

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Citation:
Zakir-Hassan G, Punthakey Jehangir F, Shabir G, *et al*. 2024. Assessing the potential of underground storage of flood water: A case study from Southern Punjab Region in Pakistan. Journal of Groundwater Science and Engineering, 12(4): 387-396.

View online: https://doi.org/10.26599/JGSE.2024.9280029

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Research Article

Assessing the potential of underground storage of flood water: A case study from Southern Punjab Region in Pakistan

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Abstract: An intensively irrigated area in southern part of Punjab Province, Pakistan, has been selected by the Punjab Irrigation Department (PID) to implement a Managed Aquifer Recharge (MAR) project. This project involves diverting floodwater from the Islam Headwork on Sutlej River into the abandoned Mailsi Canal. Utilizing various structures such as depressions, abandoned canals, flood channels, open fields, and deserts for MAR can reduce the flood intensity while recharging aquifer and wetlands. The study area, known for its fertile lands and serving as a food basket for the Punjab Province, is experiencing groundwater depletion at the rate of 0.30 m to 0.70 m per year, significantly increasing pumping costs. This study aims to evaluate the suitability of the sites for the MAR project and assess the storage capacity of the aquifer for floodwater retention. Historical groundwater level data from 25 observation wells across an area of 1,522 km^2 were analysed, with the study area divided in to 25 polygons using ArcMap10.6 software. Specific yield method was employed to assess the available storage capacity of the aquifer. Results indicate that the site is suitable for MAR and has the potential to store approximately 1.88 km^3 of floodwater as of 2020, thereby reducing flood intensity and enhancing eco-hydrogeological conditions. MAR is identified as a Nature-Based Solution (NBS) for both flood mitigation and groundwater sustainability.

Keywords: Groundwater; Managed Aquifer Recharge; Indus River Basin; Aquifer; Vehari; Punjab; Pakistan

Received: 14 Oct 2023/ Accepted: 21 Aug 2024/ Published: 06 Dec 2024

Introduction

In Pakistan's arid and semi-arid regions, groundwater is a primary water resource widely used across domestic, agricultural, and industrial sectors. Most viable site for large surface storage have already been developed (Papa and Frappart, 2021; Wisser et al. 2013), and groundwater is frequently extracted at unsustainable rates, posing a threat to future water security in many areas (Konikow and Kendy, 2005; Ross, 2018; Zhongming et al. 2014). In addition to other water supply augmentation strategies like desalination and recycling, storing additional water underground emerges as a feasible way to meet long-term water supply objectives (Kuang et al. 2024). In Many water-stressed places, the challenge is less about the total amount of precipitation and more about how effectively it is stored for future use (Hasan et al. 2019; Shiklomanov, 2000). Managed Aquifer Recharge (MAR) offers a solution by capturing extra water during wet seasons and storing it underground for use during dry seasons, thereby reducing water shortages. MAR has proven to be an effective technique for both the storage and treatment of water (Dillon, 2005; Gale et al. 2006; Gale et al. 2002; Missimer et al. 2015; Pérez-Uresti et al. 2019). If MAR is economically and technically feasible, it

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DOI: 10.26599/JGSE.2024.9280029

Zakir-Hassan G, Punthakey Jehangir F, Shabir G, et al. 2024. Assessing the potential of underground storage of flood water: A case study from Southern Punjab Region in Pakistan. Journal of Groundwater Science and Engineering, 12(4): 387-396.

can reduce evaporation losses and help irrigators manage surface water variability during droughts. The viability and cost-effectiveness of MAR are influenced by technical and financial factors, such as infiltration, injection, and recovery rates, which are dependent on local hydrogeological conditions (Dillon, 2009; Ross and Hasnain, 2018).

