PUNJAB MUNICIPAL DEVELOPMENT FUND COMPANY
(PMDFC)

RAINWATER HARVESTING FEASIBILITY STUDY ACROSS PUNJAB

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Submitted By:

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ABBREVIATIONS

BCM	Billion Cubic Meter
DRR	Disaster Risk Reduction
dS/m	desi Siemen Per meter
EC	Electrical Conductivity
GWL	Ground Water Level
IRB	Indus River Basin
LPC	Lower Punjnad Canal
MAR	Managed Aquifer Recharge
MES	Military Engineering Services
NSDWQ	National Standard For Drinking Water Quality
PCP	Punjab Cities Program
PICP	Punjab Inclusive Cities Program
PMDFC	Punjab Municipal Development Fund Company
PPM	Parts Per Million
RCC	Reinforced Concrete Cement
RSC	Residual Sodium Carbonate
RWH	Rainwater Harvesting
RWHSA	Rain Water Harvesting For Sustainable Agriculture
SAR	Sodium Adsorption Ratio
SCS-CN	US Soil Conservation Service Curve Number
SPU	Strategic Planning Unit
TDS	Total Dissolve Solids
TMA	Tehsil Municipals Administration
WAPDA	Water And Power Development Authority
WASA	Water And Sanitation Agency
WHO	World Health Organization

EXECUTIVE SUMMARY

Punjab is facing an accelerating water crisis driven by rapid population growth, climate change, unregulated groundwater abstraction, and extensive urbanization. Pakistan has crossed the international water scarcity threshold, with per capita water availability declining from nearly 5,000 m^3 in 1951 to approximately 660–860 m^3 per year by 2025. Punjab, home to over 130 million people and the country's primary agricultural and economic hub, reflects this crisis with per capita availability estimated at 850–900 m^3, firmly placing the province in the water scarce category.

Climate change has significantly altered the hydrological regime, with nearly 80 percent of annual rainfall concentrated in the monsoon season (July–September) and increasingly occurring as high intensity events. Recent years (2024–2025) have recorded rainfall departures exceeding +40 percent above normal in parts of Punjab, overwhelming urban drainage systems and causing recurrent flooding, infrastructure damage, and loss of life. At the same time, large volumes of freshwater are rapidly discharged from cities without utilization, while Pakistan's surface water storage capacity remains critically low at approximately 30 days.

Groundwater has consequently become the dominant source of water for domestic, industrial, and agricultural use. In Punjab, groundwater abstraction now exceeds natural recharge by approximately one billion cubic meters annually, leading to persistent water table declines in major urban centers, including Lahore, Gujranwala, Gujrat and Vehari etc,etc. Rapid and largely unplanned urban expansion has further reduced natural recharge areas through increased impervious surfaces and encroachment on drainage corridors, intensifying both groundwater depletion and urban flood risks.

Within this context, Rainwater Harvesting (RWH) and Managed Aquifer Recharge (MAR) represents technically feasible, cost effective, and climate resilient solutions. International experience demonstrates that RWH can simultaneously enhance water security, mitigate urban flooding, and support groundwater sustainability when integrated into urban planning and disaster risk reduction frameworks.

This feasibility study, commissioned by the Punjab Municipal Development Fund Company (PMDFC), Government of Punjab, assesses the technical, hydrogeological, climatic, and institutional feasibility of implementing RWH and MAR across the province. Using rainfall analysis, aquifer characterization, groundwater depletion trends, salinity zoning, and land use assessment, the study identifies suitable engineering interventions, including recharge wells, infiltration trenches, check dams, rooftop rainwater harvesting systems, and storage based recharge structures.

Based on hydrogeological conditions, Punjab has been classified into three Rainwater Harvesting Planning Zones:

(i) Zone A (Northern and Piedmont Belt) with high recharge potential, suitable for surface based recharge structures;

(ii) Zone B (Central Urban and Alluvial Doabs) with severe groundwater stress, where managed recharge through storage supported recharge wells offers both recharge and flood mitigation benefits; and

(iii) Zone C (Southern and Western Punjab) with climatic and salinity constraints, where interventions must be selective and focus on surface storage and agricultural rainwater harvesting.

The study highlights that water quality management is critical to the long term viability of urban RWH and MAR. Past urban recharge pilot projects demonstrate that recharge wells failed in polluted, high sediment catchments with steep slopes, without adequate pretreatment and storage. Therefore, standardized designs must incorporate enhanced filtration and strict siting criteria to protect freshwater aquifers.

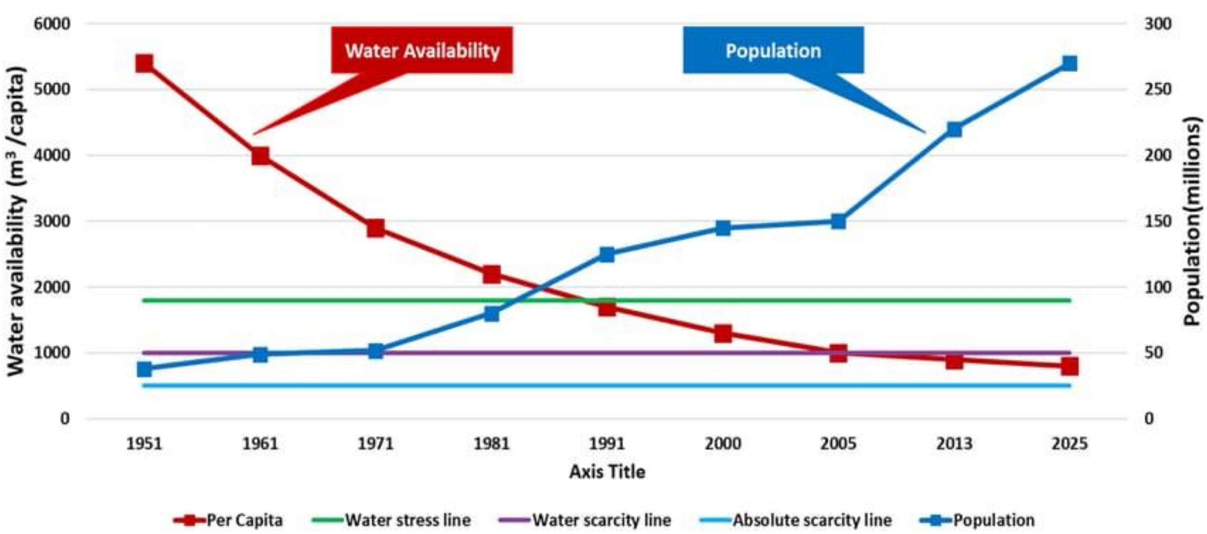
Overall, the study concludes that rainwater harvesting is not merely a supplemental water supply option but a strategic climate adaptation, groundwater protection, and urban flood management measure. Systematic integration of RWH and MAR into the Punjab Cities Program (PCP) and Punjab Inclusive Cities Program (PICP) can enable Punjab to transition from isolated pilot projects to a province wide, resilient, and sustainable urban water management framework.

1) INTRODUCTION

1.1 Background and Context of Water Scarcity in Pakistan

Pakistan is on the brink of absolute water scarcity driven by rapid population growth, climate change, inefficient water management, and over reliance on agriculture. The Indus Basin, the lifeline of the nation, is under immense stress. A key indicator of this crisis is the current hydrological imbalance. Recent estimates suggest that groundwater withdrawals across the Indus basin now exceed the natural recharge rate by approximately 1 billion cubic meters (BCM) per year. The overexploitation of groundwater particularly in the high density urban areas and agriculturally critical zones (Particularly Punjab) resulted the continuous decline of water table.

Per capita water availability is a key figure for assessing water stress, levels above 1,700 cubic meters (m^3) indicate no stress, 1,000–1,700 m^3 indicate water stress, and below 1,000 m^3 indicate scarcity. By 2025, Pakistan is firmly in the scarcity category. Based on recent analyses and projections, Pakistan's per capita water availability in 2025 is estimated in the range of approximately 660 m^3 to 860 m^3. This represents a sharp decline from historical levels, down from about 5,000 m^3 in 1951 and 1,017 m^3 in 2021 and positions the country among the world's most water-stressed nations, ranking 14th globally for extreme baseline water stress.



Source: Pakistan water resource management: Ensuring water security and sustainable development. Waseem Ishaque *et al*.

Figure 1 Pakistan Water Availability and Demand by 2025.

Punjab, which accounts for over 50% of national agricultural output and hosts about 130 million residents in 2025, relies heavily on the Indus River Basin (IRB) for its water supply, primarily for irrigation, which accounts for over 90% of water use in the region. Punjab is experiencing acute water stress due to a combination of population growth, climate change impacts (e.g., erratic monsoons and glacier melt) and over abstraction of groundwater. While national per capita water availability has declined to approximately 660 - 860 m³ per person annually, crossing the international water scarcity threshold of 1,000 m³, the projected and recently assessed figure of Punjab around 850 – 900 m³ per capita per year in 2025 indicates that it slightly exceeds the national average. This places Punjab in the " water scarcity" category with average groundwater depletion of 1.00 meter annually in high abstraction urban areas of Lahore, 0.4 meter in Gujranwala, 0.3 to 1.00 meter in Gujrat, and 0.3 to 0.5 meter in Vehari worsened by unpredictable monsoons and urban flooding.

Groundwater resources in Punjab are facing a severe and escalating crisis driven by excessive abstraction and inadequate natural replenishment. The challenge is magnified by rapid urbanization, which simultaneously intensifies water demand and results in the substantial loss of precious freshwater resources through urban flooding during the monsoon season. Managed Aquifer Recharge (MAR) through comprehensive Rainwater Harvesting (RWH) provides a strategic, dual purpose solution, stabilizing critical aquifer depletion and mitigating urban inundation.

1.2 Rationale for Rainwater Harvesting in Punjab

Rainwater harvesting (RWH) is the ancient, yet modern practice of collecting, storing, and using rainwater that falls on rooftops, land surfaces, or other catchments, instead of letting it run off into drains or evaporate. It's a simple sustainable way to capture free water from the sky for domestic, agricultural, or industrial needs.

RWH is one of the oldest water-management techniques in human history. Ancient civilizations such as Indus Valley Civilization, Rome, Middle East, and China developed ideas and technologies for rainwater harvesting systems more than 4000 years ago to manage water in arid or variable climates. These included reservoirs, cisterns, wells, and channels designed to capture, store, and distribute rainwater for drinking, irrigation, and sanitation purposes.

RWH is an easy, affordable and low cost solution that can be done right where people live or work. It does not rely on a large, central water system and people can do it individually. This strategy is very important for adapting to climate change because it not only gives an instant, ready to use source of water but also can be used to recharge the depleting groundwater, that perfectly supports national and sustainable water resources utilization.

Pakistan, where monsoon rains can be intense but unevenly distributed, has promoted rainwater harvesting and small dams in recent decades, especially after the 2000–2003 drought and again with the 2022 & 2025 floods highlighting groundwater over exploitation.

In Punjab, where aquifer is under stress and rate of groundwater depletion is increasing day by day due to over exploitation in cities like Lahore, Gujranwala, Gujrat and Vehari, RWH is a simple, low cost, and environment friendly technique. In addition, RWH is also ecofriendly, reduces strain on municipal supplies, prevents urban flooding, recharges aquifers, and cuts erosion.

The urgency for RWH implementation is driven by a dual mandate in Punjab:

First, RWH is required to directly counter the alarming rate of groundwater depletion in major urban cities of Punjab. To reduce this decline in water table long term water security is essential for Lahore, and other urban centers, necessitating large scale Managed Aquifer Recharge (MAR) through RWH.

Second, RWH acts as critical Disaster Risk Reduction (DRR) infrastructure. Climate change has intensified heavy monsoon rainfall, leading to increasingly frequent and devastating urban flooding. These high intensity, concentrated precipitation episodes exceed the capacity of existing inadequate drainage systems, a vulnerability aggravated by unplanned urban growth. The implementation of RWH systems, especially in urban areas, enables the rapid clearance of surface ponding, thereby mitigating infrastructural collapse and the associated catastrophic loss of life and property.

Rainwater harvesting is not new to Punjab. Historically, rural communities used dug wells, ponds, and small earthen embankments to store water. However, modern dependence on groundwater displaced these traditional methods. Reviving RWH, using modern designs and scientific planning can provide a sustainable, low cost supply mechanism for households, farms, communities, and industries.

To address these challenges, the Punjab Municipal Development Fund Company (PMDFC), Government of Punjab, plans to conduct a feasibility study for rainwater harvesting across Punjab to evaluate the possibility of groundwater recharge through recharge wells, roof top rainwater harvesting and other possible system to conserve the rainwater for future utilization.

Consequent upon conclusion of the bidding process completed by the PMFDC, Govt. of the Punjab, Geo-Research signed the Contract Agreement with PMDFC client as the successful bidder for the work of RAINWATER HARVESTING FEASIBILITY STUDY ACROSS PUNJAB. In response, Geo-Research fulfilled the requisite formalities agreeing on performing the work.

1.3 Goal and Scope of the Feasibility Study

The primary objective of this study is to evaluate RWH feasibility in Punjab by analyzing climate patterns, hydrology, groundwater data, technical designs and institutional capacities. The scope covers the entire province, differentiating between three major hydrological zones, Barani/rainfed (Northern and Piedmont Belt), urban (Central Urban and Alluvial Doabs) and arid/desert regions (Southern and Western Punjab).

2) PAKISTAN DYNAMICS AND CONTEXTUAL CONSIDERATIONS FOR RAINWATER HARVESTING

Dynamics and Contextual considerations of Pakistan in relation to the rainwater harvesting (RWH) or water resource planning means to understand the country specific factors, patterns, and challenges that influence how water behaves, is managed, and can be effectively harvested. Following describes it.

2.1 Climatic and Rainfall Variability

Pakistan is among the world's most climate-vulnerable countries and is already experiencing significant climate-induced stress on its water resources. Observable impacts include altered monsoon patterns, accelerated glacial retreat in the northern regions, rising temperatures, and an increasing frequency of both floods and droughts. These changes have resulted in heightened hydrological uncertainty and are expected to reduce overall water availability in the future.

Rainfall in Pakistan is characterized by pronounced spatial and temporal variability, largely governed by a dual monsoon system. Mean annual rainfall varies widely, from less than 100 mm in the arid areas of southern Sindh and Balochistan to over 1,500 mm in the northern and sub mountainous regions. This variability makes rainwater an important source of relatively soft water, particularly in water stressed regions. Approximately 80% of the annual rainfall occurs during the monsoon months (July–September), leading to intense precipitation over a short period followed by prolonged dry spells.

Climate change has further intensified rainfall events while reducing their frequency, contributing to recurrent urban flooding in major cities such as Lahore and Karachi and increasing surface runoff losses. These dynamics highlight the limitations of uniform water management approaches. Effective rainwater harvesting systems in Pakistan must therefore be designed with regional climatic conditions, rainfall distribution, and future climate risks in mind to enhance water security and climate resilience.

2.2 Water Scarcity and Groundwater Stress

Pakistan is facing a serious and deepening water crisis, driven by rapid population growth, urban expansion, increasing agricultural demand, and the impacts of climate change. As a result, the country is transitioning from being classified as water stressed to water scarce, with annual per capita water availability declining to below 1,000 cubic meters. At the same time, surface water resources have become increasingly unreliable due to climatic variability and seasonal fluctuations.

Compounding this challenge is Pakistan's limited water storage capacity, which is restricted to approximately a 30-day supply, far below the 1,000 day storage capacity recommended for countries with similar climatic conditions. This shortfall has led to a growing dependence on groundwater as the primary source of water for domestic, industrial, and agricultural uses, particularly in major urban centers such as Lahore, Islamabad, and Quetta.

Excessive groundwater abstraction has resulted in declining water tables, aquifer depletion, deterioration of water quality, and an increased risk of land subsidence. In response to these escalating pressures, rainwater harvesting (RWH) in Pakistan has evolved from a traditional survival strategy in arid regions into a legal and strategic necessity in urban areas. Through interventions such as recharge wells, recharge shafts, and infiltration trenches, RWH offers a technically viable and cost effective means of augmenting groundwater recharge and reducing stress on depleted aquifers. Consequently, rainwater harvesting is now widely recognized as a pillar of national water security.

2.3 Rapid Population Growth and Unplanned Urbanization

Pakistan's water security is increasingly undermined by rapid population growth and unplanned urbanization, resulting in declining per capita water availability and escalating pressure on limited water resources. Between 1972 and 2020, Pakistan's population increased by 2.6 times, raising its global population rank from 9th to 5th. During the same period, total renewable water resources remained largely static at about 246.8 billion cubic meters (BCM), while water use increased at an average rate of 0.7 percent per year between 1977 and 2017.

Consequently, per capita water availability declined from 3,478 cubic meters per year in 1977 to 1,117 cubic meters in 2017, and has since fallen further to approximately 800 cubic meters per person per year. This imbalance is reflected in the rising ratio of water withdrawals to renewable water resources, which increased from 62 percent to 82 percent between 1977 and 2017, indicating growing water stress.

Future projections further worsen this challenge. Pakistan's population is expected to increase by 53 percent, reaching around 338 million by 2050, while the urban population share is projected to rise from 37.2 percent in 2020 to 52.2 percent by 2050. If current water use efficiencies persist, total water withdrawals may exceed available renewable resources in the coming decades, pushing the country toward severe water scarcity.

Rapid and poorly planned urbanization has significantly altered natural hydrological processes, particularly in major cities. The expansion of impervious surfaces has reduced groundwater recharge and increased stormwater runoff, while inadequate and encroached drainage systems have led to frequent urban flooding during monsoon events. In this context, rooftop rainwater harvesting and decentralized recharge systems offer a practical response by reducing peak runoff, easing pressure on urban drainage networks, and enhancing local groundwater recharge. When integrated into urban planning and building design, rainwater harvesting can simultaneously support stormwater management and augment urban water supplies.

2.4 Hydrogeological and Soil Conditions

Pakistan's hydrogeological conditions vary considerably across regions and are increasingly stressed by severe groundwater depletion, waterlogging, rising salinity, and pollution resulting from excessive groundwater abstraction for irrigation. These challenges have significantly affected both groundwater quality and availability, particularly in the Punjab plains.

Aquifer characteristics also differ markedly across the country, with wide variations in hydraulic conductivity, porosity, and transmissivity. Some regions, especially those dominated by coarse sand and gravel deposits, have a high potential for groundwater extraction and recharge, while others are constrained by poor aquifer properties or hard rock formations that limit infiltration.

The alluvial plains of the Indus Basin generally provide favorable conditions for groundwater recharge due to highly permeable soils and extensive, laterally continuous aquifer systems. In contrast, hard rock terrains, piedmont zones, and arid regions often exhibit low natural infiltration rates and the presence of shallow impermeable layers. In such settings, engineered recharge structures such as recharge shafts and wells are required to bypass low permeability strata and enable effective aquifer replenishment.

Given this variability, careful assessment of site specific factors, including soil texture, depth to groundwater, presence of clay lenses, aquifer transmissivity, and groundwater quality, is essential to ensure the technical feasibility, effectiveness, and long term sustainability of proposed rainwater harvesting and groundwater recharge interventions.

2.5 Flood Drought Paradox

Pakistan is experiencing an intensifying water crisis driven by climate variability, population pressure, and structural deficiencies in water management. Over the past decade, the country has faced increasingly frequent and severe hydrological extremes, manifested in recurrent droughts alongside destructive monsoon flooding. Historical evidence highlights the severity of this challenge. The 1998–2002 drought remains the most severe in Pakistan's recorded history, affecting over three million people and causing extensive socio economic disruption, particularly in arid and semi-arid regions. More recent drought episodes in 2018 and 2019 severely impacted Balochistan and Sindh, resulting in widespread crop losses, water shortages, and population displacement. In 2023, mild drought conditions affected more than 80% of the country, with only short term relief observed in 2024.

