Assessment and Optimization of Rainwater Harvesting Potential for Urban Sustainability: A Case of Lahore

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Abstract

This study employs a multi-criteria decision analysis method utilizing Geographic Information System (GIS) to pinpoint appropriate locations for rainwater harvesting (RWH) structures, to fulfill water demand in Lahore, Pakistan. Data from satellite imagery, soil composition, climate, and digital elevation models (DEM) were integrated into GIS layers and amalgamated to establish a ranking system. This ranking system was then employed to identify suitable areas for rainwater harvesting. Thematic layers, encompassing variables such as rainfall, land use/land cover, soil type, slope, runoff depth, drainage density, and stream order, were combined into a comprehensive overlay, resulting in a map delineating RWH suitability. The outcomes revealed that based on Average Annual Rainfall, 1.44% of the study area is classified as 'very highly suitable,' while 5.67% is designated as 'highly suitable.' Conversely, 24.54% of the region is labeled as 'moderately suitable.' Additionally, 65.44% of the region, situated in the east and southeast, exhibits 'low suitability,' and 2.91% is deemed 'unsuitable.' The findings of this research are poised to foster the broader adoption of RWH in the Lahore region to meet water demands. Furthermore, the developed methodology holds adaptability for implementation in other regions or countries.

Keywords: GIS; Multi-criteria Decision Analysis; Rainwater Harvesting; Site Suitability.

Introduction

Water, an invaluable natural resource, plays a vital role in sustaining both human and animal life, as well as fostering economic growth and development. The challenge of freshwater scarcity has emerged as a pivotal concern in the realm of sustainable development, affecting communities not only in agricultural and industrial sectors but also in meeting domestic water needs. The globe faces five primary global factors—climate change, population expansion, rapid industrialization, and excessive groundwater usage—that collectively exert immense pressure on the availability of safe water worldwide. Consequently, the prudent management of freshwater resources becomes imperative. Concurrently, researchers worldwide have explored various alternative measures to address the issue of water scarcity. Rainwater harvesting (RWH) has gained widespread adoption in several water-stressed regions, earning recognition as one of the most economically and ecologically advantageous water conservation methods. RWH not only addresses water scarcity challenges but also mitigates the risks associated with flash floods and alleviates problems stemming from the over-extraction of groundwater.

The South Asia region, which includes countries like Afghanistan, Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan, and Sri Lanka, hosts about 24% of the world's population within

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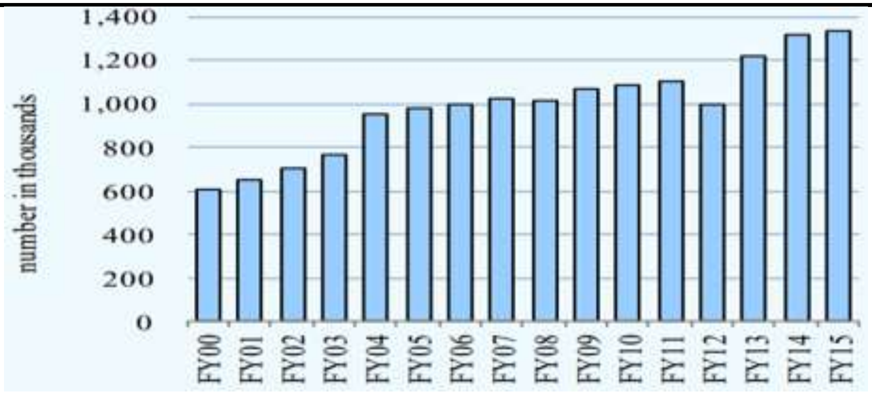
only ~4% of the total global land area The region encompasses three of the most extensive riverine systems of the world (Indus, Ganges, and Brahmaputra River basins) that host several high groundwater-producing aquifers. However, the availability of safe and sustainable groundwater in the region is not consistent. There is a growing concern about the accessibility of safe water in many of these aquifers due to the presence of geo-genic pollutants. The region is also the most extensive user of groundwater resources in the globe, leading to severe concern about groundwater availability, even for groundwater-affluent aquifers.

Several anthropogenic activities, particularly irrigation (which accounts for >80% of the groundwater withdrawal), lead to groundwater depletion in most areas within the region. Varying precipitation rates and subsurface hydraulic conditions are providing more challenges to groundwater governance.

