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Enhanced Groundwater Availability Through Managed Aquifer Recharge in Indus River Basin of Pakistan

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Abstract

Punjab, Pakistan, is experiencing severe groundwater depletion due to excessive and unplanned extraction, declining surface water availability, rapid population growth, and increasing climate variability. Groundwater has become the primary source of irrigation and drinking water across the province, contributing about 50%, 90% and 95% of the requirements of agricultural, domestic, and industrial water demands. Natural recharge rates have been reduced due to construction, pavements, and the lining of irrigation channels. This study presents the first pilot-scale Managed Aquifer Recharge (MAR) initiative implemented by the Irrigation Research Institute (IRI) of the Punjab Irrigation department. Floodwater has been diverted into the bed of the abandoned Old Mailsi Canal (OMC), which off-takes from Islam Headworks. About 144 recharge wells have been constructed in the bed of the OMC. During the 2025 flood season, approximately 12,000 acre-feet of floodwater was diverted and stored through engineered ponding, canal-bed rehabilitation, and recharge wells. A comprehensive monitoring program was established, including piezometers, automated data loggers, groundwater quality sampling, pumping tests, geophysical surveys, and sediment analyses. The results indicate a maximum groundwater level rise of up to 11 ft., with average increases ranging from 2.6 to 5.2 ft across the recharge ponds. Groundwater quality also showed an improvement following MAR implementation; electrical conductivity decreased from 900 to 650 µS/cm in Pond-I and from 850 to 750 µS/cm in Pond-III. These findings demonstrate that repurposing abandoned canal infrastructure for floodwater-based MAR provides a technically feasible, environmentally sustainable, and climate-resilient strategy for enhancing groundwater availability for sustainable management in Punjab and other water-stressed regions.

Keywords: managed aquifer recharge; floodwater harvesting; groundwater sustainability; Punjab; Pakistan; climate resilience

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1. Introduction

Groundwater is the principal source of irrigation, domestic, and industrial water supply in Punjab, Pakistan, underpinning regional food security and socio-economic development [1]. A tremendously increasing population coupled with global climatic changes are putting extraordinary pressure on global water resources, and, consequently,

aquifers are under stress [2,3]. Compared to conventional surface reservoirs, MAR offers substantial advantages in terms of reduced evaporation losses, naturally improved water quality, and enhanced resilience to climate variability [4–6]. Consequently, MAR has been widely implemented in arid and semi-arid regions of Australia, the United States, China, and India, using techniques such as spreading basins, recharge wells, riverbank filtration, and aquifer storage and recovery [7–10]. Improvements in groundwater quality have been reported in MAR projects implemented in many parts of the world where the infiltration of surface water has diluted saline groundwater and promoted beneficial geochemical reactions [5,7,9,11,12]. Subsurface geochemical processes may also contribute to water quality improvements during the MAR [13,14]. During infiltration, river water interacts with aquifer sediments, leading to ion exchange, mineral dissolution, and adsorption reactions, which can further stabilize groundwater chemistry [15,16].

MAR has emerged globally as an effective and adaptable strategy to enhance groundwater through intentionally recharging the aquifers using surface-water, storm-water, or floodwater under controlled conditions [1,4,17,18]. The over-pumping of aquifers poses adverse results like land subsidence and other related hazards. Research has indicated that large-scale land subsidence can cause flood amplification [19].

MAR is widely recognized as a type of Nature-Based Solution (NBS) because it works with natural hydrological processes to improve water availability and resilience. By enhancing the natural recharge of aquifers through methods such as infiltration basins, recharge wells, and restored landscapes, MAR provides sustainable water storage while supporting ecosystem functions. As a nature-based solution, MAR helps address water scarcity, climate variability, and groundwater depletion using approaches that integrate engineered systems with natural environmental processes. MAR demonstrates how nature-based solutions can deliver multiple co-benefits, including improved water security, drought resilience, reduced flood risk, and healthier groundwater-dependent ecosystems. The implementation of MAR aligns with global NBS principles by promoting sustainable groundwater management, climate adaptation, and long-term environmental resilience.

Despite the proven success elsewhere, MAR remains underutilized in Pakistan due to the limited adaptation to local conditions, low awareness of its cost-effectiveness, and weak institutional support [1,20]. The existing initiatives are small-scale, fragmented, and poorly documented, with little scientific evaluation. The National Water Policy 2018 [21] emphasizes the promotion of technically and economically feasible options for the artificial recharge of groundwater. MAR has potential and can be adopted as a tool for enhancing groundwater storage leading towards sustainable food production in the Indus Basin of Pakistan [22,23].

Surface water supplies, historically the backbone of Punjab's irrigation system, have become increasingly unreliable due to the sedimentation of reservoirs, aging conveyance infrastructure, and growing inter-annual variability in river flows [24–26]. Climate change has further amplified hydrological extremes, increasing the frequency and magnitude of floods during monsoon seasons while intensifying drought conditions during dry periods [27–29]. The domestic water demand projections show an increase from 2.91 BCM in 2017 to 5.49 BCM in 2050 in Punjab [30], and similar increasing trends in agricultural and industrial water demands have been reported [29].

Punjab's groundwater mosaic has shifted dramatically over recent decades—from a drainage burden in the 1980s, to a livelihood opportunity in the 2000s, and, now, to an environmental concern in the 2020s as shown in Figure 1. The past two to three decades witnessed exponential growth in tube wells, driven by the need to produce more food for a growing population [26]. Market forces, ease of technology, and attractive returns on investment further accelerated adoption [22]. The rapid growth of tube-wells has led

to the persistent over-abstraction of groundwater resources across the province [31]. In many areas, groundwater extraction now exceeds natural recharge, resulting in declining water tables, increasing pumping costs, and the deterioration of groundwater quality. Groundwater contamination around Lahore, a city with a population of 14 million, has raised serious health concerns [32]. These trends pose a serious threat to long-term water security and climate resilience in Pakistan's most productive agricultural region. Urban centers like Lahore—the provincial capital—are facing the challenges of groundwater depletion and quality as well [33].

