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# Rainwater Harvesting for Managed Aquifer Recharge (MAR)—A Case Study from Urban Centre in Punjab Pakistan

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**Abstract:** Rising trends in global population have resulted in increased urbanization, industrialization, and food demands. This has resulted in the rapidly increasing water demands for domestic, agricultural and industrial sectors; which have severely depleted groundwater resources in Pakistan. The urban centres like Lahore city—the capital of Punjab province and the 2$^{nd}$ largest city of Pakistan. To address this challenge, a field-scale Managed Aquifer Recharge (MAR) system integrated with Rainwater Harvesting (RWH) was developed and tested to evaluate its feasibility and efficiency for urban groundwater recovery. In this system, rainwater collected from paved surfaces was filtered and injected into a Pleistocene sand aquifer through recharge wells. Double filtration mechanism has been introduced in the model to ensure good quality rainwater is recharged into the aquifer. Field monitoring during multiple rainfall events demonstrated successful infiltration and aquifer-storage, with recharge volumes of 150,700, 281,097, and 89,887 L of rainwater corresponding to potential domestic water supplies for 132, 246, and 79 days for an average household respectively. The results confirm that decentralized RWH–MAR systems can significantly enhance aquifer replenishment in overexploited urban aquifers. The study underscores the viability of such systems for broader implementation in Punjab and other similar semi-arid regions, contributing to sustainable groundwater management and urban water resilience in Pakistan.

**Keywords:** Rainwater Harvesting (RWH); Managed Aquifer Recharge (MAR); Lahore; Punjab; Pakistan

## 1. Introduction

Groundwater resources in Pakistan are undergoing rapid depletion due to accelerated urbanization, increased water demand, and reduced natural aquifer recharge. These challenges are further intensified by changing monsoon patterns and extreme precipitation events linked to climate change, particularly within the Ravi Basin [1]. Global research has indicated that rainwater can be used through MAR to enhance the groundwater availability [2]. According to Vision 2025, Pakistan may experience severe water shortages in the near future, posing critical risks to domestic water supply, food security, and economic stability [3]. In Pakistan, the agricultural sector's growing dependence on groundwater further exacerbates the problem, as surface water resources are increasingly insufficient to meet demand [4]. Different human activities contaminate groundwater, care must be taken during RWH for MAR [5].

Efforts to achieve sustainable freshwater management in Pakistan have primarily focused on centralized approaches, emphasizing the development of alternative water sources rather than optimizing local recharge and conservation systems [6]. Rainwater harvesting can be used effectively for recharging the aquifers to alleviate water scarcity. and alleviate pressure on conventional water reservoir [7]. Physico-Chemical properties of groundwater during different seasons help to analyse the behavioural characterization of the groundwater [8]. The central role of groundwater in meeting domestic, industrial, and agricultural needs, comprehensive assessments of its status remain limited. Lahore, the second-largest metropolitan area in Pakistan, exemplifies the severity of this issue, with groundwater levels declining rapidly due to unsustainable pumping by municipal authorities, private housing societies, and industries. This decline is compounded by reduced recharge zones, low flows in the Ravi River, and frequent urban flooding during the monsoon season.

This study investigates the potential of decentralized RWH and MAR systems to mitigate groundwater depletion in Lahore. Previous research has demonstrated the effectiveness of RWH as a sustainable engineering solution for enhancing groundwater storage [9–12], with additional benefits such as energy savings—each meter rise in groundwater level can save approximately 0.4 kWh of electricity [13]. In 2018, the International Research Institute (IRI) implemented an experimental RWH–MAR system at its Experimental Research Station in Thokar Niaz Beg, Lahore, under the Punjab Government's Annual Development Program. The system provides a platform to evaluate the technical feasibility and performance of RWH–MAR approaches under local hydrogeological and climatic conditions. Although global case studies compiled by UNESCO [14] highlight the broad application of MAR, many small-scale or micro-level systems remain under-documented, particularly regarding recharge quantification, groundwater recovery, and post-recharge water quality. Data from the IRI experiment aims to address these limitations by contributing empirical evidence on RWH–MAR effectiveness in urban Pakistan.

Lahore, the second-largest urban center in Pakistan, exemplifies the severity of this issue. The city's groundwater levels are declining by approximately 0.5–1.0 m annually due to uncontrolled abstraction by municipal, industrial, and private users. In addition, reduced infiltration areas, low surface flows in the Ravi River, and recurrent monsoon flooding have further restricted natural recharge.

Although previous studies have highlighted the potential of Managed Aquifer Recharge (MAR) and Rainwater Harvesting (RWH) for sustaining groundwater resources, their integrated application and field-scale validation under Pakistan's semi-arid and rapidly urbanizing conditions remain limited. This study introduces a field-based RWH–MAR system specifically designed for Lahore's hydrogeological environment, providing quantitative insights into its recharge efficiency, water quality, and scalability. Groundwater quality must be taken into account while implementing any MAR scheme as it poses severe effects on human health [15].

Research aims to evaluate the technical feasibility and effectiveness of a decentralized RWH–MAR system for augmenting urban groundwater resources in Lahore, Pakistan. Previously, rainwater was harvested but not used for recharging the depleting aquifer under Lahore city [16]. Objectives of this research study consist of utilizing rainwater for groundwater recharge, managing storm drainage and sewerage load on existing drainage system, and establishing a policy for an appropriate rainwater harvesting system and techniques (collection, diversion, storage, sedimentation, filtration, and groundwater recharge) in Lahore and other parts of the Punjab Province under varying local conditions. This is a novel approach being adopted and implemented in the $2^{nd}$ largest city of Pakistan. Research studies have been carried out which have concluded that the rainfall, if captured directly or from rooftops, green plots, etc., is suitable for recharging [17].

- Assess the potential of rainwater harvesting for groundwater recharge in Lahore;
- Design and evaluate a sustainable RWH–MAR model tailored to local conditions;
- Monitor the impacts of RWH–MAR implementation on groundwater levels and quality;
- Develop policy recommendations for the adoption of decentralized recharge systems in other urban areas of Punjab.

## 2. Data and Methodology

### 2.1. Studied Site and Data Sources

The experimental work was carried out at the Experimental Research Station (ERS), Thokar Niaz Beg Lahore, where one recharge well has been constructed as the most practical MAR approach for use with surface runoff RWH methods for use in this urban area. The purpose of the work was to create artificial aquifer recharge for the city of Lahore. The Lahore metropolitan area is ranked as the world's most populous urban area and is Pakistan's second-largest city. It covers a total area of 1,014 $km^2$ and is located between 31°15′–31°45′ N and 74°01′–74°39′ E. The Irrigation Research Institute under the ADP Scheme designed and constructed a recharge well as a pilot project at ERS Thokar Niaz Beg Lahore on an Engineering Procurement Construction (EPC) basis. The performance evaluation of recharge wells based on recharge rate and ponding area clearance time, as well as the analysis of recharged water's water quality, are related to post-harvesting measures.

Daily rainfall data was collected from the Pakistan Meteorological Department (PMD) [18], Lahore office and also measured from the rain gauge installed at the site for rainwater runoff estimation. Samples of rainwater collected during the monsoon season were sent to the laboratory of the Irrigation Research Institute (IRI) for physiochemical analysis. Recharge well performance was the subject of data collection. An experimental setup was used to measure how well the recharge wells' filtering mechanism worked.

The rapid population growth and increase in urbanized areas have increased pressure on the limited available GW resources in Lahore, as the city's population has increased three times over the last three decades [19]. The other factor which has affected the groundwater recharge is the decrease due to physical activities, which has affected water quality and quantity. Rainwater can also be used for drinking [20]. Throughout recent years, and even more significantly since the mid of the 1990s, expanding private lodging has resulted in reducing the groundwater recharge area due to the increase of impervious surface area due to the expansion of the urbanized area. Groundwater cannot be recharged in this manner by this mushrooming of the concrete jungle, which is crucial to its sustainability.

### 2.2. Layout of Rainfall Harvesting Model

**Figure 1** illustrates the conceptual and operational layout of the rainwater harvesting (RWH) system designed for artificial groundwater recharge at the study site, ERS Thokar Niaz Beg Park, Lahore. The system comprises several integrated components: Rainwater Collection Surface: Rainwater is captured from paved areas and rooftops, which serve as primary catchments. Rooftop collection is prioritized to minimize contamination from urban runoff containing sediments, oils, and heavy metals. Pre-Filtration Unit: Collected rainwater passes through a coarse filter and sediment trap to remove debris, suspended solids, and other contaminants. This ensures that only relatively clean water enters the recharge well, preventing clogging and preserving infiltration efficiency. Recharge Well/Injection Borehole: Filtered rainwater is directed into a vertical recharge well that extends into the Pleistocene sand aquifer. The well is designed so that water passes through natural sandy strata, allowing further filtration and gradual percolation into the aquifer. Recharge chambers are positioned above the water table to maximize infiltration potential. Overflow Management/Runoff Control: During heavy rainfall events, excess water is diverted to bio-retention basins or grassed drainage channels to prevent flooding and facilitate additional infiltration. These structures also help remove heavy metals and suspended solids before water reaches the aquifer. Monitoring and Maintenance Access: The system includes access points for routine inspection, sediment removal, and maintenance of filtration media. Regular monitoring allows evaluation of recharge efficiency, water quality, and groundwater-level response. Function and Relevance: This integrated system enables decentralized groundwater recharge by capturing urban runoff that would otherwise contribute to flooding or be lost. It ensures high-quality water is recharged, improves local aquifer levels, and provides a sustainable water resource for domestic and municipal use. **Figure 1** visually summarizes the flow of water from collection, filtration, and controlled recharge to the aquifer, highlighting the system's feasibility and replicability in urban Lahore. Location of the model is shown in **Figure 2**.