In parallel, Pakistan continues to suffer from increasingly intense flood events. Recurrent monsoon flooding causes significant loss of life, large scale economic damage, and widespread disruption of infrastructure and livelihoods. The catastrophic floods of 2022, which displaced approximately 33 million people, followed by major flood events in 2025, underscore the growing frequency and magnitude of climate induced disasters.

This simultaneous occurrence of floods and water scarcity reflects a fundamental imbalance between water availability and storage capacity.

Within this context, rainwater harvesting (RWH) emerges as a technically viable and strategically important intervention. By capturing excess runoff during high intensity rainfall events and storing it or facilitating groundwater recharge, RWH systems can mitigate flood peaks while enhancing water availability during dry periods. From a feasibility perspective, appropriately designed and site specific RWH interventions offer a cost effective, scalable, and climate resilient solution capable of improving flood management, strengthening drought resilience, and enhancing long term water security at both urban and rural scales.

2.6 Socio Economic and Community Considerations

Water scarcity disproportionately affects low income and marginalized communities, particularly in rural and peri urban areas where access to reliable water supply infrastructure is limited. Community scale RWH interventions, such as ponds, recharge pits, contour bunds, and small check structures, are generally affordable, easy to construct, and locally manageable. Their long term success depends heavily on community participation, awareness, and capacity building, especially for operation and maintenance. Incorporating local knowledge and ensuring stakeholder ownership enhances the sustainability and social acceptance of RWH systems.

2.7 Institutional, Policy, and Regulatory Environment

Although water scarcity is widely recognized at the national level, the implementation of rainwater harvesting remains fragmented across Pakistan. In recent years, however, the regulatory foundation for RWH has been significantly strengthened through the approval of the Green Building Code of Pakistan. This landmark policy mandates rainwater harvesting in all new residential, commercial, and industrial buildings and has been formally adopted as part of the Pakistan Engineering Council (PEC) Bye Laws. The Code represents a major step toward mainstreaming RWH within the built environment. Nevertheless, effective enforcement, institutional coordination among development authorities and water agencies, and integration of RWH into urban planning and water resource management frameworks remain critical challenges for large scale implementation.

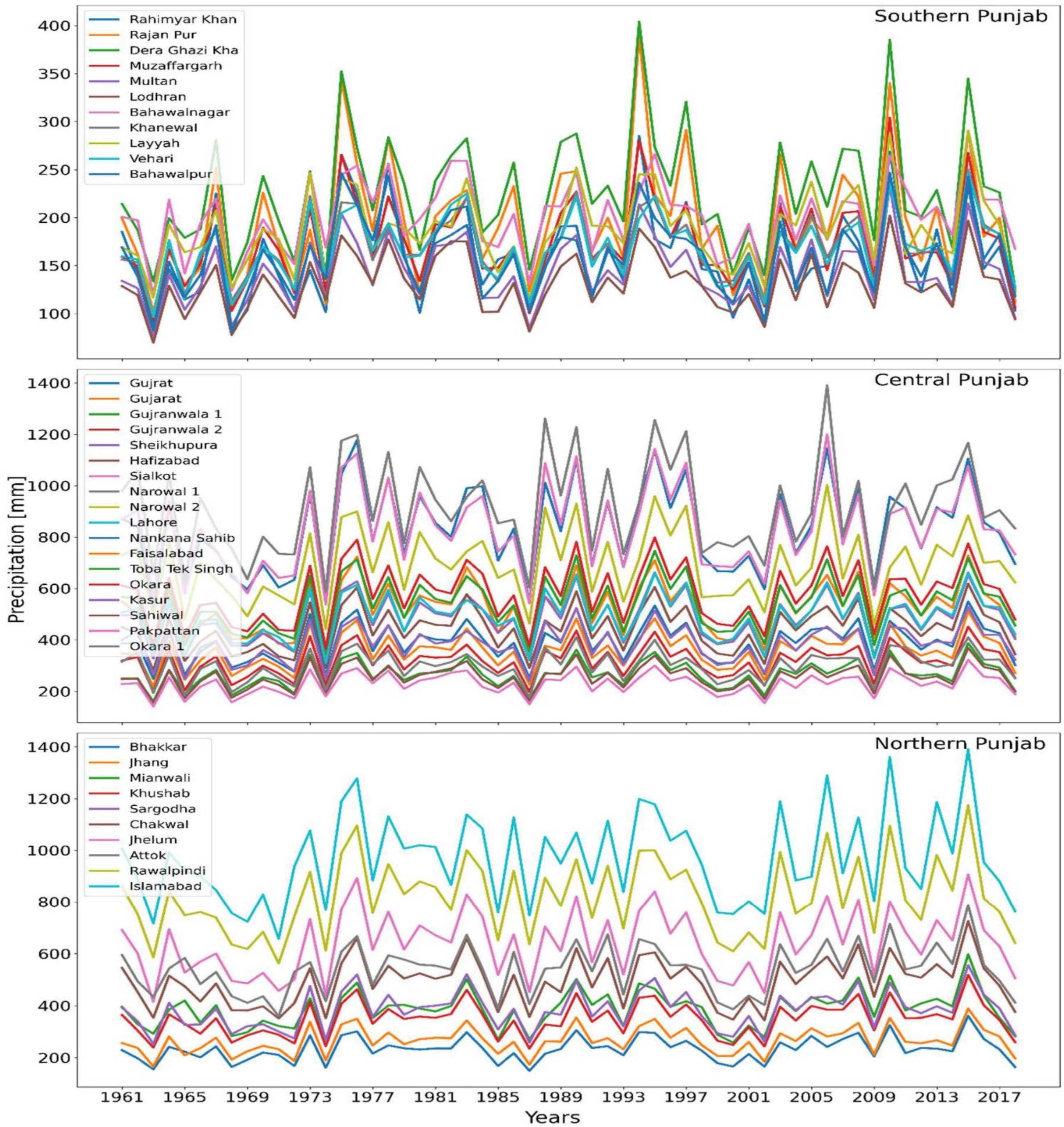
Given Pakistan’s high climatic variability, increasing groundwater dependence, rapid urbanization, and escalating climate risks, rainwater harvesting emerges as a technically viable and contextually appropriate solution. Its effectiveness, however, is contingent upon region specific design, sound hydrogeological assessment, strong institutional support, and active community engagement. When systematically integrated into national policies, urban planning regulations, and broader water resource management strategies, rainwater harvesting can make a substantial contribution to Pakistan’s long term water security and climate resilience.

3) RAINFALL AND CLIMATE ANALYSIS OF PUNJAB

Rainfall is a vital element of the Earth's hydrological cycle and exerts a significant influence on climate regulation, ecosystem functioning, and human activities. The mechanisms controlling the generation, spatial distribution, and intensity of rainfall have been widely studied in disciplines such as atmospheric science and hydrology. A clear understanding of the spatial and temporal variability of rainfall, its sensitivity to climate change, and its effects on environmental and socioeconomic systems is crucial for tackling major issues related to water resources planning, flood risk management, and agricultural sustainability. Rainfall replenishes fresh water resources including lakes & rivers and groundwater reservoir.

3.1 Historical Rainfall Trends and Monsoon Characteristics

Punjab experiences highly variable monsoon seasons, which often deviate significantly from historical averages.



Source: Spatio Temporal Analysis of Precipitation In Punjab Province, Aarish Maqsood *et al*

Figure 2 Annual averaged precipitation series for 39 ground-based stations

Analysis of recent monsoon data illustrates this instability; for instance, specific periods during the 2024 monsoon season showed the Punjab region receiving rainfall departures as high as +48% and +41% during 2025 above the normal average. This recent trend highlights the concentration and intensity of rainfall which effects existing infrastructures and necessitates large scale rainwater harvesting and Managing Aquifer Recharge (MAR) solution, particularly in high risk zones like Lahore, which are simultaneously experiencing swear groundwater depletion. This variability also necessitates that RWH systems must be designed both for high volume runoff capture and long term storage resilience against drought. This pattern also establishes that RWH infrastructure, particularly surface runoff harvesting designed to rapidly manage ponding water, is fundamentally a Disaster Risk Reduction (DRR) mechanism. By enabling the quick clearance of accumulated floodwater, RWH directly mitigates the catastrophic impact of these climate change induced high intensity storms.

3.2 Extreme Rainfall Events: Analysis and Variability

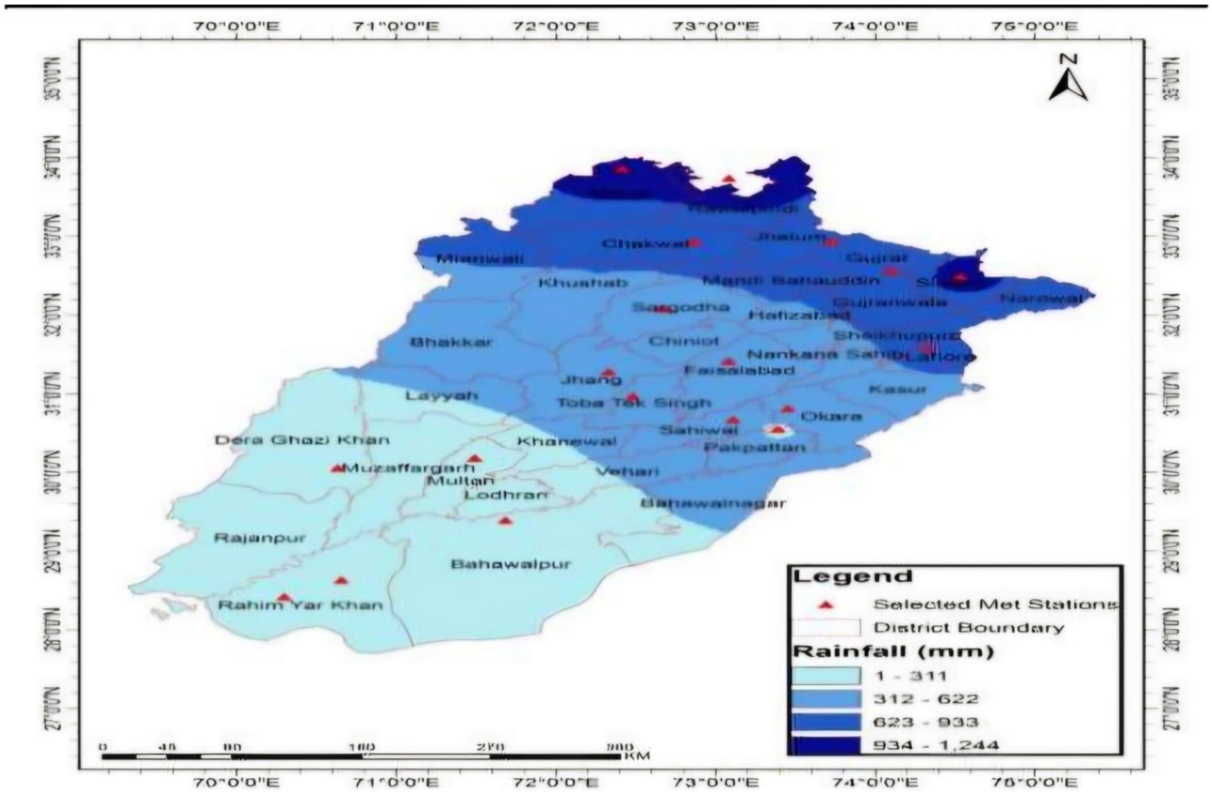
A crucial dimension of climate change impacting Punjab is the intensification of heavy rainfall events. Studies confirm that a warmer atmosphere holds significantly more moisture, which leads to amplified and extreme rainfall when the monsoon system arrives.

The consequences are severe, during one specific event documented in 2025, over 300 fatalities were recorded nationwide, with 162 deaths occurring in Punjab alone, primarily linked to urban flooding and subsequent house collapses. This demonstrates that even a moderate overall monsoon season, when combined with structural vulnerabilities and inadequate drainage, is capable of triggering widespread disruption.

3.3 Runoff Potential Assessment in Different Zones

The potential for rainwater harvesting varies significantly depending on the local topography, land use, and soil characteristics.

In urban areas characterized by extensive impervious surfaces, runoff generation is high, presenting significant volumes of water that can be channeled for MAR or storage. Conversely, in Barani and arid regions, the physical characteristics dictate the feasibility of different techniques. For instance, the Cholistan desert area exhibits fine textured soils with low to very low infiltration rates due to poor porosity. This characteristic, typically viewed as a constraint, is, in fact, advantageous for surface water harvesting and collection because the poorly drained topography generates maximum runoff after absorbing minimum water. This technical assessment provides the foundation for differential design strategies across the province.



Source: Demarcation of Micro Agro Climatic Zones of Punjab, Pakistan. (Muhammad Waseem *et al.*)

Figure 3 Mean Annual Rainfall

4) Geologic and Hydrogeologic Characterization of the Punjab Plains Alluvium

4.1 The Punjab: Land of Five Rivers

The Punjab region is defined by its vast alluvial plain, which is traversed by the Indus River and its four major tributaries, the Chenab, Sutlej, Jhelum, and Ravi Rivers. Toward the north the Punjab is 'bordered by the Himalayan Foothills, the Salt Range, and the Potohar Plateau. The Indus and Sutlej Rivers are, respectively, the western and southeastern boundaries of the area.

The Punjab Plains are primarily composed of Quaternary alluvium deposited at top of semi-consolidated Tertiary rocks or a basement of Precambrian metamorphic and igneous rocks. This alluvium represents the latest phase of sedimentation, extending from the Pleistocene to the Recent epoch. This depositional environment originated in the mid Tertiary period as a subsiding trough adjacent to the rising Himalayan ranges, resulting in the deposition of primarily fluviatile sediments. The alluvial complex consists of fine to medium sand, silt and clay. Beds of gravels or very coarse sand are uncommon. Pebbles of siltstone or mud stone, however may be found embedded in silty or clayey sand in many places. Concretions of secondary origin locally known as kankar are also associated with fine grained strata.

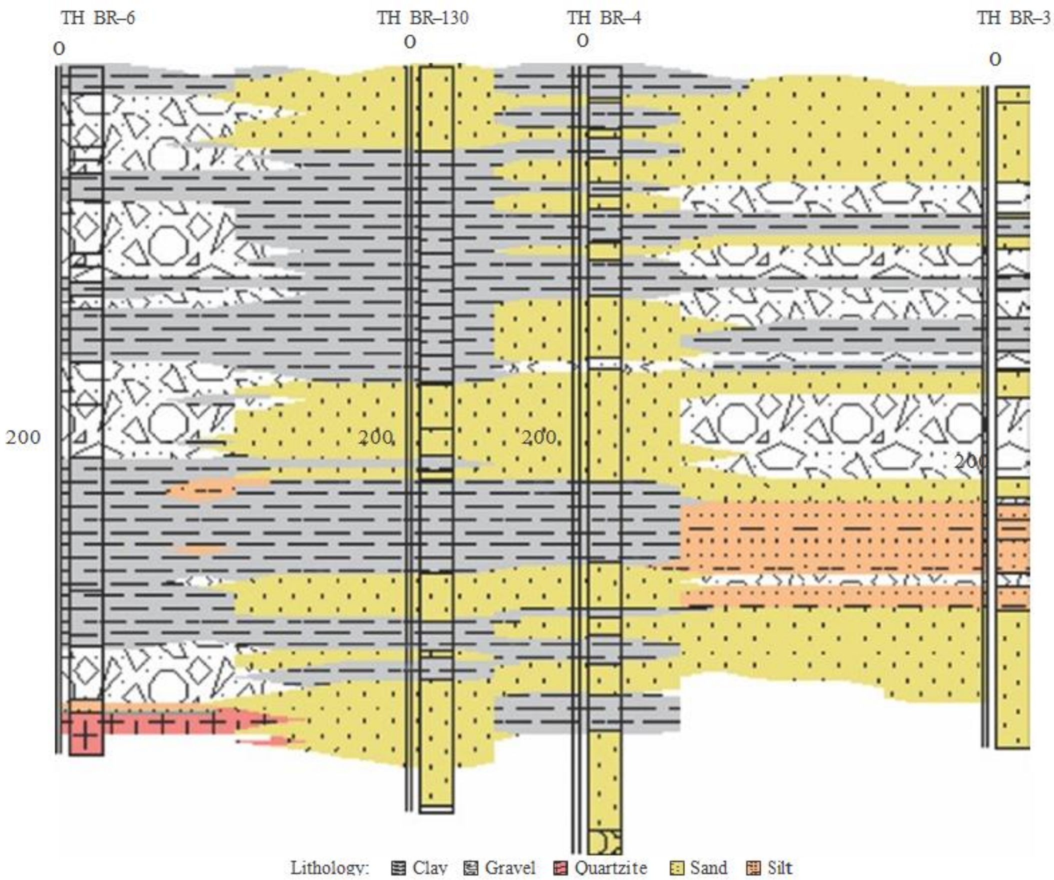


Figure 4 Cross-Section of the Upper Reaches of Bari Daob, through Lahore and Kasur

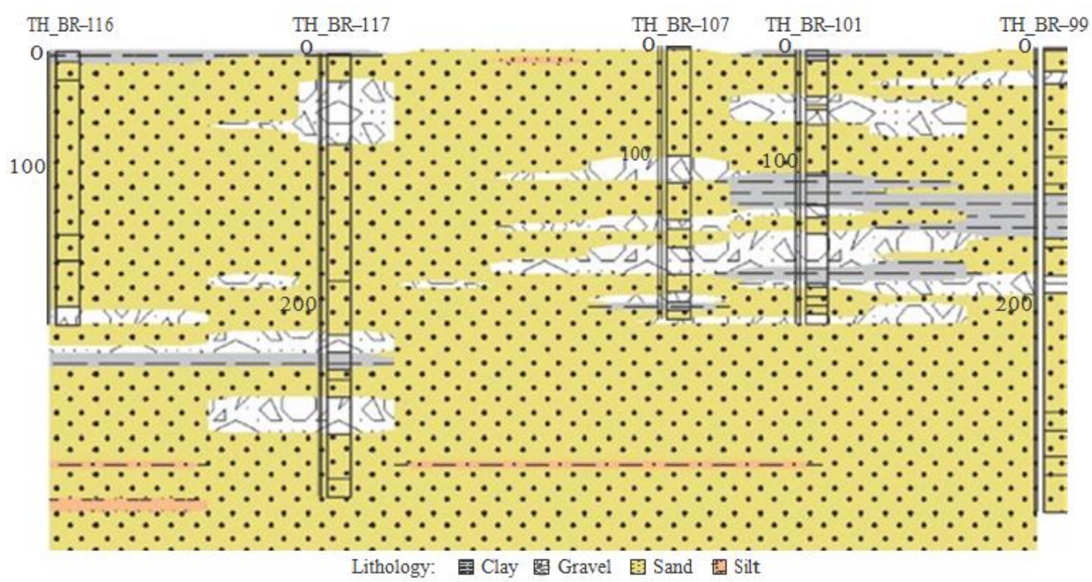


Figure 5 Cross-Section of Lower Reaches of Bari Daob through Multan and Lodhran

Source: Groundwater in Pakistan’s Indus Basin.