Managed aquifer recharge, also known as groundwater replenishment, water banking, or artificial recharge, involves the intentional replenishing of aquifers with water for later recovery or environmental benefits (Sloan et al. 2023). MAR techniques, which include riverbank filtration, stream bed weirs, infiltration ponds, and injection wells, can significantly increase groundwater storage, improved water quality, and provide drought and emergency supplies (Sherif et al. 2023; Dillon, 2020). These techniques often use water sources such as appropriately treated urban stormwater and treated wastewater. An expanding body of scientific evidence affirms that MAR is an essential management tool for the sustainable use of water resources worldwide (IAH-MAR, 2018). There are various technologies available for managed recharge, categorized into five primary technologies with 14 sub-type (Fig. 1), based on whether the focus is on recharging aquifers or intercepting water for subsequent surface infiltration (IGRAC, 2014).

	Technology	Sub type	
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds & basins	
		Flooding	
		Ditch, furrow, drains	
		Irrigation	
	Induced bank infiltration		
	Well, shaft and borehole recharge	Deep well injection	AS(TR)
			ASR
		Shallow well S hafu pit infiltration	
Technique S referring primarily to interc eping the wrater	In-channel modifications	Recharge dams	
		Sub surface dams	
		Sand dams	
		Channel spreading	
	Runoff harvesting	Barriers and bunds	
		Trenches	

Fig. 1 Applications and MAR technology classification (sub-type) (IGRAC, 2014)

Pakistan is the eighth-largest food producer in the world, where agriculture plays a crucial role in supporting food security, reducing poverty, and driving economic growth in Punjab Province (ADB, 2018; Imran et al. 2018; WB, 2017). However, the potential for agricultural output and the capacity to cultivate more land is heavily dependent on water availability. The area faces severe challenge from droughts and floods, as water is unevenly distributed throughout the year and is subject to seasonal change (Abid et al. 2019; Qureshi and Ashraf, 2019). Groundwater is vital to sustaining food security and rural livelihoods in Punjab, supplying between 40% and 50% of the water needed for irrigation (Siddiqi and Wescoat, 2013). Climatically linked disasters like floods and droughts are fairly prevalent in Pakistan; for instance, during the 2010 flood, one fifth of the nation's geographical area was inundated (WB, 2017). Groundwater recharge from floodwater can be substantial. For instance, in Iran, studies have shown that 57% to 61% of the total groundwater recharge comes from floodwater spreading (Pakparvar et al. 2016). Floodwater is a source of groundwater recharge, according to Hassan et al. (2019). Similarly, research in India has demonstrated that controlled aquifer recharge techniques can mitigate flood damage while replenishing depleted aquifers by dispersing floodwater (Chinnasamy et al. 2017).

In Pakistan, floods are very common, especially during the monsoon season, which generally extends from June to September/October. These floods have severe consequences, causing significant loss of life, property, agricultural crops and other infrastructure. Moreover, the excess water often flows into the Arabia Sea. Properly harvesting or diverting floodwater into underground reservoir can serve the dual purpose of mitigating flood and addressing water scarcity. In the present study, groundwater level data were analysed to assess the available storage capacity of the aquifer for diverting floodwater in Vehari district of the South Punjab Region in Pakistan.

1 Methodology

1.1 Description of study area

This study was carried out in the Vehari district of Punjab Province, Pakistan, located at latitude 29.9719°N and longitude 72.4258°E. The study area covers 1,522 km^2 and is bordered by the Pakpattan Islam Link Canal to the east, the Sindhnai Mailsi Bahawal Link (SMB-link) Canal to the west, the Pakpattan Upper Canal to the north, and the Sutlej River to south. The region comprises both rural and urban areas, with an elevation of approximately 140 m above sea level. Vehari district has a population of over 2.9 million, growing at a rate of 2.23% (GOP, 2018; Sindhu, 2010). The majority of residents depend on agriculture for their livelihood. Fig. 2 shows the study