Aerial view of the Experimental Research Station (ERS), Thokar Niaz Beg, Lahore, Pakistan, showing the study site where the field-scale rainwater harvesting and managed aquifer recharge (RWH–MAR) system was installed. The site features urban catchments with impervious surfaces, collection areas, and recharge wells, enabling evaluation of recharge efficiency, water quality, and aquifer response under real urban conditions.

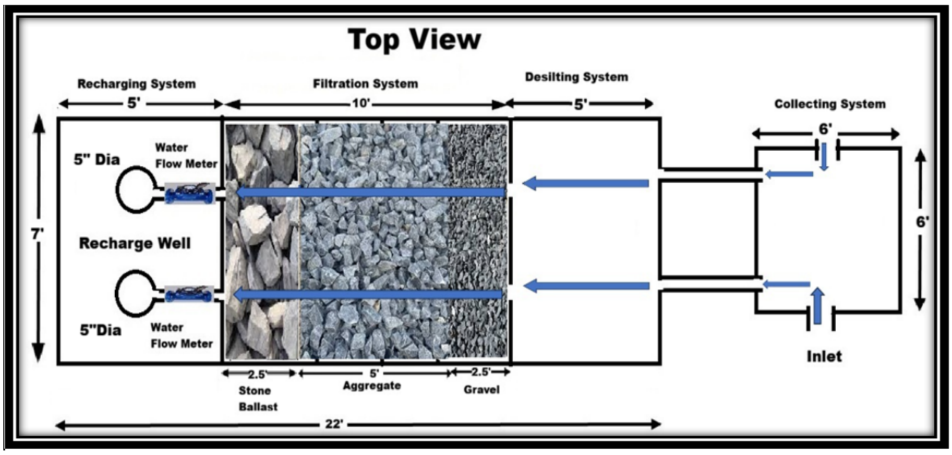



**Figure 1.** Typical design of a rainwater harvesting (RWH) Model at Experimental Research Station Thokar Niaz Beg Lahore.

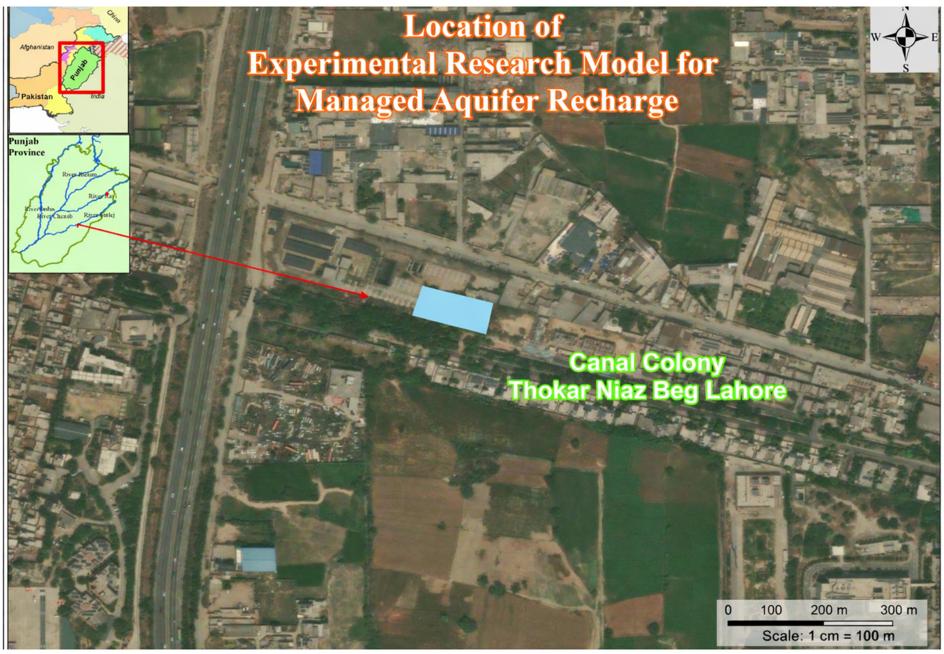



**Figure 2.** Experimental Research Station Niaz Beg, Lahore: showing the location of the RWH-MAR site.

## 2.3. Site for the RWH Model

Based on recorded information and an established RWH system by IRI of Punjab Irrigation Department (PID), a research station at Thokar Niaz Beg in Lahore, Pakistan, was chosen as the experimental location for rainfall harvesting and its use for MAR. Field visits at the site before and during the rainy season were carried out to collect data and information about the existing drainage system and the catchment area of residents. The field surveys were required to find out the rainwater harvesting potential in the catchment area of parks and roads/streets. Similarly, the data on MAR through harvested rainwater was also collected.

Rainwater harvesting systems consist of the following elements/components at the experimental site of IRI.

- **Catchment area:** to collect and store the captured rainwater.
- **Conveyance system:** to transport the harvested water to the recharge well zone from the catchment.
- **Filters:** for treatment and removing pollutants from the rainwater that is collected before recharge.
- **Storage and rechargeable tanks:** Used to store the filtered water, which is ready for groundwater recharge.

- **Recharge well:** to recharge the filtered water into the groundwater through the sandy strata.

#### 2.3.1. Catchment Area

The MAR catchment area is similar to the hydrological catchment area, which is a land area consisting of parks and roads that are used to collect rainwater and drain runoff. To get the most out of your harvest, you need clean catchments. Paved (roofs, courtyards, roads, etc.) or unpaved (open spaces, playgrounds, lawns, etc.). The catchment area of this study is unpaved—large open land with soil, grasses, and vegetation and some hard roads. Rainwater harvesting can't use all of the rain that falls in the catchments. Evaporation and seepage into the ground may result in the loss of a portion of the water that falls on catchments, as the groundwater table is deep and direct seepage/infiltration into soil actually does not reach the groundwater. The actual volume can be determined by determining the catchment's run-off coefficient, which considers some loss caused by evaporation or absorption by catchment surfaces. It shows how much of the total rainfall can be used to collect rainwater. The effectiveness of the water collection is significantly influenced by these elements and the efficient catchment area. Soils and unpaved areas cause more infiltration, which can contribute to the natural recharge if the groundwater table is shallow or rainfall continues for a longer duration. In the current situation, the water table is deep, therefore, the MAR has been planned through RWH. The harvested rainwater is collected, filtered, and then recharged through an artificial intervention i.e., the recharge well. The amount of water that is absorbed by various catchment materials varies depending upon the vegetation, land cover, topography, etc. [21]. Another important parameter for the suitability of rainwater for MAR is its quality. In another study by IRI [17], it has been found that the quality of rainwater in the study area is suitable if harvested properly and safely diverted to the recharging systems [22]. The most important parameter for designing the RWH system's recharge wells is the catchment area, its characteristics and especially the sources of pollution. It should not have major sources of water contamination [23]. The dimensions of the catchment area used for rainwater harvesting at the Experimental Research Station (ERS), Thokar Niaz Beg, Lahore, are summarized in **Table 1**. These dimensions include the total collection area from paved surfaces and rooftops, which directly influence the volume of rainwater available for recharge. Accurate characterization of the catchment area is essential for estimating potential recharge volumes, designing filtration and storage systems, and evaluating the overall efficiency of the RWH–MAR system.

**Table 1.** Catchment area dimensions.

| Location | Area (Width × Length) | Total Area ($ft^2$) |
|---|---|---|
| Catchment area of Park side | 109 × 269 | 29,320 $ft^2$ |
| Catchment area of roadside | 18.5 × 269 | 4,976 $ft^2$ |

Water flows through conduit systems from the catchment area to the storage area, to the filtration chamber, and finally to the recharge chamber through the recharge well. Most of the water that falls onto the roof can be diverted by a conveyance system that has been carefully designed and built.

#### 2.3.2. Design and Construction of RWH Model

The process of introducing rainwater into the subsurface through the construction of civil structures like recharge wells is known as artificial recharge. The design of the optimum capacity of the collection, pretreatment, and recharge tanks was carried out based on the following key parameters:

1. Catchment Size area.
2. Intensity of rainfall.
3. Location and accessible space.
4. The rate of recharge, which is determined by the site's geology, and the rate at which standing water is drawn into the groundwater table, ought to be as quick as possible. It has been investigated by drilling boreholes that the geology of the study area supports the MAR [21].

After completing the prerequisite site preparation measures, the recharge well system was designed and constructed with four interconnected chambers, each serving a specific purpose: a collection tank, a settlement tank, a filtration tank, and the recharge well itself. The rainwater storage capacity of each chamber is summarized in **Table 2**, which guided the system design to optimize infiltration, sedimentation, and water quality prior to aquifer recharge.