4.2 Interfluvial Tracts (Doabs)

The Punjab is naturally divided into four major interfluvial tracts, known as Doabs, by two principal streams. Each doab is a large interfluvial area bounded by two of the principal streams of the Punjab. Rechna, Bari, and Thal Doabs are almost similar in size, having a length of about 250 miles and a maximum width of about 70 miles between the rivers. Chaj Doab is about one half as large as the others. Lahore, capital of the province and the principal center of trade, industry, and education is the largest city in Bari Doab. Other major cities are Multan and Sahiwal in Bari Doab, Jhang, Faisalabad, Gujranwala, and Sialkot in Rechna Doab, Sargodha and Gujrat in Chaj Doab, and Mianwali and Muzaffargarh in Thal Doab. The total area of these Doba’s comprises about 25.3 million Acres as shown in Table-1.

Table 1 Total area of Doabs in Punjab Indus Plain

Doab	Rivers Bounding the Area	Total Area (Million Acres)	Major Urban Centers
Thal	Indus and Jhelum/Chenab	7.9	Mianwali, Muzaffargarh
Bari	Ravi and Sutlej	7.2	Lahore, Multan, Sahiwal
Rechna	Chenab and Ravi	7.0	Faisalabad, Gujranwala, Sialkot
Chaj	Jhelum and Chenab	3.2	Sargodha, Gujrat

4.3 Punjab Indus Plain Aquifer: An Overview

The aquifer consists of deep deposits of unconsolidated, highly permeable alluvium primarily fine to medium sand, silt, and clay with minor gravels. This composition results in a highly transmissive unconfined aquifer.

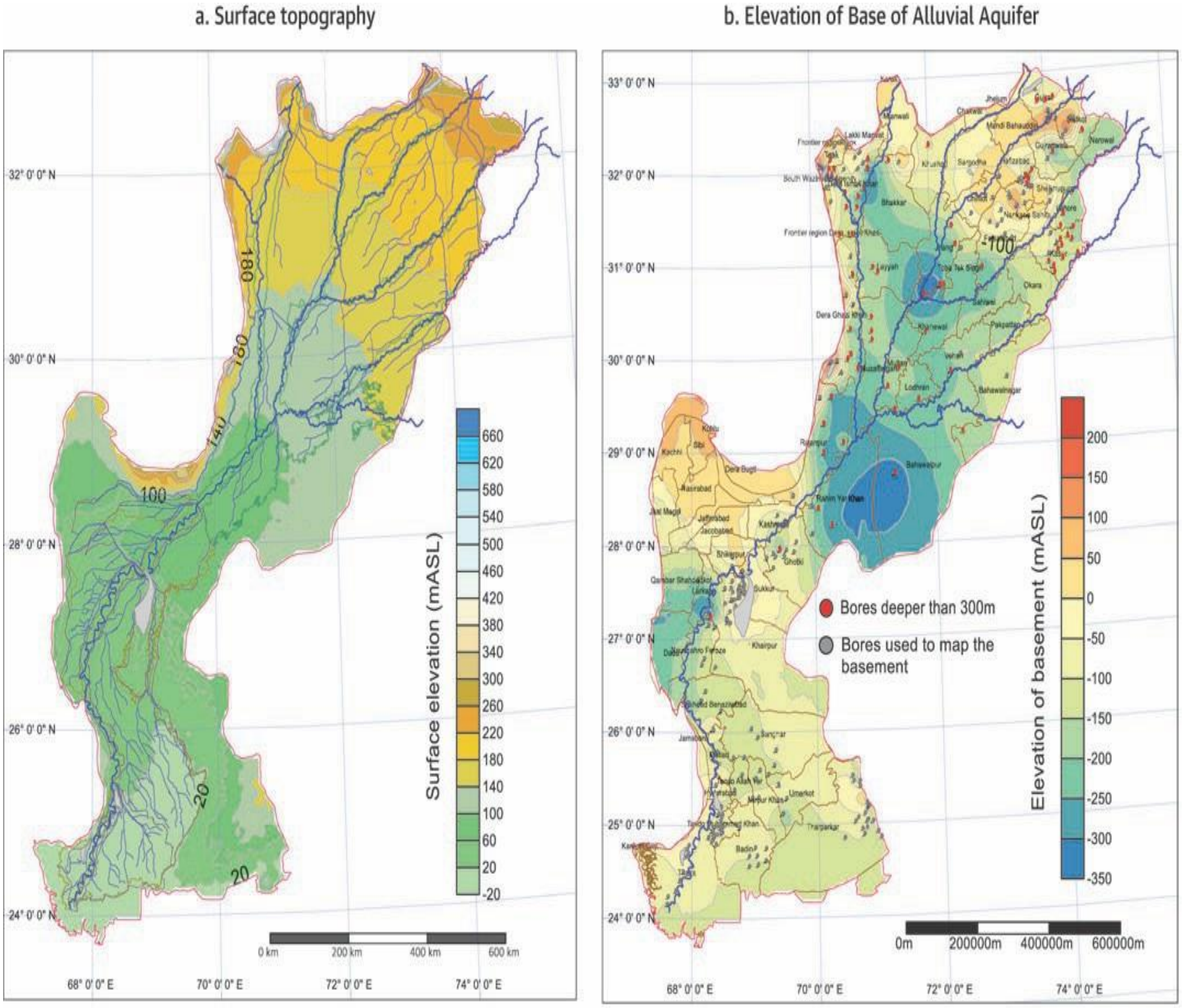
Within Pakistan, the Indus Basin aquifer covers approximately 31.5 million hectares, largely extending across the provinces of Punjab and Sindh. The Indus Basin groundwater system is considered as a single, regionally extensive unconfined aquifer, although local heterogeneities exist where sedimentary layers are discontinuous or where deeper, semi confined aquifers may occur.

Due to its shallow and unconfined nature, the aquifer is easily accessible for groundwater abstraction, however, it is also highly vulnerable to contamination from surface derived pollutants. Groundwater levels respond rapidly to both recharge and abstraction and are strongly influenced by the extensive canal and river network that traverses the basin.

4.4 Aquifer Geometry and Hydrogeological Parameters

The geometry of the unconfined alluvial aquifer is defined by the land surface at the top and by the base of the alluvial sediments at depth, which overlie igneous and metamorphic basement rocks. Surface topography and basement elevation across the

Indus Basin are illustrated in Figure 6.



Source: Groundwater in Pakistan's Indus Basin.

Figure 6 Surface Topography and Elevation of Base Alluvial Aquifer

Within the alluvial plains of Pakistan, surface elevations range from approximately 654 meters above mean sea level (m ASL) in the northern uplands to about 4.3 (m ASL) in the southern deltaic areas.

The thickness of alluvial sediments in Punjab is reported to exceed 1,000 meters in some locations (ACE, AGC, and SMEC, 2011). However, data used in the present analysis indicate a maximum observed sediment thickness of approximately 520 meters in Gujranwala District. This substantial sediment thickness contributes to the aquifer's high storage capacity and long term groundwater availability.

Sediment grain size within the aquifer varies systematically with distance from the Himalayan source areas. Near the mountain front, deposits are dominated by coarse gravels and sands, accounting for up to 85 percent of the material. These grade southward into predominantly fine to medium grained sands (approximately 70 percent) in the central Indus Plain. Despite its heterogeneous composition the Punjab alluvium functions as a unified highly transmissive aquifer system. Groundwater within this system occurs predominantly under water table condition.

4.5 Status of Groundwater Depletion (Rate and Extent)

Groundwater depletion rates vary widely across Punjab, dictating site specific intervention strategies. The most alarming rates are concentrated in metropolitan and intensive agricultural zones. Lahore exhibits an accelerated decline of approximately 0.92 m/year.

In the agricultural plains, depletion is severe in specific canal command areas, notably Lower Punjnad Canal (LPC) Multan, where the decline rate reaches 0.35 m per annum. Conversely, some areas, like Saddiqia, show a milder decline rate of 0.04 m per annum.

A detailed analysis of water table depth reveals an essential geographical disparity, water tables are shallower at the heads of the canals, likely due to seepage from the surface irrigation network, but they become progressively deeper at the tail end of the canals, where water demand is simultaneously higher. This phenomenon has critical implications for equity and resource sustainability. The maximum hydraulic and socio economic benefit from MAR schemes will be achieved by targeting implementation in these water stressed, tail end regions to rectify the localized groundwater deficit and promote equitable resource access. Table 2 summarizes the spatial differentiation required for RWH planning based on current groundwater conditions.

Table 2 Groundwater Depletion and Salinity Risk Prioritization

Region Type	Example Districts	GWL Depletion Rate (m/yr)	Salinity Status (TDS mg/L)	RWH Technique Priority
Urban Over-exploited	Lahore	Approx.0.92 (Accelerating)	Low-Moderate	Groundwater Recharge Wells
Irrigated Canal Tail Ends	LPC Multan	Approx. 0.35 (Severe)	Variable	Managed Aquifer Recharge (MAR)
Central Irrigated/Effluent	Samundri/ Mamukanjan	N/A	High (Up to 1,700)	Controlled Surface Storage (Non-Recharge)
Barani (Rainfed)	Pothohar (Rawalpindi, Chakwal)	Low/Moderate	Fresh	Check Dams / In-situ Conservation

5) Evolution of Groundwater Use, Urban Depletion, and the Role of Rainwater Harvesting in Punjab, Pakistan

Groundwater constitutes the backbone of water supply for both urban and agricultural sectors in Punjab, Pakistan. Over time, the role of groundwater has shifted from a supplementary and naturally replenished resource to a heavily exploited and increasingly stressed source. This chapter traces the historical evolution of groundwater abstraction in Punjab, examines current patterns of urban & agricultural depletion, and establishes rainwater harvesting as a critical strategy for restoring the balance between groundwater recharge and withdrawal.

5.1 Historical Development of Groundwater Use in Punjab

Prior to large scale mechanization, groundwater uses in Punjab remained limited and largely sustainable. Water was abstracted through traditional methods such as shallow dug wells, Persian wheels, and hand pumps, which extracted relatively small quantities of water. These systems were closely aligned with natural recharge processes and did not result in long term declines in groundwater levels.

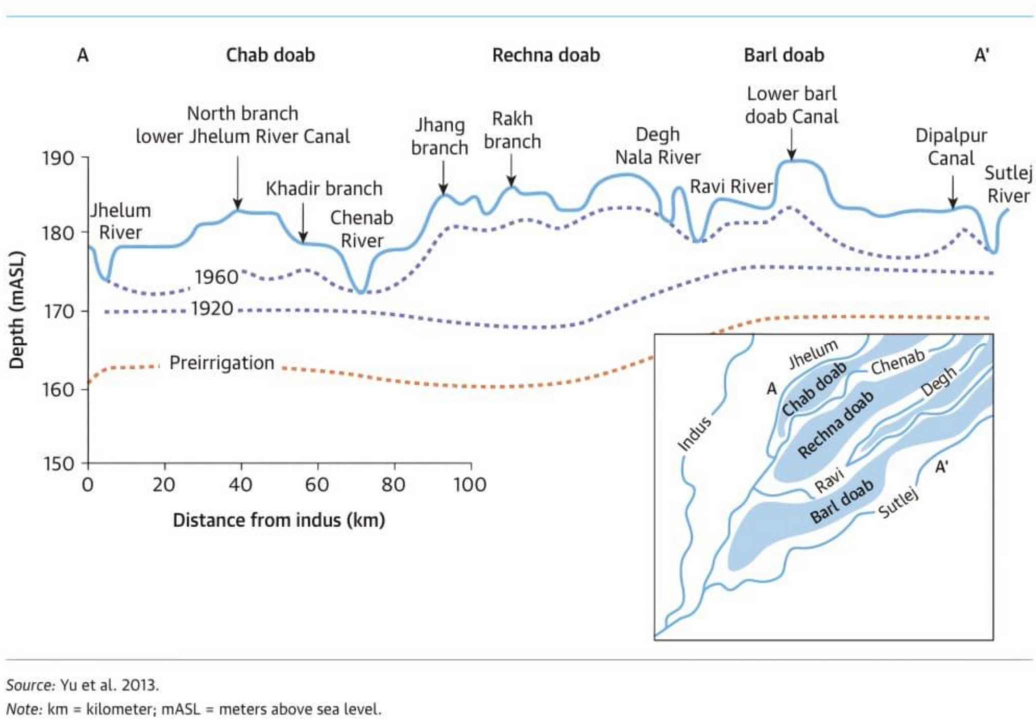


Figure 7 Historical Rise in Water Table in Punjab

Recharge during this period occurred through multiple natural pathways, including monsoon rainfall, seasonal river flooding, seepage from unlined canals, and infiltration across open agricultural fields. Groundwater functioned primarily as a buffer resource, supplementing surface water supplies during dry periods rather than replacing them.

A gradual shift began during the late colonial period with the expansion of canal irrigation systems. While canals significantly increased agricultural productivity, they also altered natural hydrological processes and encouraged more intensive land and water use. However, the most significant transformation occurred after the creation of Pakistan, particularly during the Green Revolution between the 1960s and 1980s.

5.2 Post-Independence Intensification and Aquifer Stress

The introduction of high yield crop varieties, increased fertilizer use, and the large scale installation of private tubewells fundamentally changed groundwater use patterns in Punjab. Between 1965 and 2002, groundwater abstraction increased nearly fivefold, shifting groundwater from a supplementary source to a primary input for irrigated agriculture and urban water supply.

Although this expansion generated substantial economic benefits and strengthened food security, it severely disrupted the balance between groundwater recharge and discharge. The contribution of groundwater to irrigated agriculture increased from 31.6 billion cubic meters in 1976 to approximately 59.95 billion cubic meters by 2012. More recently, improved pumping technologies, particularly solar powered tubewells, along with increasing climate variability, have further intensified abstraction pressures on the Indus Basin aquifer of Punjab, Pakistan.

5.3 Urban Groundwater Dependency and Governance Framework

Urban groundwater depletion has emerged as one of the most critical water management challenges in Punjab. Approximately 90 percent of Punjab's urban areas rely almost entirely on groundwater for domestic, commercial, and industrial water needs. Major cities such as Lahore, Faisalabad, Gujranwala, Multan, Rawalpindi, Sheikhupura, Gujrat, and Vehari depend heavily on aquifer abstraction.

Groundwater management and extraction are carried out by multiple institutions, including Water and Sanitation Agencies (WASAs), municipal authorities, Cantonment Boards, Military Engineering Services (MES), and a rapidly expanding number of private housing societies. This fragmented governance structure has contributed to weak regulation, limited monitoring, and uncontrolled abstraction, accelerating groundwater depletion across urban areas.

5.4 Impacts of Urbanization on Groundwater Recharge

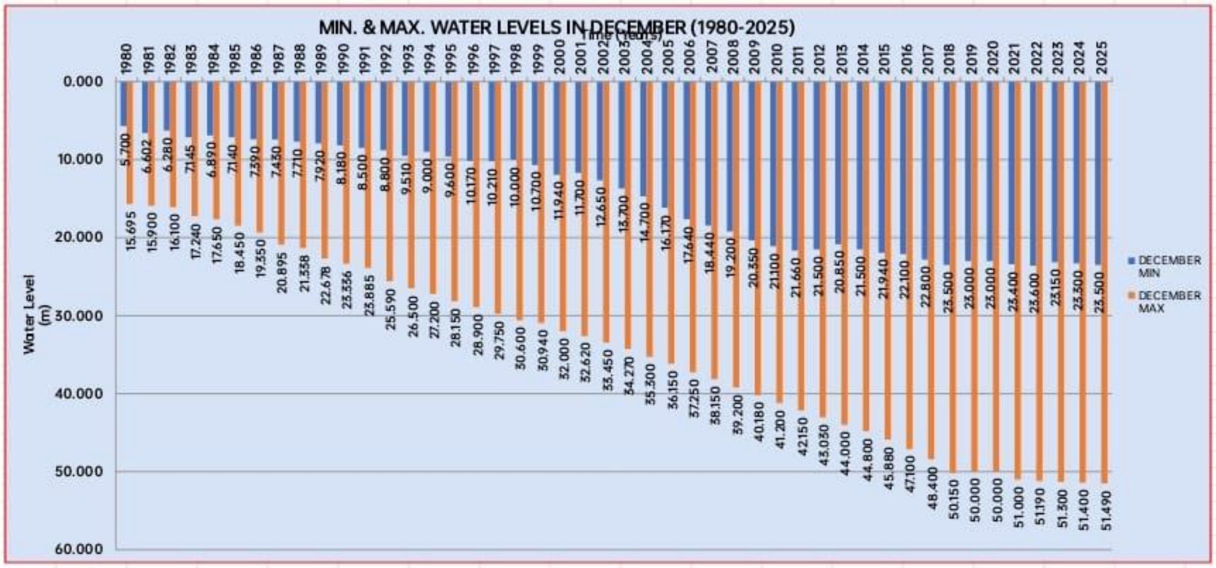
Rapid urbanization, population growth, and industrial expansion have placed unprecedented stress on the Punjab aquifer. While groundwater extraction has increased exponentially, recharge mechanisms have not expanded accordingly. As pumping exceeded natural recharge, institutions like WASAs and the private users responded by deepening wells and installing higher capacity pumps, further accelerating abstraction.

Urban land use change has significantly reduced natural recharge potential. Expansion of housing schemes, roads, industrial estates, and paved surfaces has replaced permeable soil and vegetation with impermeable concrete and asphalt. Natural recharge zones that once facilitated infiltration have been largely eliminated, resulting in reduced infiltration and increased surface runoff. Rainfall that previously contributed to aquifer recharge is now rapidly conveyed into drainage and sewerage systems, intensifying urban flooding while simultaneously wasting freshwater resources.

5.5 Spatial Variability of Groundwater Depletion in Punjab

Groundwater depletion rates vary significantly across Punjab, reflecting differences in land use, irrigation intensity, and surface water availability. The most severe declines are observed in large urban centers and intensively farmed regions.

Lahore represents the most critical urban case, with groundwater levels declining at an average rate of approximately 1.00 meters per year due to heavy domestic, industrial, and commercial pumping.



Source: WASA, Lahore

Figure 8 Groundwater Depletion History of Lahore

In agricultural regions, depletion is particularly pronounced in certain canal command areas. For example, groundwater levels in the Lower Panjnad Canal (LPC) command area of Multan are declining at around 0.35 meters per year, indicating sustained abstraction in excess of recharge.

Within canal systems, groundwater depth varies spatially. Head reach areas typically have shallower water tables due to canal seepage, while tail-end areas experience deeper groundwater levels because of limited surface water supplies and higher dependence on groundwater pumping. These tail-end areas are therefore among the most water-stressed and present the greatest potential for Managed Aquifer Recharge (MAR) interventions.

5.6 Agricultural Intensification and Reduced Natural Recharge

In agricultural land areas, reduced fallow periods and intensive cropping patterns have further limited opportunities for rainfall infiltration. Although monsoon rainfall continues annually, a large proportion of this water is lost as surface runoff through drainage networks rather than contributing to aquifer recharge. This represents a significant departure from historical conditions, when rainfall and floodwater played a major role in sustaining groundwater levels.

5.7 Rainwater Harvesting as a Managed Recharge Strategy

Rainwater harvesting directly addresses the long standing imbalance between groundwater abstraction and recharge in Punjab. It represents a shift from passive and incidental recharge to deliberate and managed recharge by capturing rainfall at the point where it falls and directing it into the subsurface.

From a hydrogeological perspective, Punjab's extensive alluvial aquifer system is highly suitable for rainwater harvesting. The high permeability and transmissivity that once supported large scale groundwater abstraction also allow efficient recharge when appropriate structures are implemented. Recharge basins, percolation ponds, infiltration trenches, recharge wells and rooftop rainwater harvesting systems can effectively convey harvested rainwater into depleted aquifers, particularly in areas experiencing sustained water table decline.

