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DIVERTING FLOOD WATER FOR SUSTAINABLE USE OF GROUND WATER THROUGH MANAGED AQUIFER RECHARGE

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By

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Abstract:

Surface water availability in Indus River Basin is highly variable in temporal and spatial domains, which results in high dependence of irrigated agriculture on ground water. Pakistan have become the fourth global largest user of ground water, due to ever increasing pressure on ground water. Resultantly ground water levels are depleting especially in fresh ground water zones. Ground water is a hidden common pool resource, and its governance and management is much more complex as compared to the surface water. Due to global climatic changes, patterns of rainfall, floods and droughts have changed; which has aggravated the situation. Flood water during monsoon is a viable source of surplus water which can be diverted and stored underground to replenish the depleted aquifer through managed aquifer recharge (MAR). Nature has blessed Pakistan with a large alluvial aquifer, which can store, transmit, and yield a large volume of ground water for supporting food-security and livelihood in the basin. Irrigation Research Institute (IRI) of Punjab Irrigation Department (PID) has started a project of managed aquifer recharge (MAR) by diverting flood water from Islam Headwork into the bed of Old Mailsi Canal; where the flood water is to be recharged through construction of 144 recharge wells. Ground water levels in this area are depleting on an average rate of 0.5 m per year. The area in district Vehari is hub for intensive irrigated agriculture which is highly dependent on ground water. Current paper encapsulates the investigations carried out for potential of storing the flood water in the aquifer through MAR. Data from about 20 observation wells have been analysed which resulted that adequate volume of water (> 1 km^3) can be stored underground which can be pumped during drought/peak demand period. This project will improve the ground water availability leading towards reducing the disputes and transboundary issues of ground water.

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Key Words: ground water, MAR, Indus-River-Basin, aquifer, Vehari, Punjab, Pakistan

1. INTRODUCTION

Ground water is a main resource of water for household, agricultural, and industrial sectors of Pakistan's arid and semi-arid regions. Traditional irrigation practices involve huge water losses which can be somehow recovered through ground water recharge **(Imran, 2018)**. The majority of viable locations for big surface storages have already been exploited **(Wisser et al., 2013)**, and ground water is now being extracted at alarmingly unsustainable rates, posing a threat to future water security **(Zhongming et al., 2014)**. In addition to other water supply augmentation strategies like desalination and recycling, storing additional water underground seems a feasible way to meet long-term water supply objectives. In numerous regions facing water scarcity, the emphasis lies not so much on the quantity of precipitation received, but rather on the efficient storage of water for future usage. This explains why water security and reliability often hinges more on effective storage practices rather than the overall volume of precipitation **(Shiklomanov, 2000)**. For the storage and treatment of water, managed aquifer recharge (MAR) has proven effective in a number of nations **Dillon, 2005; Gale et al., 2006; Gale et al., 2002; Missimer et al., 2015)**. If MAR is economically and technically feasible, then the storage of excess water in aquifers can reduce evaporation losses and assist irrigators in adjusting surface water variability during droughts. Technical and monetary factors, such as infiltration, injection, and recovery rates, which are reliant on the local hydrogeology, play a role in the viability of MAR and its cost in relation to other options **(Dillon, 2009)**.

Managed aquifer recharge, also known as ground water replenishment, water banking, or artificial recharge, is the intentional replenishing of aquifers with water for later recovery or environmental benefit. Increased ground water storage, improved water quality, and drought and emergency supplies can all be achieved with the help of MAR techniques, which include riverbank filtration, stream bed weirs, infiltration ponds, and injection wells. They also use water sources like appropriately treated urban storm water 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, and that it should be used fast **(IAH-MAR, 2018)**. There are several different technologies available for managed recharge. However, based on whether the technology focuses on the process of recharging aquifers or is focused on water interception (capture) for subsequent surface infiltration, five primary technologies with 14 sub-types (applications) have been identified **(Figure)(IGRAC, 2014)**.