Throughout South Asia, the history of protective well irrigation goes back to millennia. However, intensive groundwater use on the scale we find today is a story of the last 50 – days and 30 – years. In India, the total number of mechanized wells and tube wells rose from less than a million in 1960 to an estimated 19 million in 2000. In Pakistan Punjab, it increased from barely a few thousand in 1960 to 0.5 million in 2000. In Bangladesh, which hardly had any groundwater irrigation until 1960, the area irrigated by groundwater wells shot up from 4% in 1972 to 70% in 1999.

Figure 1: Number of tube wells installed over the years



Due to the unpredictability associated with canal water supplies, farmers have turned to groundwater pumping in Punjab, Pakistan. Thus, the number of tube wells installed has increased sharply over the years (figure attached), and groundwater has now become a significant source of water, as its contribution to irrigated agriculture has doubled in the last 40 years from (25.6 to 50.2 MAF). This is equivalent to 50 percent of overall canal water withdrawal for irrigation. Industries and the domestic sector also rely on groundwater resources for water supply.

Indeed, precipitation and river flows constantly recharge most of these groundwater aquifers – a process that enables people to have reliable access to this key water resource even for a very long period. However, no matter how large these aquifers may be, excessive pumping would also deplete this valuable resource. This is what is happening in many regions across Pakistan, where unregulated and excessive use of groundwater is leading to falling water tables and reduced quality. The situation is a lot worse in Balochistan where the water table is. Thus, water tables in Pishin district have receded down to 1,000 feet. In Sindh, cities like Hyderabad and Benazirabad are also facing a decline in groundwater levels on a similar scale.

The unsustainable pumping rate has even led to the intrusion of brackish water into freshwater resources, thereby reducing the availability of quality groundwater as per the standards of the World Health Organization (WHO). In KP, Kohat, Bannu, and D.I Khan are some regions where over-pumping has lowered water tables and resulted in contamination from deep saline groundwater. In Balochistan, there are reports of intrusion of saline water into aquifer zones in coastal areas.

For instance, Lahore has seen a reduction in water tables at 0.5 meters annually for the past 30 years (Table attached). This is even though Lahore is provided water by the river Ravi and has an extensive canal system.

Table 1: Reduction in water tables in Lahore

Period	**Rate of Decline**	
	Feet/year	**Meter/year**
1960-1967	0.98	0.30
1967-1973	1.80	0.55
1973-1980	1.97	0.60
1980-2000	2.13	0.65
2007-2011	2.60	0.79
2011-2013	3.00	0.91

Objectives

The main objective of this study revolves around optimization of rainwater which is otherwise wasted. The study encompasses data collection at several locations along with the quantum of rainwater for effective transportation to storage facilities keeping in view the topography (elevation) and distance relevance. The stored water is idealized to be filtered which is then proposed to be used for drinking/ cleaning purposes.

Importance

Sustainable Water Source

One of the primary benefits of rainwater harvesting is its role as a sustainable water source. By capturing rainwater during periods of rainfall, individuals, communities, and industries can reduce their dependence on conventional water supplies. This not only helps meet immediate water needs but also contributes to long-term water security, especially in regions prone to droughts or unreliable water sources.

Mitigation of Water Scarcity

Water scarcity is a global challenge affecting millions of people, and the situation is exacerbated in many urban areas. Rainwater harvesting provides a decentralized and localized solution to mitigate water scarcity. By harvesting rainwater, communities can supplement their water supply, particularly for non-potable uses like irrigation, industrial processes, and sanitation. This reduces the burden on centralized water distribution systems and promotes a more sustainable and equitable water distribution.

Environmental Conservation

Rainwater harvesting supports environmental conservation efforts by reducing the demand on natural water sources such as rivers, lakes, and groundwater. Over-extraction of groundwater, in particular, has led to the depletion of aquifers and adverse environmental impacts. Rainwater harvesting helps in preserving these precious natural resources and promotes ecosystem health by maintaining adequate water levels in rivers and other bodies of water.

Reduced Runoff and Erosion

In urban areas, impervious surfaces such as roads and rooftops contribute to increased surface runoff during rainfall. This runoff can lead to soil erosion, flooding, and contamination of water bodies. Rainwater harvesting systems, which capture runoff from rooftops, help in reducing the volume and velocity of runoff. This not only prevents soil erosion but also minimizes the risk of flooding and improves the quality of water entering local rivers and streams.