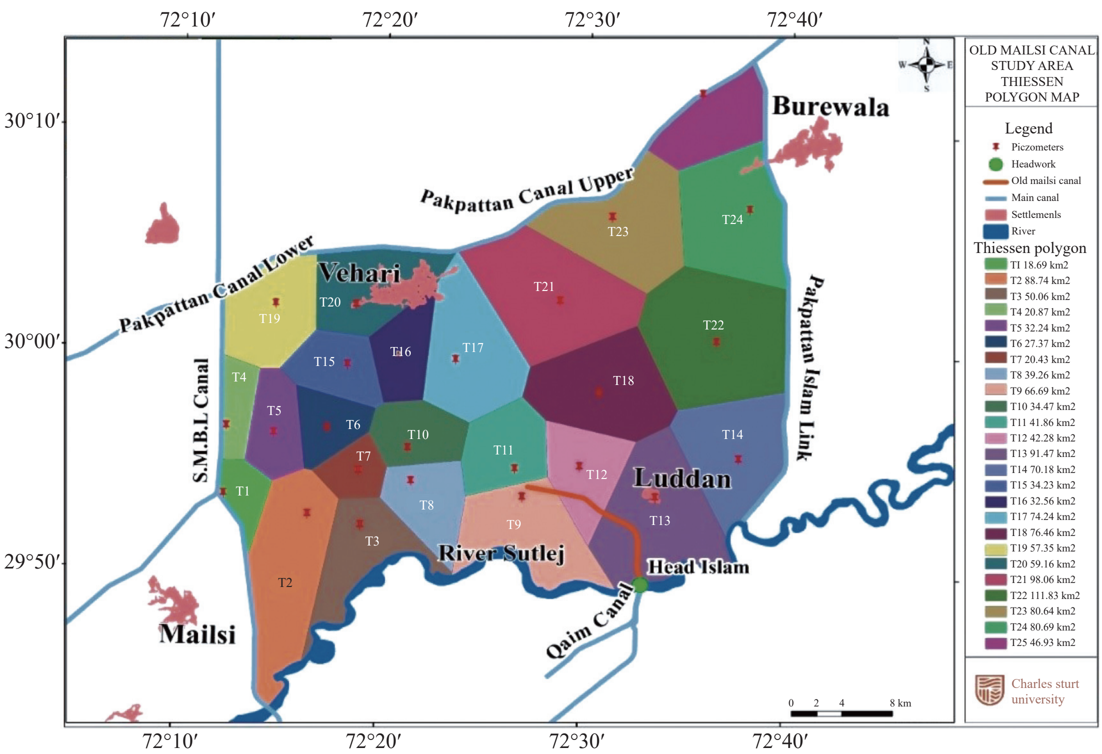

Fig. 2 Map of study area and Thiessen Polygons

area and the Thiessen Polygons. Groundwater in the study area is used for agriculture, industry, livestock, drinking, fish-farming and other commercial purposes.

Vehari district is situated in the nation's agricultural heartland, where there has been little industrial growth. Cotton-wheat cultivation was the predominant kind of agriculture in the Vehari until 2012; however, maize-wheat has recently become the district's main planting pattern (Khalid et al. 2020). Groundwater is essential for agriculture in this region, as rainfall and non-perennial canals provide only 32% of the water required for irrigation. The cropping pattern in the study region includes food crops such as wheat, rice, and maize; cash crops like cotton and sugarcane; and fodder crops, including Kharif and Rabi varieties. Rabi fodders include berseem, lucern, shaftal, and senji, while Kharif fodders contains jowar, maize, and bajra. The main crops of the area are wheat, cotton, fodder, rice, maize, sunflower, and sugarcane. Vehari is known as "the city of cotton" and serves as a key contributor to the province's food supply.

1.2 Rainfall and temperature

Climatological data in the Indus River Basin (IRB) is collected by two organizations: The Pakistan Meteorological Department (PMD) and the Punjab Irrigation Department (PID), with the latter solely collects precipitation. The average monthly rainfall of Multan, Sahiwal, Bahawalnagar, and Bahawalpur in the surrounding of the study area is displayed in Fig. 3. The region experiences a hot, dry climate, with summer beginning in April and lasting until October. The hottest months are May, June, and July, with average maximum temperatures of approximately 47°C and minimum temperatures of around 28°C. The cold season extend from November through March, with December, January, and February being the coldest months, featuring average maximum and lowest temperatures of around 22°C and 4°C, respectively. Wintertime sees a lot of fog. In the study region, there are no meteorological stations operated by the Pakistan Meteorological Department (PMD). As a result, data were gathered from four nearby stations: Sahiwal, Multan, Bahawalpur, and Bahawalnagar (Fig. 4).