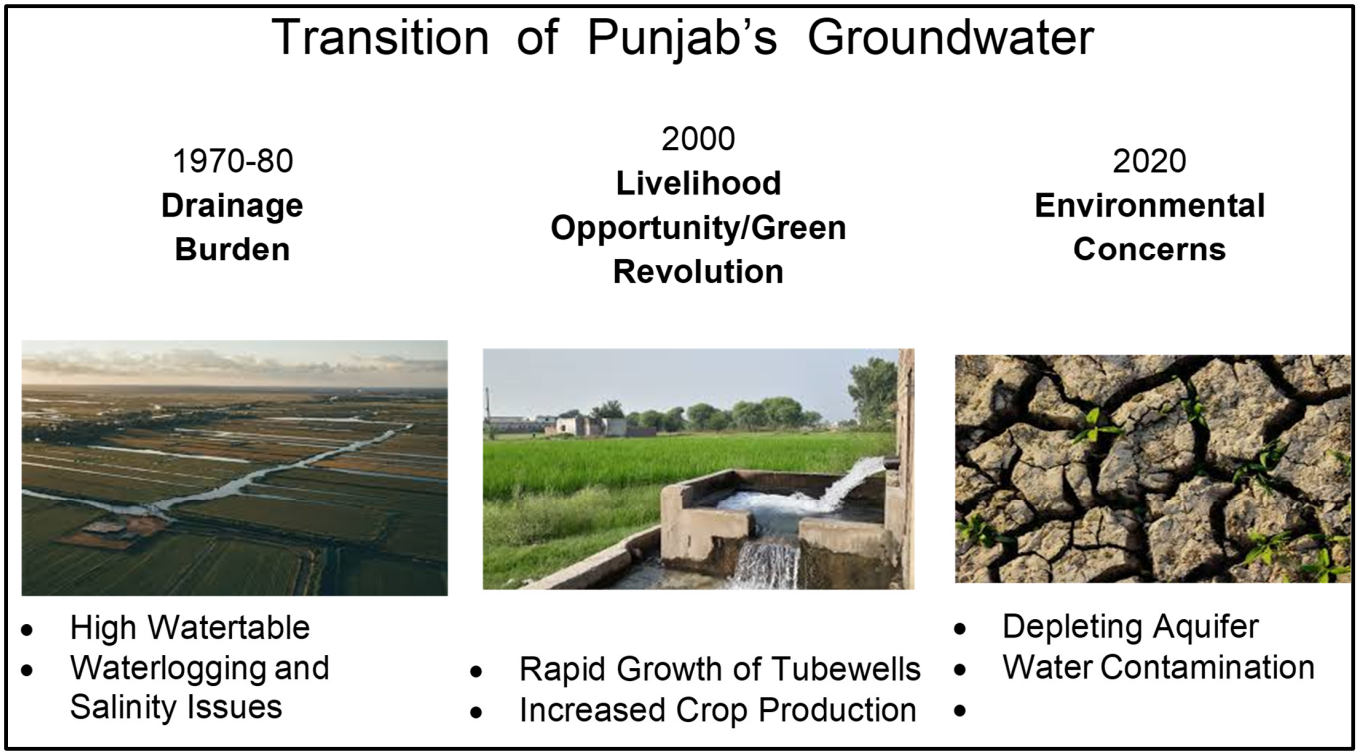


Figure 1. Historical transition of groundwater in Punjab, Pakistan.

Although floods are often perceived primarily as hazards, they also represent a substantial but largely underutilized water resource. In most cases, floodwater is rapidly conveyed downstream and lost to the sea, while adjacent aquifers continue to experience depletion. Punjab Water Policy 2018 [34] recognizes groundwater depletion and pollution as the main threat to sustainable development. MAR offers an opportunity to reduce the water supply stress in some of the critically water scarce regions. Floods and rains are a major source of water, which, when in surplus, can be harvested for beneficial storage through MAR [34].

A promising but overlooked option is the reuse of abandoned irrigation canals for groundwater recharge. Punjab's extensive canal network, partly decommissioned after the Indus Waters Treaty, offers a ready-made infrastructure for floodwater harvesting and large-scale MAR. Their linear geometry, established rights-of-way, and proximity to floodwater sources make them a cost-effective alternative to new construction [35]. Punjab Water Policy 2018 [34] encourages the beneficial use of floodwater through artificial groundwater recharge, where feasible. The reuse of abandoned canal infrastructure further reduces the capital costs and land acquisition requirements, making this approach particularly suitable for large-scale implementation in Punjab in the Indus Basin of Pakistan and other similar water-stressed regions of South Asia [36].

In response to the escalating groundwater depletion and increasing flood risks, the Government of Punjab, through the Irrigation Research Institute (IRI), initiated the country's first pilot-scale floodwater-based MAR project using the abandoned Old Mailsi Canal (OMC) off-taking from Islam Headworks [37]. The project aims to evaluate the technical viability, recharge efficiency, and groundwater-quality impacts of diverting surplus floodwater into the canal and recharging underlying aquifers through controlled ponding and recharge wells.

This paper presents the design, implementation, and performance assessment of this pioneering MAR initiative with specific objectives, as found under [38]:

i. Quantify the groundwater-level responses to floodwater recharge under different experimental configurations;
ii. Assess the changes in groundwater quality associated with MAR operations;
iii. Generate scientific evidence and operational insights to support scaling up MAR interventions across Punjab and similar alluvial settings.

By demonstrating the productive reuse of abandoned canal infrastructure for groundwater recharge, this study contributes a novel, cost-effective, and climate-resilient approach to groundwater management in Pakistan and other water-stressed regions of South Asia.

2. Materials and Methods

2.1. Study Area

The study area is located along the Old Mailsi Canal between RD (reduced distance—a unit to measure canal length commonly used in South Asia region—1 RD = 1000 ft.) 0 and RD 45, off-taking from Islam Headworks in southern Punjab. The canal was originally constructed in 1924 to convey irrigation supplies from the Sutlej River. Following the Indus Waters Treaty of 1960 [39], flows in the Sutlej River were significantly reduced, rendering the canal non-operational. The canal was formally abandoned in 1965 and curtailed up to RD 129 [40]. The abandoned canal corridor provides a unique opportunity for groundwater recharge due to its existing right-of-way, linear geometry, and proximity to floodwater sources. The surrounding area is characterized by intensively cultivated agricultural land, with cropping patterns dominated by wheat, cotton, sugarcane, and fodder crops. Groundwater abstraction through private tube wells is widespread, and long-term monitoring data indicate a persistent decline in groundwater levels [38]. Hydrogeologically, the area comprises thick alluvial deposits of sand, silt, and clay with varying permeability. Shallow aquifers are generally unconfined and respond rapidly to recharge events. These conditions make the study area well-suited for controlled MAR experiments using surface and floodwater [1]. Study area with major features is shown in Figure 2. There is network of piezometers for monitoring of groundwater levels and quality on an approximate grid of 6 × 6 km. Recently, about twenty online automatic data loggers have been installed in the study area to observe and record the temporal and spatial changes in groundwater levels and quality [36]. The data on the geology and bore longs in the area is available in [1].

2.2. Project Design and Infrastructure

The MAR project involved rehabilitation of the Old Mailsi Canal (OMC) head regulator, reconditioning of the earthen canal section between RD 0 and RD 45, and installation of recharge wells. Canal has been divided into three sections, each called a pond. Construction of cross-regulators is carried out to divide the canal into three canal ponds, with each canal pond to be used as infiltration basin. One of the canal sections has been equipped with additional recharge wells in the canal bed. Cross-regulators are the hydraulic structure to completely cut off the flow of water in the canal, to keep the three infiltration ponds

separate from each other. Additional infrastructure included road crossings, inspection huts, and monitoring facilities to support long-term operation and data collection. Major project components [36] included the following:

- Rehabilitation of the canal head regulator at Islam Headworks;
- Rehabilitation of the earthen canal section (RD 0–45);
- Construction of cross-regulators to establish recharge ponds;
- Development of three experimental ponds with distinct recharge configurations;
- Construction of 144 recharge wells (6′ × 10′) in Pond-III;
- Construction of road crossings, inspection huts, and meteorological observatory;
- Installation of lines of piezometers and data loggers for monitoring of groundwater levels and quality;
- Installation and calibration of gauges to observe the floodwater being diverted to the canal;
- Field testing and investigations including drilling of bore-holes, electrical resistivity surveys, infiltration tests, and permeability tests.