The historical trajectory of groundwater abstraction demonstrates the limitations of continued reliance on supply side measures such as deeper tubewells and increased pumping capacity. As abstraction depths increase, energy requirements rise sharply, and groundwater quality often deteriorates due to salinity and mineralization.

Rainwater harvesting provides an alternative and complementary approach by reducing dependence on groundwater pumping while simultaneously replenishing aquifer storage. It functions both as a demand management tool and a supply augmentation measure. Urban areas can utilize rooftop rainwater harvesting and recharge wells to offset municipal demand, while agricultural regions can capture monsoon runoff, field drainage, and canal escape flows to recharge shallow and intermediate aquifers.

6) Groundwater Salinity Zones in Punjab Districts, Pakistan

Punjab, Pakistan, spans 41 districts, depends heavily on groundwater to meet domestic and agricultural water demands, with more than 50% of total water use extracted from groundwater reservoir.

Water quality in Punjab, is currently one of the province's most critical environmental challenges. Total Dissolved Solids (TDS), which represent the concentration of dissolved organic and inorganic substances in water, are a key indicator of groundwater hardness and salinity. High salinity poses serious risks to drinking water safety, agricultural productivity, and soil health. Current assessments indicate that approximately 17% of Punjab's land area is affected by saline groundwater, where TDS concentrations exceed 3,000 mg/L, rendering the water largely unsuitable for potable use. Salinity problems are most pronounced in the southern and southwestern districts of the province. These conditions are driven by a combination of low annual rainfall, limited natural recharge, canal seepage into saline formations, excessive groundwater abstraction, and poor drainage that renders much of the province's groundwater non drinkable. In contrast, northern and central Punjab generally has better groundwater quality due to sustained recharge from major river systems, including the Indus, Jhelum, Chenab, Ravi, and Sutlej, which help in maintaining lower salinity levels.

6.1 TDS Standards and Current Groundwater Quality

In Pakistan, drinking water quality is regulated under the National Standards for Drinking Water Quality (NSDWQ), which are largely harmonized with World Health Organization (WHO) guidelines. Both prescribe a maximum permissible limit of Total Dissolved Solids (TDS) of less than 1,000 mg/L for potable water. TDS is a critical indicator of salinity, drinkability, and long-term suitability of water for both human consumption and agricultural use.

The Punjab Irrigation Department and PCRWR (Pakistan Council of Research in Water Resources) use the following standard parameters to classify the groundwater for drinking and agricultural purposes. These parameters include Electrical Conductivity (EC), Total Dissolved Solids (TDS), Sodium Adsorption Ratio (SAR), and Residual

Sodium Carbonate (RSC). The classification thresholds used in provincial assessments are summarized below.

Table 3 Provincial Assessment Thresholds

Parameter	Fit (Fresh)	Marginal	Unfit. (Saline)
dS/m)	< 1.5	1.5 – 2.7	> 2.7
TDS (mg/L)	< 1000	1000 – 2000	> 2000
SAR	< 10	10 – 18	> 18
RSC (meq/L)	< 2.5	2.5 – 5.0	> 5.0

The spatial distribution of high TDS in Punjab is governed by both geogenic factors including sediment mineralogy, evaporative concentration, and stagnant groundwater flow and anthropogenic pressures, notably intensive groundwater abstraction, agricultural return flows, excessive fertilizer application, and localized industrial effluents.

6.2 Groundwater Salinity Zonation of the Punjab Plain

Based on hydrogeological setting and concentration of Total Dissolved Solids (TDS), the Punjab Plain is divided into three major groundwater salinity zones.

6.2.1 FRESH GROUNDWATER ZONE (Low Salinity)

This zone is characterized by low mineralization, typically with TDS less than 1,000 ppm (parts per million) or EC less than 1.5 dS/m, lower salinity, and is more suitable for drinking and irrigation for all crops without treatment. Areas near Indus, Jhelum, Chenab, Ravi and Sutlej, often have fresher groundwater due to high rainfall and sufficient recharge from these rivers.

- **Drinking Quality**: Generally safe and "sweet" (low TDS), though urban areas face biological contamination and heavy metal issues (e.g., arsenic in Lahore).
- **Agricultural Quality**: Excellent, Low Electrical Conductivity (EC) due to monsoon recharge & rivers and Sodium Absorption Ratio (SAR) make it fit for all crops without treatment. Best quality typically near Indus & tributaries and in portions of northern & central Punjab.

- **Major Districts / Areas include:** Rawalpindi Division (e.g., Rawalpindi, Jhelum, Chakwal), North & North-Central Rechna Doab, Gujranwala Division (e.g., Gujranwala, Sialkot, Narowal), Sheikhupura, Nankana Sahib, Parts of Central Doabs near rivers / canals, Lahore, Kasur (near Ravi), Faisalabad, Toba Tek Singh, Chiniot (areas closer to the recharge zone of Chenab/Ravi/Sutlej canal systems), Jhang (areas closer to the Chenab/river recharge zones), Parts of Upper Chenab & Indus plains, Mianwali (areas closer to the Indus recharge reach).

6.2.2 MARGINAL / BRACKISH GROUNDWATER ZONE (Moderate to High Salinity)

This zone contains moderately saline water having TDS between 1,000 and 3,000 ppm and EC values from 1.5 to 4.0 dS/m. It is primarily located in interfluvial areas (doabs) further away from direct river recharge. Water quality in this zone is highly variable and can change with depth. Salinity generally increases with distance from recharge zone (rivers and canals) and often worsens in deeper aquifer horizons.

- **Drinking Quality**: Drinking water quality is considered marginal. Higher concentrations of fluoride and nitrates are common, and many communities depend on filtration plants or blended supplies
- **Agricultural Quality**: Groundwater is moderately fit for agricultural purposes and is often used in conjunctive irrigation with canal water to reduce the risk of soil salinity and sodicity.
- **Major Districts/ Areas include**: Faisalabad, Jhang, Toba Tek Singh Sahiwal, Okara, Khanewal and Central Bari Doab interior plains.

6.2.3 BRAKISH/SALINE ZONE (HIGH SALINITY)

This zone represents the most critical groundwater quality conditions in Punjab. It occurs in arid and semi arid regions, particularly in downdip and stagnant aquifer zones where recharge is limited and evaporation is high.

- **Drinking Quality:** Groundwater typically exhibits TDS exceeding 3,000 mg/L and EC values greater than 4.0 dS/m, making it unfit for drinking purposes. In districts such as Bahawalpur and Vehari, up to 80% of groundwater samples are reported as hazardous for drinking due to high salinity and arsenic contamination.

- **Agricultural Quality**: Groundwater is highly problematic for irrigation. Agricultural use of this water, without blending or treatment, leads to rapid soil degradation, yield decline, and eventually land abandonment. In the Thal and Cholistan desert fringes, groundwater is predominantly saline across most depths.
- **Major Districts/areas include, Southern and southwestern Punjab**: Bahawalpur (Cholistan), Bahawalnagar, Layyah, Multan (industrial and peri urban areas such as Sameejabad, Shujabad, Jalalpur Pirwala), Vehari (Muslim Town, TBZ colony, Sharqy colony, Danewal, Stadium Road and Y Block), Lodhran (deep aquifer zones and unlined canal fringes), Rahim Yar Khan (western arid parts), Muzaffargarh (lower interfluvial plains), Dera Ghazi Khan and Rajanpur.
  In many of these districts, shallow groundwater near canals may be marginally usable, while deeper aquifers are predominantly saline.

6.3 District-Wise Groundwater Salinity Status

The following table summarizes median EC values and irrigation suitability for selected districts based on aggregated monitoring data from central and southern Punjab. While no comprehensive 2024–2025 district level report exists, trends indicate stable to mildly deteriorating conditions.

Table 4 District Wise Groundwater Salinity Status

District	Median EC (dS/m)	Salinity Zone

Sialkot	~1.0	Fresh
Gujranwala	~1.2	Fresh
Narowal	~1.4	Fresh/Marginal
Lahore	~1.3	Fresh/Marginal
Kasur	~1.4	Fresh/Marginal
Sheikhupura	~1.3	Fresh
Rawalpindi	~1.1	Fresh
Jhelum	~1.2	Fresh
Chakwal	~1.2	Fresh
Sargodha	~1.5	Marginal/Brackish
Faisalabad	~2.0	Brackish
Toba Tek Singh	~1.8	Marginal/Brackish
Multan	~1.6	Marginal/Brackish
Khanewal	~1.7	Marginal/Brackish
Vehari	~1.7	Marginal/Brackish
Bahawalpur	~2.5	Brackish
Rahim Yar Khan	~2.8	Brackish
D.G. Khan	~2.6	Brackish
Rajanpur	~2.6	Brackish

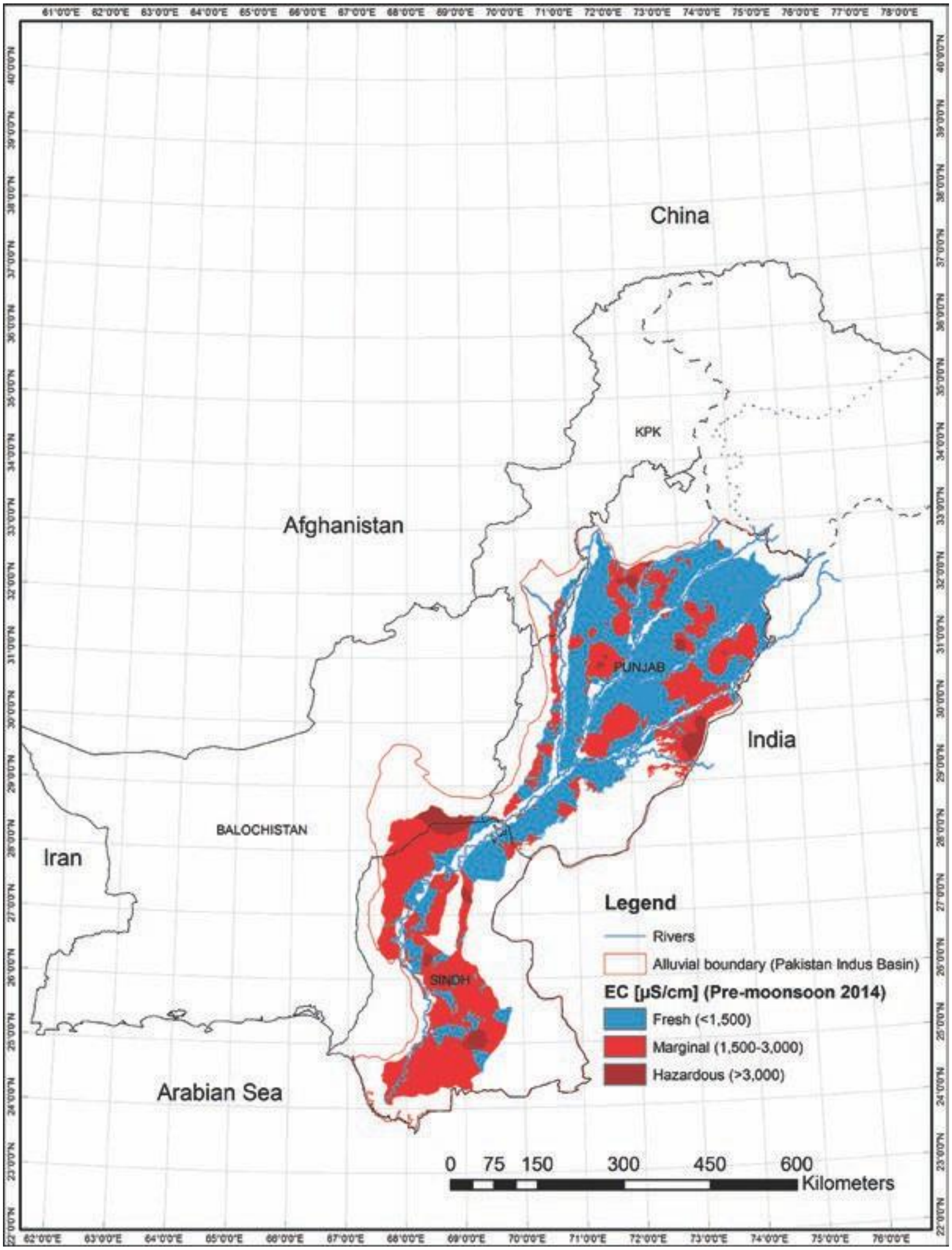


Figure 9 Fresh and Saline Groundwater in Indus Basin

Source: Groundwater in Pakistan's Indus Basin

7) HYDROGEOLOGICAL ZONING FOR RWH SUITABILITY

Effective rainwater harvesting (RWH) planning necessitates the subdivision of Punjab into clearly defined zones based on an integrated assessment of hydrogeological parameters, long term average annual rainfall, depth to groundwater, subsurface lithology, with particular emphasis on soil, aquifer permeability and the presence or proximity of saline groundwater horizons. This integrated approach enables informed selection of appropriate RWH structure, such as recharge wells or surface ponding and infiltration systems, ensuring that each structure is matched to local recharge potential while minimizing the risk of mobilizing or upconing of saline groundwater.

As such the Punjab has been divided into three primary zones for RWH, each requiring a customized technical approach.

7.1 INTEGRATED RWH PLANNING ZONES FOR PUNJAB

Based on the integrated assessment of hydroclimatic conditions, groundwater availability, abstraction stress, aquifer characteristics, and water quality risk, Punjab can be systematically divided into three primary Rainwater Harvesting (RWH) planning zones. Each zone exhibits distinct hydrogeological behavior and therefore requires a customized technical strategy for sustainable recharge and water conservation. The zoning framework enables targeted selection of RWH interventions while minimizing risks related to aquifer degradation, urban flooding, and saline water intrusion.

7.1.1 Zone A: High Potential Recharge Zone (Northern / Piedmont Belt)

Zone A encompasses the northern and northeastern piedmont areas of Punjab, including northern Attock, Rawalpindi, Sialkot, and Narowal districts. This zone receives the highest average annual rainfall in the province, typically ranging between 934 and 1,244 mm, with a pronounced monsoonal peak.

Hydrogeologically, the zone is dominated by piedmont and alluvial fan deposits, consisting of gravels, sands, & cobbles, which impart high superficial permeability and infiltration capacity. Groundwater levels are generally shallow to moderate, and aquifer transmissivity is comparatively high, making this zone naturally favorable for recharge.

7.1.1.1 Recommended RWH Approach:

Rainwater harvesting in Zone A should primarily focus on surface based recharge and runoff management structures capable of handling large storm flows. These include:

Infiltration basins and recharge ponds, Small to medium check dams across seasonal streams, Agricultural ponding and field level water spreading under Rainwater Harvesting for Sustainable Agriculture (RWHSA).

Recharge wells may be deployed only as supplementary measures, particularly in urbanized pockets where land availability limits the construction of surface basins.

7.1.1.2 Key Design Constraint:

Due to high rainfall intensity and rapid runoff generation, special emphasis must be placed on, Runoff velocity control, Energy dissipation at inlets, Bank and bed erosion protection.

Failure to incorporate these measures may result in structural damage and sediment overloading of recharge facilities.

7.1.2 Zone B: High-Stress Managed Recharge Zone (Central Alluvial / Urban Doabs)

Zone B comprises the central alluvial plains and major urban and peri urban centers, including Lahore, Faisalabad, Sheikhupura, Gujranwala, and surrounding areas. This zone is characterized by, very high groundwater abstraction rates, dense population and industrial activity, deepening water tables, particularly beneath urban cores and recurrent urban flooding due to inadequate storm water drainage capacity.

Although the alluvial aquifer has substantial storage potential, natural recharge has become insufficient to offset abstraction, necessitating active managed aquifer recharge (MAR) interventions.

7.1.2.1 Recommended RWH Approach:

In this zone, recharge wells represent the most feasible and effective RWH technique. These systems allow rapid evacuation of storm water from flooded roads and underpasses and simultaneously support high volume, targeted recharge directly into deeper aquifer horizons and efficient use of limited urban space.

The preferred source water includes pre-treated rooftop runoff and selected road runoff, conveyed through a controlled drainage network.

7.1.2.2 Key Design Constraint:

The principal risk in Zone B is well clogging and groundwater quality deterioration, arising from, high suspended solids load, hydrocarbons, heavy metals, and organic pollutants and elevated microbial (coliform) contamination from urban runoff

Accordingly, recharge wells must be supported by stringent multi stage pretreatment systems, including sedimentation chambers, oil grit separators, sand filtration, and disinfection where required. Regular monitoring and maintenance are critical for long term system performance.

7.1.3 Zone C: Constraint Driven Targeted Recharge Zone (Southern / Western Punjab)

Zone C covers parts of southern and southwestern Punjab, including Multan, Khanewal, Vehari, Lodhran, Bahawalpur, and adjacent areas. This zone is typified by, arid to semi arid climatic conditions, lower annual rainfall and higher evapotranspiration, finer grained soils with reduced permeability and a complex hydrogeological setting where fresh groundwater overlies saline water at variable depths. Groundwater quality constraints dominate planning decisions in this zone, and recharge interventions must be carefully controlled.

7.1.3.1 Recommended RWH Approach:

The strategic focus in Zone C should shift from aggressive aquifer recharge to Rainwater Harvesting for Sustainable Agriculture (RWHSA), emphasizing, Soil moisture conservation, improved infiltration at the root zone and reduction in irrigation demand

Passive recharge measures, such as utilizing large natural depressions, seasonal wetlands, and urban parks, may be employed where site conditions permit. Recharge wells are highly selective interventions and should be considered only after comprehensive site investigations.

7.1.3.2 Key Design Constraint:

The most critical risk is freshwater mounding, which can induce upward migration of underlying saline groundwater, irreversibly degrading the freshwater aquifer. To mitigate this risk, injection rates must be conservative, recharge durations should be limited and continuous groundwater quality monitoring is mandatory.

Any proposal for recharge wells must be supported by detailed geophysical surveys and hydro stratigraphic mapping to accurately delineate the fresh saline water interface.

7.2 Planning Implications

The differentiated zoning framework underscores the necessity of site specific, risk informed RWH planning in Punjab. The strategic deployment of RWH infrastructure must be guided by a structured evaluation of localized hydrogeological parameters, abstraction stress, and water quality considerations. This evaluation process is formalized through a RWH suitability and decision matrix, which supports transparent, defensible selection of appropriate recharge technologies for each planning zone.

7.3 Review of Rainwater Harvesting Techniques Suitable for Punjab

The selection of rainwater harvesting (RWH) techniques in Punjab must be guided by physiographic conditions, rainfall regime, land use, and groundwater characteristics. Punjab exhibits three broad functional contexts for RWH implementation, rainfed (Barani) rural areas, urban centers, and arid desert regions, each requiring a tailored technical approach. The following sections review the RWH techniques most suitable for these settings and assess their relevance for feasibility analysis.

7.3.1 Rural / Barani Rainwater Harvesting Techniques

Rainfed (Barani) regions, particularly the Potohar Plateau, depend almost entirely on precipitation for agricultural productivity. In these areas, RWH strategies emphasize runoff moderation, in-situ moisture conservation, and localized storage to enhance crop resilience and reduce land degradation.

7.3.1.1 Earthen Structures (Check Dams and Farm Ponds)

Small earthen structures such as check dams, farm ponds, and dug wells are widely applicable in Barani catchments. These structures function by reducing surface runoff velocity, promoting temporary water storage, minimizing soil erosion, and enabling limited groundwater recharge. Farm ponds constructed near seasonal or perennial drainage lines can provide supplemental irrigation to command areas ranging from 2 to 6 hectares, depending on rainfall and storage capacity.