**Table 2.** The dimensions and capacity of each tank of the RWH model.

| Tank No. | Length of Tank (ft) | Width of Tank (ft) | Depth of Tank (ft) | Volume of Each Tank (L × W × D) ($ft^3$) |
|---|---|---|---|---|
| Collection tank = 1 | 6 | 6 | 5.25 | 189 |
| Sediment/settlement Tank = 2 | 6 | 6 | 5.25 | 189 |
| Filtration tank = 3 | 6 | 10 | 5.25 | 315 |
| Recharging tank = 4 | 6 | 6 | 5.25 | 189 |
| | Total volume | | | 882 |
| | Volume in Liters | | | 24,975 |

Note: Capacity of the Model is 882 $ft^3$.

A pre-filtration system has been installed to remove debris and any suspended solid particles prior to flow into the well to prevent clogging, as clogging has been identified as a potential threat to the success of any MAR system [24,25]. To replenish the groundwater, the filtration mechanism supplies water that is free of silt and clay and suitable for MAR. Sediment-free water supports the enhanced rate of recharge during the MAR process [26,27]. The head difference will cause the water to drain into groundwater under gravity—this reduces the cost of any injection mechanism [27]. An experimental setup was set up to see how well the media filter met all of the requirements, as shown in **Figure 1**. This design's advantages include a high groundwater recharge rate because water rapidly drains into the groundwater from the surface. As a result, the design structure is simple to construct and simple to maintain, and the inflow rate will roughly match the recharge rate.

By incorporating the following water quality measures into the design, this design strategy became more suitable for recharging groundwater. i) The borehole PVC pipe with a strainer of 6 inches diameter was kept in sandy strata, 40 ft above the water table, because soil is a natural filter that cleans rainwater before it enters the groundwater [28,29]. ii) The recharge chamber was paired with settlement chambers, silt trapper structures, where appropriate and necessary. Rainwater was cleaned of silt and other floating impurities in these settlement chambers, which is a prerequisite for a successful MAR setup [30]. Additionally, recharge rates may not coincide with rainfall events/rates in cases of excessive and intensive precipitation. These chambers hold the excess water until it is absorbed by the recharge structure in such circumstances. As a result, the settlement chamber serves as a system buffer [22].

### 2.3.3. Design and Construction of Filter Media

An experimental setup was set up to see how well the media filter that was used to build recharge wells for infiltration worked. The length of the filter media of the well is 20 ft. The filter media consist of the following layers from bottom to top:

i) 12-inch layer of crushed stone aggregate (size range = 1–1.5 ft),
ii) 12-inch layer of aggregate (size range = 0.5–1.0 inch),
iii) 12-inch layer of aggregate (size range = 0.25–0.5 inch),
iv) 24-inch layer of a mix of sands (coarse, medium, and fine).

Rainwater harvesting is the process of collecting and storing rainwater using man-made or artificially designed systems that run off naturally or artificially created catchment areas like rooftops, compounds, rock surfaces, hill slopes, and artificially repaired impervious or semi-pervious land surfaces [30,31].

The collection and storage of rainwater is greatly influenced by different factors. Some of these factors are:

- The intensity, frequency, and duration of rainfall;
- Quality of the rainfall, characteristics of the catchments (land cover, type of vegetation, topography, etc.);
- The quantum of runoff generated;
- Climatic Conditions;
- Accessibility and availability of the technology;
- The storage capacity of tanks;
- Types of the housing's roof, its slope, and its materials;

- Sub-soil strata which controls the speed and ease with which the rainwater penetrates through the subsoil to the aquifer.

### 2.4. Installation of Piezometers Near Recharge Model

To monitor groundwater level fluctuations and estimate aquifer recharge from the rainwater harvesting system, three piezometers (P-1, P-2, and P-3) were installed at the study site, ERS Thokar Niaz Beg. The piezometers were positioned along a horizontal transect at distances of 100 ft, 220 ft, and 500 ft from the recharge well, respectively, as summarized in **Table 3**. This setup allowed spatial assessment of groundwater response to recharge and evaluation of the effective radius of influence of the recharge well.

**Table 3.** Location of Installed Piezometers Near Recharge Well at ERS Thokar Niaz Beg Lahore.

| Piezometers No. | Latitude | Longitude | Bore Depth (ft) | Distances of Piezometers from Recharge Well ft) |
|---|---|---|---|---|
| P-1 | 31.474056 | 74.230437 | 100 | 10 |
| P-2 | 31.474081 | 74.230143 | 100 | 91 |
| P-3 | 31.473946 | 74.229495 | 100 | 194 |

## 3. Results

### 3.1. Hydro-Climatology of the Study Area

The direct natural recharge to an aquifer from the land surface in any area is generally controlled by rainfall (intensity, frequency, duration), water losses due to evaporation, and land use changes. In our study area, the latter has significantly affected the water balance due to the increased urbanization, which has reduced the natural recharge significantly increased temperature significantly changed the water losses due to evapotranspiration; the studied area falls in the semi-arid region with average highs routinely exceeding 40 °C (104.0 °F) in June. Cold winters are in January with minimum mean temperatures of about 4 °C (39.2 °F). The study area experiences significant seasonal temperature variation, with the average monthly minimum and maximum temperatures over a 30-year period (1990–2019) ranging from 4 °C to 40 °C, as illustrated in **Figure 3**.

The other key climatic variables that significantly control GW recharge include surface runoff, and soil moisture storage generated from the rainfall. The historic rainfall of the area is significantly variable over the year. **Figure 4** illustrates the annual average rainfall in the study area over a 30-year period (1990–2019), with a mean value of approximately 650 mm per year, while inter-annual variability ranges from 300 mm to 1200 mm. The Southwest monsoon, which lasts from June to September, accounts for about 65% of total precipitation, while the northeast monsoon contributes nearly 20%, and the remainder falls during the pre-monsoon period It is estimated that 20–25% of rainfall contributes to groundwater recharge in a year [22], this could vary due to the rainfall intensity, and time of the year as more persistent rainfall in the winter/autumn could be effective for the GW recharge as compared to the summer intense rainfall. A study in the selected area suggests that the rainwater in the area per 650 mm per year is generating runoff of 1,553,842 L (80% of rainfall), which is disposed of into the drainage system. Therefore, maintaining both the quantity and quality of urban groundwater supplies necessitates a deeper comprehension of the interactions between surface water and groundwater [32].

In addition to the climatic variables, GW/aquifer recharge also depends on recharge from the Ravi River flows. The aquifer underlying the study area is highly dependent on recharge from the Ravi River—the smallest eastern river of the Indus River System (IRS)—and from the Babakwal-Ravi-Badian-Depalpur (BRBD) link canal, which is fed by the Upper Chenab Canal (UCC) off-taking from Marala Barrage on the east. The river flows have significantly changed after the Indus Water Treaty (IWT) [33], signed with the neighboring country in 1960. With a catchment area of 24,960 km$^2$, the Ravi River flows in India's lesser Himalayan range. The Ravi River enters Pakistan from India at Jassar, 120 km upstream of Lahore, and joins the Chenab River near Kabirwala. The Marala-Ravi Link Canal and five flash streams that enter the Ravi River in Pakistan provide most of the river's flow. From 1922 to 1961, the Ravi River in Pakistan had an average annual flow of 7-million-acre feet (MAF), after IWT between the years 1985 and 1995, the average annual flow reduced to 5 MAF, which further reduced due to the construction of the Thein Dam by India. **Figure 5** presents the annual variation in inflow of the Ravi River at Shahdara Bridge, located near Lahore city, highlighting fluctuations in surface water availability over the study period.

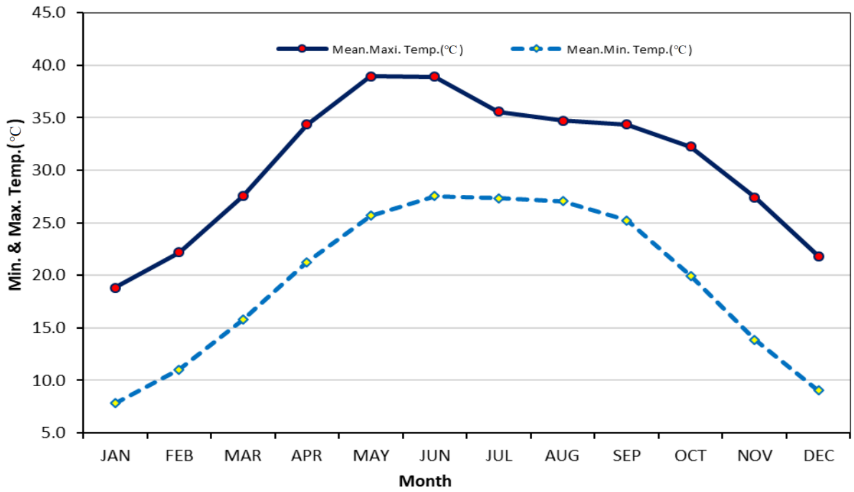



**Figure 3.** Historical Avg. Maxi. & Mini. Monthly Temp at Lahore (1990–2019).

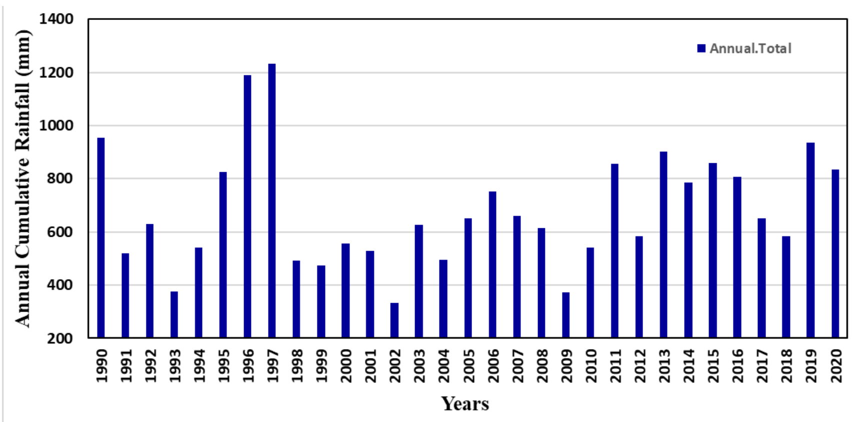



**Figure 4.** Historical annual rainfall in Lahore (1990–2020).

Data Source: Pakistan Meteorological Department.