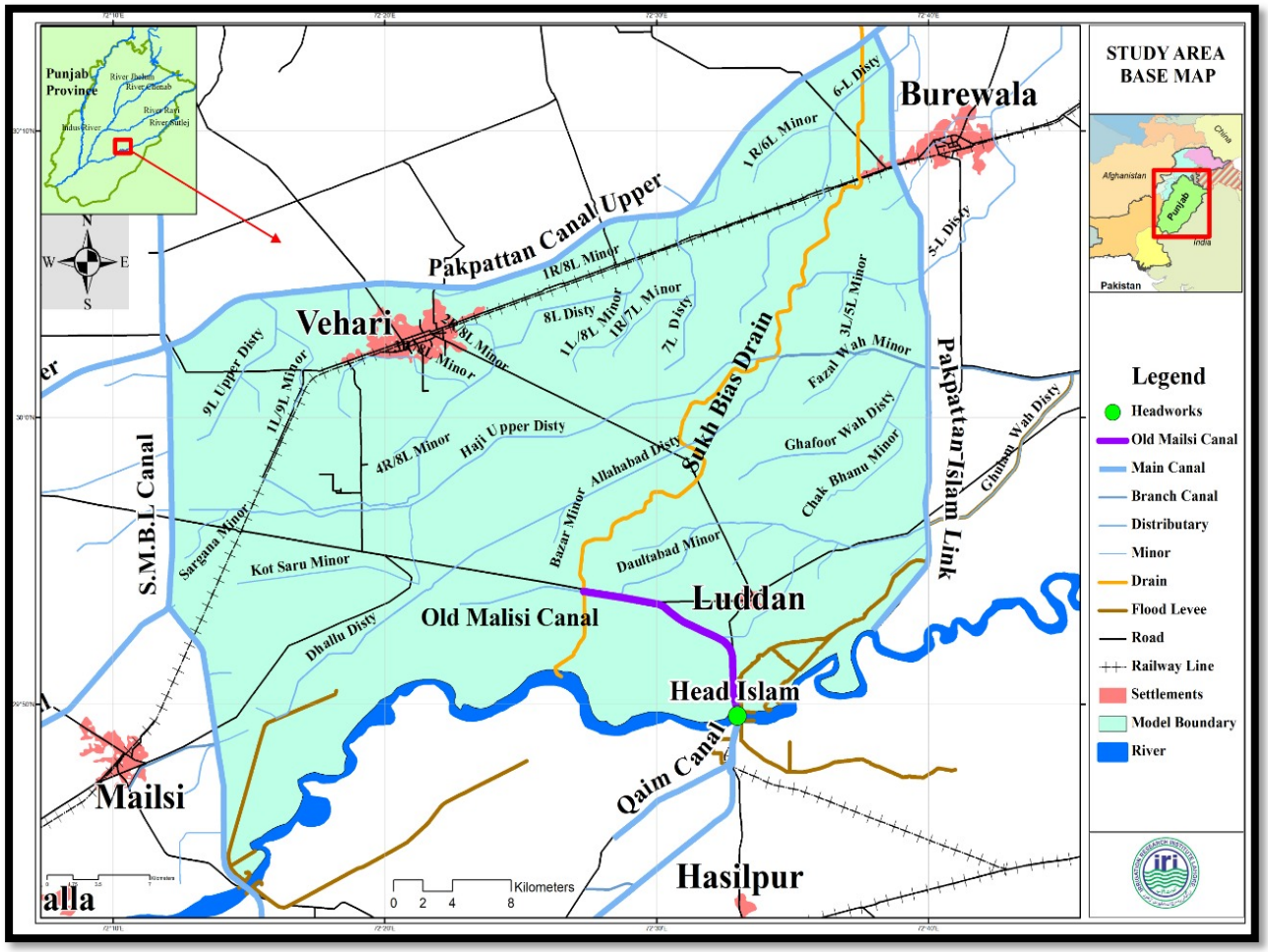


Figure 2. Location of the study area showing major features.

Three experimental ponds were developed to assess recharge performance under different design configurations, which are shown in Box 1.

Flood and surplus water from Islam Headworks was diverted into the Old Mailsi Canal during the 2025 flood season. Water releases were managed to maintain controlled ponding depths, minimize erosion, and optimize infiltration. Approximately 12,000 acre-feet of floodwater was diverted into the canal over the monitoring period, for recharging

the aquifer through three ponds. A view of head regulator and three ponds filled with floodwater during the MAR project implementation in 2025 flood season is shown in Figure 3.

Box 1. Design configuration of three ponds at MAR site.

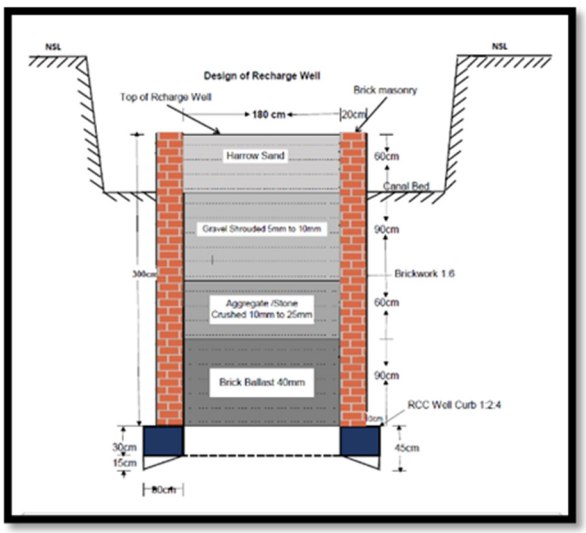
Pond-I (RD 0–19) was excavated and dressed to the approved design bed level, representing natural canal bed conditions.
Pond-II (RD 19–30) was excavated below the design bed level by removing the relatively less pervious clay layer to a depth of approximately 2 ft to enhance the infiltration rate.
Pond-III (RD 30–45) was excavated to the design bed level and supplemented with recharge wells measuring 6 ft deep and 10 ft deep, installed at 100 ft intervals in the canal. bed.



Figure 3. A view of head regulator and filled ponds for MAR at Old Mailsi Canal.

The canal is primarily operated for floodwater conveyance and managed aquifer recharge during the flood season. Outside the flooding season, the canal generally carries little or no flow depending on regional water availability and operational requirements.

About 144 recharge wells have been constructed in the bed of canal in Pond 3 to accelerate the infiltration rates. Design and filed pictures of recharge wells are depicted in Figure 4.



Drawing of the Recharge Well



View of the Recharge Wells in the Canal Bed



View of the Recharge Wells



View of the Recharge Wells

Figure 4. Different views at site and design of recharge well.

2.3. Monitoring and Investigations

A comprehensive monitoring network was established, including piezometers and automatic data loggers to record groundwater levels and electrical conductivity as shown in Figure 5. A line of piezometers in the center of each pond was installed perpendicular to the canal/pond. Daily data on groundwater water levels was observed during the implementation of MAR project at site. Groundwater samples were collected periodically for laboratory analysis, including major ions and heavy metals. Pumping tests and permeability tests were conducted to determine aquifer parameters, while geophysical investigations using electrical resistivity surveys supported subsurface characterization. Sediment sampling

and soil analysis were carried out to assess infiltration constraints and potential impacts on water quality [1]:

RP = Right-side piezometer;

LP = Left-side piezometer.