From a feasibility perspective, proper site selection, hydraulic design, and safety provisions are critical. Design standards require protective measures such as fencing, parapet walls, or protective covers to prevent accidents involving humans and livestock. Poorly designed or unprotected structures significantly increase safety risks and long term maintenance costs.

7.3.1.2 Contour Bunds and Trapezoidal Bunds

Contour bunds and trapezoidal bunds are earthen embankments constructed along contour lines to intercept and retain surface runoff on cultivated land, rangelands, and degraded slopes. These structures improve soil moisture availability, reduce slope erosion, and enhance rainwater utilization efficiency.

However, historical experience in Punjab indicates that unsupervised and empirically designed bunding schemes have suffered from early failure due to overtopping, breaching, or improper alignment. This highlights the necessity for scientific design based on rainfall intensity, runoff coefficients, soil type, and slope characteristics. For feasibility assessment, only properly engineered bunds with defined design return periods and maintenance provisions should be considered viable.

7.3.2 Urban Rainwater Harvesting Techniques

In major urban centers such as Lahore, Faisalabad, Rawalpindi, and Multan, RWH interventions serve a dual purpose, urban flood mitigation and Managed Aquifer Recharge (MAR). Urban RWH systems must be designed to operate within dense built up environments while addressing groundwater depletion and stormwater management challenges.

7.3.2.1 Rooftop Rainwater Harvesting Systems

Rooftop rainwater harvesting involves collecting runoff from building roofs and storing it for non potable domestic uses such as toilet flushing, gardening, vehicle washing, and laundry. These systems reduce dependence on municipal groundwater supplies and contribute to decentralized water security.

Empirical evidence from Islamabad indicates that a rooftop area of approximately 90 m² can yield up to 103,000 liters per year, sufficient to meet the non potable water demands of up to five individuals. For feasibility studies, rooftop RWH systems are particularly suitable for public buildings, housing societies, and commercial complexes where standardized designs and maintenance regimes can be enforced.

7.3.2.2 Recharge Wells and Recharge Pits

Recharge wells and pits are engineered MAR structures designed to intercept stormwater runoff from roads, parking areas, and urban depressions and convey it directly into shallow aquifers. These systems are especially effective in cities experiencing frequent urban flooding and declining groundwater levels.

The successful implementation of recharge wells at Gaddafi Stadium, Lahore, has demonstrated the technical and economic viability of this approach. The project validated recharge wells as one of the most effective urban MAR solutions for Punjab, provided that adequate pretreatment (silt traps, oil grit separators) and groundwater quality safeguards are incorporated into the design.

7.3.3 Arid Region Rainwater Harvesting Techniques (Cholistan)

In arid regions such as the Cholistan Desert, average annual rainfall is extremely low (approximately 166 mm), and groundwater is typically deep, saline, or unsuitable for direct use. Consequently, RWH in these areas is entirely focused on surface water harvesting and storage for domestic and livestock needs.

7.3.3.1 Tobas (Traditional Surface Storage Ponds)

The traditional Toba system, excavated ponds or reservoirs, represents the most effective and culturally accepted RWH solution in Cholistan. The feasibility of Tobas is strongly supported by the region's physical characteristics. Fine textured soils with low permeability significantly reduce seepage losses, allowing efficient surface water storage despite minimal rainfall.

As a result, the limited runoff generated during rainfall events can be captured and stored with relatively high efficiency. Tobas are simple, low cost, and well adapted to local socioeconomic conditions. Approximately 480 settlements in Cholistan maintain their own Tobas, often supplemented by shallow wells. This widespread and historically proven system provides a strong foundation for modern upgrading, lining, desilting, and catchment improvement programs under contemporary RWH feasibility frameworks.

8) SITE SELECTION CRITERIA FOR RAINWATER HARVESTING SYSTEMS

Appropriate site selection is fundamental to the effectiveness, sustainability, and economic viability of rainwater harvesting (RWH) systems. Sites should have adequate and reliable rainfall, suitable catchment characteristics, and favorable topography to generate and convey runoff efficiently without causing erosion or drainage obstruction. Hydrogeological conditions must support infiltration and storage, with permeable aquifers, sufficient groundwater depth, and declining water levels preferred for recharge based systems. Soil and geological conditions should allow stable construction and adequate infiltration, while groundwater quality must be assessed to ensure that recharge does not degrade existing aquifers, particularly in saline or polluted zones. Land use compatibility, absence of conflicts with existing infrastructure, environmental protection, and community acceptance are essential for long term operation. Finally, selected sites should be technically feasible and cost effective, enabling efficient construction, operation, and maintenance while maximizing water conservation and groundwater recharge benefits.

8.1 SITE SELECTION CRITERIA FOR CHECK DAMS (For Barani Areas, Hill Torrents, Seasonal Nullahs)

Check dams are small, temporary or permanent barriers constructed across a gully or natural water channel to reduce velocity, slow runoff, store water temporarily and promote infiltration. Site selection is the most critical factor determining their performance and lifespan.

8.1.1 Topography and Drainage Characteristics

The catchment area upstream should be located in narrow valley, sufficiently large to generate runoff but not so large that peak flows exceed the structural capacity of the dam. For small to medium check dams, an upstream catchment area typically ranging from 50 to 500 hectares (.5 million m² to 5 million m²) is preferred. The longitudinal slope of the stream should ideally be between 1 and 6 percent (1% longitudinal slope means that for every 100 feet/meter of horizontal distance, there is a 1 feet/meter change in vertical elevation). Steeper slopes can lead to high velocity water that may undercut or wash away the structure, while flat slopes reduce storage efficiency.

8.1.2 Valley Geometry and Storage Potential

A narrow valley with stable abutments is preferred because it reduces construction volume and cost while increasing storage efficiency. Wide floodplains should be avoided, as they require longer structures and higher embankment volumes. The valley upstream of the dam should be able to hold water without flooding nearby villages, roads, farms, or important structures.

8.1.3 Geological and Foundation Conditions

The foundation should be on hard, impermeable strata to prevent seepage underneath. However, the upstream reservoir area should ideally have permeable soil to facilitate groundwater recharge.

The foundation must rest on hard, impermeable non erodible strata such as hard clay, gravel, weathered rock, or bedrock. Loose sand, silt, or collapsible soils are unsuitable unless treated with cut off walls and proper foundation stabilization. The depth to bedrock should be shallow enough to allow anchoring of the structure. The presence of fractured rock or permeable strata upstream is highly desirable, as it enhances groundwater recharge.

8.1.4 Hydrological Considerations

Sites with high runoff coefficients (rocky or compacted catchments) are preferred. Areas with excessive sediment load should be carefully evaluated, as rapid siltation can reduce storage capacity. Spillway location and alignment must allow safe passage of design flood (typically 25 years or 50 years return period) without overtopping the structure.

8.1.5 Environmental and Social Considerations

The site should not obstruct fish migration routes or cause adverse ecological impacts downstream. Community acceptance is essential; land ownership issues must be resolved prior to construction. Sites that can provide multiple benefits such as livestock watering, groundwater recharge, and limited irrigation are preferred.

8.1.6 Accessibility and Constructability

The site must be accessible for construction equipment and future maintenance. Availability of local construction materials (stone, sand, aggregates) reduces cost and improves feasibility.

8.2 Site Selection Criteria for Rooftop Rainwater Harvesting Systems (Urban, Peri Urban, And Rural Buildings)

Rooftop rainwater harvesting systems collect rainfall from building roofs and store it for direct use or recharge. Their success depends on several key factors such as roof characteristics, rainfall, and user demand.

8.2.1 Roof Area and Geometry

Buildings with larger roof areas are more suitable because they can catch more rainwater. Flat or gently sloping roofs are the best, as they allow easy installation of gutters and downpipes. Roofs with complex shapes or many levels can still be used with proper design but may increase system cost.

8.2.2 Roof Material

Impermeable and non toxic roofing materials such as reinforced concrete, galvanized iron sheets, aluminum sheets, or tiles are ideal. Roofs made of asbestos, lead based paints, or materials susceptible to contamination are not suitable for potable use unless water is treated. Rough or dusty roofs will need enhanced filtration to remove dirt and sediment.

8.2.3 Rainfall Characteristics

Rooftop RWH is most effective in areas receiving annual rainfall above 300 millimeters. Cities in northern Punjab and central districts are the best suitable. Even in low rainfall areas, rooftop systems can provide extra water if storage is designed properly.

8.2.4 Water Demand and Usage Pattern

Buildings with regular water demand such as residences, schools, mosques, hospitals, and offices are ideal for rooftop rainwater harvesting. Before site selection, it must be decided whether the water will be used for potable, non potable purposes or just to recharge the groundwater reservoir, as it determines the type of filters and storage requirements.

8.2.5 Structural Safety and Load Bearing Capacity

The building structure must be capable of supporting additional loads from storage tanks if placed on roofs, if the building's strength is unknown, ground level storage tanks are preferred and there must be enough clear ground space to install a filter unit and a storage tank without compromising the building's foundation.

8.2.6 Proximity to Storage and Pollution Sources

The storage tank or recharge point should be located as close to the downspouts as possible to minimize piping. The site should be away from chimneys, vent pipes, or overhanging trees to reduce the entry of soot, gasses, and leaves into the system.

8.2.7 Drainage and Overflow Management

During very heavy rain, the tanks may get full. The site must permit to handle this overflow water so that it doesn't cause flooding. Overflow should be directed safely to recharge pit, gardens, or recharge well.

8.2.8 User Willingness and Maintenance Capacity

Rooftop rainwater harvesting systems require regular cleaning of roofs, gutters, and filters. Buildings with committed owners, dedicated staff/active management (like school’s mosques and offices) are considered more suitable due to organized maintenance and arrangements.

8.3 Site Selection Criteria for Recharge Wells (Urban and Semi Urban Aquifer Recharge)

8.3.1 Recharge Wells

Recharge wells are used to convey filtered rainwater directly into deeper aquifers. Incorrect site selection can cause aquifer contamination, making this the most technically sensitive RWH structure, choking and failure of recharge well.

8.3.2 Groundwater Quality and Aquifer Type

Recharge wells should only be constructed where the target aquifer contains fresh or marginally fresh groundwater. Areas with saline or brackish aquifers should be avoided, as recharge may mobilize saline fronts. Hydrogeological investigations, including borehole logs and water quality data, are essential.

8.3.3 Soil and Subsurface Conditions

Highly permeable strata such as sand, gravel, and fractured rock are ideal for recharge. Thick clay layers or impervious strata reduce recharge efficiency and increase clogging risk. The site should allow construction of a proper filter pack around the well.

8.3.4 Depth to Water Table

Recharge wells are most effective where the water table is deeper than 15 meters, indicating declining groundwater levels. In very shallow water table areas, surface recharge methods are more suitable.

8.3.5 Source of Recharge Water

Recharge water must be relatively clean stormwater or rooftop runoff. Untreated runoff should never be recharged directly into a well. Sites receiving industrial effluents, sewage, or heavily polluted runoff are unsuitable and strictly prohibited.

8.3.6 Distance from Contaminants

A sufficient setback distance from septic tanks, sewer lines, and solid waste dumps is mandatory (typically at least 20 to 30 meters).

8.3.7 Space for Pretreatment Structures

Adequate space must be available for silt traps, filtration chambers, and inspection chambers upstream of the recharge well. Without pretreatment, recharge wells fail rapidly.

8.3.8 Urban Infrastructure Compatibility

The site must not conflict with underground utilities such as gas pipelines, sewer lines, or electrical ducts. Public parks, green belts, wide roads, and institutional campuses are often ideal locations.

8.3.9 Regulatory and Institutional Approval

Recharge well sites must comply with local groundwater regulations and receive approval from relevant authorities. Monitoring arrangements for water quality and recharge performance should be feasible.

8.4 Site Selection Criteria for Contour Bunds (Barani Agriculture and Soil Moisture Conservation)

Contour bunds are earthen embankments constructed along contour lines to reduce runoff velocity, increase infiltration, and conserve soil moisture.

8.4.1 Land Slope and Topography

Contour bunds are suitable on gently to moderately sloping agricultural lands with slopes typically ranging from 1 to 6 percent. Very steep slopes increase failure risk, while flat land does not generate sufficient runoff for effective moisture conservation.

8.4.2 Soil Type and Infiltration Capacity

Soils with moderate infiltration rates, such as loam and sandy loam, are ideal. Heavy clay soils may cause prolonged ponding and crop damage, while very sandy soils may not retain moisture effectively.

8.4.3 Rainfall Pattern and Intensity

Contour bunds are most effective in regions with moderate rainfall and high runoff intensity, such as the Potohar plateau. They help retain moisture during short, intense rainfall events typical of monsoon storms.

8.4.4 Field Size and Land Use

Large, continuous fields are preferred for efficient layout and construction. Bunds should align with existing farming practices and not interfere with farm machinery. Cropping patterns must be compatible with moisture retention.

8.4.5 Drainage and Spillway Provision

Each bund area must include a properly designed spillway to safely dispose of excess runoff and prevent bund breaching during heavy rainfall.

8.4.6 Farmer Acceptance and Maintenance

Farmers must be willing to maintain bunds through periodic reshaping and repair. Sites with active farmer participation and extension support show higher success rates.

8.4.7 Environmental Benefits

Contour bunds are especially suitable in erosion prone areas, as they significantly reduce soil loss and improve long term land productivity.

Correct site selection determines more than 70 percent of the success of rainwater harvesting structures. Detailed topographic surveys, hydrogeological investigations, soil testing, and community consultation must precede final site approval. When these criteria are rigorously applied, rainwater harvesting systems in Punjab are technically sound, cost effective, and sustainable.

9) TECHNICAL DESIGN FEASIBILITY

Technical feasibility hinges on accurate hydrological modeling to size and design RWH structures correctly. The standard methodology commonly adopted for estimating peak rainwater runoff volume (Q) is the Rational Method or U.S. Soil Conservation Service Curve Number (SCS-CN) method. The SCS-CN method requires several inputs, including the maximum 24 hour rainfall for a specified design return period (often 2 years), calculated using the Gumbel Extreme Value frequency distribution, the catchment area, and the Composite Curve Number (CN) specific to the land use and hydrological soil group.

The governing equations for the SCS-CN method are:

$$Ia=0.2S$$

$$S=(1000/CN)-10$$

$$Q = (P - 0.2\ S)^2 / (P + 0.8\ S)$$

where Q is runoff (in inches), P is 24 hour rainfall (in inches), S is potential maximum retention after runoff begins (in inches), and Ia is initial abstraction before runoff begins (in inches).

The mandatory use of this rigorous, scientific approach ensures that all RWH infrastructure designed under the Green Building Code mandate and sanctioned by local authorities are adequately sized for localized rainfall extremes.

9.1 Technical Design of Check Dam

9.1.1 Site Selection and Alignment

Check dams are constructed across seasonal streams, nalas, or minor drainage channels where flow is well confined between stable banks. Narrow channel sections with firm abutments are preferred to ensure structural stability and economy. Foundations should consist of competent material such as rock, gravel, or dense sand to minimize seepage, piping, and settlement risks.

9.1.2 Hydrological Design

Hydrological analysis is carried out to estimate runoff from the contributing catchment considering rainfall, land use, soil type, and slope. For small catchments, the Rational Method or SCS–Curve Number method is commonly adopted. The design flood is typically selected for a 10 to 25 years return period, with a freeboard of about 0.5 to 1.0 m above the maximum water level.

9.1.3 Structural Dimensions and Layout

The height of a check dam is generally limited to about 1.0 to 5.0 m for safety and constructability. The crest length follows the natural channel width, while the top width is designed for adequate stability, usually not less than 0.6 to1.0 m for masonry or concrete structures. Upstream and downstream slopes are selected based on construction material and hydraulic conditions.

9.1.4 Spillway and Overflow Arrangement

A properly designed spillway or overflow section is provided to safely pass the design flood without overtopping the structure. The overflow may be centrally located or offset depending on site conditions. Energy dissipation arrangements such as stone pitching, aprons, or stilling basins are provided downstream to prevent scour and erosion.

9.1.5 Foundation Design and Seepage Control

The foundation is excavated up to firm strata to ensure adequate bearing capacity. Cutoff walls or key trenches are provided to reduce under seepage. Where seepage is significant, graded filters or drainage layers are incorporated to safely relieve pore water pressure and prevent piping.

9.1.6 Materials and Construction Practices

Check dams are commonly constructed using stone masonry in cement mortar, reinforced cement concrete, or gabion structures. Material selection depends on hydraulic loading, site conditions, availability of local materials, and cost. Proper workmanship, curing, and quality control are essential for durability and long term performance.

9.1.7 Sediment Management and Maintenance

Check dams facilitate sediment deposition upstream, contributing to bed stabilization and groundwater recharge. Provisions for periodic desilting and access for maintenance are included in the design to maintain storage capacity and hydraulic efficiency.

9.1.8 Structural Stability and Safety Checks

The structure is checked for stability against sliding, overturning, bearing capacity failure, and uplift under normal and flood conditions. Appropriate safety factors are applied in accordance with relevant design standards and manuals.

Specific safety standard must be adhered to protect against accidental falls by humans and livestock which includes constructing a fence wall along the sides of the check dam.

9.1.9 Environmental and Operational Considerations

Design ensures minimal disturbance to natural drainage and downstream water availability. Environmental impacts are considered to protect aquatic habitats and downstream users. Regular inspection and maintenance are integral to sustainable operation.

9.1.10 Design Standards and Guidelines

This description provides a general engineering overview. Detailed engineering design must be carried out in accordance with the standard design manuals, specifications, and drawings of the Punjab Irrigation Department and WAPDA, based on detailed site specific investigations.

Figure 10 Brushwood Check Dam

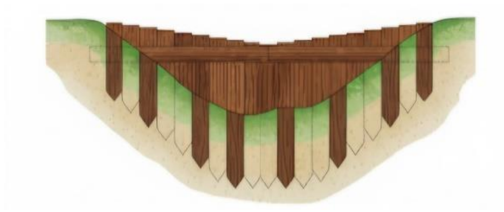


Figure 11 Log Check Dam

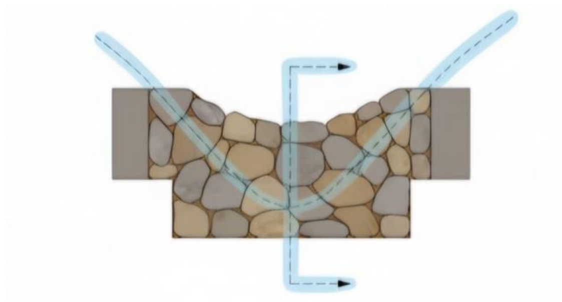


Figure 12 Loose Stone Check Dam

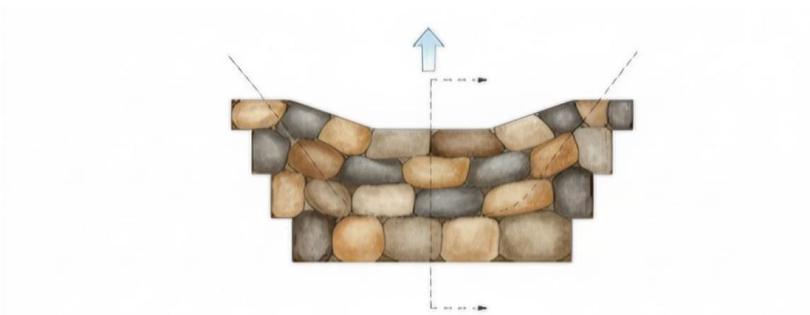


Figure 13 Boulder Check Dam

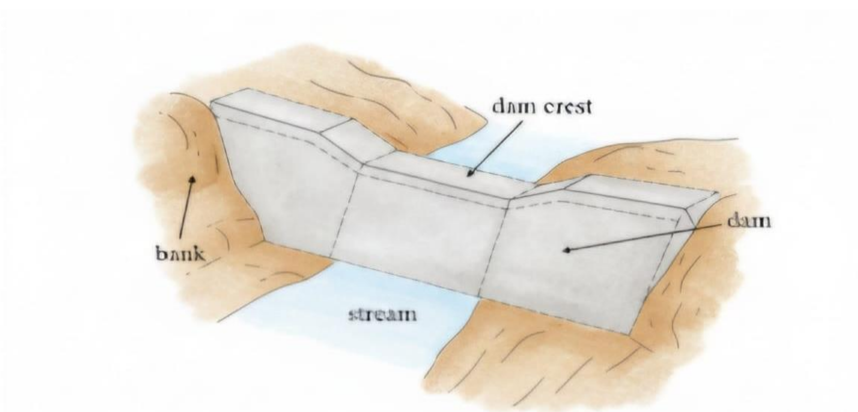


Figure 14 Masonry Check Dam

9.2 Technical Design of Rooftop Rainwater Harvesting (RWH) Systems

Designing a rooftop rainwater harvesting (RWH) system requires an integrated engineering approach that balances the hydrological potential of the site with the physical capacity of the building's infrastructure.