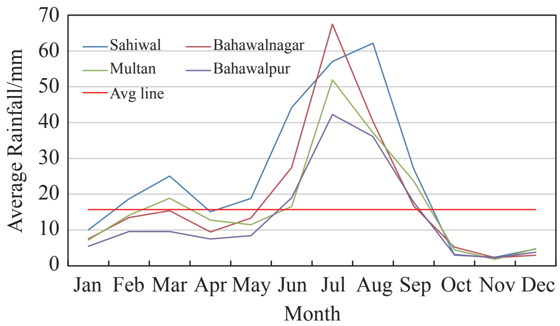

Fig. 3 Average monthly rainfall (mm) at Multan, Sahiwal, Bahawalnagar and Bahawalpur

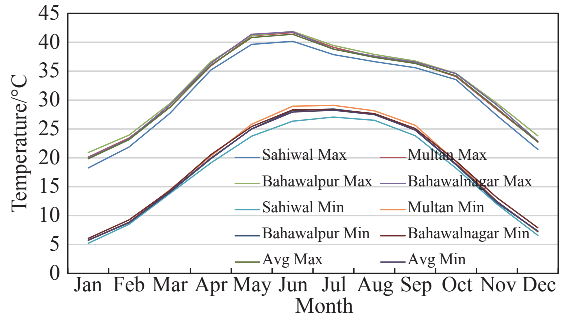

Fig. 4 Long-term (1967–2020) mean monthly maximum and minimum temperatures at four stations

1.3 Water quality sampling

Water samples were collected from the field during May and June 2021 following the standard procedures and methods prescribed by American Public Health Association (APHA, 2021). Field measurements included parameters such as temperature, Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH, bore depth, well locations (using x, y geo-referencing coordinates), ground elevations, static water levels, source of water sampling. The samples were collected using portable multi-parameter devices. Additionally, some heavy metals were also analysed. The groundwater quality in the study area was evaluated to determine its suitability for drinking and irrigation purposes, as well as to assess its potential to support MAR (Zakir-Hassan, 2023).

1.4 Sub-surface lithology

Different organizations have drilled boreholes in the study area and throughout Punjab over time. These bore logs have been analysed, and geological cross-sections have been plotted, as shown in Fig. 5.

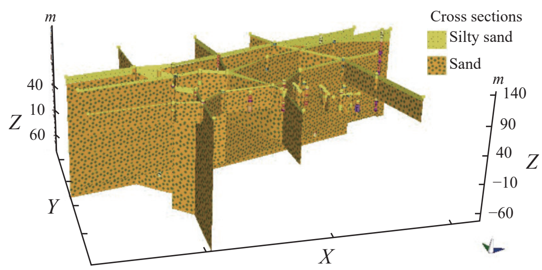

Fig. 5 Fence diagram showing of the study area showing subsurface lithology

The surficial deposits typically encountered along the bed of Old Mailsi Canal, through which surface water flows, vary in thickness from 1 m to 5 m. These deposits are mostly alluvial, generally comprised of water deposited silt, silty sand, interspersed silty clay. These surficial sediments rest on the underlying sandy aquifer throughout the course of canal. The silt particles in the top layer are well-graded and generally not well permeable. Given the extent and geological composition of the surficial materials, direct recharge of water from the ground surface into the underlying sandy aquifer is unlikely to be substantial due to the low hydraulic conductivity of the surficial materials. These findings suggest that to effectively recharging the main aquifer would require drilling and installing injection or recharge wells at the project site to facilitate and accelerate the recharge of water from the ground surface into the more permeable underlying sandy aquifer (Zakir-Hassan, 2023).