Financial Savings

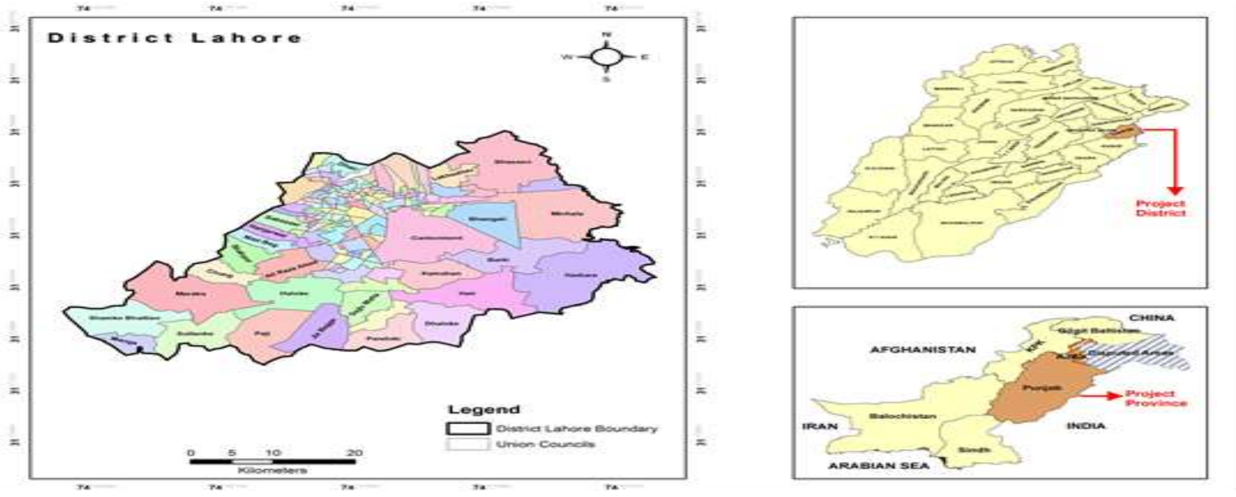
Implementing rainwater harvesting systems can result in significant financial savings for individuals and communities. By relying on rainwater for non-potable uses like gardening, flushing toilets, or washing cars, households can reduce their water bills. Additionally, industries can benefit from lower water supply costs, contributing to overall economic sustainability.

The remainder of this paper is organized as follows, the study region and data are described in section 2. The methodology is presented in section 3. The data collection and analysis presented in sections 4 and 5. Identification of suitable locations their rainwater harvesting potential presented in sections 6 and 7. The results, conclusions and recommendations for future research are discussed in sections 8 and 9.

Study Area and Data

Lahore, Pakistan, a vibrant city nestled in the heart of the country, boasts a rich cultural heritage, and serves as a significant economic and cultural hub. With 14.407 million residents living there, the population density for the complete area of 1772 sq. km comes out to be 8130.36 residents per sq. km. The mean AAR (Average Annual Rainfall) is about 732 mm/year.

Figure 2: Map of the study region i.e., Lahore where the present study was undertaken



With a history dating back centuries, Lahore is renowned for its historical landmarks, including the Lahore Fort and Badshahi Mosque, reflecting the grandeur of Mughal architecture. The city's lively atmosphere is complemented by bustling bazaars, vibrant street life, and a diverse culinary scene. Lahore is a melting pot of traditions, where modernity seamlessly blends with tradition, making it a captivating destination for both locals and visitors alike. Additionally, Lahore is recognized for its educational institutions, contributing to the intellectual and artistic landscape of the region. As one of Pakistan's most populous cities, Lahore continues to evolve while preserving its unique identity, making it a dynamic and enchanting metropolis.