9.2.1 Design Basis and Standards

Long term rainfall data obtained from the Pakistan Meteorological Department (PMD) shall be used for the design of rooftop rainwater harvesting systems. Mean annual rainfall shall be adopted for estimation of harvestable rainwater quantities, while peak rainfall intensity shall be considered for the hydraulic sizing of gutters, downpipes, and overflow arrangements to ensure safe conveyance during extreme rainfall events.

9.2.2 Roof Catchment Characteristics

The roof shall serve as the primary catchment surface and shall be impervious, structurally sound, and constructed of non toxic materials. Roof slopes shall be sufficient to prevent ponding and to ensure rapid drainage towards collection points. Runoff losses due to wetting and evaporation shall be accounted for by adopting appropriate runoff coefficients, typically 0.85–0.95 for RCC roofs, 0.90–0.95 for metal sheet roofs, and 0.75–0.85 for tiled roofs. The selected coefficient shall be justified in the design calculations based on roof condition and maintenance practices.

9.2.3 Estimation of Harvestable Rainwater

Harvestable rainwater shall be estimated using the standard runoff relationship, which considers roof area, design rainfall, and runoff coefficient. This estimation shall provide the basis for sizing storage tanks, groundwater recharge structures, and overflow arrangements.

9.2.4 Conveyance System Design

The conveyance system shall consist of gutters and downpipes designed to safely carry peak runoff without overtopping to filtration or first flush units. Gutters shall be laid with a minimum slope of 1 in 150 to 1 in 200 and constructed of corrosion resistant materials. Downpipes shall convey collected rainwater to downstream components by gravity. The minimum internal diameter of downpipes shall generally be 75 mm, increasing as required for larger roof areas or higher rainfall intensities. and shall be securely fixed and provided with access for inspection and maintenance.

9.2.5 First Flush Provision

A first flush system shall be provided to divert the initial runoff containing accumulated dust and organic contaminants from the roof surface. The system shall be designed to exclude approximately 1–2 mm of rainfall over the roof area. First flush devices may be manual or automatic and shall be located upstream of the filtration unit. Easy access for cleaning and periodic maintenance shall be ensured.

9.2.6 Filtration Requirements

All harvested rainwater shall be filtered prior to storage or groundwater recharge to remove suspended solids and prevent clogging. Filters shall consist of graded layers of gravel and sand, with optional charcoal or geotextile layers where improved water quality is required. The effective filter depth shall generally be in the range of 600 to 900 mm. Filters shall be designed to allow easy cleaning or replacement of media and shall include bypass arrangements for extreme rainfall events.

9.2.7 Storage and Utilization

Where rainwater is intended for direct use, storage tanks shall be covered. It shall be stored in mosquito proof storage tanks, provided either above ground or underground. Tanks shall be constructed of RCC, brick masonry, or approved prefabricated materials, in accordance with Punjab Building Bye-Laws. Tank storage capacity shall be determined based on water demand, rainfall availability, and roof area.

Where storage is not required, or surplus rainwater is available, filtered rainwater shall be diverted to groundwater recharge structures such as recharge wells, soak pits, or infiltration trenches considering soil permeability, depth to groundwater, and local hydrogeological conditions. Recharge structures shall be located away from sources of contamination, including septic tanks and sewer lines.

9.2.8 Overflow, Operation, and Maintenance

Overflow arrangements shall be provided to safely dispose excess rainwater during peak or extreme rainfall events, preferably to recharge systems or designated stormwater drains.

Regular operation and maintenance, including cleaning of roofs, conveyance systems, first flush devices, filters, and storage tanks, shall be ensured prior to the monsoon season periodically to maintain long-term system performance and regulatory compliance. Storage tanks shall be cleaned at least once annually, and water quality shall be monitored where rainwater is used for domestic purposes.

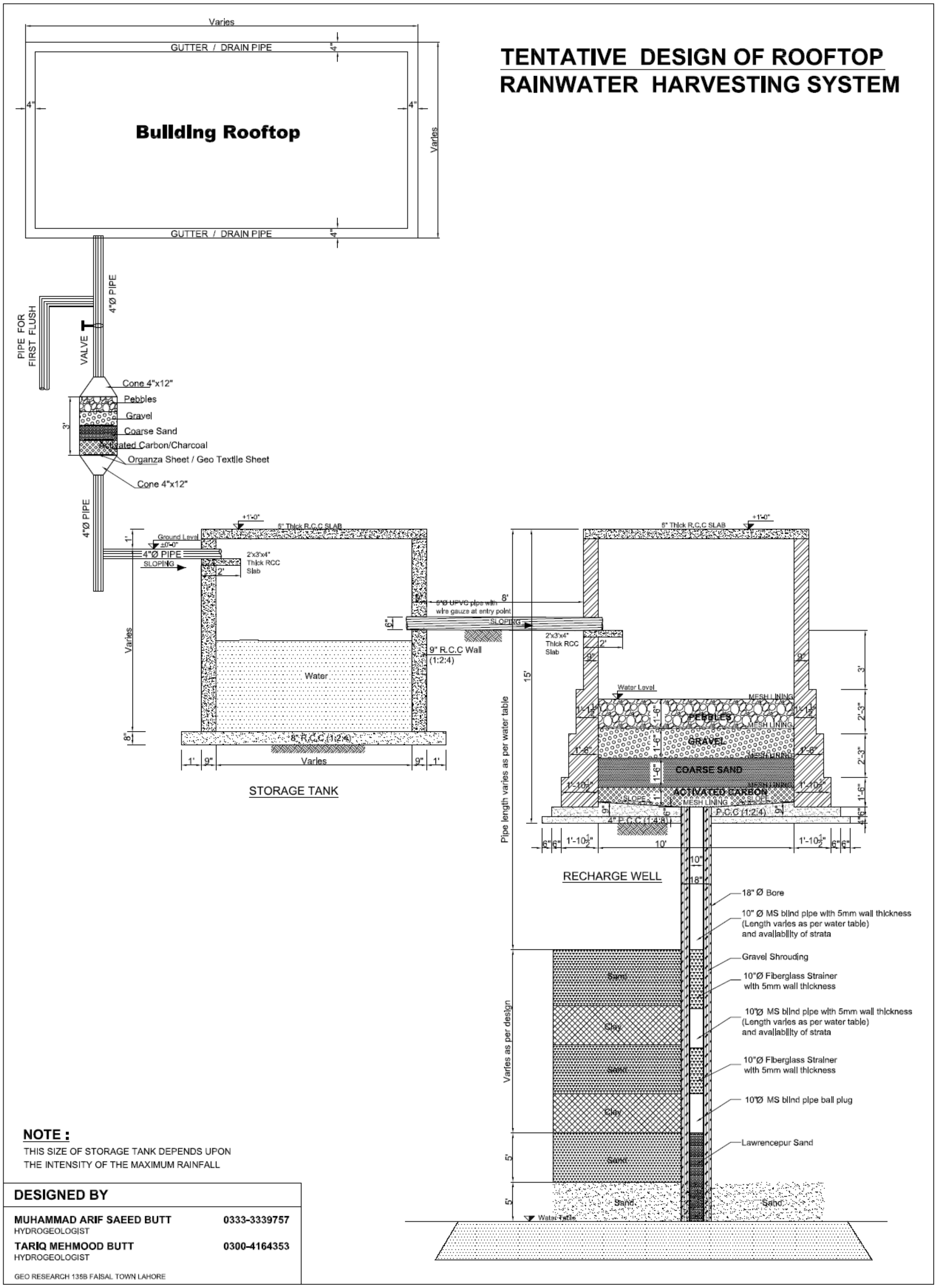


Figure 15 Tentative Design of Rooftop Rainwater Harvesting System

9.3 Technical Design of Recharge Well

9.3.1 Purpose and Functional Requirement

A recharge well is designed to artificially augment groundwater by directly conveying filtered storm water or rooftop runoff into deeper aquifer zones. The system shall ensure rapid infiltration, prevention of aquifer contamination, and long term structural and hydraulic stability.

9.3.2 Hydrogeological Considerations

The recharge well shall be located in areas experiencing groundwater decline and underlain by permeable strata such as sand, gravel, or fractured formations. The site shall be free from contamination risks and located at a minimum horizontal distance of 15 to 30 m from septic tanks, sewer lines, drains, and waste disposal areas. The groundwater table should preferably be deeper than 15 m below ground level to allow effective recharge.

9.3.3 Catchment Assessment and Design Rainfall

The contributing catchment may include rooftops, paved surfaces, or open areas. The runoff coefficient shall be selected based on surface type, typically 0.80 to 0.90 for rooftops and 0.60 to 0.75 for paved areas. Design rainfall shall be based on maximum 24 hour rainfall for a return period of 2 to 10 years, depending on the importance of the structure.

9.3.4 Borehole Design

The recharge well shall consist of a drilled borehole with a diameter ranging from 350 to 450 mm (14 to 18 inches). The depth of the borehole shall extend down to the targeted aquifer, typically between 20 and 60 m, based on site specific lithological data and hydrogeological conditions. Drilling shall be carried out using reverse rotary/straight rotary methods or percussion methods ensuring verticality and borehole stability.

9.3.5 Casing and Screen Design

The borehole shall be provided with fiberglass casing. Blank casing shall be installed through impervious strata, while slotted casing shall be provided across the medium to coarse sand. Slot openings shall be of 1.5 mm to permit recharge while preventing soil ingress.

9.3.6 Gravel Packing Arrangement

The annular space between the slotted casing and borehole wall shall be filled with clean, well rounded gravel of 2 to 6 mm size free from calcareous material. The gravel pack thickness shall be maintained not less than 100 mm. This layer shall act as a filter and enhance lateral dispersion of recharge water into the aquifer.

9.3.7 Filter Chamber (Recharge Pit) Design

A surface filter chamber shall be constructed to remove silt, debris, and suspended solids before water enters the recharge well. The chamber shall be constructed in RCC or brick masonry with plastered internal surfaces. The minimum recommended internal dimensions are 2.0 m × 2.0 m × 3.0 m. The actual dimensions depend upon the intensity of rainfall, size of catchment, area runoff and material of surface.

9.3.8 Filter Media Configuration

The filter chamber shall be filled with graded filter media arranged from top to bottom as follows:

Minimum Coarse gravel or pebble layer, 450 to 600 mm thick, minimum fine gravel layer, 300 to 450 mm thick, minimum coarse sand layer, 300 to 450 mm thick and minimum activated charcoal layer, 300 mm. The grading shall ensure effective filtration and prevent clogging of the recharge bore. An organza sheet must be placed between each layer in order to avoid mixing of materials.

9.3.9 Inlet, Conveyance, and First Flush System

Rainwater shall be conveyed to the filter chamber through PVC or RCC pipes of 150 to 300 mm diameter. A first flush arrangement shall be provided to divert the initial runoff containing higher pollutant loads. A silt trap or desilting chamber shall be incorporated at the inlet for ease of maintenance.

9.3.10 Well Head Protection and Safety Measures

The recharge well head shall be sealed with an RCC platform of approximately 1.0 m × 1.0 m, provided with a raised collar to prevent entry of surface runoff. A lockable and removable inspection cover shall be installed for access and maintenance.

9.3.11 Hydraulic Performance and Recharge Capacity

The recharge capacity of the well shall depend on aquifer transmissivity, well diameter, and effective filter design. Typical recharge rates range from 5 to 15 m^3/hour under favorable hydrogeological conditions.

9.3.12 Overflow and Excess Runoff Management

An overflow arrangement shall be provided at the filter chamber to safely dispose excess runoff during high intensity rainfall events.

9.3.13 Operation and Maintenance Requirements

Routine maintenance shall include periodic cleaning of the filter chamber, removal of accumulated silt after monsoon seasons, and inspection of inlet and first flush systems. Filter media may require replacement every 3 to 5 years depending on sediment load.

9.3.14 Monitoring and Performance Evaluation

Groundwater levels in nearby observation wells shall be monitored periodically to assess recharge effectiveness. Visual inspection of water clarity and infiltration rates shall be carried out during rainfall events.

9.3.15 Spacing between Recharge Wells

A minimum spacing of 100 m between recharge wells is required to avoid localized hydraulic interference, while the installation of a fiberglass pipe extending approximately 5 ft below the water table and backfilled with coarse sand facilitates efficient conveyance of recharge water to the deeper aquifer.

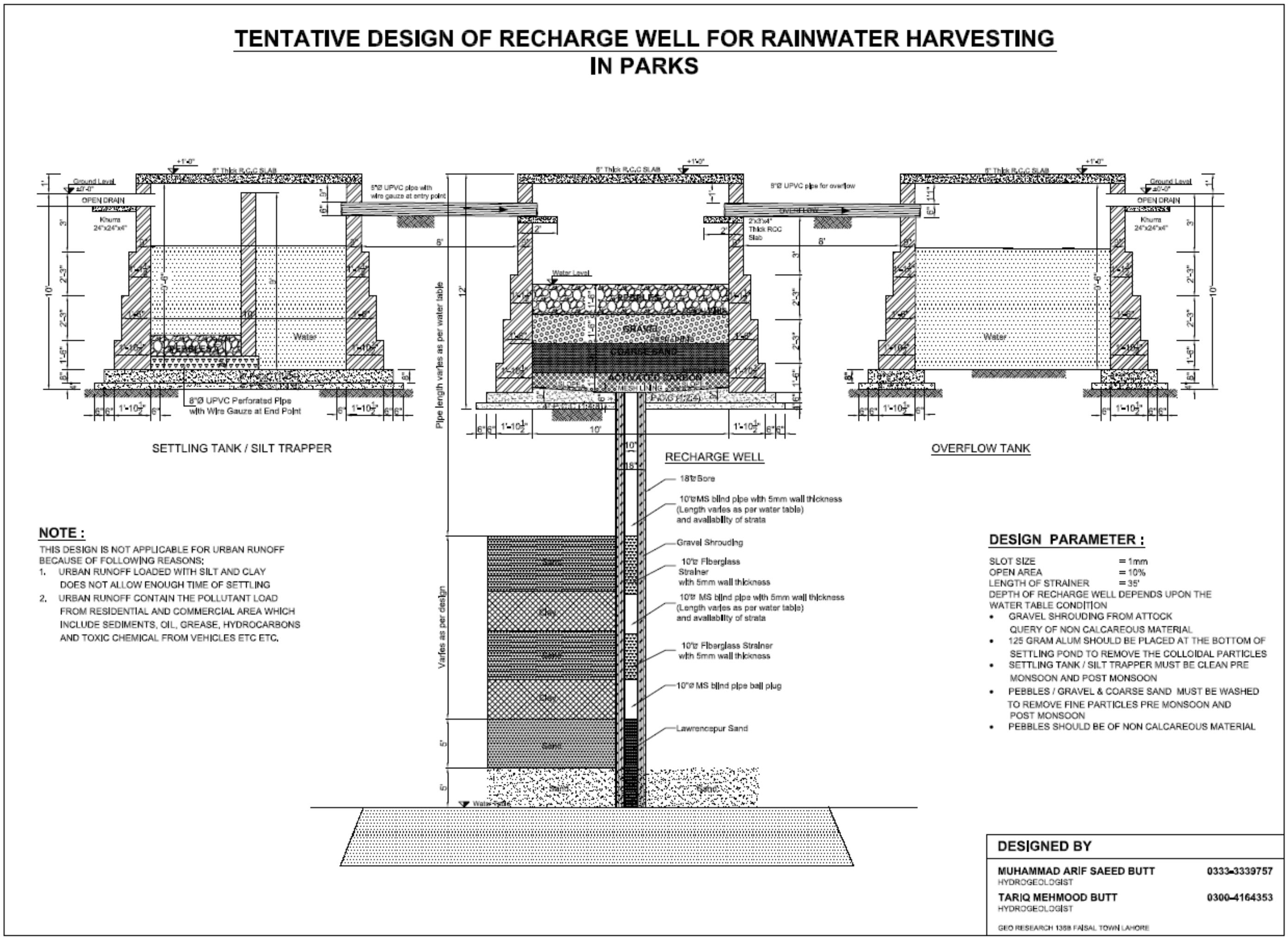


Figure 16 Tentative Design of Recharge Well for RWH

9.4 Technical Design of Infiltration Trenches

9.4.1 Function and Design Objective

Infiltration trenches are linear subsurface recharge structures designed to collect surface runoff and facilitate its controlled percolation into permeable soil layers. The primary objectives are groundwater recharge, reduction of surface runoff, and mitigation of localized flooding.

9.4.2 Soil Type and Basic Requirements

Infiltration trenches shall be located in areas underlain by permeable soils such as sand or sandy loam. The groundwater table should preferably be at a depth of 10 m below ground level. Sites shall be free from potential contamination sources including septic tanks, soak pits, solid waste disposal areas, and industrial effluent zones. The ground slope should generally be less than 5 percent to ensure uniform infiltration and structural stability. A "grass buffer strip" or a small silt trap is necessary to prevent the trench from clogging with sediment.

9.4.3 Geometric Design Parameters

The trench depth is typically kept between 2.0 m and 3.0 m, or until a suitable permeable stratum is encountered. Trench width and length are determined based on runoff volume, catchment characteristics, and available land. The trench bottom is kept nearly level with a nominal slope of 0 to 0.5 percent to avoid ponding and ensure uniform distribution of flow.

9.4.4 Side Slopes

The side slopes of the trench excavation are maintained at 1V: 1H (where, V represents the vertical depth of excavation and H represents the horizontal projection.

A slope of 1V: 1H means that for every 1 unit of vertical depth, the trench side extends 1 unit horizontally, corresponding to an approximate 45 degree slope. This slope is adopted to ensure stability of trench walls in loose or sandy soils, reduce the risk of collapse during construction, and provide safe conditions for long term operation and maintenance.

9.4.5 Filter Media and Internal Configuration

The trench is filled with graded filter material to enhance infiltration and prevent clogging. The top layer consists of coarse pebbles or boulders to provide storage and rapid drainage. Below this, a gravel layer supports flow distribution, while a bottom layer of coarse sand acts as a filter for finer particles. A non woven geotextile filter is provided along the sides and bottom of the trench to prevent migration of fines from surrounding soils into the filter media.