1.5 Groundwater levels and behaviour

According to Bennett et al. (1967) and Greenman et al. (1967), and several other sources, the water table was quite high during the pre-irrigation period, particularly in the doabs' centres, and the groundwater hydraulic system was in a state of dynamic balance. From 1900 to 1960, groundwater levels in Chaj Doab rose by 50 feet to 70 feet (USGS, 1967). However, in many sections of Punjab, waterlogging and salinity became serious problems between the 1960s and the 1970s due to an extremely shallow water table (Hassan and Bhutta, 1996; Qureshi et al. 2008). After that the water table started to decline, and at present groundwater budget is negative- pumping exceeds recharge. The aquifer in the study area has been over-exploited due to excessive groundwater extraction (Zakir-Hassan et al. 2023). An analysis of data from 25 piezometer between 2015 to 2022 reveals a pre-monsoon depletion ranging from 5.6 m to 23.8 m and a post-monsoon depletion ranging from 5.8 m to 22.6 m.

1.6 Groundwater Recharge Potential (GWRP) estimation by the specific yield method

Using directly observed groundwater levels data, the specific yield approach was used to estimate the gross recharge to the aquifer. As shown in Fig. 2, 25 piezometers with seasonal water level data were selected in the study area. Data was available from 2015 to 2020, collected on a six-monthly basis, during both pre-monsoon and post-monsoon periods. The rise or fall in water level for each season at each piezometer was calculated using the difference between the observed water levels at its start and end of the season. Each piezometer was given an effective area using the Thiessen Polygon Method, as illustrated in Fig. 5. The rise or fall in water level in each piezometer was calculated to represent the effective area of that particular piezometers. By multiplying the rise or fall at a piezometer with the piezometer's effective area, the change in reservoir storage was estimated (volume of porous matrix). This process was repeated for each season across all piezometers. Equation 1 was used to determine the rise/fall in each polygon and consequently, the change in storage of the aquifer (Maréchal et al. 2006; Zakir-Hassan et al. 2021).

$$GWRP = \sum_{i=1}^{n} (R_i \times A_i \times Sy_i) \quad (1)$$

Where: $GWRP$ is groundwater recharge potential, n is number of polygons, R is rise/fall in GWL, A is area of polygon, and Sy_i is the specific yield.

2 Results and Discussion

2.1 MAR Potential

Statistical and geospatial analysis of the data revealed that groundwater levels in the study area are depleting, with a decrease in aquifer storage on a seasonal basis from Pre monsoon (Pre) of 2015 to Post monsoon (Post) of 2020. Groundwater levels at selected points within each polygon were analysed to assess fluctuations between pre-2015 and post-2020. The result showed that the average water table was declining at different locations from pre-2015 to pre-2020 (Fig. 6). However, during post 2015 to post 2020 period, the average water table was rising at different locations (Fig. 7).

Table 1 provides a summary of statistical parameters of depth to water table data from Pre 2015 to Post 2020. Fig. 8 indicates the trends of Depth To Water Table (DTWT) increased in Pre 2020,

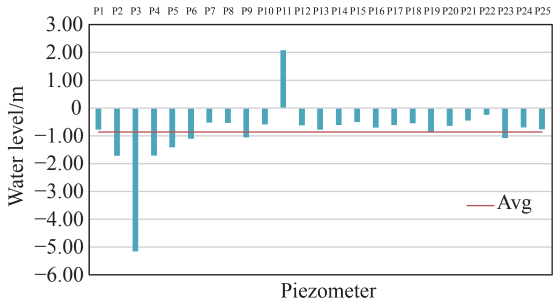

Fig. 6 Average water level rise/fall at different locations in study area in pre monsoon 2015–2020

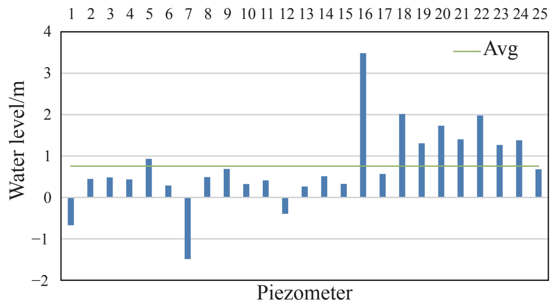

Fig. 7 Average water level rise/fall at different locations in study area in post monsoon 2015–2020

except in piezometer 11, where at some points in post-2020, a decrease in the groundwater table was observed in the study area (Fig. 9).