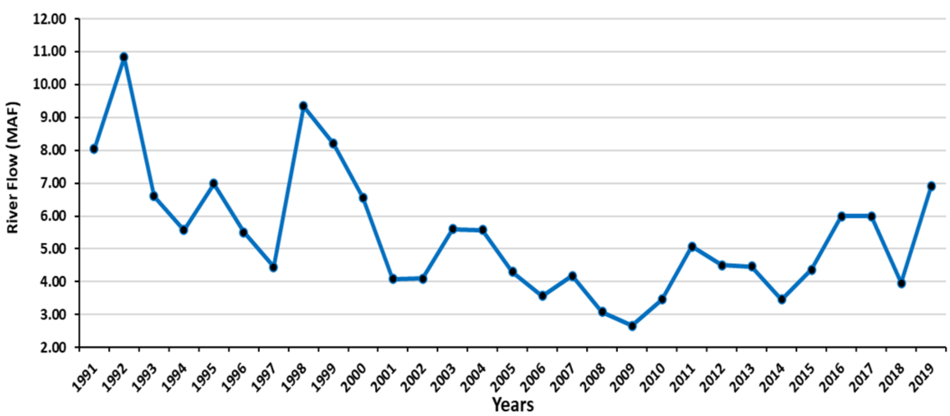



**Figure 5.** Historical annual Ravi River Flow at Shahdara Bridge for years (2000–2019).

It is clear from **Figure 6** that flow ranges from approximately 1,686 cusecs in December to 23,500 cusecs in August, reflecting pronounced seasonal variability associated with the monsoon. However, peak flows rising to more than 100,000 cusecs were also observed in this period. This indicates that monthly flows are highly variable during the year.

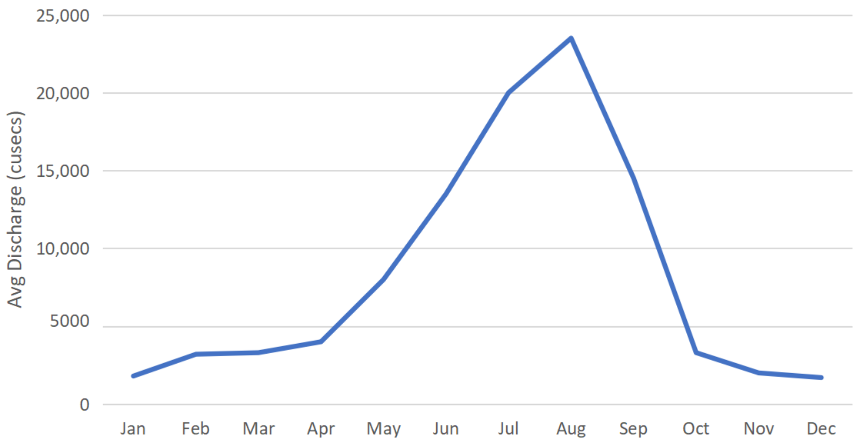



**Figure 6.** Average monthly flows of the Ravi River at Shahdara Bridge for the period 1991–2019.

### 3.2. Current Groundwater Situation

Analysis of available data/records has indicated that groundwater is an important source of drinking water in Lahore, like many other developing countries. The groundwater is not only used for domestic purposes but is also used for irrigation, industries, and municipalities [34]. There are currently 1,800 public and private tube wells that are extracting approximately 100 $m^3$ per day of groundwater [16]. It has been reported that approximately 585 tube wells with varying depths (from 400 to 850 ft) are being used to extract up to 540 million gallons per day (MGD), or 2.45 million $m^3$ per day, of groundwater [35]. In 1960, the groundwater table was 4.6 m deep, and water for drinking was extracted from 120 to 200 m below the surface [36]. The water table's depth ranged from 8 to 20 m in 1987. The extensive use of groundwater has resulted in an annual water table drop of about half a meter over the past 30 years, bringing the water table in Lahore to 45 m in 2017 [37]. The annual groundwater depletion rate in the study area ranges from 0.43 to 1.5 m, with an average rate of 0.78 m per year, as illustrated in **Figure 7**. The minimum annual groundwater depletion occurs in areas adjacent to the Ravi River, whereas the maximum depletion, approximately 1.5 m per year, was observed in the Doungi (deep) aquifer near Gulberg III, located at the center of the groundwater depression cone (**Figures 8** and **9**). This spatial pattern highlights excessive groundwater extraction in central urban areas and underscores the urgent need for implementing managed aquifer recharge (MAR) strategies to restore aquifer levels and maintain a sustainable water supply. Research studies have shown that managed aquifer recharge through rainwater harvesting can improve the depleted groundwater systems [38].