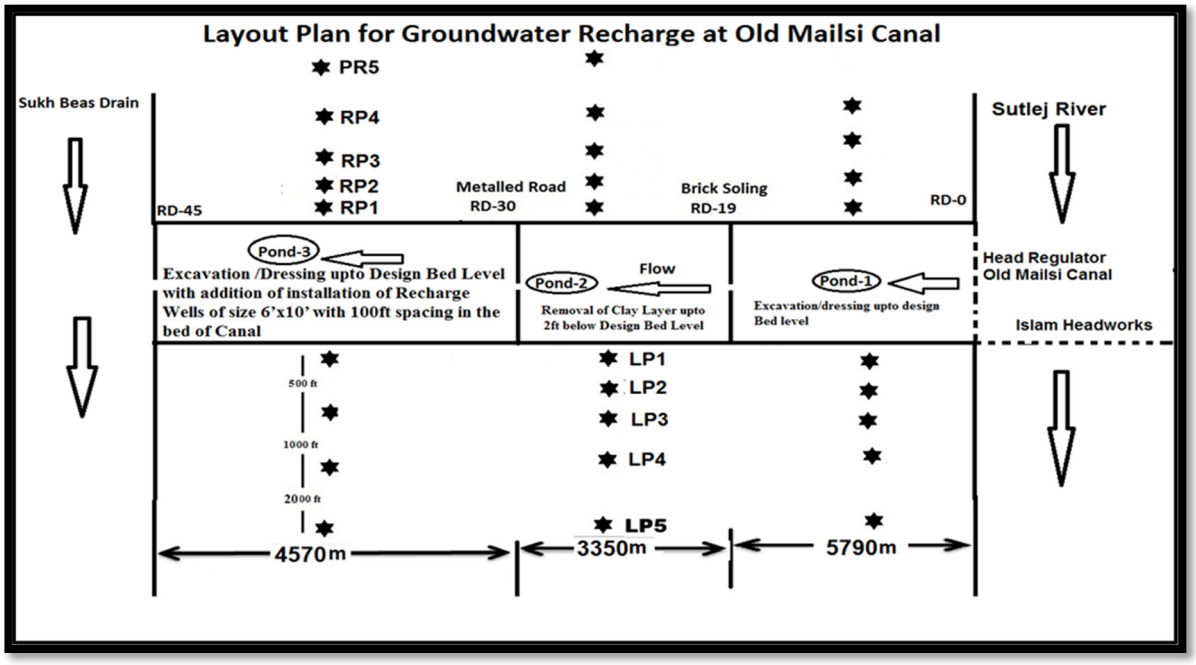


Figure 5. Experimental layout of MAR project [1].

3. Results and Discussions

3.1. Groundwater Level Response

Significant increases in groundwater levels were observed across the monitoring network following the diversion and ponding of floodwater in the rehabilitated section of the Old Mailsi Canal. The observed groundwater responses confirm the effectiveness of floodwater-based MAR under the hydrogeological conditions of the Indus alluvial plain.

Across the three experimental ponds, groundwater levels exhibited a clear rising trend during the recharge period, indicating rapid infiltration through the canal bed and lateral groundwater movement within the unconfined alluvial aquifer system. The diversion of approximately 12,000 acre-feet of floodwater into the rehabilitated Old Mailsi Canal during the 2025 flood season produced a clear and measurable response in the underlying aquifer system. Groundwater levels increased significantly across the monitoring wells surrounding the recharge ponds, confirming that a large proportion of the diverted water infiltrated through the canal bed and contributed to aquifer storage [37]. A rapid groundwater rise indicates high hydraulic conductivity within the alluvial sediments underlying the bed of canal. Alluvial aquifers consisting primarily of sand and sandy loam typically allow rapid vertical infiltration and lateral groundwater movement, making them highly suitable for surface-spreading MAR systems [41].

The monitoring well at RD-13 recorded a rise in the water table by 11 feet during May 2025, demonstrating that recharge effects extended beyond the immediate ponding area and influenced regional groundwater conditions. An average 5–11 ft rise in the water table occurred along the canal. Substantial groundwater level rises were observed following floodwater recharge across the study area [42]. The pond-wise results observed are described in the following sections:

Pond-I: Pond-I exhibited the highest recharge response among the three experimental configurations, being in the beginning of the experimental setup. The maximum groundwater level rise of 11 ft has been observed in this pond with an average increase of 5.2 ft as shown in Figures 6 and 7. Another reason for the higher water table rise in Pond 1 is the fact that this pond is closer to the Sutlej River, which contributes towards recharging the aquifer.

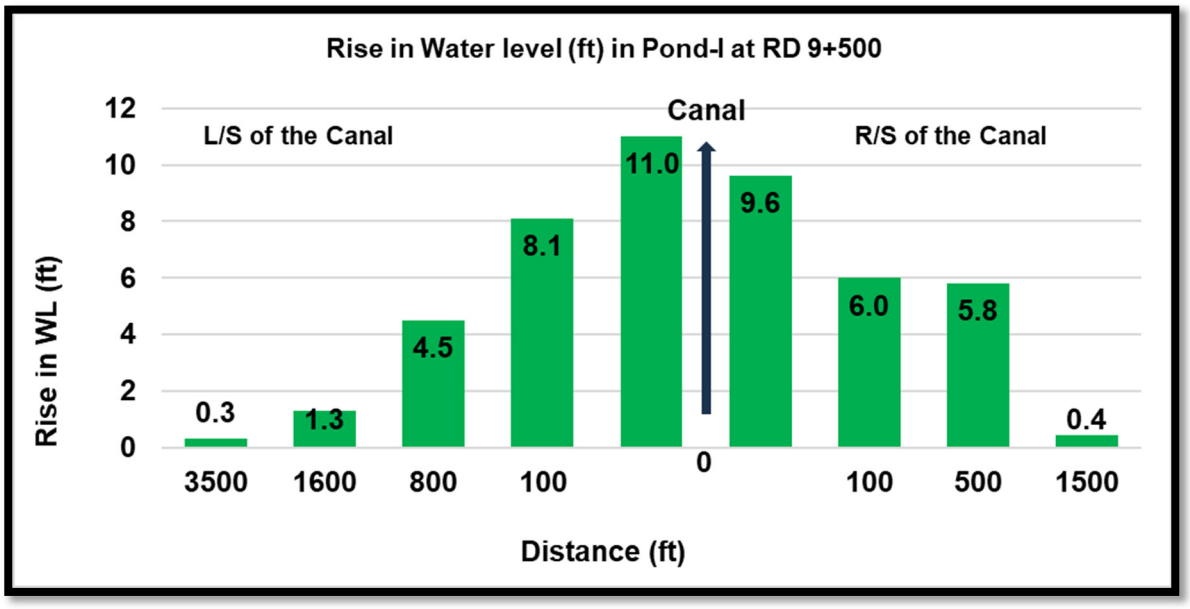


Figure 6. Rise in water level in first pond at RD 9 + 500.

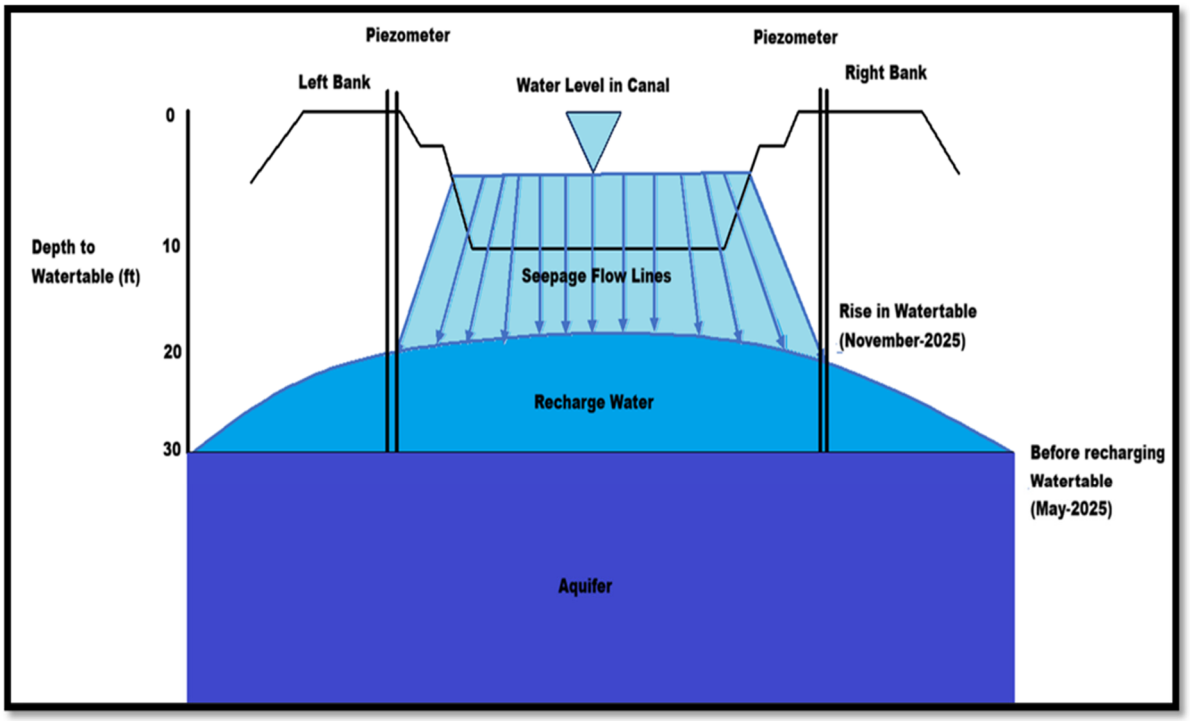


Figure 7. Conceptual diagram for MAR results, Old Mailsi Canal, district Vehari, Punjab.