Land use map of the study area is presented as under:

Figure 3: Land Use Map of Study Area i.e., District Lahore

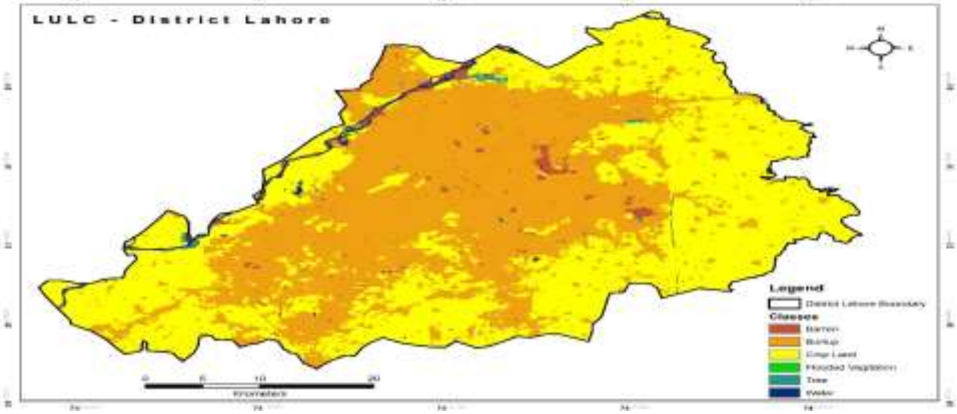


Figure 4: Rainfall Stations in District Lahore

Methodology

This study is being conducted to highlight the importance of water conservation through water harvesting technique with the help of credible data information and GIS Mapping of potential zones of Lahore.

Following key parameters have been taken in consideration:

- Kind of soil having sufficient clay to retain water.
- Topology of the study area.
- Quantum of Rainfall measured in fixed intervals at certain locations in the study area.
- Land use/land cover of the study area.
- Elevation Appropriation for the study area.
- Natural slope, drainage density, and stream order.
- Adequate quantum of runoff that can be stored in properly designed and constructed rainwater tanks.

Data Collection

The study undertook the collection of openly accessible images and remote sensing data for Lahore. Also, information was gathered on surface elevation, land use and land cover, soil maps, drainage maps, and depression maps for Lahore. The study employed Geographic Information

System (GIS) techniques to analyze the collected data. Further, the Soil Conservation Service - Curve Number (SCS-CN) method has been implemented to assess surface runoff availability in various regions of Lahore.

Moreover, utilization of appropriate equations has been done to weigh curve numbers relative to the size of the watershed area.

Identification of Suitable Locations

Based on the analyzed data, locations suitable for rainwater harvesting structures have been pinpointed in Lahore. During the process, factors such as surface elevation, land use and land cover, soil type, drainage patterns, and depression volume have also been considered.

The identified locations have then been classified according to the proposed criteria as either excellent, good (with provisions for overflow structure), or not suitable for rainwater harvesting.

Estimation of Rainwater Harvesting Potential

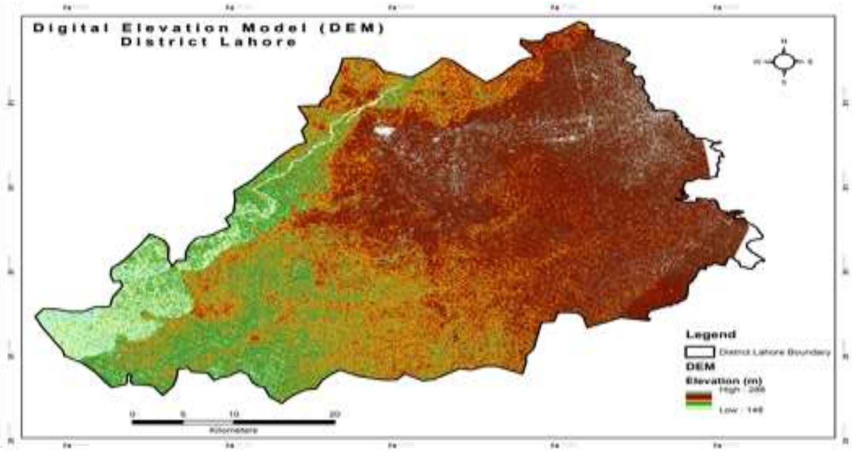
The overall potential for rainwater harvesting in Lahore has been determined based on the identified suitable locations. Results attached in the respective head "results and discussions"

Figure 5: Conceptual methodology flowchart used in this study

Digital Elevation Model (DEM)

A Digital Elevation Model (DEM) is a three-dimensional representation of the Earth's surface that quantifies terrain elevation values across a specific geographic area. It is commonly represented as a grid or raster, where each cell contains a numerical value corresponding to the elevation of the land surface at that specific location. DEMs can be derived from various sources, such as satellite and airborne remote sensing technologies, and are instrumental in understanding and modeling the Earth's topography. The DEM map of the study area is shown in figure below.