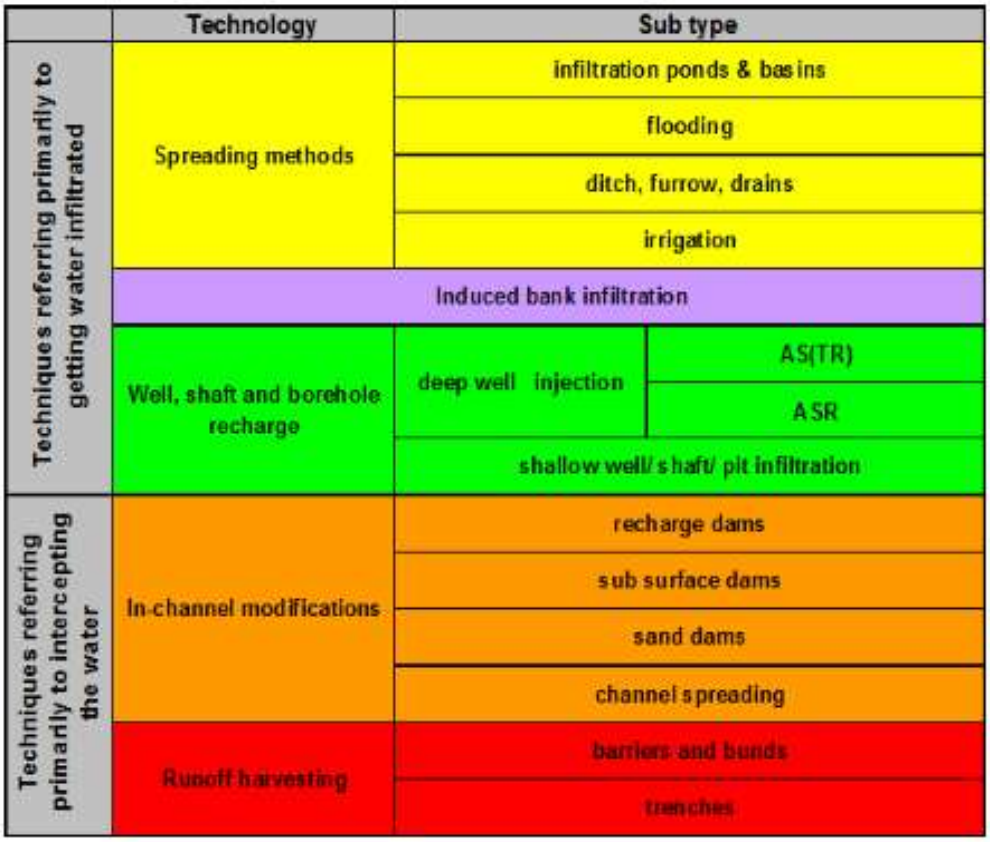


Figure-1: Applications and MAR technology classification (sub-type) **(IGRAC, 2014)**

Punjab's ground water levels have risen as a result of rising irrigation needs brought on by intensifying agricultural production **(Punthakey et al., 2016)** a growing population, fragmented farm sizes, and insufficient irrigation supplies **(ADB, 2018; Azam & Shafique, 2017; Qureshi & Ashraf, 2019)**. In Punjab, ground water supports the food security and way of life of rural populations and supplies between 40 and 50 percent of the water needed for irrigation **(Siddiqi & Wescoat, 2013)**. In Pakistan, climatically linked calamities like floods and droughts are also fairly prevalent; for instance, the 2010 flood, one fifth of the nation's geographical area was inundated **(WB, 2017)** and also during flood 2022, one third of the country was inundated. Ground water recharge from flood water can be large; for instance **(Pakparvar et al., 2016)** found that in Iran, between 57 and 61 percent of the entire recharge to ground water came from flood water spreading. Flood water is a source of ground water recharge, according to G. Z. Hassan and F. R. Hassan **(Zakir-Hassan & Hassan, 2018)**. While doing research in India, **(Chinnasamy et al., 2017)** discovered that controlled aquifer recharge techniques can lessen flood damage and replace depleted aquifers by dispersing flood water. In Pakistan, floods are very common, especially during the monsoon period of heavy rainfall which generally ranges from June to September/October. If flood

water harvested or diverted properly to the underground reservoir, it can serve the dual purpose of flood mitigation and combating the water scarcity. In the current study, data on ground water levels have been analysed to determine available storage capacity of aquifer to divert the flood water in Vehari district of South Punjab region in Pakistan.

2. Materials and Method

2.1 Description of Study Area

This study was carried out in the Vehari district of Punjab province, Pakistan, at latitude 29.9719°N and longitude 72.4258°E. The study area, which is 1522 km^2, is bordered on the eastern, western, northern, and southern sides by the Pakpattan Islam Link Canal, the Sindhnai Mailsi Bahawal Link (SMB-link) Canal, the Pakpattan Upper Canal, and the river Sutlej. The region comprises both rural and urban areas, and the elevation is around 140 meters above sea level. Vehari district has a population of over 2.9 million and is growing at a pace of 2.23 percent annually. The majority of residents depend on agriculture for a living **(GOP, 2018; Sindhu, 2010)**. Figure shows the study area and Thiessen Polygons is a graphical technique which calculates station weights based on the relative areas of each measurement station in the Thiessen polygon network. Thiessen polygons are generated from a set of sample points such that each polygon defines an area of influence around its sample point, so that any location inside the polygon is closer to that point than any of the other sample points. All points are triangulated into a triangulated irregular network (TIN) that meets the Delaunay criterion. The perpendicular bisectors for each triangle edge are generated, forming the edges of the Thiessen polygons. The location at which the bisectors intersect determine the locations of the Thiessen polygon vertices. Ground water in the study area is being used for agriculture, industry, livestock and fish-farming, domestic and other commercial uses.

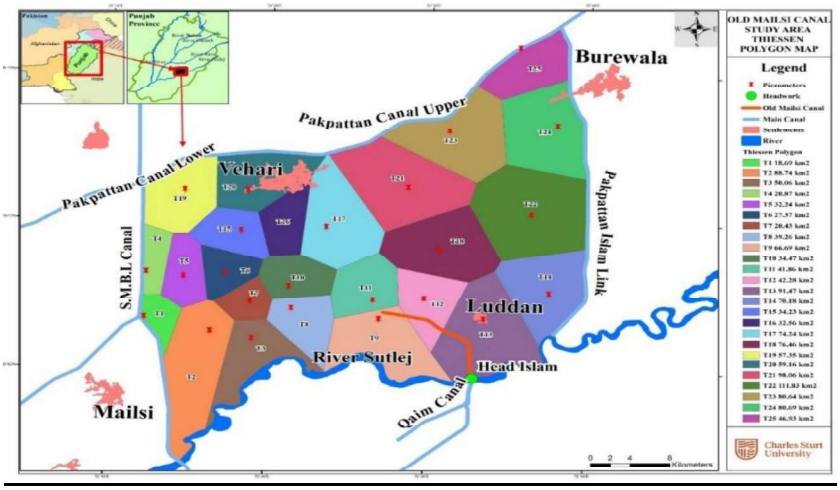


Figure-2: Map of study area and Thiessen Polygons

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 Vehari until 2012. However, maize-wheat has recently become the district's main planting pattern **(Khalid et al., 2020)**. Rainfall and non-perennial canals can only supply 32% of the water needed for irrigation, so ground water supply is necessary for agriculture in the study region.