Table 2 and Table 3 show the statistics of DTWT over five years for the post-monsoon and pre-monsoon periods, respectively. The maximum rise of DTWT was 3.49 m, and the maximum fall was 1.49 m during post-monsoon periods, indicating an increase in aquifer storage during the post-2015 and 2020 seasons. Conversely, the maximum rise of DTWT was 2.08 m and the maximum fall was 5.16 m during the pre-monsoon period, indicating an overall depletion of the aquifer and a consequent the increase in aquifer storage from 2015 to 2020.

The filling water table for the aquifer was considered as 5 m below the natural land surface to access the potential of available groundwater storage. The threshold was selected because, above 5 m, the root zone of crops is affected, and trend of

Table 1 Statistics of DTWT below natural land surface from 2015–2020

Parameter	*Pre 2015	**Post 2015	Pre 2016	Post 2016	Pre 2017	Post 2017	Pre 2018	Post 2018	Pre 2019	Post 2019	Pre 2020	Post 2020
Max	23.2	22.6	23.8	22.6	23.8	22.7	24.0	22.7	24.1	22.8	24.3	22.8
Min	5.6	6.0	5.6	6.0	5.8	5.9	6.1	6.0	6.2	6.2	6.3	6.2
Avg	16.6	16.4	16.7	16.6	16.8	16.8	17.0	17.0	17.2	17.1	17.4	17.1
STDDEV	4.5	4.3	4.6	4.4	4.5	4.3	4.5	4.3	4.5	4.4	4.6	4.4

Notes: *Pre monsoon; **Post monsoon

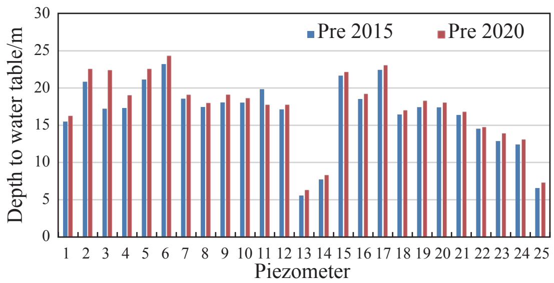

Fig. 8 Depth to water table (DTWT-m) at different piezometers in Pre 2020 and Pre 2015

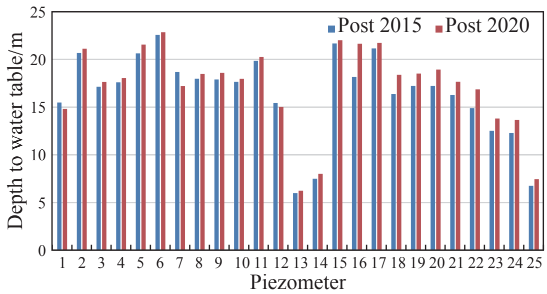

Fig. 9 Depth to water table (DTWT-m) at different piezometers in Post 2020 and Post 2015

Table 2 Statistics of DTWL during Post-Monsoon periods from 2015 to 2020

Total	Water level Rise/fall in Post monsoon in 5 years (m)	Drop/Rise in water level in Post monsoon in per year (m)
Max	3.49	0.70
Min	−1.49	−0.30
Avg	0.75	0.15
STDDEV	0.97	0.19

Table 3 Statistics of DTWL in Pre-Monsoon periods from 2015 to 2020

Total	Water level Rise/fall in Pre monsoon in 5 years (m)	Drop/Rise in water level in Pre monsoon in per year (m)
Max	2.08	0.42
Min	−5.16	−1.03
Avg.	−0.87	−0.17
STDDEV	1.13	0.23