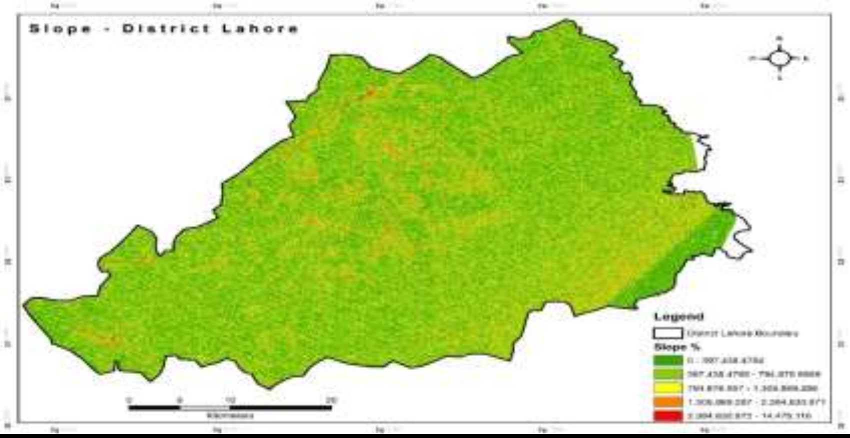
Figure 6: Digital Elevation Model (DEM) of District Lahore



Slope

A slope map is a graphical representation or visual depiction of the topographic gradient or incline across a landscape or geographic area. It illustrates the variation in elevation or steepness of the terrain, typically derived from digital elevation models (DEM) or other elevation datasets. The slope is an important parameter to consider when choosing a location for a RWH structure since it affects the size of the harvesting structure and the amount of water stored. The slope map of the study area is shown in figure below.

Figure 7: Slope Map of District Lahore



Data Collection

Gathering Freely Available Imagery/Remote Sensing Data for Lahore

Satellite imagery and remote sensing data from sources like the USGS Earth Explorer has been acquired for the GIS analysis, ensuring the availability of up-to-date and accurate information. DEM and Slope Map are attached above.

Collecting Data on Precipitation, Land Use/ Land Cover, Soil Map, Drainage Map, and Depression Map for Lahore

The comprehensive data collection process involved obtaining information from the Punjab Land Record Authority & WASA, covering precipitation data collection record, land use, soil type, drainage patterns, and depression volume.

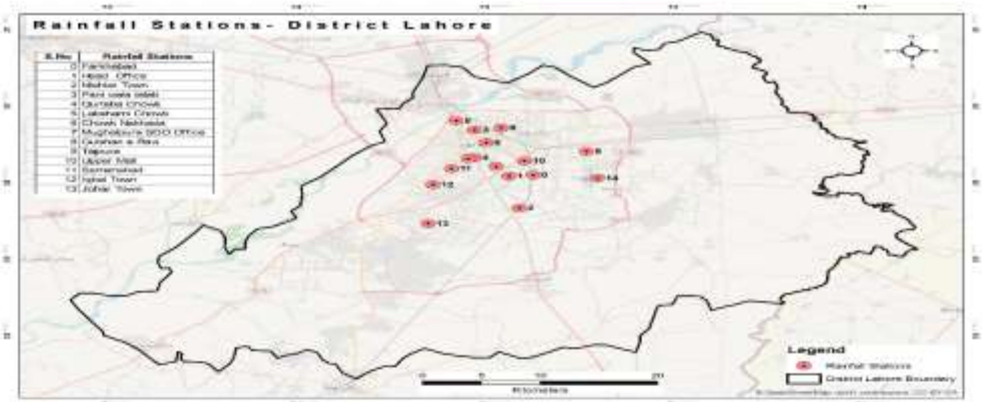
The rainfall data for different years and locations has been obtained from WASA which is attached below:

Table 2: Rainfall data of various locations obtained from WASA (Study based on Year 2016-2023)