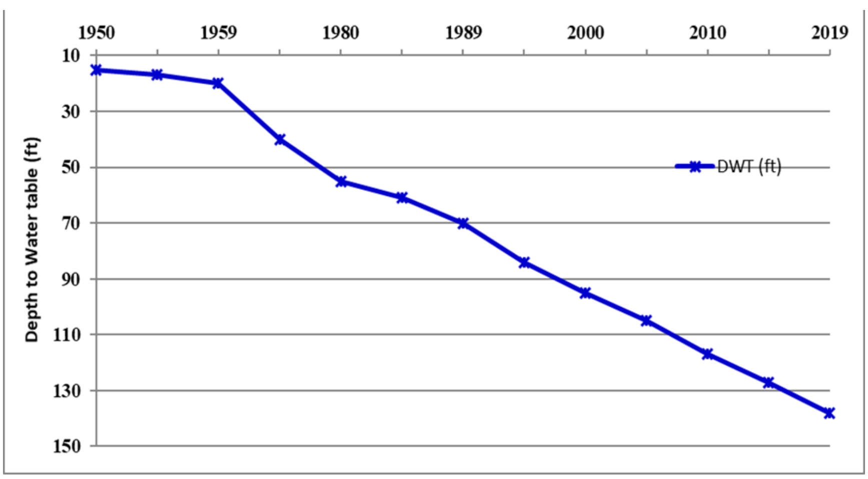



**Figure 7.** Temporal trend of groundwater levels in Lahore city.

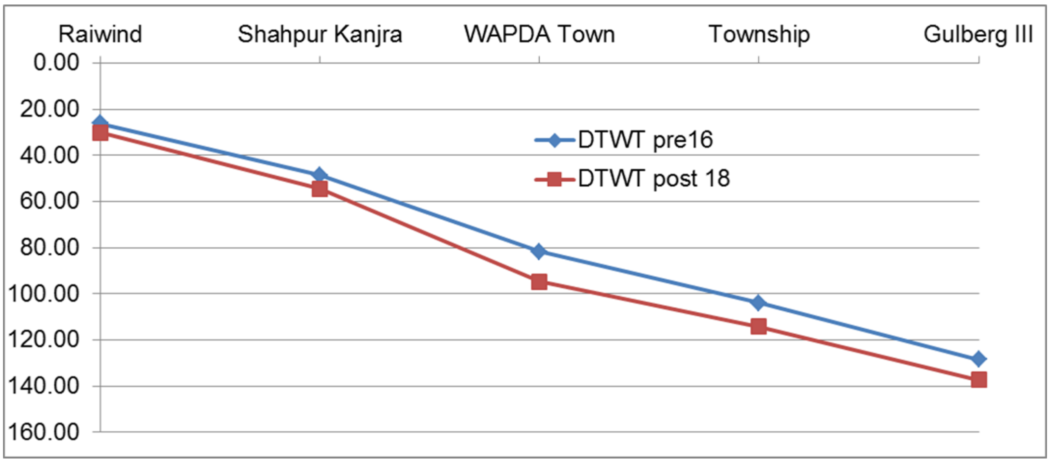



**Figure 8.** Spatial profile of depth to water table from Ravi Syphon to Lahore city.

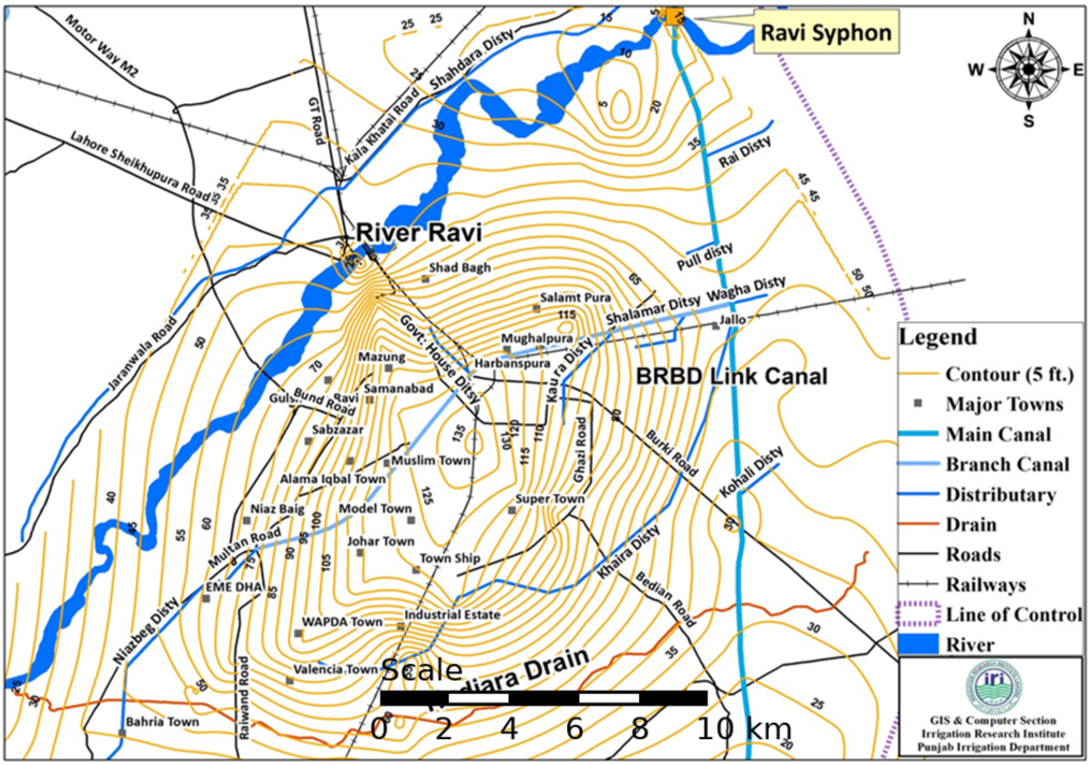



**Figure 9.** Depth to water table (ft) contour map for year 2019.

Data Source: Irrigation Research Institute (IRI) Lahore [39].

## 3.3. Rainwater Harvesting (RWH)

Pakistan gets its water from a variety of sources, but the monsoon rains account for 60% of all rain during the year. Desertification may have dire repercussions if groundwater levels continue to drop over time. The water recharge can be addressed by storing rainwater in small ponds. Additionally, rainwater harvesting at the household level in urban areas is one method that can be used to recharge groundwater; constructing ponds, recharge galleries, ditches, recharge wells, injection wells, and other suitable structures at feasible sites [21].

Rainwater harvesting is the straightforward process or technology used to conserve rainwater by collecting, storing, conveying, and purifying rainwater from rooftops, parks, roads, and open grounds for reuse on-site rather than allowing it to run off [17]. Rainwater harvesting is an environmentally friendly method that contributes to the preservation of water for future uses. In the current scenario, water scarcity is a major concern. Rainwater harvesting is an effective method for water conservation. The idea of RWH is not new; it is frequently used in many parts of the world to deal with water scarcity and urban flooding [40]. It is a significant means of recharging the groundwater, which can be used for both drinking and non-drinking activities like farming, irrigation, and gardening [41–45]. The RWH technique is now receiving more attention and is equally popular in the western and eastern worlds, as evidenced by the history of the growing global interest in RWH after the 1980s. Throughout recent years, various experiments connected with RWH have been done at numerous locations in the world [46,47]. According to these extensive studies, RWH has numerous advantages for society, the economy, the environment, and technology [48]. This study primarily focuses on surface runoff RWH systems for rainwater storage and mitigating the urban flooding in Lahore city. Based on the literature review's findings that rainwater is a fresh source for recharging groundwater and a soft approach to dealing with urban flooding [49].

## 3.4. RWH Performance Evaluation

The recharge rate and volume were used as key indicators to evaluate the performance of the recharge well system. Rainfall data collected during different events are summarized in **Table 4**, providing the basis for estimating potential recharge. The actual volume of rainwater recharged through the RWH–MAR system was measured using flow meters installed on the recharge wells, and the results are presented in **Table 5**. These measurements allowed quantitative assessment of recharge efficiency and facilitated comparison between rainfall input and groundwater replenishment. It has been observed that during the rainfall events, water began to flow toward the recharge wells after 15 to 30 min of rainfall. The lower rainfall at first slowed the recharge rate, but as rainfall intensity increased, the recharge rate increased. Recharge wells performed satisfactorily, and it was observed that both infiltration pipes cleared the volume of the recharge tank within 3 to 3.5 h after the end of the rainfall. The condition of recharge wells and the sites where rainwater entered were investigated during the second rainfall event. Clay and silt were observed mixed with plant leaves, plastic bags, and other loose materials in the entering channels and settling tanks. The Reinforced Cement Concrete (RCC) slab ensured the safety of the main chambers of the model. According to these observations (see **Figure 10**), the proper infiltration of rainwater necessitates the operation and upkeep of recharge chambers. Due to clogging within the well, the recharge rate of recharge wells decreased over time. In order to restore the recharge rate prior to each monsoon, the well must be developed using surging, jetting, or any other conventional well development method [22].

**Table 4.** Rainfall data at ERS Thokar Niaz Beg Lahore for the year 2020.

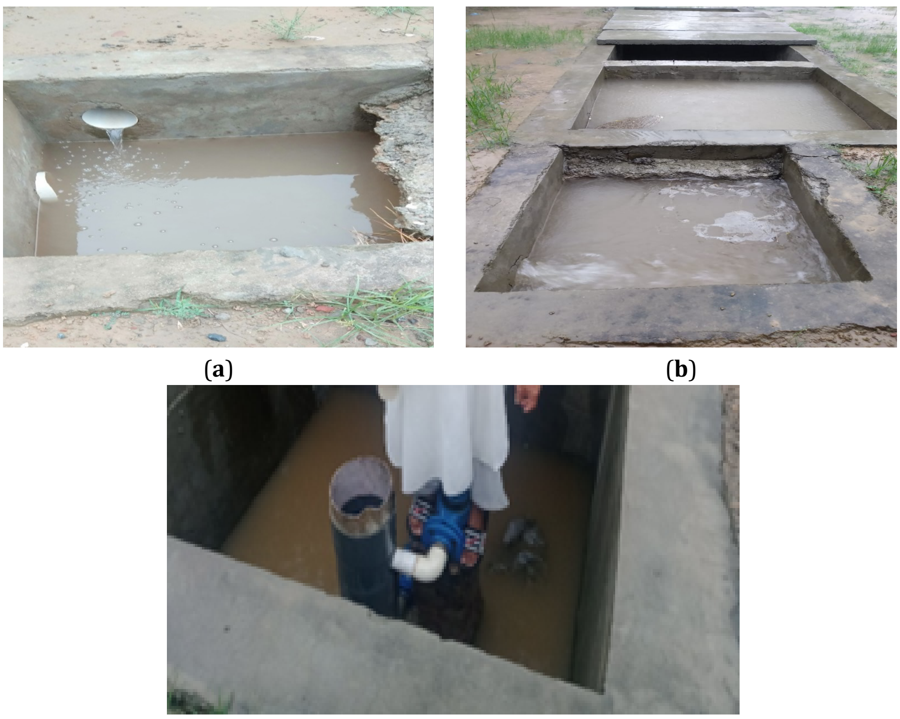
| Date | Rainfall (mm) | Date | Rainfall (mm) |
|---|---|---|---|
| 21.7.20 | 55.50 | 3.9.21 | 45.00 |
| 10.8.20 | 67.00 | 9.9.21 | 40.50 |
| 19.8.20 | 19.20 | 10.9.21 | 61.50 |
| 20.8.20 | 120.00 | 11.9.21 | 89.25 |
| 26.8.20 | 21.00 | 12.9.21 | 20.25 |
| 27.8.20 | 38.25 | 6.1.22 | 28.50 |
| 4.9.20 | 136.50 | 8.1.22 | 27.00 |
| 5.1.21 | 45.00 | 20.6.22 | 18.75 |
| 26.6.21 | 18.75 | 21.6.22 | 24.00 |
| 29.7.21 | 22.50 | 5.7.22 | 40.50 |
| 2.8.21 | 56.00 | 15.7.22 | 38.25 |
| 6.8.21 | 34.50 | 21.7.22 | 28.50 |
| 20.8.21 | 45.00 | 23.7.22 | 39.75 |
| 1.9.21 | 42.00 | 6.8.22 | 36.00 |

**Table 5.** Volume of groundwater recharged from the rainwater harvesting model.

| Date | Rainfall (mm) | M-1 ($m^3$) | M-2 ($m^3$) | Total ($m^3$) | Total ($ft^3$) | Total (L) |
|---|---|---|---|---|---|---|
| 21.7.20 | 55.5 | 10.1 | 6.0 | 16.1 | 564.94 | 16,100 |
| 10.8.20 | 67.0 | 13.3 | 9.3 | 22.6 | 790.65 | 22,600 |
| 19.8.20 | 19.2 | 3.1 | 2.1 | 5.2 | 183.4 | 5,200 |
| 20.8.20 | 120.0 | 20.6 | 19.5 | 40.1 | 1,401.79 | 40,000 |