2.2 Meteorological Profile of the Study Area

The study area experiences a hot, dry climate. According to Pakistan Meteorological Department and the Punjab Irrigation Department (PID), the average monthly rainfall of Multan, Sahiwal, Bahawalnagar, and Bahawalpur in the surrounding of the study area has been displayed in Figure. April marks the beginning of the summer season, which lasts until October. May, June, and July are the warmest months. Approximately 47 ° C and 28 ° C, respectively, are the mean maximum and lowest temperatures for these months. November through March are considered the cold months. These three-month December, January, and February are the coldest. For this time period, the average maximum and lowest temperatures are around 22 ° C and 4 ° C. 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 from the PMD were gathered for four nearby stations: Sahiwal, Multan, Bahawalpur, and Bahawalnagar.

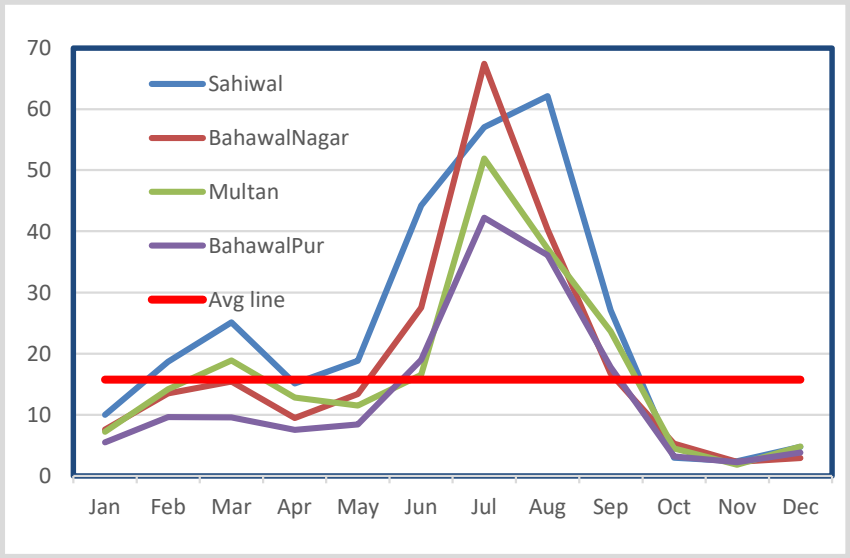


Figure-3: Average Monthly Rainfall (mm) at Multan, Sahiwal, Bahawalnagar and Bahawalpur

2.3 Sampling for Water Quality Analysis

Water samples were collected from the study area during the month of May and June 2021 as per standard procedures and methods prescribed by American Public Health Association (APHA, 2021). Some of the parameters like

temperature, EC, TDS, pH, depth of bore, well locations (x, y georeferencing coordinates), ground elevations, static water levels, source of water sampling (like tube well, drain, canal, river) were noted down while sampling using portable multi-parameter devices.

2.4 Ground water levels and behaviour

According to **(Bennett et al., 1967; 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 ground-water hydraulic system was in a condition of dynamic balance. Over the years from 1900 to 1960, a rise in ground water levels has been seen in Chaj Doab, ranging from 50 to 70 feet **(USGS, 1967)**. 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 & Bhutta, 1996; Qureshi et al., 2008)**. 25 piezometer's data from 2015 to 2022 have been analysed and depletion have been found in pre-monsoon within the range of 5.6m to 23.8m and post-monsoon within the range of 5.8m to 22.6m.

2.5 Ground water Recharge Potential (GWRP) estimation by the specific yield method

Using data on ground water levels that were directly observed, the specific yield approach was used to estimate the gross recharge to the aquifer. As seen in Figure, 25 piezometers with seasonal water level data were selected in the research area. Piezometer data was available from 2015 to 2020 on six month basis i.e., pre-monsoon and post-monsoon periods. Each piezometer's rise or fall was calculated for each season using the difference between observed water levels at its start and finish. Each piezometer was given an effective area using the Thiessen Polygon Method, as illustrated. The rise or fall in water level in each piezometer was calculated to represent the effective area of that particular piezometers. By dividing the increase or fall at a piezometer with the piezometer's effective area, the change in reservoir storage was estimated (volume of porous matrix). For the piezometers for each season, this process was repeated. 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)**.

$$GWRP = \sum_{i=1}^{n} (Ri * Ai * Syi) \quad (1)$$

Where **GWRP** is ground water recharge potential, **n** is number of polygons, **R** is rise/fall in GWL, **A** is area of polygon, $\mathbf{S_y}$ is the specific yield.