9.4.6 Hydraulic and Runoff Design

Runoff contributing to the trench is estimated using standard hydrological methods such as the Rational Method or SCS–Curve Number method, depending on catchment size. The trench storage and infiltration capacity are designed to accommodate at least the initial runoff (first flush). The infiltration capacity is verified based on in-situ soil infiltration rates and effective infiltration area.

9.4.7 Inlet, Pretreatment, and Conveyance

Surface runoff is conveyed to the trench through stone lined drains, grassed swales, or pipes. A desilting chamber or silt trap is provided upstream of the trench inlet to remove sediments and debris, thereby minimizing clogging and extending the functional life of the structure.

9.4.8 Overflow and Safety Provisions

An overflow pipe or weir is provided at the design water level to safely divert excess runoff during high intensity rainfall events to a nearby recharge well, drain or natural watercourse. The trench is covered with perforated RCC slabs, precast concrete covers, or a gravel layer to ensure public safety and allow inspection access.

9.4.9 Construction Methodology

Construction involves excavation to the specified dimensions and slopes, preparation of the trench base, placement of geotextile lining, sequential filling of graded filter media, installation of inlet and overflow arrangements, and restoration of the ground surface.

9.4.10 Operation and Maintenance

Routine maintenance includes periodic removal of silt from pretreatment chambers, inspection after major rainfall events, and cleaning or replacement of the top sand layer if clogging is observed. Proper maintenance is essential to sustain long-term infiltration performance.

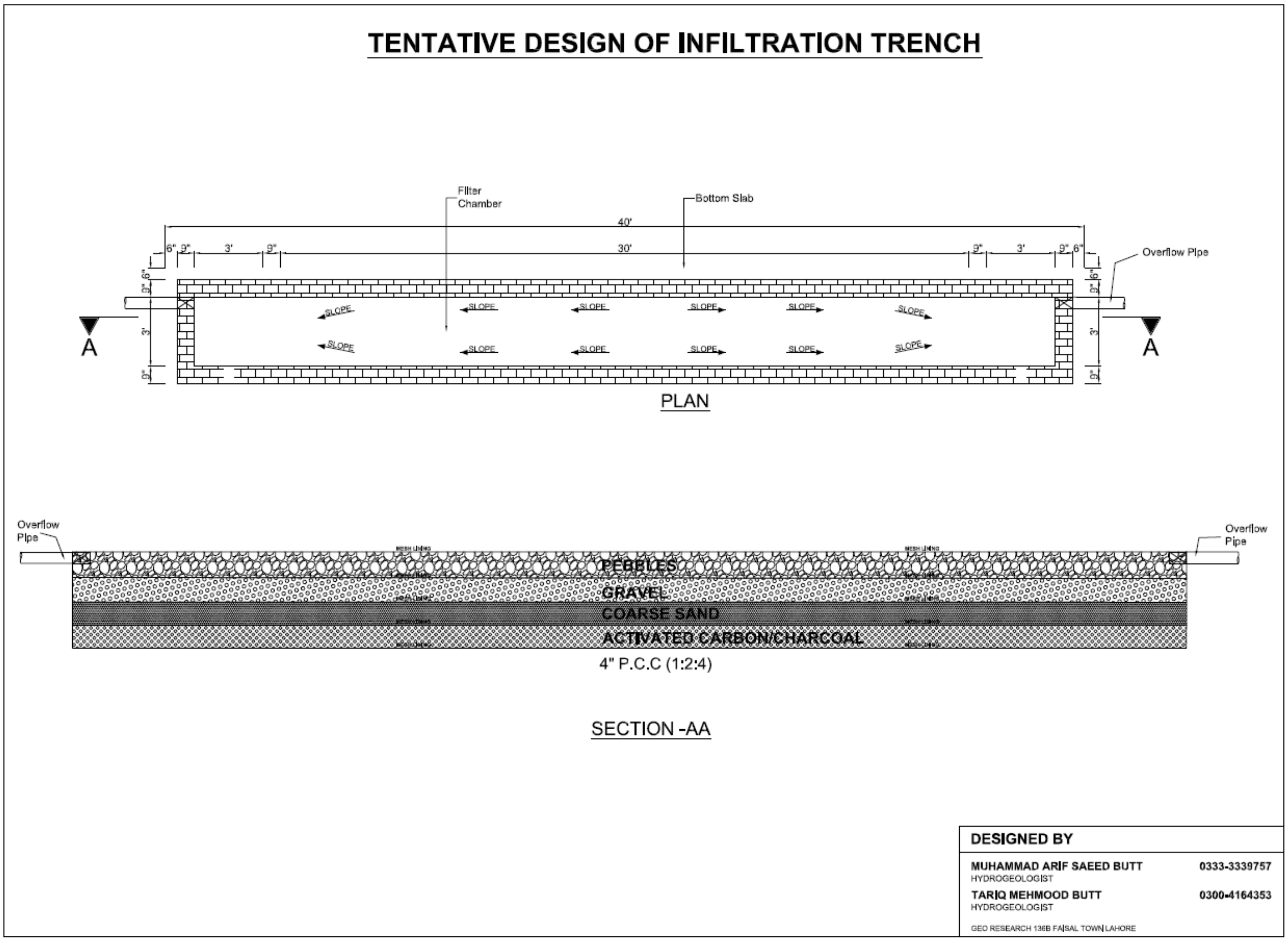


Figure 17 Tentative Design of Infiltration Trench for RWH

9.5 HYBRID STORMWATER MANAGEMENT SYSTEM

(Infiltration Trench Combined with Recharge Well)

9.5.1 Concept and Purpose

A hybrid storm water management system combines an infiltration trench with one or more recharge wells to improve groundwater recharge under difficult soil conditions. This system is mainly used where the surface soil is clayey or compacted and does not allow water to infiltrate easily, but permeable sand or gravel layers exist at greater depths.

This approach is also suitable in areas where large volumes of runoff are generated during heavy rainfall. In this system, the infiltration trench collects and spreads storm water horizontally, while the recharge well provides a direct vertical path for water to reach deeper aquifers by bypassing low-permeability soil layers.

9.5.2 Working Mechanism of the Hybrid System

The hybrid system manages storm water in three simple stages:

9.5.2.1 Collection and Pre treatment

Storm water runoff from roofs, roads, or paved areas enters the gravel-filled infiltration trench. Before infiltration, pre-treatment measures such as filter strips, silt traps, or sedimentation chambers remove large particles, debris, and sediments to protect the recharge well from clogging.

9.5.2.2 Shallow Soil Infiltration

Stored water in the trench begins to infiltrate into the surrounding shallow soil through the trench base and sidewalls, depending on the infiltration capacity of the near-surface soils.

9.5.2.3 Deep Groundwater Recharge

If the trench fills faster than the shallow soil can absorb water, the excess water flows into the recharge well. The recharge well consists of a perforated pipe that extends through low-permeability clay layers and allows water to enter a deeper, highly permeable aquifer, thereby increasing recharge efficiency.

9.5.3 Suitable Conditions for Use

This combined system is recommended under the following site conditions:

9.5.3.1 Low Permeability Surface Soils

Sites where surface soils have very low infiltration rates (typically less than 0.3 inches per hour), but permeable sand or gravel layers are present at depths of about 10–20 feet.

9.5.3.2 Limited Available Space

In dense urban areas where there is not enough open land to construct large infiltration trenches, recharge wells are used to provide vertical infiltration and compensate for the limited surface area.

9.5.3.3 Urban Retrofit Projects

Existing developed areas such as parking lots, rooftops, roads, and paved surfaces that generate high runoff but have little or no pervious land available must be managed.

9.5.4 Site Selection and Hydrogeological Requirements

Hybrid systems require careful subsurface evaluation to ensure safe and effective recharge:

9.5.4.1 Subsurface Investigation

Soil borings should extend at least 5–10 feet below the proposed bottom of the recharge well to confirm that a continuous permeable layer exists and that the well does not end in another impermeable layer.

9.5.4.2 Groundwater Separation Distance

A minimum vertical clearance of 2–4 feet must be maintained between the bottom of the recharge well and the highest seasonal groundwater level to allow natural filtration and prevent groundwater contamination.

9.5.4.3 Water Quality Considerations

Since recharge wells bypass the biologically active topsoil layer, runoff from polluted or high-risk areas (such as fuel stations, industrial sites, or loading zones) should not be connected unless advanced pre-treatment systems are provided.

9.5.5 Design Features and Maintenance Requirements

Important design and operational components include:

9.5.5.1 Recharge Well Casing

Recharge wells are usually constructed using 4 to 12 inch diameter perforated PVC or fiberglass pipes, wrapped in geotextile fabric to prevent sediment entry while allowing water flow.

9.5.5.2 Venting System

A vent is required to allow trapped air to escape as water enters the well. Without proper venting, air locking can significantly reduce infiltration performance.

9.5.5.3 Maintenance Access

The recharge well should have a removable access cap at the surface, allowing regular inspection, flushing, or vacuum cleaning to remove accumulated sediments and maintain long-term performance.

9.5.6 Importance in Rainwater Harvesting Feasibility Studies

The hybrid infiltration trench and recharge well system is a practical, space-efficient, and technically reliable solution for managed aquifer recharge, especially in urban and semi-urban areas. It is particularly suitable where surface infiltration is limited due to soil conditions, groundwater levels are declining, and controlled recharge to deeper aquifers is required through a properly designed and monitored system.

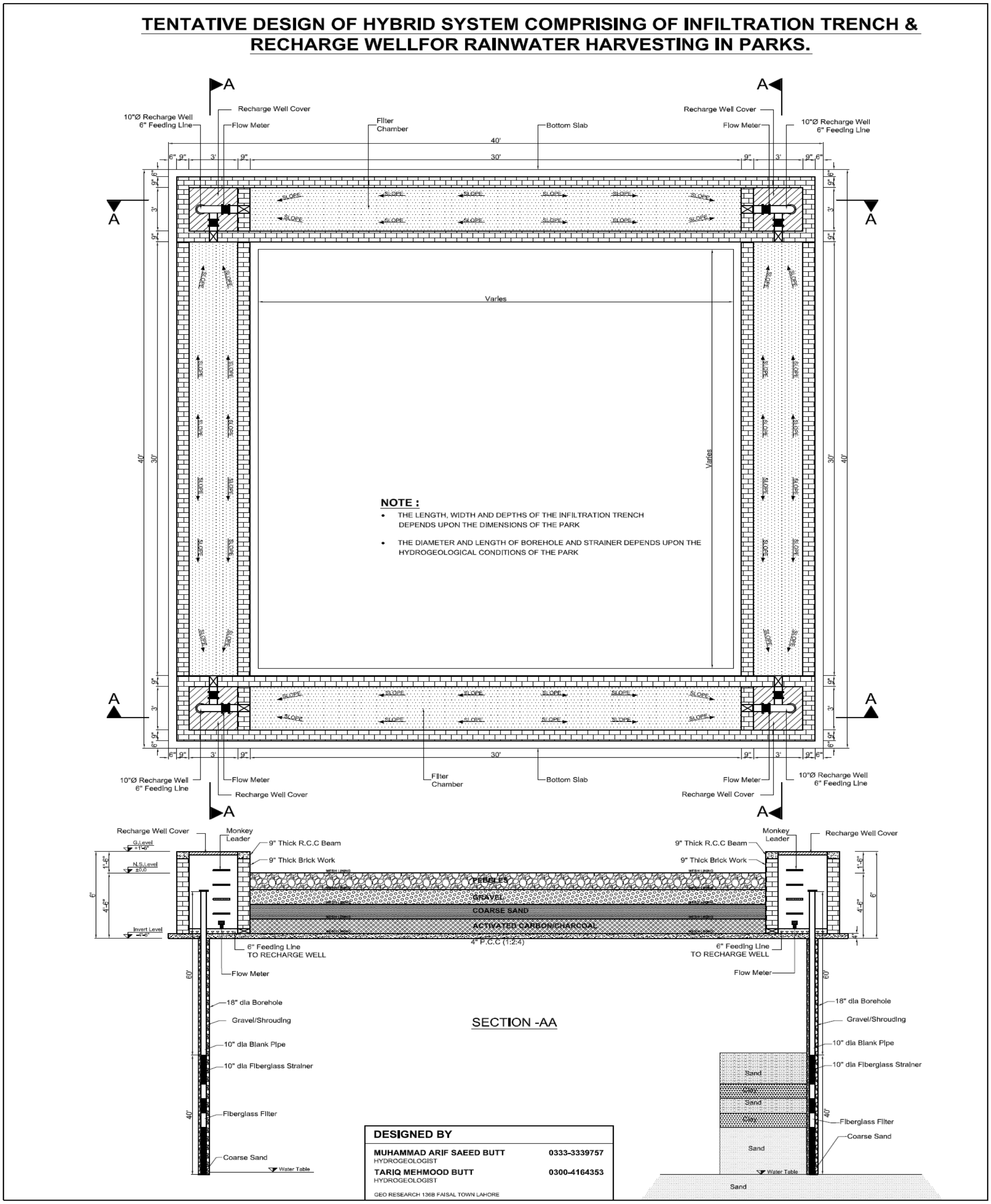


Figure 18 Tentative Design of Hybrid System for RWH

9.6 Water Quality Management and Pre treatment requirements

The successful, long term technical feasibility of urban RWH for MAR is conditional on effective water quality management. The urban runoff during monsoon period contains most of the pollutant loads from residential and commercial areas, industrial activities, construction, streets & parking lot and atmospheric deposition which includes, Sediments, oil, grease, hydrocarbons and toxic chemicals from motor vehicles, pesticides, nutrients and nitrates & phosphorus from fertilizer used in residential lawns, parks and golf courses, viruses, bacteria & nutrients, heavy metals and synthetic organic compounds.

For potable uses, rain water must be treated before harvesting through recharge well in order to avoid the pollution of the aquifer, in particular to remove or kill disease causing organisms present in it. As such rain water must go through several steps, screening, settling, filtration and disinfection before harvesting. Studies have demonstrated that while the layered filter media (sand, gravel and pebbles) performed satisfactorily for turbidity, the overall contamination removal rate was only 25%–30% and the other pollutants i.e. viruses & bacteria, toxic elements, pesticides, nutrients and phosphorus from fertilizers used in the park will directly enter into the aquifer, which in turn will pollute the aquifer. Critically, these pollutants/ coliform bacteria exceeding permissible limits, pose a direct threat to aquifer health. It is further mentioned that once the aquifer is polluted, it will take millennium to retrieve it back.

To ensure the environmental sustainability, future RWH system designs must incorporate enhanced pre treatment measures. These should include advanced filtration media such as activated carbon/charcoal and, where appropriate, advanced disinfection methods (e.g., UV treatment for non recharge uses) must be integrated into the standardized urban RWH design. Although such measures increase initial capital cost, they are essential for protecting aquifer integrity and securing long term fresh water supply.

10) INTERNATIONAL PRACTICES AND GENERAL GLOBAL TRENDS OF RAINWATER HARVESTING

10.1 Introduction and Global Context

Rainwater harvesting (RWH) has emerged as a widely recognized and adaptable water supply augmentation strategy across diverse climatic, socio economic, and institutional contexts. In contemporary practice, RWH is applied in arid, semi arid, and humid regions, and increasingly integrated with stormwater management, groundwater recharge, and urban flood mitigation strategies. Its relevance has grown substantially due to escalating water scarcity, rapid urbanization, groundwater depletion, and climate induced variability in rainfall patterns.

Globally, the role of RWH varies according to levels of development and water infrastructure. In developed regions, it functions primarily as a supplementary source to centralized water supply systems, while in many developing countries it serves as a critical or primary source of domestic water. This dual role highlights the flexibility of RWH and its potential contribution to sustainable and climate resilient water resources management.

10.2 Rainwater Harvesting in Developed Countries

In developed regions such as Europe, North America, Japan, Australia, and Singapore, RWH is predominantly applied for non potable purposes, including toilet flushing, laundry, landscape irrigation, and cleaning. The primary objectives are to reduce potable water demand, alleviate pressure on centralized supply systems, and manage urban runoff. These regions typically benefit from well defined regulatory frameworks, technical standards, and financial incentive mechanisms that encourage RWH adoption.

Germany represents a global benchmark in RWH implementation. RWH systems are widely integrated into residential, commercial, and industrial buildings, supported by building codes, technical guidelines, and public acceptance. A significant proportion of new buildings incorporate RWH systems, reflecting its mainstream integration into urban water management strategies. Similarly, Belgium and parts of Australia mandate RWH installation in new developments, particularly in water-stressed areas.

Japan has institutionalized RWH within broader disaster risk reduction and urban flood management policies. National legislation and municipal subsidy programs promote rooftop rainwater storage in public buildings, schools, and private developments. These systems enhance emergency water availability during earthquakes and droughts while simultaneously reducing stormwater runoff during intense rainfall events.

Australia exhibits one of the highest household adoption rates of RWH globally, driven by chronic water scarcity and highly variable rainfall. Rainwater tanks are commonly used for both indoor and outdoor non potable applications, supported by public awareness campaigns and government rebate schemes. Collectively, experiences from developed countries demonstrate that RWH is most effective when embedded within integrated urban water management frameworks and supported by clear policy instruments.

10.3 Rainwater Harvesting in Developing Countries

In developing countries, RWH plays a more fundamental role in ensuring water security, particularly in regions with limited or unreliable centralized water supply systems. Household water consumption levels in low and middle income countries are generally lower than in developed regions, enabling RWH systems to meet a substantial proportion of domestic water needs. Harvested rainwater is frequently used for potable purposes, including drinking and cooking, as well as for sanitation and small scale agriculture.

10.3.1 Asia

Asia hosts some of the largest and most diverse RWH initiatives worldwide. In China, large scale government supported programs have been implemented to address rural water scarcity, groundwater depletion, and drought vulnerability. Since the early 2000s, millions of rainwater storage tanks and small reservoirs have been constructed, supplying drinking water and supporting supplemental irrigation in water stressed regions. These programs illustrate the scalability of RWH when backed by strong institutional capacity and sustained public investment.

India has also institutionalized RWH through mandatory rooftop harvesting regulations in several states, particularly in urban areas experiencing severe groundwater decline.

Traditional RWH practices have been revived and combined with modern engineering approaches to enhance recharge and water availability. In Thailand, low cost household jar tank systems have been widely promoted, enabling communities to store rainwater during the monsoon for use throughout extended dry seasons. These examples highlight the adaptability of RWH technologies to local socio economic and climatic conditions.

10.3.2 Africa

Across Africa, RWH has been widely promoted as a decentralized and climate resilient solution to water scarcity, particularly in rural and semi arid regions. Empirical studies demonstrate that RWH can supply a significant proportion of household water needs where alternative sources are distant, unreliable, or expensive. Large scale spatial assessments using GIS techniques have identified extensive potential for RWH across countries such as Botswana, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, Zambia, and Zimbabwe.

Kenya stands out for its strong institutional and community based approach, with widespread adoption of household and communal RWH systems. The growth of national and regional Rainwater Harvesting Associations across Africa reflects increasing institutional recognition and community engagement. These initiatives emphasize the importance of local capacity building, stakeholder participation, and context specific design.

10.4 Latin America and Small Island States

In Latin America, RWH is applied in both urban and rural settings for domestic water supply and agricultural runoff collection, particularly in semi arid regions. Brazil's "One Million Cisterns" program represents one of the most ambitious RWH initiatives globally, aimed at improving water access for rural populations in drought prone areas. By providing decentralized storage systems, the program has enhanced water security for millions of people while reducing vulnerability to climate variability.

Small island states such as Bermuda and Malta present unique cases where RWH is an essential component of national water supply systems. Due to limited freshwater resources and constrained groundwater reserves, RWH is often mandated by law and integrated into building design standards. These experiences demonstrate how geographic constraints can drive innovative and compulsory adoption of RWH at a national scale.