Year	Pre & post monsoon rain (mm/year)	Monsoon season rainfall (mm/year)	Annual record (mm/year)
2016	154	442	596
2017	182	216	398
2018	212	451	663
2019	76	634	710
2020	34	651	685
2021	90	578	668
2022	172	560	732
2023	416	988*	1404

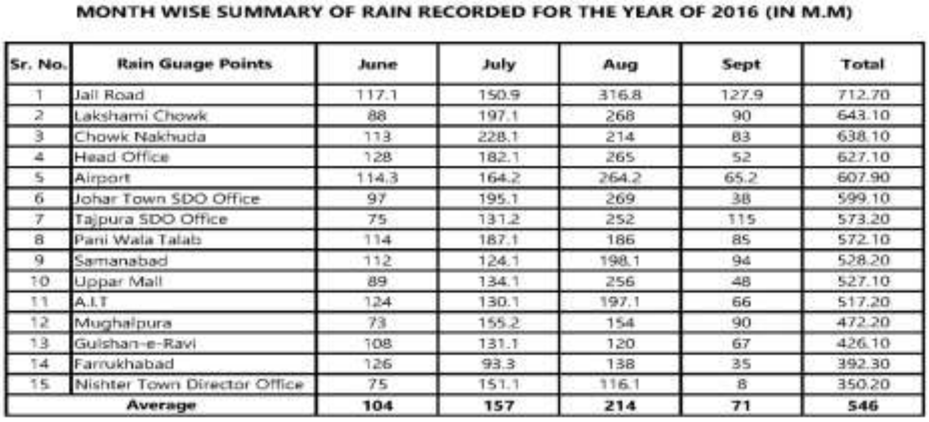
Station Locations

Figure 8: Rainfall Station Locations in District Lahore



Detailed Station wise Data

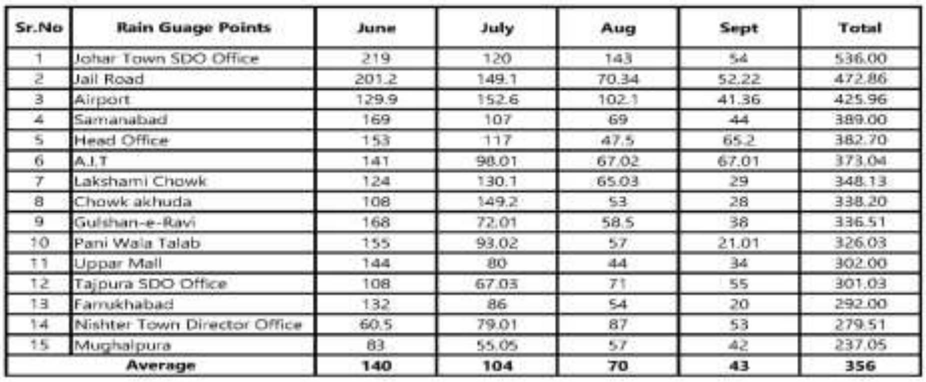
Table 3: Month Wise Summary of rain obtained from WASA (Study based on Year 2016-2023)



MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2016 (IN M.M)

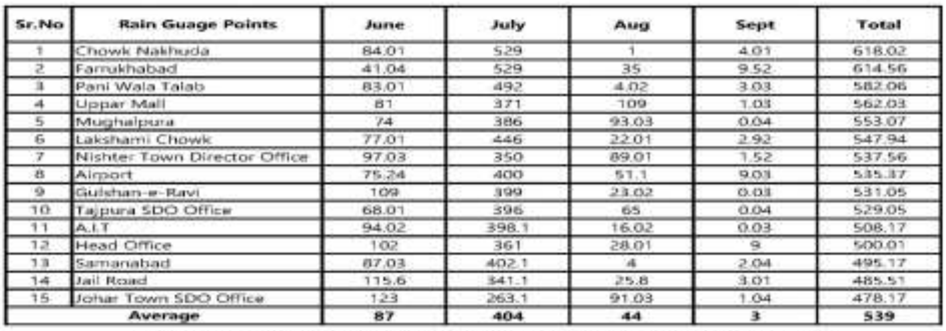
Sr. No.	Rain Guage Points	June	July	Aug	Sept	Total
1	Jail Road	117.1	150.9	316.8	127.9	712.70
2	Lakshami Chowk	88	197.1	268	90	643.10
3	Chowk Nakhuda	113	228.1	214	83	638.10
4	Head Office	128	182.1	265	52	627.10
5	Airport	114.3	164.2	264.2	65.2	607.90
6	Johar Town SDO Office	97	195.1	269	38	599.10
7	Tajpura SDO Office	75	131.2	252	115	573.20
8	Pani Wala Talab	114	187.1	186	85	572.10
9	Samanabad	112	124.1	198.1	94	528.20
10	Uppar Mall	89	134.1	256	48	527.10
11	A.I.T	124	130.1	197.1	66	517.20
12	Mughalpura	73	155.2	154	90	472.20
13	Gulshan-e-Ravi	108	131.1	120	67	426.10
14	Farrukhabad	126	93.3	138	35	392.30
15	Nishter Town Director Office	75	151.1	116.1	8	350.20
Average		**104**	**157**	**214**	**71**	**546**