3. Results and Discussions

Statistical and geo-spatial analysis of data have revealed that ground water levels in study area are depleting and there was decreasing in aquifer storage on seasonal basis during the season of pre monsoon (Pre) 2015 to post monsoon (Post) 2020. Ground water levels at selected points (in each polygon) have been

analysed for pre-2015 to post-2020, to see the ground water level fluctuations. Result showed that the average water table was decreasing at different locations during pre-2015 to pre-2020. While, during post 2015 to post 2020 the average watertable will rise at different locations 4&5.

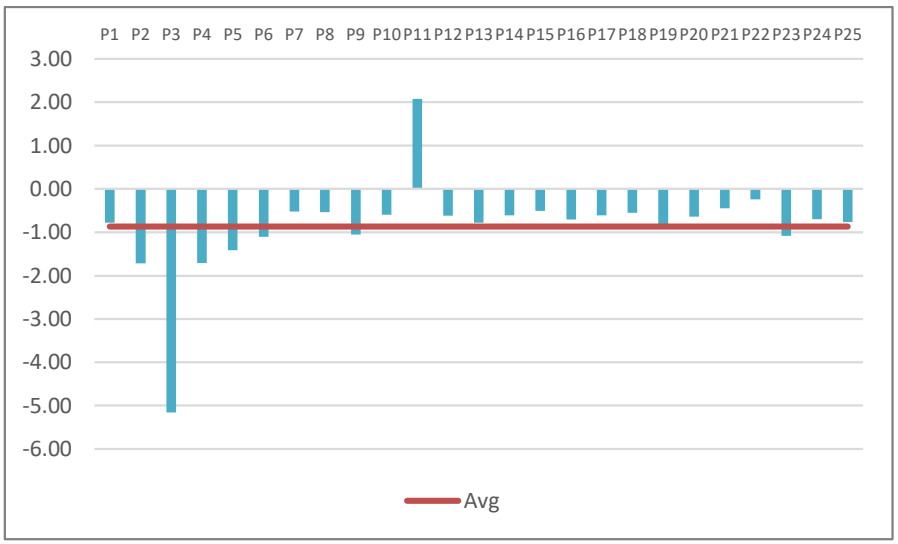


Figure-4. Average water level rise/fall (m) at different locations in Study Area in pre monsoon 2015-2020

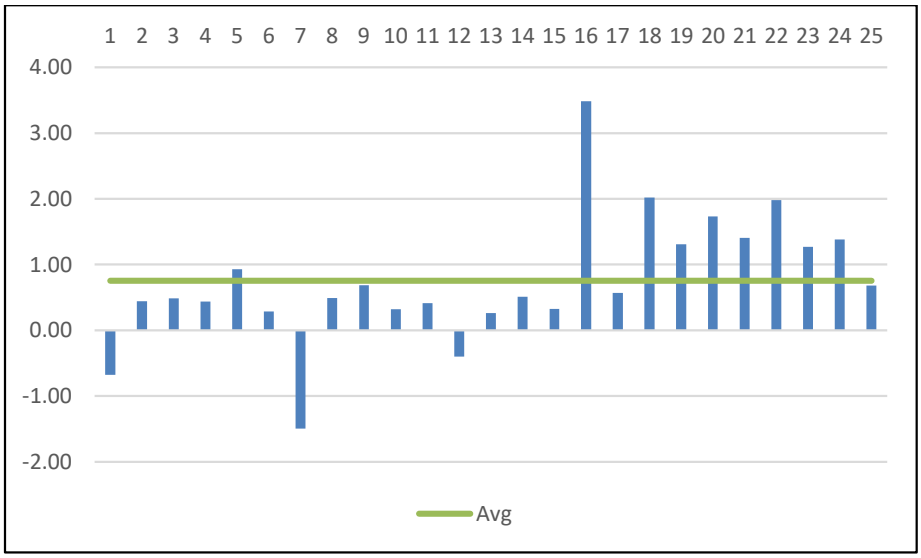


Figure-5. Average water level rise/fall (m) at different locations in Study Area in post monsoon 2015-2020

Summary of statistical parameters of depth to water table data has been given in Table from Pre 2015 to Post 2020.

Table-1: Statistics of Depth to watertable (DTWT) below natural land surface (m) 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
STD	4.5	4.3	4.6	4.4	4.5	4.3	4.5	4.3	4.5	4.4	4.6	4.4

*Pre monsoon **Post monsoon

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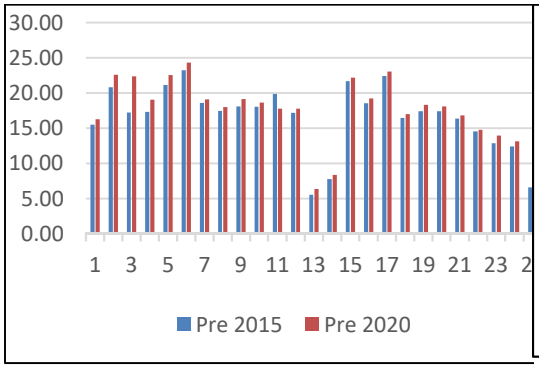


Figure-6: Depth to water table (DTWT-m) at different piezometers in Pre 2020 and Pre 2015