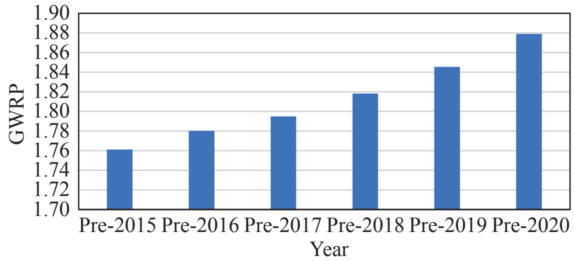

Fig. 10 Increasing trend of GWRP for pre-2015 to pre-2020

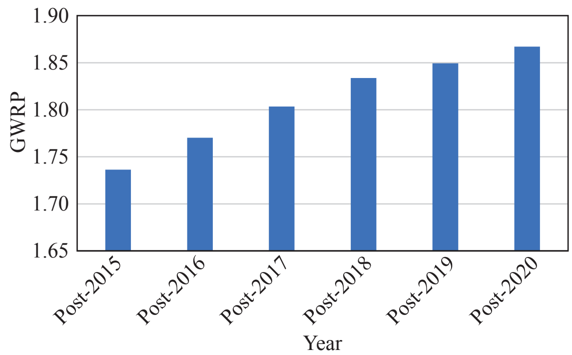

Fig. 11 Increasing trend of GWRP for post-2015 to post-2020

waterlogging starts (IWASRI, 1995). The increasing trend of GWRP for the pre-monsoon period is shown in Fig. 10 and for the post-monsoon period in Fig. 11. The GWRP for the Post is shown in Fig. 10 and for Pre it shown in the Fig. 11.

Table 4 shows the GWRP from Pre-2015 to Pre 2020 in the study area, Punjab, Pakistan. This table indicates that the GWRP is increased from pre-2015 to pre-2020, reflecting a decreasing trend of groundwater table in the study area (Fig. 12).

Table 5 shows the GWRP from Post-2015 to Post-2020 in the study area, which similarly indicates a decreasing groundwater table (Fig. 13). These findings reveal that, over the time, the groundwater reservoir is depleting, while storage potential is increasing. It has been found that a MAR recharge project appears to be feasible, given

Table 4 GWRP for the period of pre-2015 to pre-2020 at different locations in the study area

Parameter	Area of polygon (km^2)	Natural Surface Level (NSL) (m-amsl)	GWRP (BCM)					
			Pre-2020	Pre-2019	Pre-2018	Pre-2017	Pre-2016	Pre-2015
Total	1522		1.88	1.85	1.82	1.79	1.78	1.76
Max	111.83	148	0.186	0.185	0.184	0.183	0.182	0.181
Min	18.69	134	0.003	0.002	0.001	0.000	−0.001	−0.002
Avg	55.88	139	0.075	0.074	0.073	0.072	0.071	0.070
STD	26.66	4	0.047	0.047	0.046	0.046	0.045	0.045

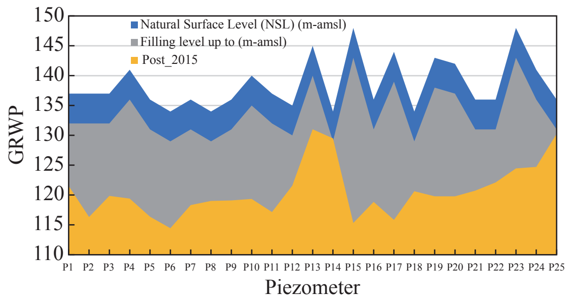

Fig. 12 Ground water recharge potential during post-2020

the underground storage potential. A separate study revealed that an adequate flow of floodwater is available at Islam headwork during the monsoon period, mainly in June and July (IRI, 2019).

2.2 Source of water for MAR

Hydrological investigations were conducted at the site to evaluate the availability of floodwater for MAR. It was found that an adequate volume of water is available during the rainy season at the Islam Headwork, which can be diverted into the bed of the Old Mailsi canal for MAR (Zakir-Hassan, 2023). This water, when recharge to the aquifer, will improve ecological conditions and help replenish the depleted aquifer, leading to the sustainable use of groundwater.