The relatively high hydraulic conductivity of the canal bed sediments in this section allowed for the efficient infiltration of ponded floodwater. The absence of significant low-permeability layers at the pond base likely facilitated vertical percolation and lateral

redistribution within the aquifer. This is in line with the documented subsurface lithology [1]. These results are consistent with previous studies indicating that spreading basins and infiltration ponds are among the most effective MAR techniques in coarse alluvial aquifers [4,5]. Water was released in the canal section (Pond-I) on 29 May 2025, and the rise in the water level was observed as shown in the graph. When the water release/discharge decreases into the canal from the head due to some unavoidable situation, the water level starts go down. Data logger records at RD 13 (Pond 1) further confirmed the recharge rates of a similar impact to MAR on groundwater levels as shown in Figure 8.

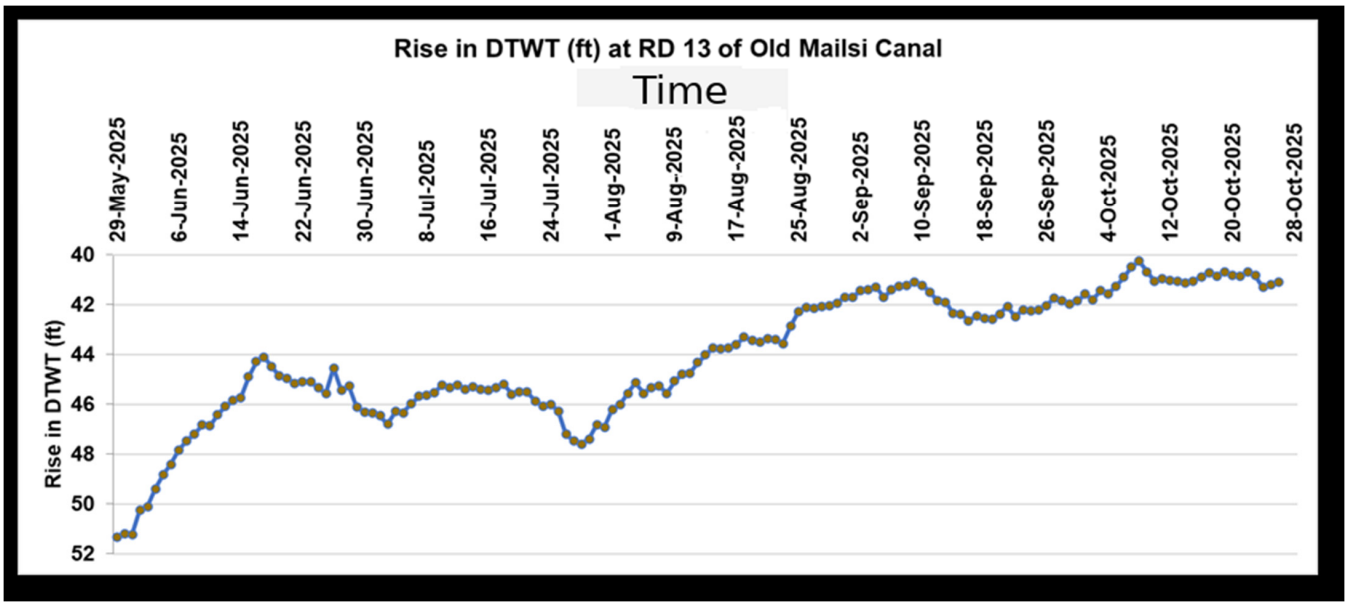


Figure 8. Depth to water table rise of 11 feet recorded by data logger at RD 13.

Pond-II: The removal of a 2 ft-thick clay layer significantly enhanced infiltration rates. Clay layers often act as hydraulic barriers that limit vertical percolation. Their removal allowed recharge water to directly infiltrate into the more permeable sandy aquifer beneath. Similar findings have been reported in MAR studies where surface-clogging layers reduce infiltration rates and require periodic maintenance to maintain recharge efficiency. Effective sediment management is therefore critical for the long-term performance of infiltration basins. Water was released in the canal section (Pond-II) on 20 August 2025, and the rise in the water level was observed as shown in the graph. When the water release/discharge decreases into the canal from the gates due to some unavoidable situation, the water level starts to go down. The depth to the water table reduced from 64 ft to 58.5 ft after releasing water in the second pond as shown by the data logger installed at RD 19 on the left side of the Old Mailsi Canal (Figure 9). This indicated a water table rise of 6.5 ft.

Pond-III: A different recharge strategy has been designed for this pond which involves vertical recharge wells installed within the canal bed to facilitate deeper infiltration pathways. About 144 recharge wells have been constructed in the bed of the canal to accelerate the recharge process. The results of the water table rise in Pond 3 recorded by the data logger at RD 37 of the canal are shown in Figure 10.

A summary of the design parameters and resulting rise in the water table in the three ponds is tabulated in Table 1.

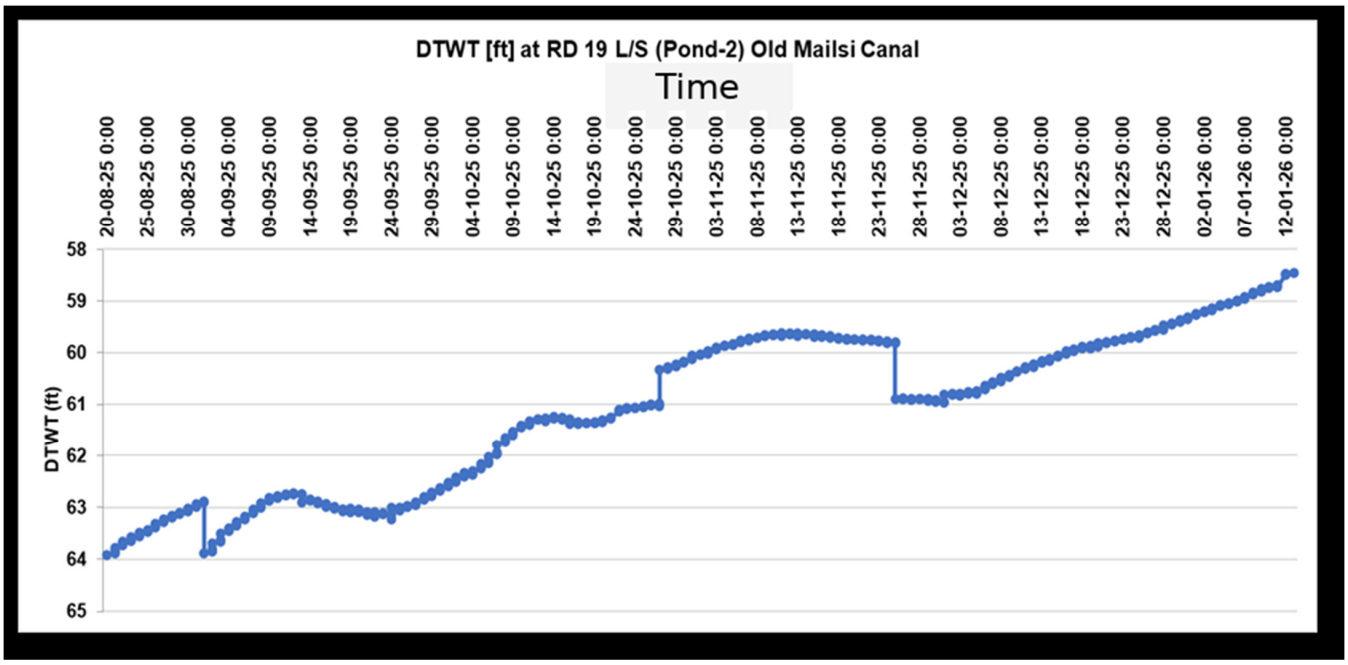


Figure 9. Depth to water table rise of 5 ft recorded in data logger at RD 19 (Pond 2).