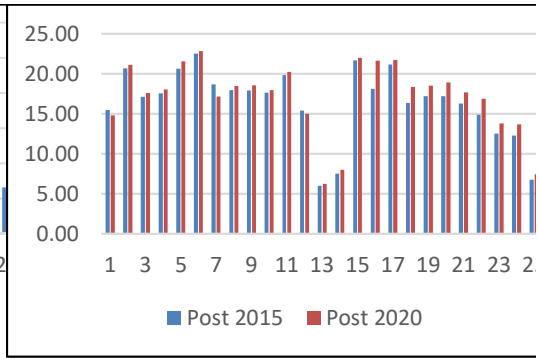


Figure-7: Depth to water table (DTWT-m) at different piezometers in Post 2020 and Post 2015

Table2 and Table3 show the statistics of DTWT in five years for post and pre monsoon, respectively. The maximum rise of DTWT was 3.49 m and fall was -1.49 m during post-monsoon periods. It indicates that the rise in water table during post 2015 and 2020, which indicates the aquifer storage was increased during post season (2015-2020). While The Maximum rise of DTWT was 2.08 m and fall was -5.16 m in pre-monsoon which indicates the overall depletion of aquifer and consequently the increase in aquifer storage from 2015 to 2020.

Table-2: Statistics of Depth to watertable (DTWT) 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
STD	0.97	0.19

The filling water table for the aquifer was considered as 5 m below the natural land surface to access the potential of available ground water storage. As above 5 m the root zone of crops is affected and trend of waterlogging starts **(IWASRI, 1995)** was selected. The increasing trend of GWRP for the Pre is shown in **Error! R eference source not found.** and for post is shown in **Error! Reference source not found.**.

Table-3: Statistics of Depth to watertable (DTWT) 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
STD	1.13	0.23

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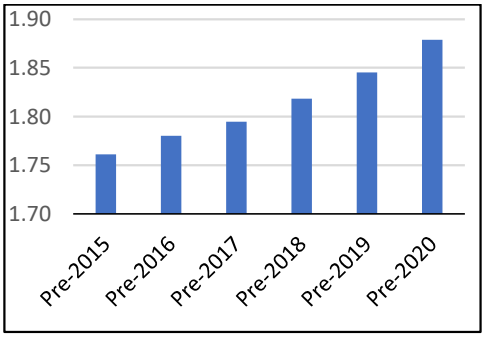


Figure-8: Increasing trend of GWRP for pre-2015 to pre-2020

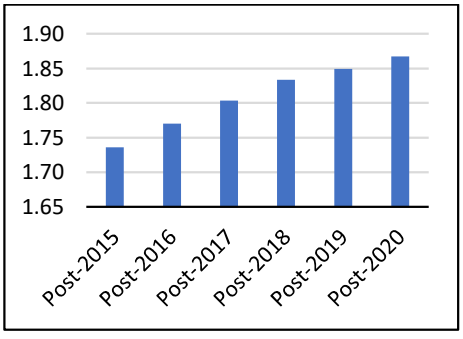


Figure-9: Increasing trend of GWRP for post-2015 to post-2020

Table4 shows GWRP (Pre 2015 to Pre 2020) in the study area, Punjab, Pakistan. This table indicate that the GWRP is increasing as we move from pre-2015 to pre-2020, which indicates decreasing trends of ground water table in the study area.

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

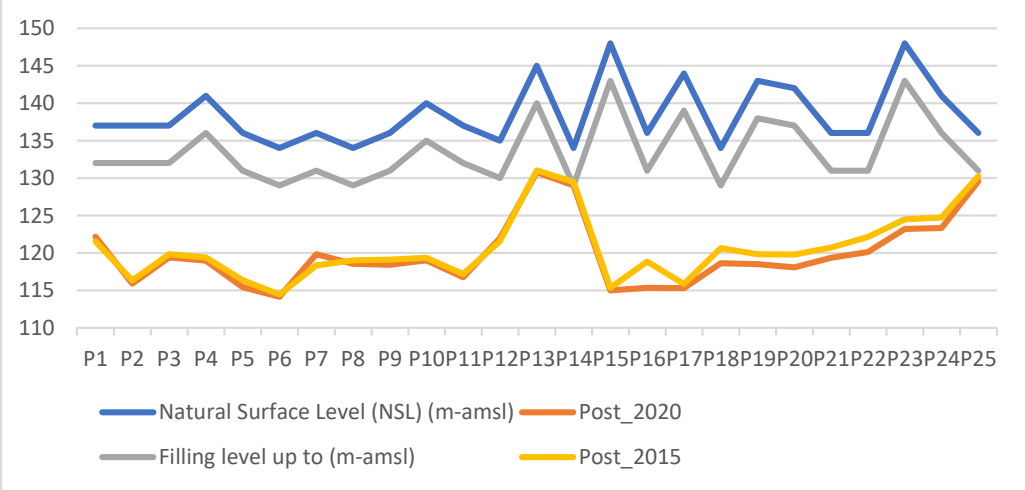


Figure-10: Ground water recharge potential during post-2020

Table5 shows GWRP (Post 2015 to Post 2020) in the study area. This table indicates that the GWRP is increasing as we move from post-2015 to post-2020, which indicates decreasing trends of ground water table in the study area Figure. This reveals that over the time the ground water reservoir is depleting, and storage potential is increasing. It has been found that Managed Aquifer Recharge (MAR) recharge project seems to be feasible as long as the underground storage potential

is concerned. A separate study has been carried out which has revealed that adequate flow of flood-water is available at Islam headworks during the monsoon period i.e., mainly the months of June and July **(IRI, 2019)**.