**Table 5.** *Cont.*

| Date | Rainfall (mm) | M-1 ($m^3$) | M-2 ($m^3$) | Total ($m^3$) | Total ($ft^3$) | Total (L) |
|---|---|---|---|---|---|---|
| 26.8.20 | 21.0 | 0.4 | 9.5 | 9.9 | 345.22 | 9,800 |
| 27.8.20 | 38.3 | 0.4 | 11.6 | 12.0 | 420.49 | 12,000 |
| 4.9.20 | 136.5 | 5.9 | 39.1 | 45.0 | 1,575.35 | 45,000 |
| 5.1.21 | 45.0 | 6.0 | 25.5 | 31.5 | 1,101.99 | 31,486 |
| 26.6.21 | 18.8 | 0.0 | 4.3 | 4.3 | 151.27 | 4,322 |
| 29.7.21 | 22.5 | 0.4 | 9.8 | 10.2 | 357.13 | 10,204 |
| 2.8.21 | 56.0 | 6.4 | 26.2 | 32.6 | 1,141.79 | 32,623 |
| 6.8.21 | 34.5 | 0.4 | 10.6 | 11.0 | 385.18 | 11,005 |
| 20.8.21 | 45.0 | 5.7 | 25.7 | 31.5 | 1,100.9 | 31,454 |
| 1.9.21 | 42.0 | 4.6 | 21.1 | 25.7 | 900.68 | 25,734 |
| 3.9.21 | 45.0 | 5.8 | 25.9 | 31.7 | 1,109.64 | 31,704 |
| 10.9.21 | 61.5 | 7.0 | 28.2 | 35.2 | 1,232.82 | 35,223 |
| 11.9.21 | 89.3 | 8.3 | 30.9 | 39.2 | 1,371.73 | 39,192 |
| 12.9.21 | 20.3 | 0.0 | 3.9 | 3.9 | 136.06 | 3,888 |
| 6.1.22 | 28.5 | 0.7 | 8.7 | 9.4 | 329.61 | 9,417 |
| 8.1.22 | 27.0 | 1.0 | 4.6 | 5.6 | 197.47 | 5,642 |
| 20.6.22 | 18.8 | 0.0 | 3.6 | 3.6 | 124.76 | 3,565 |
| 21.6.22 | 24.0 | 1.0 | 9.0 | 10.0 | 350.95 | 10,027 |
| 5.7.22 | 40.5 | 2.1 | 10.5 | 12.6 | 442.1 | 12,631 |
| 15.7.22 | 38.3 | 2.7 | 9.0 | 11.8 | 411.46 | 11,756 |
| 21.7.22 | 28.5 | 0.7 | 10.0 | 10.7 | 373.65 | 10,676 |
| 23.7.22 | 39.8 | 3.3 | 10.8 | 14.0 | 490.2 | 14,006 |
| 6.8.22 | 36.0 | 3.1 | 9.1 | 12.2 | 425.85 | 12,167 |



(**a**) (**b**) (**c**)

**Figure 10.** Rainwater collection and treatment tanks of RWH Model: (**a**) Collection tank; (**b**) Sedimentation tank; (**c**) Recharging well and flow meter.

**Figure 10** provides a pictorial view of rainwater entering the Rainwater Harvesting (RWH) system and subsequently recharging the groundwater aquifer, illustrating the operational process of the experimental model.

### 3.5. Monitoring of Groundwater Levels from Piezometers

Groundwater levels were regularly monitored using piezometers (P-1, P-2, and P-3) installed at distances of 100 ft, 500 ft, and 1,000 ft from the recharge well, respectively. Measurements were recorded daily using a water level sounder. The observed rising trend in groundwater levels is illustrated in **Figure 11**, indicating the positive impact of rainwater harvesting (RWH) and managed aquifer recharge on the aquifer. Spatial and temporal variations in the depth to the water table, including average maximum and minimum values, are summarized in **Tables 6–10** for the years 2018, 2019, and 2020, respectively. Graphical representations of these results are also provided in **Figures 11–13.** Analysis of the data shows that aquifer recharge through the RWH system resulted in an annual groundwater level rise of approximately 2.5 ft, demonstrating the effectiveness of decentralized recharge interventions in urban Lahore.

**Table 6.** Spatial and temporal trends of depth to water table for the year 2018 at ERS Thokar Niaz Beg, Lahore.

| Month | P1-Mini. | P1-Maxi. | P1-Avg. | P2-Mini. | P2-Maxi. | P2-Avg. | P3-Mini. | P3-Maxi. | P3-Avg. |
|---|---|---|---|---|---|---|---|---|---|
| July | 65.57 | 66.96 | 66.02 | 66.46 | 67.08 | 66.90 | 66.49 | 67.04 | 66.87 |
| August | 66.17 | 66.27 | 66.24 | 67.06 | 67.19 | 67.13 | 67.00 | 67.10 | 67.06 |
| September | 66.30 | 66.50 | 66.39 | 67.21 | 67.30 | 67.26 | 67.03 | 67.22 | 67.15 |
| October | 66.42 | 66.55 | 66.48 | 67.29 | 67.53 | 67.38 | 67.18 | 67.36 | 67.23 |
| November | 66.42 | 66.55 | 66.49 | 67.33 | 67.55 | 67.42 | 67.17 | 67.33 | 67.25 |
| December | 66.33 | 66.47 | 66.38 | 67.22 | 67.33 | 67.26 | 67.05 | 67.22 | 67.14 |

**Table 7.** Spatial and temporal trends of depth to water table for the year 2019 at ERS Thokar Niaz Beg, Lahore.

| Month | P1-Mini. | P1-Maxi. | P1-Avg. | P2-Mini. | P2-Maxi. | P2-Avg. | P3-Mini. | P3-Maxi. | P3-Avg. |
|---|---|---|---|---|---|---|---|---|---|
| January | 66.22 | 66.50 | 66.44 | 67.21 | 67.39 | 67.30 | 66.28 | 67.22 | 67.13 |
| February | 66.46 | 66.55 | 66.51 | 67.33 | 67.42 | 67.38 | 67.17 | 67.30 | 67.23 |
| March | 66.50 | 66.69 | 66.60 | 66.44 | 67.56 | 67.41 | 67.23 | 67.47 | 67.33 |
| April | 66.72 | 67.03 | 66.86 | 67.56 | 67.92 | 67.75 | 67.47 | 67.72 | 67.58 |
| May | 67.03 | 67.15 | 67.09 | 67.94 | 68.08 | 68.02 | 67.75 | 67.92 | 67.83 |
| June | 67.50 | 67.70 | 67.60 | 68.38 | 68.55 | 68.48 | 68.33 | 68.49 | 68.41 |
| July | 67.71 | 67.91 | 67.82 | 68.56 | 68.77 | 68.70 | 68.47 | 68.70 | 68.58 |
| August | 67.91 | 68.08 | 67.96 | 68.77 | 68.88 | 68.82 | 68.64 | 68.73 | 68.69 |
| September | 67.97 | 68.14 | 68.05 | 68.77 | 69.05 | 68.92 | 68.63 | 69.04 | 68.68 |
| October | 67.96 | 68.11 | 68.02 | 68.77 | 68.88 | 68.81 | 68.54 | 69.04 | 68.65 |
| November | 67.93 | 68.04 | 67.99 | 68.79 | 68.81 | 68.80 | 68.54 | 68.63 | 68.57 |
| December | 68.02 | 68.05 | 68.04 | 68.79 | 68.88 | 68.83 | 68.52 | 68.69 | 68.57 |

**Table 8.** Spatial and Temporal Trends of Depth to Water Table, Groundwater Level for the Year 2020 at ERS Thokar Niaz Beg.

| Month | P1-Mini. | P1-Maxi. | P1-Avg. | P2-Mini. | P2-Maxi. | P2-Avg. | P3-Mini. | P3-Maxi. | P3-Avg. |
|---|---|---|---|---|---|---|---|---|---|
| January | 67.74 | 67.84 | 67.78 | 68.53 | 68.66 | 68.57 | 68.27 | 68.42 | 68.34 |
| February | 67.70 | 68.00 | 67.86 | 68.50 | 68.83 | 68.67 | 68.29 | 68.63 | 68.46 |
| March | 67.99 | 68.08 | 68.04 | 68.81 | 68.91 | 68.86 | 68.60 | 68.71 | 68.66 |
| April | 67.98 | 68.22 | 68.10 | 68.80 | 69.02 | 68.92 | 68.63 | 68.84 | 68.74 |
| May | 68.20 | 69.17 | 68.33 | 69.03 | 69.18 | 69.11 | 68.83 | 69.02 | 68.93 |
| June | 68.41 | 68.88 | 68.63 | 69.23 | 69.71 | 69.47 | 69.08 | 69.54 | 69.30 |
| July | 68.89 | 69.19 | 69.03 | 69.72 | 70.06 | 69.88 | 69.55 | 69.90 | 69.72 |
| August | 69.20 | 69.48 | 69.35 | 70.01 | 70.30 | 70.19 | 69.91 | 70.09 | 70.00 |
| September | 69.24 | 69.46 | 69.43 | 70.14 | 70.27 | 70.23 | 69.94 | 70.05 | 69.98 |
| October | 69.33 | 69.44 | 69.38 | 70.14 | 70.23 | 70.18 | 69.85 | 69.97 | 69.91 |
| November | 69.20 | 69.34 | 69.30 | 69.97 | 70.14 | 70.08 | 69.70 | 69.88 | 69.81 |