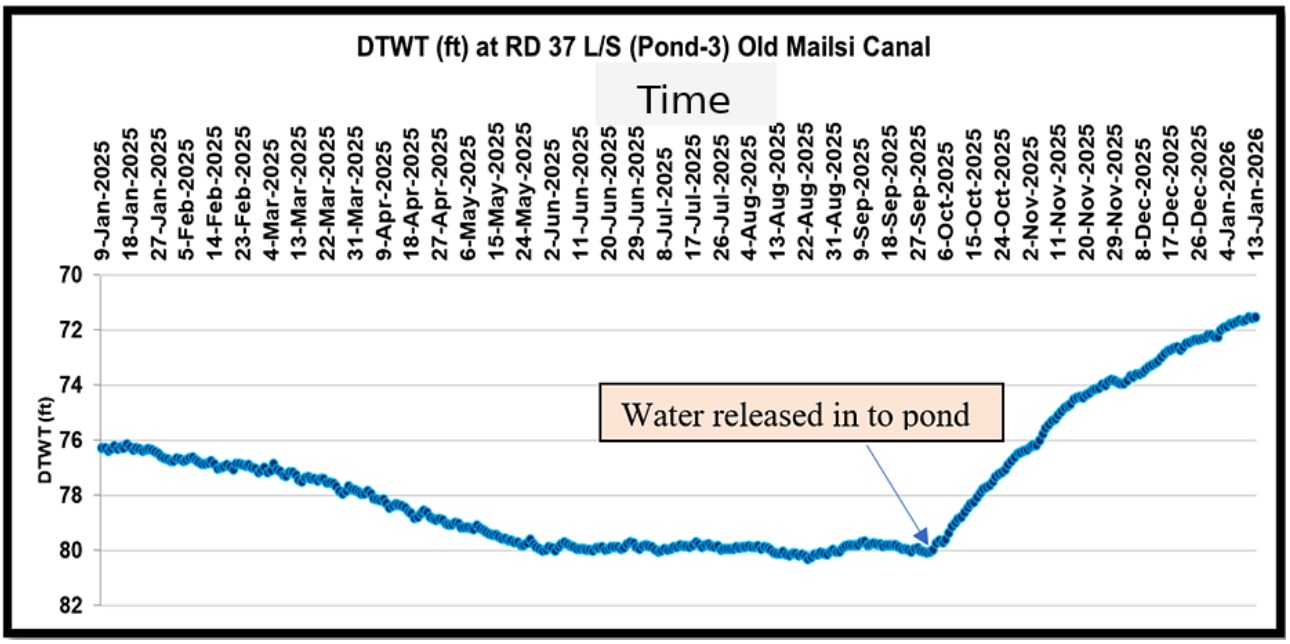


Figure 10. Depth to water table rise of 9 feet recorded by data logger at RD 37 + 500 (Pond 3).

Table 1. Summary of impact of Managed Aquifer Recharge (MAR).

Sr. No.	Storage Capacity (Cubic Meter)	Length (m)	Width (m)		Water Depth in Canal (m)	Avg Wetted Perimeter (m)	Piezometers Installed at RDs of Old Mailsi Canal (OMC)	Rise of Watertable (ft.)		
			Bed Width	Top Width				Min	Max	Avg
Pond-I	916,476	5791	47	53	3.14	56	At RD 9 + 500	0.3	11	5.2
Pond-II	625,374	3353	46	53	3.75	57	At RD 23 + 740	0.9	10.4	4.9
Pond-III	722,819	4572	47	53	3.14	56	At RD 37 + 500	0.13	8.48	4.3

The recharge wells can provide important advantages under long-term operation, particularly in areas where surface infiltration becomes limited due to sediment clogging or fine-grained deposits. Vertical recharge structures have been widely used in MAR systems worldwide to enhance the recharge efficiency in heterogeneous aquifer environments [43–45].

The improved infiltration performance highlights the importance of surface sediment characteristics and permeability contrasts in determining recharge efficiency. The removal of fine-grained sediment layers has been shown to substantially enhance infiltration rates in recharge basins by reducing hydraulic resistance [7,46]. Although the maximum rise was slightly lower than that observed in Pond-I, the performance of Pond-II demonstrates that the targeted modification of canal bed sediments can significantly improve MAR effectiveness, particularly in systems where natural clogging layers exist. Overall, the groundwater responses observed across the three ponds demonstrate that floodwater ponding within abandoned canal systems can generate a rapid and measurable aquifer recharge, particularly in permeable alluvial aquifers typical of the Indus Basin. People of the area are pleased with the results and have benefited from a reduction in pumping costs. Hand pumps which had long become dry have been noted to be working again after the execution of the MAR project. This is a data-supported and visually observed success story of the MAR project. The project has improved the eco-hydrology of the area. Dry trees have been witnessed to turn green.

It is further added that this area serves as a food-basket for national food security. Groundwater is a major source of livelihood; adequate underground storage potential is also available, and the sub-surface geology is supportive for MAR. A water balance study has been performed for this area [1], which covers the detailed information about the aquifer parameters and infiltration rates. The underground storage potential has been estimated by [41]. A groundwater modeling study has also been carried out for this area [43].

3.2. Groundwater Quality Improvement

In addition to increasing groundwater storage, the MAR system produced measurable improvements in groundwater quality, particularly in terms of salinity reduction. Electrical conductivity (EC) measurements showed a noticeable reduction during the recharge period. In Pond-I, EC decreased from 900 µS/cm to 650 µS/cm, indicating the dilution of saline groundwater by relatively fresh floodwater [47]. Here, it is important to elaborate that the aquifer has been recharged through the natural recharge through floods in the river as well as the managed recharge through the canal bed. Floodwater recharge introduces low-salinity surface water into the aquifer system, which can dilute accumulated salts and improve groundwater quality. In addition, subsurface geochemical processes such as ion exchange, mineral dissolution, and adsorption may further modify groundwater chemistry during infiltration [1]. The absence of heavy metal contamination in groundwater samples suggests that the recharge process did not mobilize harmful trace elements from aquifer sediments, indicating that floodwater from the Sutlej River is suitable for recharge operations. Further studies on the heavy metals in the region have been performed [1].

In addition to increasing groundwater storage, the MAR intervention resulted in measurable improvements in groundwater quality. Electrical conductivity (EC) values decreased from 900 µS/cm to 650 µS/cm in Pond-I (RD 13) and from 850 µS/cm to approximately 750 µS/cm in Pond-III (RD 37 + 500). These reductions indicate the results of the dilution of relatively saline groundwater by the infiltration of lower-salinity floodwater. Water was released in the canal section (Pond-I) on 29 May 2025 and on 25 September 2025 in Pond-III of the canal. The results recorded by the data loggers are shown in Figures 11 and 12 for Pond 1 and Pond 3, respectively.