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

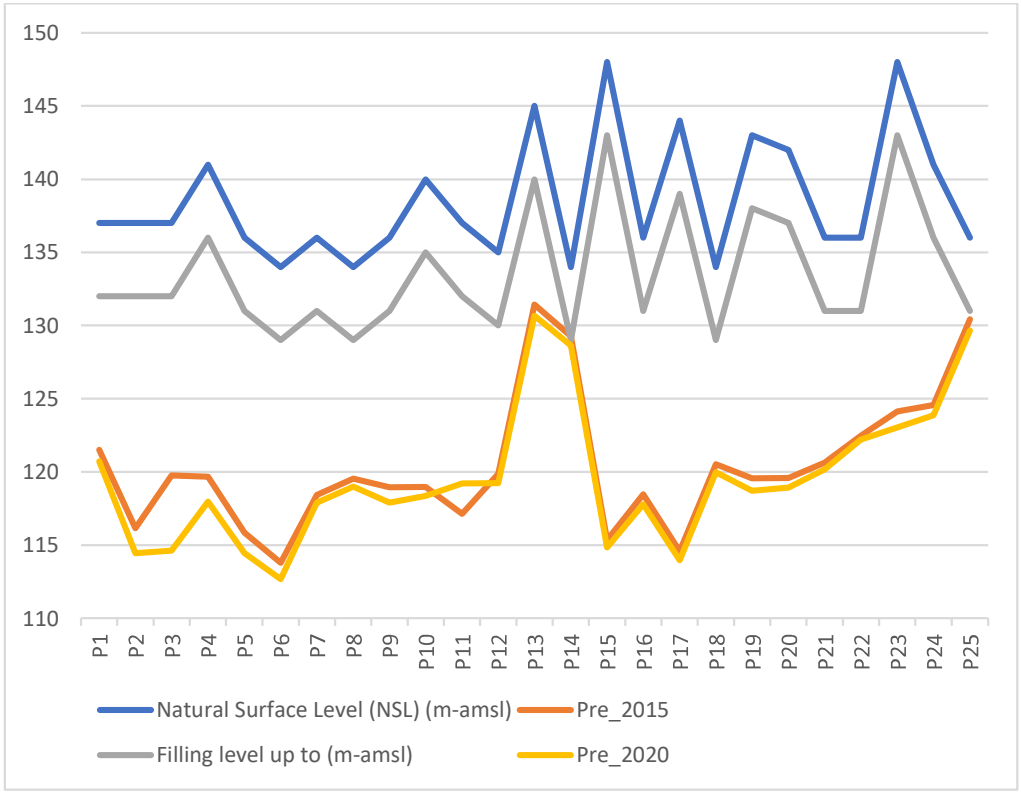


Figure-11: Ground water Recharge Potential in Pre 2020

4. Conclusion and Recommendations

4.1 Conclusions

According to research, the average water table drops by 0.87 meters from 2015 to 2020 and 0.75 meters. Using the specific yield approach, GWRP was 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. There are several uses for ground water which include industry, domestic, agriculture, aquaculture, cattle farming, and other commercial and miscellaneous sectors. Uncontrolled and unplanned over-pumping in freshwater regions due to rising food and fibre needs, untreated effluents (domestic, industrial, agricultural), lack of capacity and awareness, ineffective implementation of regulations, inadequate aquifer recharge (natural as well as artificial), population growth, low water use efficiency, changing cropping patterns, complex governance of ground water, diminishing and highly variable surface water supplies are the major impediments for sustainable use and management of ground water in the study area. Due to over-depletion of ground water reserves in the area cost of extraction have escalated manifolds. Farmers are shifting to solar power for ground water pumping due high prices of electricity, diesel and installing of deep wells. This trend of solar power may pose adverse impacts on ground water use- as the solar power may entail the lavish and wasteful use of ground water. Various government departments/agencies, as well as diverse stakeholders including managers, NGOs, consumers, extension workers do not communicate or coordinate with each other- rather prefer to work in isolation.

Ground water being generally fit for irrigation is depleting at the rate ranging from 0.30 to 0.70 m per year due to which cost of pumpage has increased tremendously. Ever increasing population and climatic changes are the major drivers for excessive use of ground water. Suitability of site for MAR project has been evaluated with respect to water availability, storage potential, ground water quality, soil strata to store flood water in the study area. Historical data of ground water levels from 25 observation wells in an area of 1522 km^2 have been analysed which have revealed the depletion of aquifer over the long-term basis. Study area has been divided in to 25 polygons using ArcMap10.6 software. Assessment of available storage capacity of aquifer in the project area has been carried using specific yield method. It has been found that the site is suitable for MAR project and can store about 1.88 km^3 in 2020, which is approximately 1.2 m depth of water over the whole study area of 1522 km^2. MAR can reduce the flood intensity besides improving the eco-hydrogeology and ground water availability. MAR can be a nature-based solution (NBS) for flood mitigation and well as for ground water sustainability.