10.5 Policy, Regulation, and Institutional Frameworks

The extent and effectiveness of RWH implementation worldwide are strongly influenced by policy, regulatory, and institutional factors. Countries with comprehensive legislation, technical standards, and incentive mechanisms tend to exhibit higher adoption rates and better system performance. Conversely, in regions where RWH relies primarily on voluntary or localized initiatives, implementation remains fragmented.

A persistent challenge in many countries is the lack of unified water quality standards for harvested rainwater, particularly for potable uses. This regulatory gap limits broader acceptance and integration of RWH into formal water supply systems. Institutional coordination between water supply agencies, urban planners, and environmental authorities is also often insufficient, reducing the potential benefits of integrated RWH and stormwater management.

10.6 Future Prospects and Research Needs

The future of RWH is closely linked to integrated water resources management, climate change adaptation strategies, and urban sustainability agendas. Advances in GIS, remote sensing, hydrological modeling, and multi criteria decision analysis are improving site selection, system design, and performance evaluation. These tools enable more accurate assessment of RWH potential under varying climatic and socio economic conditions.

Despite widespread implementation, significant knowledge gaps remain. Many existing studies assess RWH performance under historical climate conditions or apply inconsistent assumptions, limiting comparability across regions. Given projected changes in rainfall intensity, seasonality, and variability due to climate change, there is a critical need to evaluate RWH system reliability under future climate scenarios. Moreover, key design parameters, such as household water demand, roof catchment area, and storage capacity, must be optimized for different climatic zones and income levels to ensure long term effectiveness.

In conclusion, rainwater harvesting has demonstrated its effectiveness as a flexible, scalable, and climate resilient water management strategy across diverse global contexts. While its role varies from supplementary non potable supply in developed regions to a primary water source in many developing countries, its contribution to water security, groundwater protection, and flood mitigation is increasingly recognized. Strengthening policy frameworks, harmonizing water quality standards, and integrating RWH into broader water management and climate adaptation strategies are essential to fully realize its global potential.

11) PERFORMANCE REVIEW OF URBAN RECHARGE WELLS INSTALLED BY WASA AND SPU, LDA (FAILURE AND LESSON LEARNED)

11.1 Background

As part of early urban rainwater harvesting (RWH) and managed aquifer recharge (MAR) initiatives in Lahore, recharge wells were installed by the Water and Sanitation Agency (WASA) at Tajpura and Triangular Park in front of MAO College. In parallel, the Strategic Planning Unit (SPU) of the Lahore Development Authority implemented a pilot program consisting of twelve recharge wells at locations identified as critical urban flooding points. The objective of these installations was to intercept monsoon runoff and recharge groundwater directly in areas historically affected by severe surface flooding.

11.2 Description of Installed Recharge Wells

The SPU pilot program comprised two large scale installations, referred to as Mega Pilots, located at Lakshmi Chowk and Gaddafi Stadium, along with ten street level recharge wells. These street level installations were constructed at Islamia College on Railway Road, Napier Road, Nila Gumbad, Beadon Road and Hall Road junction, Bhati Gate, Mochi Gate, Cooper Road, Sanda Road, Fazlia Colony, and Malik Park. Site selection was primarily based on flood recurrence rather than detailed hydrological and water quality suitability assessments.

11.3 Performance During Monsoon Events

Monitoring during the first monsoon season indicated that most of the recharge wells failed immediately after the onset of significant rainfall. With the exception of the Gaddafi Stadium and Mochi Gate installations, the recharge wells became non functional during the first major storm event. The failures were systemic and reflected fundamental limitations in siting, hydraulic capacity, and pre treatment design rather than construction or operational shortcomings.

11.4 Siltation and Debris Induced Failure

A primary cause of failure was rapid choking of the recharge systems due to excessive silt and solid waste loads. Most of the recharge wells were located in catchments with surface slopes exceeding the recommended range of 1 to 6 %. These steep slopes generated high velocity runoff during monsoon rainfall, mobilizing fine sediments, organic matter, and plastic debris. The adopted recharge well design incorporated a small settling chamber of approximately ten feet, which proved inadequate to detain the heavy first flush pollutant load. Consequently, filter media became clogged (choked) almost immediately, resulting in a sharp decline in infiltration capacity and rendering the recharge wells ineffective.

11.5 Hydraulic Capacity and Design Volume Mismatch

At major low lying flood prone locations, particularly Lakshmi Chowk, the volume of runoff generated during peak rainfall events far exceeded the hydraulic intake and infiltration capacity of the recharge wells. As a result, runoff bypassed the recharge wells and continued to accumulate on the surface, providing no meaningful flood mitigation. This highlighted a fundamental mismatch between urban flood volumes and the capacity of direct recharge well systems.

11.6 Groundwater Contamination Risk

Several recharge wells were constructed in older urban areas characterized by aging and leaking sewerage infrastructure. During monsoon conditions, sewer overflows and leakages led to mixing of blackwater with stormwater runoff. The direct injection of inadequately treated runoff into the subsurface posed a serious risk of groundwater contamination and contradicted the basic principles of managed aquifer recharge.

11.7 Lessons Learned from the Pilot Program

Despite widespread failure, the pilot program generated critical technical lessons. The most important finding was that recharge wells are not suitable for managing street level or road based urban flooding in dense, high slope, and silt laden environments. Their application is technically viable only in controlled settings such as parks, green spaces, and gated or institutional complexes where catchment slopes are within 1 to 6%, runoff velocities are low, and solid waste loads are minimal.

11.8 Shift from Direct Recharge to Storage Based Systems

The failure of the street level recharge wells demonstrated the necessity of storing urban floodwater prior to recharge. It became evident that monsoon runoff in dense urban areas must first be detained in storage facilities and allowed to undergo sedimentation, filtration, and, where required, disinfection before being recharged into the aquifer. This understanding led to a strategic shift toward large underground rainwater storage tanks, including high capacity installations such as the 1.4 million gallon underground storage tank constructed at Lawrence Road in 2020.

11.9 Successful Reference Case: Gaddafi Stadium

The recharge well installed at Gaddafi Stadium emerged as a successful reference case. Its performance was attributed to its location within a protected and well maintained complex, controlled surface slopes within design limits, relatively clean runoff, and the absence of nearby sewerage contamination sources. This case demonstrated that recharge wells can perform effectively in parks and institutional boundaries but are unsuitable for heavily trafficked roads and major urban flood depressions.

11.10 Implications for Future Rainwater Harvesting in Punjab

The findings from these pilot installations indicate that direct recharge wells should not be adopted as a primary solution for urban flood management on streets and roads. Future rainwater harvesting strategies in Punjab should prioritize storage based systems with adequate pre treatment, restrict recharge wells to low risk and controlled environments, and ensure strict separation from sewerage infrastructure to safeguard groundwater quality.

12) CONSOLIDATED RECOMMENDATIONS FOR RAINWATER HARVESTING ACROSS PUNJAB (INTEGRATED WITH PUNJAB CITIES PROGRAM – PCP AND PUNJAB INCLUSIVE CITIES PROGRAM – PICP)

Rainwater harvesting should be treated as an important solution for improving water security and urban resilience in Punjab. Cities across the province are growing rapidly, groundwater levels are falling, and floods during the monsoon season are becoming more frequent. Rainwater harvesting can help reduce flooding, recharge groundwater, and support water supply systems at the same time. The Punjab Cities Program (PCP) and the Punjab Inclusive Cities Program (PICP) provide strong institutional and financial support that can be used to include rainwater harvesting in city planning, infrastructure projects, and municipal services in both large and small cities.

12.1 Policy Integration with PCP and PICP

Rainwater harvesting should be officially recognized as an important activity within PCP and PICP city investment plans. PCP mainly focuses on improving city governance, municipal performance, and service delivery, while PICP focuses on improving water supply, sanitation, drainage, and climate resilience, especially in secondary cities. Because both programs already support urban infrastructure, they offer good opportunities to introduce rainwater harvesting in a planned and systematic way.

Rainwater harvesting should be clearly included as a priority investment under PCP performance plans and PICP infrastructure projects. Provincial and city governments should align mandatory rainwater harvesting rules with PCP and PICP planning systems so that meeting rainwater harvesting requirements becomes part of building approvals, project evaluation, and readiness criteria. City master plans and development plans prepared under PCP and PICP should also include specific components for rainwater harvesting and stormwater capture, linked to long term water security and climate resilience goals.

12.2 Integration of RWH with Urban Infrastructure Investments

Under PCP and PICP, large investments are being made in water supply, sewerage, stormwater drainage, roads, and public buildings. Rainwater harvesting should be built into these projects so that the benefits of these investments are increased. Instead of only draining rainwater away, infrastructure should be designed to capture and use it.

Stormwater drainage projects should be redesigned, wherever possible, to act as rainwater harvesting systems. This means adding storage, detention, and infiltration features rather than focusing only on fast disposal of rainwater. Drainage channels, roadside drains, and natural waterways should be supported with recharge wells and infiltration trenches to collect rainwater during heavy rainfall and allow it to recharge groundwater. Road and streetscape projects should include permeable pavements and bioswales, which reduce surface runoff and improve the urban environment. This approach will turn PCP and PICP drainage investments into systems that not only control floods but also support water conservation.

12.3 Public Buildings and Municipal Assets as Demonstration Projects

Cities under PCP and PICP have many public buildings and facilities, such as government offices, schools, hospitals, parks, bus terminals, and water utility buildings. These sites should be used as demonstration examples for rainwater harvesting. All new and renovated public buildings should include rooftop rainwater harvesting systems that collect water from roofs and store it in tanks or recharge it into the ground.

Large parks and open spaces should include underground recharge systems to collect rainwater from nearby paved areas. Municipal water utilities, such as WASAs and TMAs, should also use rainwater harvesting in their own facilities to reduce the use of groundwater for non drinking purposes. When the public sector takes the lead, it will build public trust and encourage the private buildings to adopt similar systems.

12.4 City Specific and Context Sensitive RWH Planning

Cities included in PCP and PICP differ in population size, rainfall, soil conditions, groundwater depth, and urban layout. Because of these differences, rainwater harvesting solutions should be designed according to local conditions rather than using one standard approach everywhere.

City level studies should be carried out to understand rainfall, runoff patterns, and groundwater conditions. Large cities such as Lahore, need bigger systems, including stormwater detention areas, large storage tanks, and groundwater recharge wells. Smaller and medium sized cities, which are the main focus of PICP, can rely more on rooftop rainwater harvesting, small recharge wells, and community level systems. All designs should be based on local soil permeability, groundwater depth, and flood risk to ensure good performance and avoid problems.

12.5 Institutional Strengthening and Capacity Building

For rainwater harvesting to work effectively under PCP and PICP, government institutions and city staff need proper skills and knowledge. Training programs on rainwater harvesting planning, design, construction, and maintenance should be included in PCP and PICP capacity building activities. Provincial authorities should prepare standard design guidelines and technical manuals so that all cities follow the same basic principles.

Municipal performance systems under PCP should also include indicators related to rainwater harvesting, such as the number of systems installed, storage capacity created, or groundwater recharge achieved. This will help track progress and encourage cities to take rainwater harvesting seriously.

12.6 Financing and Incentives

Rainwater harvesting should be treated as a regular part of city investment under PCP and PICP, not as an extra or optional activity. A specific portion of infrastructure budgets should be set aside for water sensitive and nature based solutions, including rainwater harvesting.

Public private partnerships can be encouraged, especially for large commercial and industrial buildings in PCP cities. Municipal governments can also motivate private developers by offering incentives such as lower development fees, faster approval processes and property tax reductions for projects that go beyond minimum rainwater harvesting requirements.

12.7 Community Engagement and Inclusivity under PICP

PICP places strong importance on inclusive development, especially for low income communities. Rainwater harvesting can directly benefit these areas by improving water availability and reducing dependence on expensive or unreliable water sources.

Community level rainwater harvesting systems should be introduced in informal settlements, low income housing areas, and peri urban locations where water access is limited. Awareness campaigns should be carried out to educate households about the benefits and basic maintenance of rainwater harvesting systems. Women should be actively involved in planning and managing these systems so that local ownership and long term sustainability are ensured.

12.8 Monitoring, Evaluation, and Long Term Sustainability

To ensure long term success, rainwater harvesting activities under PCP and PICP must be properly monitored. A province wide monitoring system should be developed and linked with existing PCP and PICP reporting mechanisms. This system should track how much rainwater is captured, how much groundwater recharge occurs, how flood risks are reduced, and whether systems are working properly.

Clear responsibility for operation and maintenance should be assigned to municipal departments or utility agencies, and sufficient budget should be allocated for regular upkeep. Without proper maintenance, even well designed systems will fail.

In conclusion, by fully integrating rainwater harvesting into the planning, funding, and implementation processes of PCP and PICP, Punjab can move from small, isolated projects to a province wide system of climate resilient urban water management. This approach will help to reduce urban flooding, slow groundwater depletion, and ease pressure on water supply systems, while also improving municipal performance and ensuring that all communities benefit from sustainable water solutions

13) SUGGESTIONS & RECOMMENDATIONS

13.1 Policy and Strategic Integration

13.1.1 Adopt Rainwater Harvesting as a Provincial Water Security Strategy

Rainwater Harvesting (RWH) and Managed Aquifer Recharge (MAR) should be formally recognized as core infrastructure for water security, climate adaptation, and disaster risk reduction, rather than as isolated pilot interventions.

13.1.2 Institutionalize Hydrogeological Zoning Based Planning

All RWH and MAR investments should strictly follow the Zone A, B, C hydrogeological planning framework to ensure technically sound, risk informed, and cost effective implementation while avoiding saline groundwater upconing and aquifer degradation.

13.1.3 Mainstream RWH into PCP and PICP Frameworks

RWH should be fully integrated into PCP and PICP planning, financing, and performance assessment systems, with explicit eligibility, prioritization, and monitoring indicators in city investment plans.

13.1.4 Mandate RWH in Urban Development Regulations

Rooftop rainwater harvesting and groundwater recharge provisions should be made mandatory for new housing schemes, commercial and institutional buildings, and all public infrastructure projects financed by the Government of Punjab or development partners. Provisions of the Green Building Code of Pakistan should be harmonized with provincial and local approval processes to ensure effective enforcement.

13.1.5 Establishment of RWH Cell within PMDFC

To ensure consistent implementation and technical quality, it is recommended that PMDFC establish a dedicated Rainwater Harvesting (RWH) Cell. This Cell should function as PMDFC's technical and coordination unit for RWH and MAR, responsible for integrating RWH into PCP and PICP city investment plans, standardizing technical designs & guidelines, vetting RWH proposals for site suitability & aquifer protection, supporting capacity building of municipal engineers, and maintaining a centralized database and monitoring system for RWH assets across Punjab.

13.2 Technical Design and Implementation

13.2.1 Prioritize Managed Aquifer Recharge in High Stress Urban Centers

Severely stressed cities such as Lahore, Faisalabad, Gujranwala, and Sheikhupura should be prioritized for MAR interventions, particularly, recharge wells in flood prone locations (parks, green belts, underpasses) and storage based systems coupled with multistage pretreatment (silt traps, gravel, sand and carbon filters).

13.2.2 Scale Up Surface Based RWH in High Recharge Potential Areas

In Zone A and Barani regions, emphasis should be placed on surface based recharge measures, including check dams on seasonal nullahs, infiltration basins, recharge ponds and agricultural water spreading.

13.2.3 Restrict Recharge Wells in Salinity Constrained Zones

In Zone C (southern and western Punjab), recharge wells should only be approved following detailed hydrogeological and geophysical investigations, including aquifer stratification and fresh saline interface mapping. Interventions should primarily focus on surface storage and Rainwater Harvesting for Sustainable Agriculture (RWHSA).

13.2.4 Standardize Technical Design Practices

All RWH and MAR systems must comply with established hydrological design methods. Site specific investigations covering soil permeability, aquifer transmissivity, groundwater depth, and water quality should be mandatory prior to implementation.

13.3 Urban Flood Management and Disaster Risk Reduction

13.3.1 Integrate RWH into Urban Flood Management Systems

Urban stormwater networks should be redesigned to function as stormwater harvesting, detention, and recharge systems, rather than solely as rapid disposal infrastructure. RWH should be explicitly incorporated into urban flood management and DRR planning.

13.3.2 Target Flood Hotspots for Immediate Intervention

Flood prone urban depressions, underpasses, and low lying areas should be prioritized for storage based RWH, infiltration systems, and managed recharge to simultaneously reduce flood peaks and enhance groundwater recharge.

13.4 Water Quality Management and Aquifer Protection

13.4.1 Mandate Enhanced Pretreatment for Urban Recharge

Enhanced pretreatment systems, including activated carbon or equivalent media, should be mandatory for all urban RWH systems intended for groundwater recharge, recognizing that conventional gravel, sand filters alone are insufficient.

13.4.2 Protect Aquifers through Strict Siting Criteria

Recharge systems must be located at safe distances from sewer lines, septic tanks, and waste disposal sites to prevent contamination, acknowledging that aquifer pollution is largely irreversible.

13.4.3 Institutionalize Water Quality Monitoring

Standardized groundwater quality monitoring protocols should be adopted and enforced to safeguard freshwater aquifers and support adaptive management.

13.5 Governance, Capacity Building, and Demonstration Projects

13.5.1 Strengthen Inter Agency Coordination

PMDFC, WASAs, Local Governments, Development Authorities and Irrigation Department, should operate under a unified RWH/MAR coordination framework to ensure data sharing, regulatory alignment, and avoidance of duplication.

13.5.2 Develop Province Wide Design and O&M Guidelines

Standardized technical guidelines should be issued covering design criteria, pretreatment requirements, monitoring protocols, and clear operation and maintenance responsibilities.

13.5.3 Build Technical Capacity at the Local Level

Training programs for municipal engineers and planners, should be implemented to ensure correct design, construction, and long-term sustainability of RWH systems.

13.5.4 Lead through Public Infrastructure Demonstration

All new and rehabilitated public buildings, municipal facilities, parks, and green belts under PCP and PICP should incorporate RWH systems to reduce groundwater abstraction and demonstrate public sector leadership.

13.6 Phased Implementation and Inclusivity

13.6.1 Adopt a Phased Roll out Strategy

Phase I: High-priority urban flood hotspots and critically depleted aquifers

Phase II: Secondary cities and canal tail end agricultural areas

Phase III: Barani and arid regions

13.6.2 Promote Community Participation and Inclusivity

Community scale RWH systems should be promoted in low income and underserved areas, with active participation of women and vulnerable groups to ensure ownership, equity, and sustainability.

13.7 Monitoring, Evaluation, and Long Term Sustainability

13.7.1 Establish a Provincial RWH Monitoring Framework

A province wide system should be established to monitor groundwater levels, recharge volumes, water quality, flood reduction benefits, system functionality, and maintenance status, aligned with PCP and PICP reporting requirements.

13.7.2 Ensure Sustainable Operation and Maintenance

Clear institutional responsibility, budgetary allocation, and performance accountability for operation and maintenance of RWH systems must be defined at the municipal level.

13.8 Concluding Recommendation

This feasibility study establishes that Rainwater Harvesting and Managed Aquifer Recharge are technically feasible, economically justified, and environmentally essential for Punjab's long term water security. When implemented systematically through hydrogeological zoning, sound engineering, strong governance, and community engagement, RWH can reverse groundwater depletion trends, reduce urban flood risks, and build climate resilience across the province. PMDFC is strategically positioned to lead this transformation by translating these recommendations into targeted, zone specific investment programs under PCP and PICP.