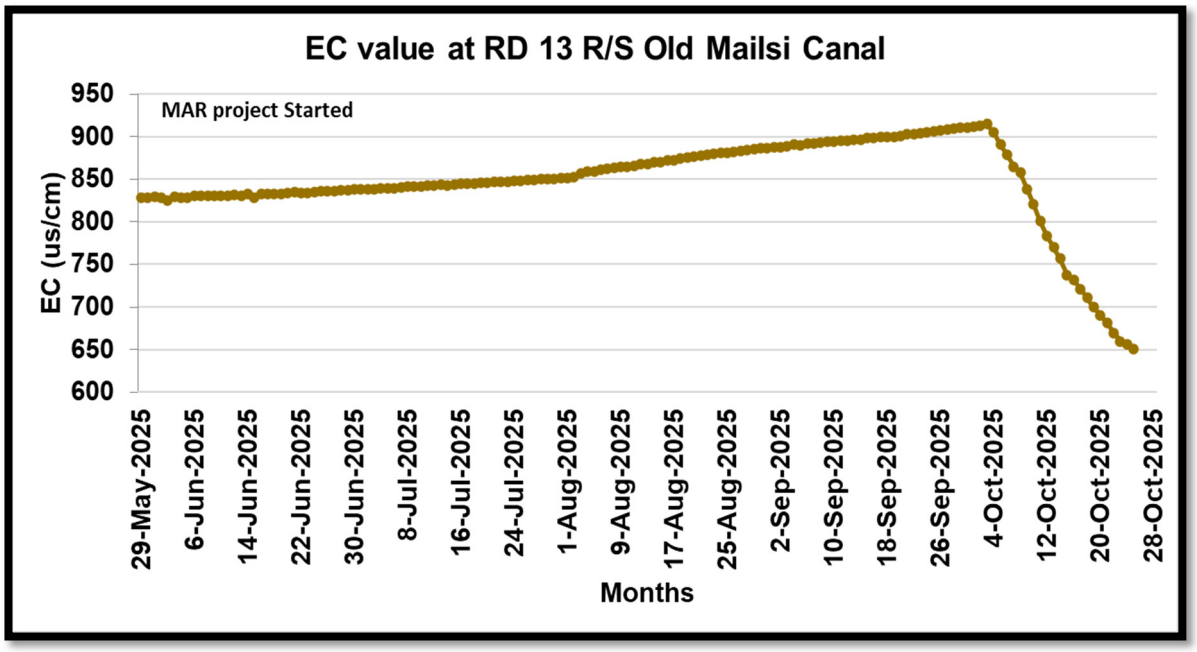


Figure 11. Decrease in Ec values as recorded at Pond 1 (data logger at RD 13).

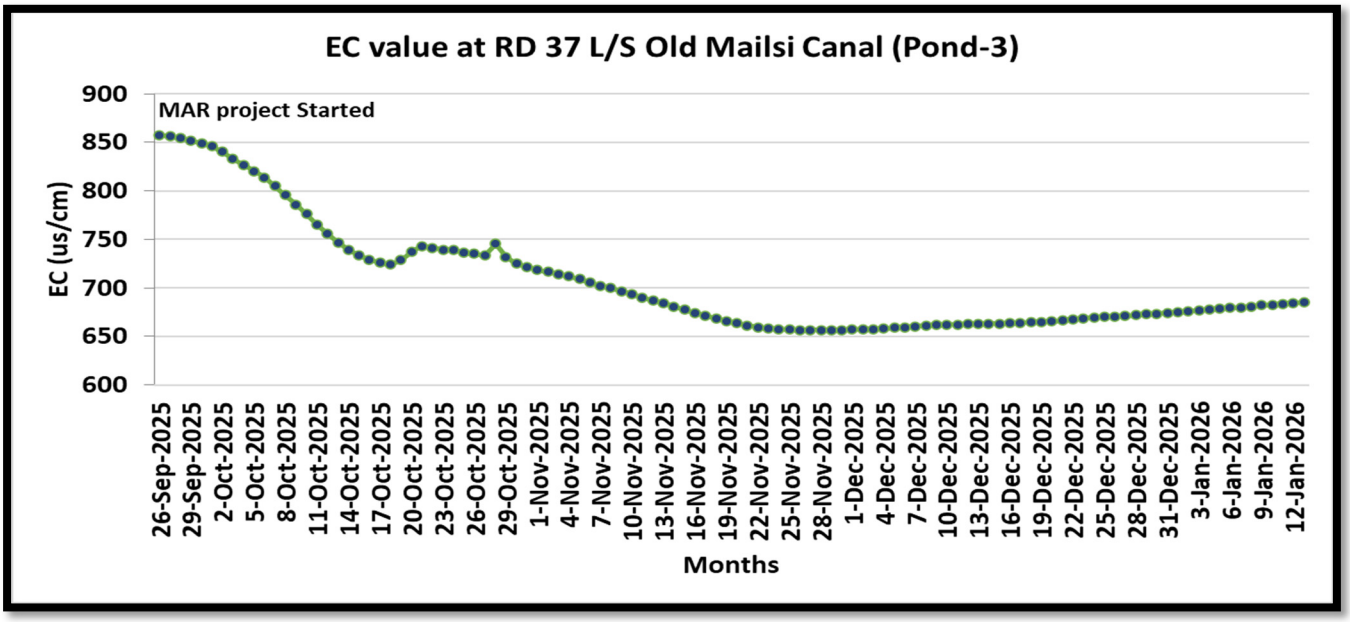


Figure 12. Decrease in Ec values as recorded at Pond 3 (data logger at RD 37 + 500).

In addition to the data loggers, twenty-one points were fixed for the groundwater quality analysis along the Old Mailsi Canal from RD 0 to 45. The electrical conductivity (EC) displayed significant variation over time. Several locations including Chaudhry Petroleum (RD 29), PL2 (RD 37/R), and (23 + 740) exhibited extremely high EC values (3000–4200 µS/cm) during August and September, indicating high salinity levels due to the reduced groundwater recharge. With the onset of the monsoon recharge in early October, the EC values dropped sharply at multiple sites, such as RD 29, where EC decreased from 4190 to 701 µS/cm, confirming the strong influence of seasonal dilution as given in Table S1 (Supplementary Materials). Other sites, such as RD 8 and RD 13, showed relatively stable EC levels throughout the period. The overall results indicate that the quality improves along the Old Mailsi Canal after releasing the floodwater into the canal. This suggests that the diverted floodwater was of acceptable quality. These findings

indicate that floodwater-based MAR can simultaneously improve groundwater quantity and quality, making it particularly suitable for regions experiencing both water scarcity and groundwater salinization. Similar results have already been observed by [47].

3.3. Hydrogeological Response and Discussions

The groundwater level responses observed in the Old Mailsi Canal pilot project clearly demonstrate the effectiveness of floodwater-based MAR under the hydrogeological conditions of the alluvial plains of the Indus Basin. The recorded groundwater level increases, ranging from 2.59 to 3.35 m across the experimental ponds, indicate that a substantial portion of the diverted floodwater infiltrated through the canal bed and contributed to aquifer storage.

The spatial differences in the groundwater rise observed between the three recharge ponds highlight the importance of local sediment characteristics and recharge design in determining infiltration performance. Pond-I exhibited the highest groundwater response, indicating that the canal bed sediments in this section likely possess a higher permeability and fewer fine-grained layers restricting infiltration.

Another important and obvious reason for the higher water table is the fact that Pond 1 is located closer to the Sutlej River, which has surely contributed towards enhancing the aquifer storage. During flood season, there were higher flows in the river which contributed to the aquifer recharge in addition to the MAR.

A slightly lower groundwater rise has been observed in Pond-III which can be attributed to the localized recharge mechanism associated with recharge wells. The lower rise is due to this pond being further away from the river and the water table being deeper as compared to Ponds 2 and 3. These findings are consistent with previous studies demonstrating that surface-spreading techniques generally achieve higher short-term recharge rates in permeable alluvial aquifers, whereas recharge wells can be advantageous in areas where surface infiltration becomes limited by sediment clogging or low-permeability layers [4,5,48].