4.2 Recommendations

i) There is an urgent need for a comprehensive ground water monitoring program to create ground water potential maps for more hydro-geological research.

ii) To slow the decline of the ground water reservoir, a variety of incentives, including strict regulation, enforcement, and well-targeted subsidies, can be used.
iii) Options for ground water management must be chosen, such as eliminating subsidies for crops that require a lot of water, charging for electricity, establishing a permit system for new wells and power lines, artificially replenishing aquifers with rainwater or flood water.
iv) Involvement of community for monitoring of aquifer levels and quality, recharge intervention by raising their awareness and capacity levels.
v) Subsidizing drip irrigation and other high efficiency irrigation systems- as saving of surface water will lessen the presser on ground water.
vi) The institutional and holistic regulatory framework with effective implementation mechanism for managing and monitoring ground water has to be strengthened and modernized.
vii) Initiatives and incentives to increase capacity and awareness among all stakeholders for and inclusive, responsive, and integrated collaboration in for sustainable use, management and governance of ground water. Aquifer User Association (AUA) shall be introduced.
viii) Formulation and effective implementation of IWRM including conjunctive use management of both surface and ground water framework and its application.

Reference

Abid, M., Scheffran, J., Schneider, U. A., & Elahi, E. (2019). Farmer Perceptions of Climate Change, Observed Trends and Adaptation of Agriculture in Pakistan. *Environ Manage, 63*(1), 110-123. doi:10.1007/s00267-018-1113-7

ADB. (2018). *Pakistan: Punjab Irrigated Agriculture Investment Program: Completion Report, Project Number: 37231-013, Asian Development Bank*. Retrieved from

Akhter, M., & Ormerod, K. J. (2015). The irrigation technozone: State power, expertise, and agrarian development in the U.S. West and British Punjab, 1880–1920. *Geoforum, 60*, 123-132. doi:10.1016/j.geoforum.2015.01.012

Asghar, A., & Zaidi, H. (1960). Soil survey, Rechna Doab, West Pakistan: West Pakistan Water and Power Development Authority (WAPDA), Water and Soils Inv. Div. *Bull, 2*, 21.

Azam, A., & Shafique, M. (2017). Agriculture in Pakistan and its Impact on Economy—A Review. *International Journal of Advanced Science and Technology, 103*, 47-60. doi:10.14257/ijast.2017.103.05

Bennett, G. D., Ata-Ur-Rehman, Sheikh, I. A., & Ali, S. (1967). *Analysis of Aquifer Tests in the Punjab Region of West Pakistan: Geological Survey Water-Supply Paper 1608-G, USGS, United States Government Printing Office, Washington D C*

Chinnasamy, P., Muthuwatta, L., Eriyagama, N., Pavelic, P., & Lagudu, S. (2017). Modeling the potential for flood water recharge to offset ground water depletion: a case study from the Ramganga basin, India. *Sustainable Water Resources Management, 4*(2), 331-344. doi:10.1007/s40899-017-0168-6

Dillon, P. (2005). Future management of aquifer recharge. *Hydrogeology journal, 13*(1), 313-316.

Dillon, P. (2009). Water recycling via managed aquifer recharge in Australia. *Boletín Geológico y Minero, 120*(2), 121-130.

Gale, I., Macdonald, D., Calow, R., Neumann, I., Moench, M., Kulkarni, H., . . . Palanisami, K. (2006). Managed aquifer recharge: an assessment of its role and effectiveness in watershed management: final report for DFID KAR project R8169, Augmenting ground water resources by artificial recharge: AGRAR.

Gale, I., Neumann, I., Calow, R., & Moench, d. M. (2002). The effectiveness of Artificial Recharge of ground water: a review.

Gilmartin, D. (2014). *Civilization and modernity: narrating the creation of Pakistan*: Yoda Press.

GOP. (2018). Pakistan Bureu of Statisctics, Governmnet of Pakistan: www.pbs.gov.pk/.

Greenman, D. W., Swarzenski, W. V., & Bennett, G. D. (1967). *Ground-Water Hydrology of Punjab-West Pakistan With Emphasis on Problems Caused by Canal Irrigation: Geological Survey Water-Supply Paper 1608-H, USGS, USAID, Washigton DC*.

Hassan, G. Z., & Bhutta, M. N. (1996). A water balance model to estimate ground water recharge in Rechna doab, Pakistan. *Irrigation and Drainage Systems, 10*, 297-317.

Hassan, G. Z., Hassan, F. R., & Shabbir, G. (2019). *Impact of climate change on ground water use for sustainable agriculture and food production in Indus Basin of Pakistan* Paper presented at the 1st International Conference on Sustainable Agriculture: Food Security under Changing Climate Scenarios: April, 3-5, 2019, Ghazi University, Dera Ghazi Khan, Punjab, Pakistan.

IAH-MAR. (2018). *International Association of Hydrogeologists Commission on Managing Aquifer Recharge. https://recharge.iah.org/*. Retrieved from

IGRAC. (2014). IGRAC MAR Portal International Ground water Resources Assessment Centre.

Imran, A. (2018). Global impact of climate change on water, soil resources and threat towards food security: evidence from Pakistan. *Adv Plants Agric Res, 8*(5), 350-355.

Imran, M., Ali, A., Ashfaq, M., Hassan, S., Culas, R., & Ma, C. (2018). Impact of Climate Smart Agriculture (CSA) Practices on Cotton Production and Livelihood of Farmers in Punjab, Pakistan. *Sustainability, 10*(6). doi:10.3390/su10062101

IRI. (2015). *Ground water Behavior in Rechna Doab-Punjab- Pakistan. : Research Report No IRR-GWMC/101, Ground water Management Cell, Irrigation Research Institute, Irrigation Department, Govt of the, Punjab, Lahore, Pakistan*.