**Table 9.** Spatial and Temporal Depth to the Water Table at Piezometers installed at ERS Thokar Niaz Beg (Year 2021).

| Month | P1-Mini | P1-Maxi. | P1-Avg. | P2-Mini. | P2-Maxi. | P2-Avg. | P3-Mini. | P3-Maxi. | P3-Avg. |
|---|---|---|---|---|---|---|---|---|---|
| January | 69.04 | 69.15 | 69.07 | 69.78 | 69.9 | 69.83 | 69.57 | 69.64 | 69.6 |
| February | 69.1 | 69.22 | 69.18 | 69.85 | 70.02 | 69.95 | 69.64 | 69.75 | 69.69 |
| March | 69.2 | 69.38 | 69.29 | 70.01 | 70.27 | 70.12 | 69.77 | 68.71 | 69.87 |
| April | 69.38 | 69.63 | 69.49 | 70.28 | 70.57 | 70.41 | 70.02 | 70.35 | 70.17 |
| May | 69.64 | 69.91 | 69.79 | 69.91 | 70.89 | 70.72 | 69.91 | 70.66 | 70.51 |

**Table 9.** *Cont.*

| Month | P1-Mini | P1-Maxi. | P1-Avg. | P2-Mini. | P2-Maxi. | P2-Avg. | P3-Mini. | P3-Maxi. | P3-Avg. |
|---|---|---|---|---|---|---|---|---|---|
| June | 69.92 | 70.63 | 70.24 | 70.92 | 71.54 | 71.19 | 70.69 | 71.36 | 71 |
| July | 70.64 | 71.25 | 70.81 | 71.55 | 72.09 | 71.73 | 71.38 | 71.96 | 71.57 |
| August | 71.26 | 71.67 | 71.48 | 72.11 | 72.58 | 72.35 | 71.98 | 72.44 | 72.2 |
| September | 71.67 | 71.75 | 71.7 | 72.53 | 72.77 | 72.65 | 72.38 | 72.57 | 72.48 |
| October | 71.68 | 71.92 | 71.79 | 72.67 | 72.8 | 72.73 | 72.47 | 72.56 | 72.51 |
| November | 71.92 | 72.93 | 72.02 | 72.78 | 72.84 | 72.81 | 72.52 | 72.61 | 72.56 |
| December | 71.97 | 72.05 | 72.01 | 72.73 | 72.83 | 72.78 | 72.54 | 72.59 | 72.56 |

**Table 10.** Spatial and Temporal Depth to the Water Table at Piezometers installed at ERS Thokar Niaz Beg (Year 2022).

| Date | Rainfall (mm) | M-1 ($m^3$) | M-2 ($m^3$) | Total ($m^3$) | Total ($ft^3$) | Total (L) |
|---|---|---|---|---|---|---|
| 21.7.20 | 55.50 | 10.12 | 6.02 | 16.14 | 564.94 | 16,100 |
| 10.8.20 | 67.00 | 13.26 | 9.33 | 22.59 | 790.65 | 22,600 |
| 19.8.20 | 19.20 | 3.10 | 2.14 | 5.24 | 183.40 | 5,200 |
| 20.8.20 | 120.00 | 20.55 | 19.50 | 40.05 | 1,401.79 | 40,000 |
| 26.8.20 | 21.00 | 0.37 | 9.49 | 9.86 | 345.22 | 9,800 |
| 27.8.20 | 38.25 | 0.43 | 11.59 | 12.01 | 420.49 | 12,000 |
| 4.9.20 | 136.50 | 5.90 | 39.11 | 45.01 | 1,575.35 | 45,000 |
| 5.1.21 | 45.00 | 5.95 | 25.53 | 31.49 | 1,101.99 | 31,486 |
| 26.6.21 | 18.75 | 0.00 | 4.32 | 4.32 | 151.27 | 4,322 |
| 29.7.21 | 22.50 | 0.39 | 9.81 | 10.20 | 357.13 | 10,204 |
| 2.8.21 | 56.00 | 6.42 | 26.20 | 32.62 | 1,141.79 | 32,623 |
| 6.8.21 | 34.50 | 0.42 | 10.58 | 11.01 | 385.18 | 11,005 |
| 20.8.21 | 45.00 | 5.74 | 25.71 | 31.45 | 1,100.90 | 31,454 |
| 1.9.21 | 42.00 | 4.61 | 21.12 | 25.73 | 900.68 | 25,734 |
| 3.9.21 | 45.00 | 5.80 | 25.90 | 31.70 | 1,109.64 | 31,704 |
| 9.9.21 | 40.50 | 4.02 | 20.25 | 24.26 | 849.17 | 24,262 |
| 10.9.21 | 61.50 | 7.02 | 28.21 | 35.22 | 1,232.82 | 35,223 |
| 11.9.21 | 89.25 | 8.27 | 30.92 | 39.19 | 1,371.73 | 39,192 |
| 12.9.21 | 20.25 | 0.00 | 3.89 | 3.89 | 136.06 | 3,888 |
| 6.1.22 | 28.50 | 0.74 | 8.67 | 9.42 | 329.61 | 9,417 |
| 8.1.22 | 27.00 | 1.02 | 4.62 | 5.64 | 197.47 | 5,642 |
| 20.6.22 | 18.75 | 0.00 | 3.56 | 3.56 | 124.76 | 3,565 |
| 21.6.22 | 24.00 | 0.98 | 9.04 | 10.03 | 350.95 | 10,027 |
| 5.7.22 | 40.50 | 2.14 | 10.49 | 12.63 | 442.10 | 12,631 |
| 15.7.22 | 38.25 | 2.74 | 9.01 | 11.76 | 411.46 | 11,756 |
| 21.7.22 | 28.50 | 0.65 | 10.02 | 10.68 | 373.65 | 10,676 |
| 23.7.22 | 39.75 | 3.25 | 10.75 | 14.01 | 490.20 | 14,006 |
| 6.8.22 | 36.00 | 3.10 | 9.06 | 12.17 | 425.85 | 12,167 |