3 Conclusion and Recommendations

3.1 Conclusion

The present study revealed that the average water table dropped by 0.87 meters from 2015 to 2020. Using the specific yield approach, the Groundwater Recharge Potential (GWRP) was estimated to be 1.76 BCM in pre-2015, 1.88 BCM in post-2015, 1.74 BCM in post-2020, and 1.87 BCM in pre-2015. The suitability of the site for a Managed Aquifer Recharge (MAR) project was evaluated based on water availability and storage potential. Historical groundwater level data from 25 observation wells over an area of 1,522 km^2 indicated the long-term aquifer depletion. The study area was divided into 25 polygons using ArcMap10.6 software, and available storage capacity of the aquifer was assessed using specific yield method. It was found that the site is suitable for an MAR project, with the potential to store about 1.88 km^3 of water in 2020, equating to a water depth of approximately 1.2 m depth across the entire study area. MAR can reduce the flood intensity while improving the eco-hydrogeology and groundwater availability. It offers a Nature-Based Solution (NBS) for flood mitigation and groundwater sustainability. The groundwater quality is also suitable for irrigation purpose to support the MAR project since agriculture is the major consumer of groundwater in the study area.

3.2 Recommendations

(1) Comprehensive Groundwater Monitoring: There is an urgent need for a comprehensive groundwater monitoring program to create groundwater potential maps for future hydro-geological research.

(2) Incentives for Groundwater Conservation: To slow the decline of the groundwater reservoir, a variety of incentives, including strict regulation, enforcement, and well-targeted subsidies, should be implemented.

(3) Groundwater Management Strategies: Groundwater management options must be considered, such as eliminating subsidies for water-intensive crops, charging for electricity, establishing a permit system for new wells and power lines, and artificially replenishing aquifers with rainwater or floodwater.

(4) Community Involvement: Engaging the community in monitoring groundwater levels and quality, then in recharge interventions by raising their awareness and capacity levels.

(5) High-Efficiency Irrigation Systems: Subsi-

Table 5 GWRP for the period of post-2015 to post-2020

Parameter	Area of polygon (km^2)	Natural Surface Level (NSL) (m-amsl)	GWRP (BCM)					
			Post-2020	Post-2019	Post-2018	Post-2017	Post-2016	Post-2015
Total	1522		1.87	1.85	1.83	1.80	1.77	1.74
Max	111.83	148	0.176	0.175	0.174	0.173	0.172	0.172
Min	18.69	134	0.000	−0.001	−0.001	−0.001	−0.002	−0.004
Avg	55.88	139	0.075	0.074	0.073	0.072	0.071	0.069
STD	26.66	4	0.047	0.047	0.046	0.046	0.045	0.044

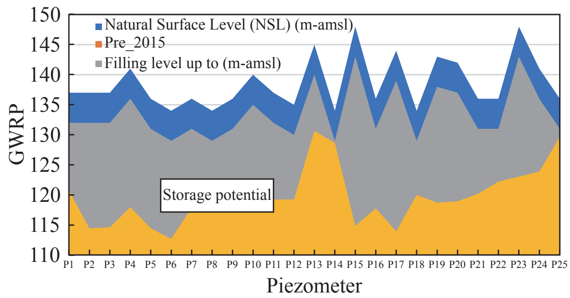

Fig. 13 Ground water recharge potential in pre_2020

dizing drip irrigation and other high-efficiency irrigation systems, as saving surface water will reduce the presser on groundwater.

(6) Strengthening Institutional Frameworks: The institutional and regulatory frameworks for managing and monitoring groundwater must be strengthened and modernized, with an effective implementation mechanism.

(7) Stakeholder Capacity Building: Initiatives and incentives should be introduced to increase capacity and awareness among all stakeholders for inclusive, responsive, and integrated collaboration in the sustainable use, management, and governance of groundwater. The introduction of Aquifer User Association (AUA), similar to water user association and Khal Panchayets for surface water management, should be introduced.

(8) Integrated Water Resources Management (IWRM): The formulation and effective implementation of IWRM, including conjunctive use management of both surface and groundwater, should be prioritized and applied in practice.

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