IRI. (2019). *Recharge of aquifer for ground water management in Punjab (2016-2019): Report No IRR-GWMC/121, Ground water Management Cell, Irrigation Reserach Institute (IRI), Irrigation Department, Lahore, Pakistan*. Retrieved from

IWASRI. (1995). *Performance Evaluation of different Types of Canal Lining in FESS, Pakistan: Interim Report of Surface Water Section of the International Waterlogging and Salinity Research Institute (IWASRI), Lahore, Pakistan.* Retrieved from

Khalid, S., Shahid, M., Natasha, Shah, A. H., Saeed, F., Ali, M., . . . Dumat, C. (2020). Heavy metal contamination and exposure risk assessment via drinking ground water in Vehari, Pakistan. *Environ Sci Pollut Res Int, 27*(32), 39852-39864. doi:10.1007/s11356-020-10106-6

Maréchal, J. C., Dewandel, B., Ahmed, S., Galeazzi, L., & Zaidi, F. K. (2006). Combined estimation of specific yield and natural recharge in a semi-arid ground water basin with irrigated agriculture. *Journal of Hydrology, 329*(1-2), 281-293. doi:10.1016/j.jhydrol.2006.02.022

Missimer, T. M., Guo, W., Maliva, R. G., Rosas, J., & Jadoon, K. Z. (2015). Enhancement of wadi recharge using dams coupled with aquifer storage and recovery wells. *Environmental Earth Sciences, 73*(12), 7723-7731.

Muzammil, M., Zahid, A., & Breuer, L. (2020). Water Resources Management Strategies for Irrigated Agriculture in the Indus Basin of Pakistan. *Water, 12*(5). doi:10.3390/w12051429

Pakparvar, M., Walraevens, K., Cheraghi, S. A. M., Ghahari, G., Cornelis, W., Gabriels, D., & Kowsar, S. A. (2016). Assessment of ground water recharge influenced by flood water spreading: an integrated approach with limited accessible data. *Hydrological Sciences Journal*, 1-18. doi:10.1080/02626667.2016.1183164

Punthakey, J. F., Khan, M., Riaz, M., Javed, M., & Hassan, G. Z. (2016). *Intensive surface and ground water use and salinity impacts in Rechna Doab, Pakistan: 43IAH Congress, paper No 1674*. Paper presented at the 43rd IAH Congress 25-29 September, Montpellier, France

Qureshi, A. S., McCornick, P. G., Qadir, M., & Aslam, Z. (2008). Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agricultural Water Management, 95*(1), 1-10. doi:10.1016/j.agwat.2007.09.014

Qureshi, R. H., & Ashraf, M. (2019). Water security issues of agriculture in Pakistan: Pakistan Academy of Sciences (PAS), Islamabad, Pakistan, pp. 41., pp. 41.

Shiklomanov, I. A. (2000). Appraisal and assessment of world water resources. *Water International, 25*(1), 11-32.

Siddiqi, A., & Wescoat, J. L. (2013). Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan. *Water International, 38*(5), 571-586. doi:10.1080/02508060.2013.828671

Sindhu, A. S. (2010). *District Vehari: Hazard, vulnerability and development profile*: Rural Development Policy Institute (RDPI), Islamabad, Pakistan.

USGS. (1967). *Ground water hydrology of the Punjab- West Pakistan with emphasis on problem caused by canal irrigation* Retrieved from U.S. Government Printing Office Washington, D.C. 20402:

USGS. (2005). *Comparison of methods for estimating ground-water recharge and base flow at a small watershed underlain by fractured bedrock in the Eastern United States: Scientific Investigations Report 2005-5038; US Geological Survey (USGS), USA: http://www.usgs.gov/*. Retrieved from

WB. (2017). *Climate-Smart Agriculture in Pakistan. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); The World Bank. Washington, D.C. 28 p.*

Wescoat Jr, J., & Muhammad, A. (2021). Irrigated gardens of the Indus River Basin: new models for water resource management. *Water and the humanities: transforming currents for uncertain futures. University of California Press, Oakland*.

Wescoat Jr, J. L. (1999). The historical geography of Indus Basin management: a long-term perspective, 1500-2000. *The Indus River: biodiversity, resources, humankind*, 416-428.

Wisser, D., Frolking, S., Hagen, S., & Bierkens, M. F. (2013). Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs. *Water Resources Research, 49*(9), 5732-5739.

Zaidi, H., & Rehman, A. (1961). Soil survey, Chaj Doab, West Pakistan: West Pakistan Water and Power Development Authority, Water and Soils Inv. Div. *Bull, 4*, 20.

Zakir-Hassan, G., & Hassan, F. R. (2018). *Ground water reservoir as a source of flood water storage: A case study from Punjab, Pakistan: 8TH Asian Regional Conference of ICID on "Irrigation in Support of Evergreen Revolution" May 2-4, Kathmandu, Nepal.*

Zakir-Hassan, G., Hassan, F. R., Shabir, G., & Rafique, H. (2021). Impact of Floods on Ground water—A Case Study of Chaj Doab in Indus Basin of Pakistan.

International Journal of Food Science and Agriculture, 5(4), 639-653. doi:10.26855/ijfsa.2021.12.011

Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z., & Wei, L. (2014). United Nations World Water Development Report 2014: Water and Energy, Volume 1.