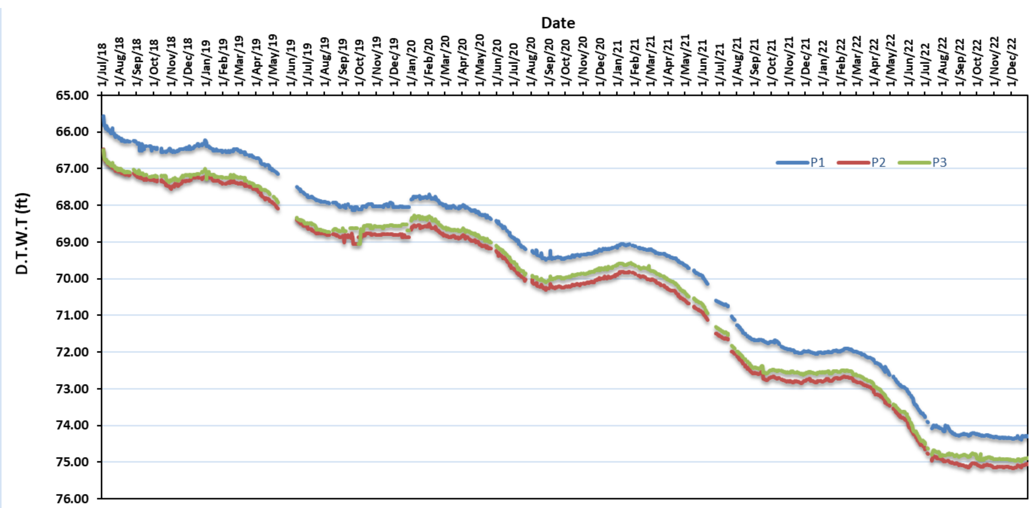



**Figure 11.** Graph of monthly variation in DWT at Thokar Niaz Beg for the years 2018–2020.

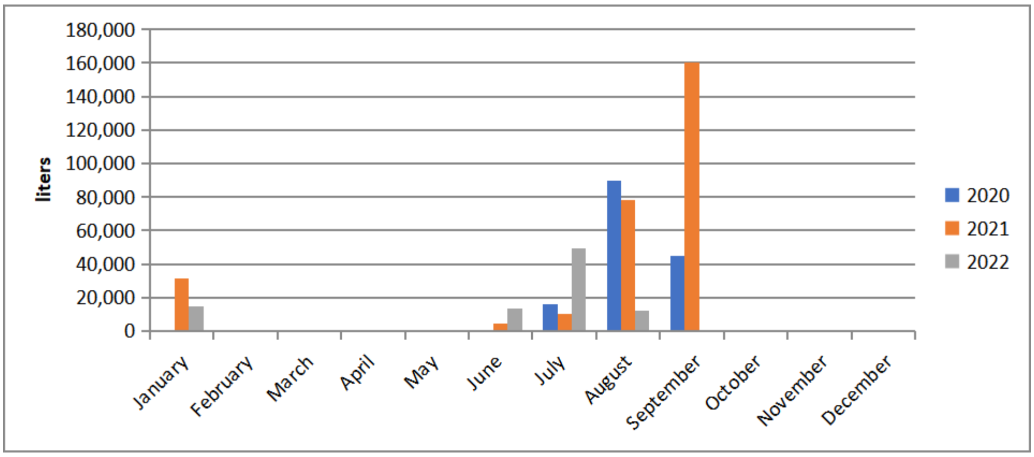



**Figure 12.** Monthly groundwater recharge at Thokar Niaz Beg through Rainwater Harvesting 2020–2022.

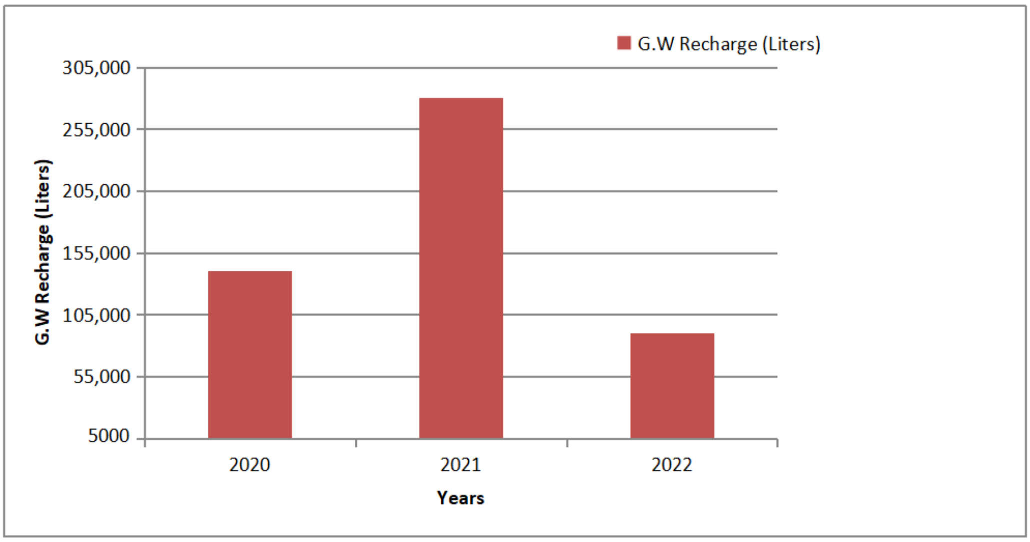



**Figure 13.** Showing annual groundwater recharge from Rain harvesting for the years 2020–2022.

### 3.6. Monitoring Harvested Rainwater Quality

After the monsoon season in 2020, water quality samples were taken from the treatment/filtration tank and the wells used for infiltration and sent to the IRI Laboratory for Physio–Aesthetic Chemical parameters analysis. It was found that the quality of rainwater is suitable for recharging if harvested directly avoiding its contact with the surface of roads/streets [17].

## 4. Conclusions

This study evaluated the performance of a recharge well–based rainwater harvesting (RWH) system installed at the Experimental Research Station (ERS), Thokar Niaz Beg Park, Lahore. Field monitoring from 2020 to 2022 recorded recharge volumes of 150,700 L, 281,097 L, and 89,887 L, respectively. Based on the average household size in Punjab (6–7 persons) and domestic water consumption of approximately 190 L per person per day, these recharge volumes are equivalent to 132, 246, and 79 days of domestic water supply for an average household.

The results demonstrate that even a small-scale RWH–Managed Aquifer Recharge (MAR) system can make a measurable contribution to local aquifer replenishment. The significant variation in recharge volumes across the three years reflects differences in annual rainfall and infiltration capacity. These outcomes confirm that seasonal rainfall in Lahore can be effectively utilized for aquifer recharge, thereby reducing pressure on the city's overexploited groundwater resources.

### 4.1. Interpretation of Recharge Performance

The infiltration efficiency observed in this system indicates the suitability of the Pleistocene sand aquifer for MAR applications. Similar recharge rates have been reported in comparable semi-arid settings in India and Iran [6–9], suggesting that Lahore's hydrogeological conditions are conducive to infiltration-based recharge. The results highlight the potential of decentralized recharge interventions to partially offset the rapid decline in groundwater levels—currently estimated at 0.5–1.0 m per year in Lahore.

Moreover, the collected rainwater exhibited good quality, comparable to groundwater and superior to surface water, when pre-filtration was used. This confirms that with appropriate design and filtration media, MAR systems can safely contribute to aquifer replenishment without degrading water quality. Such findings align with UNESCO's global assessments of MAR safety and performance [11].

### 4.2. Water Quality and System Optimization

To ensure long-term system sustainability, it is essential that recharge water remains free from contaminants. Grassed drains and small bio-retention basins can effectively intercept heavy metals and suspended solids before infiltration. Installing filtration media and sediment traps prior to recharge wells is recommended to prevent clogging and to maintain infiltration efficiency. Additionally, roof-based rainwater harvesting—which avoids contact with road surfaces—offers a cleaner source for aquifer recharge.

Regular operation and maintenance of recharge chambers are crucial. Clogging by debris, sediments, and organic matter can substantially reduce infiltration capacity over time. Periodic inspection and cleaning should be institutionalized as part of city-level water management practices.

### 4.3. Policy Implications and Broader Significance

The pilot system at ERS demonstrates the technical feasibility and practical benefits of RWH–MAR for urban Lahore. If scaled up, similar systems could make a significant contribution to groundwater stabilization while reducing storm water runoff and flood risks during monsoon events. A conservative estimate suggests that if even 10% of public and commercial buildings in Lahore implemented rooftop RWH–MAR systems, the city could recover millions of liters of groundwater annually.

Institutional collaboration among urban authorities, the Irrigation Research Institute, and the private sector is vital for replication and scaling. Mandatory rainwater harvesting requirements for new developments, supported by regulatory frameworks, incentives, and awareness campaigns, could substantially enhance adoption. Public parks, green belts, and roadside recharge galleries should be leveraged as strategic sites for groundwater recharge.

Finally, while MAR systems offer considerable promise, continuous monitoring, data collection, and model-based assessments are necessary to optimize design, predict recharge potential, and ensure water quality. Future research should focus on integrating MAR–RWH systems into urban stormwater management models, enabling cities like Lahore to adopt more resilient and sustainable groundwater management practices.

In addition, grassed drains and/or small bio-retention basins are suggested for preventing heavy metals and other pollutants from entering rainwater runoff. To aid in the removal of heavy metals, these measures could be put in place prior to runoff entering the groundwater chamber. The passing of rainfall water through a filtration media is recommended. Efforts should be made to capture the rainfall from rooftops without allowing the rainwater to touch the roads and streets, which can avoid contamination of water and can be the best water recharge for the aquifer. Similarly, the recharge well must be kept above the water level in sandy strata in the aquifer to ensure that water passes through natural filtration media before it reaches the water in the aquifer. For rainwater to properly infiltrate, recharge chambers must be regularly operated and maintained. In the initial step, debris and physical impurities must be filtered. This method can be used to artificially recharge aquifers, and it should be used on important potential ponding sites in the urban areas of Lahore to ensure the sustainability of the city's groundwater supply. It must be ensured that good quality water is recharged to the aquifer.

To keep the sustained groundwater resources everyone should be strictly forced by law to use an underground rainwater harvesting system at every new as well as existing building in the city. Rooftop rainfall harvesting models must be designed and implemented in all offices, industrial, and other commercial buildings at the first step and then at every household level. An awareness-raising campaign among the stakeholders in the private as well as public sectors can play a vital role in this initiative. Keeping in view the above-stipulated conclusions, it is recommended that the irrigation offices, rest buildings, and other suitable infrastructures under their control may be utilized for rainfall harvesting as well as storing this water for aquifer recharge, or other suitable uses like gardening, grounds, car-washing, floor washing, etc. Irrigation Research Institute and other institutions must be upgraded and strengthened to conduct more modern research for conducting research studies on water management and conservation. Adequate funding for such initiatives is ensured by both the public and private sectors. Holistic policies and regulatory frameworks with clear implementation frameworks must be promulgated. Efficient use of available water in all sectors can reduce the pressure on groundwater. If possible, harvested rainfall water must be used directly before thinking of injecting it into the aquifer, as this will save the energy required to re-pump the recharged water, and will reduce the chances of contamination of the aquifer. Green parks and belts can be a good source of rainwater harvesting and recharge galleries can be constructed along all roads in the city to recharge the aquifer naturally. The study has a wider application for GW recharge in the study region, where GW sources are considered key for water resources management and are considered more resilient to climate change compared to the surface water resources.

## Author Contributions

Conceptualization, G.Z.-H., S.A., and G.S.; methodology, J.F.P., G.Z.-H., M.A., and F.R.H.; software, M.A.H.K., F.R.H., and G.Z.-H.; validation, G.Z.-H., F.R.H., and M.A.; formal analysis, F.R.H., M.A.H.K., and G.S.; investigation, G.Z.-H.; resources, G.Z.-H., G.S., and F.R.H.; data curation, F.R.H., J.F.P., and M.A.H.K.; writing—original draft preparation, G.Z.-H. and F.R.H.; writing—review and editing, M.A., G.Z.-H., J.F.P., and G.S.; visualization, F.R.H., M.A.H.K., and S.A.; supervision, G.Z.-H., M.A., and J.F.P.; project administration, G.Z.-H. and M.A.; funding acquisition, G.Z.-H. All authors have read and agreed to the published version of the manuscript.

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## Data Availability Statement

All the data has been made part of the article. However, any further information/clarification can be obtained from the corresponding author.

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## Conflicts of Interest

The authors declare no conflict of interest.

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