The observed reduction in depth to groundwater from 15.85 to 12.50 m at RD-13 during the monitoring period further confirms that recharge impacts extended beyond the immediate ponding area and influenced the regional groundwater system. Such rapid responses suggest efficient subsurface flow pathways and indicate that the aquifer possesses sufficient transmissivity to distribute recharged water laterally.

The recharge performance observed in the Old Mailsi Canal MAR project is comparable to results reported in several international studies. Groundwater level increases of 1.52–3.05 m following MAR operations have been reported in recharge projects in India, Bangladesh, and northern China [49,50]. The maximum groundwater rise of 3.35 m observed in this study therefore represents a highly significant recharge response.

The groundwater responses observed in this study are comparable with results reported from MAR projects implemented in other semi-arid regions. Studies from India, Australia, and northern China have documented groundwater level increases ranging from 1 to 3.05 m following seasonal recharge through spreading basins or infiltration ponds.

The maximum groundwater rise of 3.35 m recorded in this study therefore represents a relatively strong aquifer response compared with many existing MAR implementations. One possible explanation for this high recharge efficiency is the favorable hydrogeological conditions of the Indus alluvial aquifer system, which typically consists of thick, permeable sediment sequences capable of storing large volumes of groundwater.

3.4. Less Land Acquisition and Infrastructure Costs

One of the most notable aspects of this project is the repurposing of abandoned irrigation infrastructure for groundwater recharge. Many MAR projects worldwide require the construction of new spreading basins or recharge facilities, which can involve significant land acquisition and infrastructure costs.

In contrast, the use of an existing canal right-of-way significantly reduces capital investment while providing a large linear recharge surface. Similar approaches have been successfully implemented in parts of Australia and the western United States, where existing irrigation channels and flood basins are used to enhance groundwater recharge [4,5,27].

The observed improvements in groundwater quality are consistent with international MAR studies, where dilution and geochemical interactions lead to reduced salinity and improved suitability for irrigation and drinking purposes. The results of this study demonstrate that floodwater-based managed aquifer recharge (MAR) using abandoned canal infrastructure can significantly enhance groundwater storage and quality in semi-arid alluvial settings.

Given the extensive irrigation infrastructure within the Indus Basin, the use of abandoned canal offers considerable potential for scaling up MAR implementation across the region.

The Indus Basin Irrigation System (IBIS) contains thousands of kilometers of canals, many of which experience seasonal or partial under-utilization.

Punjab province is currently experiencing severe groundwater depletion driven by rapid agricultural expansion, increasing irrigation demand, and declining canal water availability. In many districts, groundwater abstraction exceeds natural recharge, leading to progressive declines in water table levels and increased pumping costs for farmers. Punjab is one the most vulnerable provinces with respect to groundwater over-extraction in South Asia driven by intensive irrigation pumping, declining canal supplies, and increasing climate variability [32]. The results of this pilot project demonstrate that floodwater harvesting through MAR offers a practical and scalable solution for enhancing groundwater availability in the Indus Basin. Diverting surplus floodwater into abandoned or underutilized canal systems allows the temporary storage and infiltration of large volumes of water that would otherwise flow downstream and remain unused.

3.5. Regional Water Management

The successful implementation of the Old Mailsi Canal pilot project therefore provides important evidence supporting the integration of MAR into regional water management strategies. With appropriate planning, monitoring, and maintenance, similar recharge systems could be developed across other abandoned or seasonal canals within the Indus irrigation network. Such initiatives would contribute to climate-resilient water management by capturing episodic floodwater events and converting them into long-term groundwater storage, thereby enhancing water security for agriculture and rural communities. Key advantages of this approach include the following: (i) the utilization of surplus floodwater that would otherwise flow downstream to the sea; (ii) reduced evaporation losses compared to surface reservoirs; (iii) an improvement in groundwater quality through dilution and natural filtration; (iv) the cost-effective reuse of existing canal infrastructure, and enhanced resilience to climate variability and extreme hydrological events. If implemented at scale across the canal network of Punjab, floodwater-based MAR could play a major role in stabilizing groundwater levels and supporting sustainable agricultural production in the Indus Basin. Furthermore, the successful outcomes of this pilot project provide valuable scientific evidence to support national initiatives such as the Recharge Pakistan Program,

which aims to enhance water security through nature-based solutions and climate-resilient water management strategies.

4. Conclusions and Recommendations

This study shows that using floodwater for managed aquifer recharge (MAR), by rehabilitating the Old Mailsi Canal, can be a practical way to restore groundwater levels in alluvial over-exploited aquifers like in the South Punjab regions in Pakistan. Diverting about 12,000 acre-feet of floodwater led to a rise of 5–11 feet in nearby wells, which is a significant improvement and evidence of success. The removal of low-permeability clay layers helped water soak into the ground more easily, making the recharge process more effective. At the same time, the incoming floodwater—being relatively fresh—helped dilute saline groundwater, improving the overall quality of groundwater. This has enhanced the availability of groundwater both in quantitative and qualitative aspects.

Another key takeaway is that the benefits were not limited just to the recharge ponds; groundwater levels increased over a broader area, showing that the aquifer is well-connected and can spread the recharge effects over a larger area. This means that even a few well-planned recharge sites can positively impact a much larger region, making MAR a strong option for managing groundwater resources more efficiently on the basin and sub-basin level. Overall, the study highlights that reviving unused canal systems for MAR is both cost-effective and scalable, especially in regions like Punjab where groundwater is under heavy stress. Expanding this approach across the wider canal network could play an important role in minimizing the effects of the over-extraction of aquifers. This project is a successful step towards improving long-term water security, ensuring food security. Another lesson learnt from this project is that community is very responsive and towards the MAR project, as this project has created a lot of opportunities of livelihood for them. One evidence observed at site is that the cost of the extraction of groundwater has reduced. Gender mainstreaming and social inclusiveness can be another support for such a nature-based solution for the sustainable use of groundwater, as involving youth and women in such interventions can enhance the success rates of the projects.

Future efforts should focus on tracking these impacts over time, using models to better understand groundwater behavior, and addressing practical challenges like clogging and changing climate conditions. The project also underscores the importance of robust monitoring frameworks, sediment management, and adaptive operation to ensure long-term sustainability and minimize environmental risks. There is a clear need to move from pilot projects to wider implementation. Suitable locations should be carefully selected, especially in areas facing severe groundwater decline. Simple steps like managing the sediment in floodwater and regularly maintaining recharge sites can go a long way in keeping the system efficient. Strengthening monitoring systems will also help in making better decisions and improving performance over time. Most importantly, MAR should be integrated into broader water management planning so that it becomes a regular part of how water resources are managed, rather than a one-off solution.

Since the ponds were located at different sites and operated under varying initial water levels and local hydrogeological conditions, a direct quantitative comparison among measures may introduce uncertainty and bias. This study represents the overall MAR demonstration site. Further ion data is required to be collected and analyzed to identify the geochemical processes to predict and distinguish the changes in groundwater quality due to dilution and subsurface processes as the water travel through porous media to the aquifer.

This is the first run of an MA project on the ground. Many further studies, analyses, and investigations are recommended. Statistical tests are recommended to be performed

once a time series of observation is available for testing significance and carrying out the sensitivity analysis of different parameters.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18111371/s1, Table S1: Groundwater quality along and in the vicinity of Old Mailsi Canal.

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Abbreviations

The following abbreviations are used in this manuscript:

OMC	Old Mailsi Canal
MAR	Managed Aquifer Recharge
IRI	Irrigation Research Institute
PID	Punjab Irrigation Department
FRS	Field Research Station
RD	Reduced Distance

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