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2017 (IN M.M)



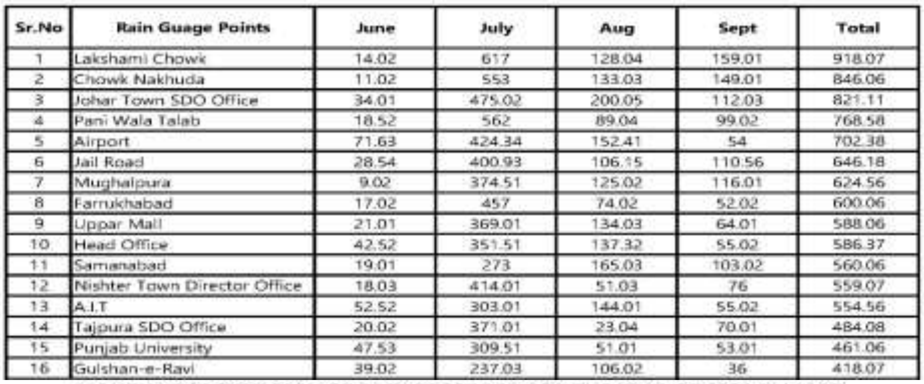
Sr.No	Rain Guage Points	June	July	Aug	Sept	Total
1	Johar Town SDO Office	219	120	143	54	536.00
2	Jail Road	201.2	149.1	70.34	52.22	472.86
3	Airport	129.9	152.6	102.1	41.36	425.96
4	Samanabad	169	107	69	44	389.00
5	Head Office	153	117	47.5	65.2	382.70
6	A.I.T	141	98.01	67.02	67.01	373.04
7	Lakshami Chowk	124	130.1	65.03	29	348.13
8	Chowk akhuda	108	149.2	53	28	338.20
9	Gulshan-e-Ravi	168	72.01	58.5	38	336.51
10	Pani Wala Talab	155	93.02	57	21.01	326.03
11	Uppar Mall	144	80	44	34	302.00
12	Tajpura SDO Office	108	67.03	71	55	301.03
13	Farrukhabad	132	86	54	20	292.00
14	Nishter Town Director Office	60.5	79.01	87	53	279.51
15	Mughalpura	83	55.05	57	42	237.05
Average		**140**	**104**	**70**	**43**	**356**

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2018 (IN M.M)



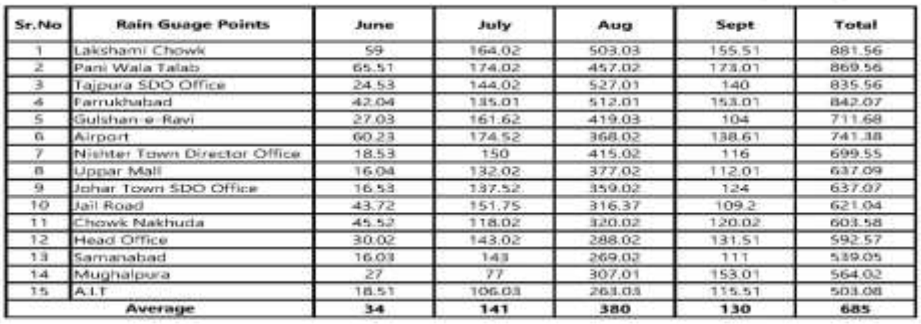
Sr.No	Rain Guage Points	June	July	Aug	Sept	Total
1	Chowk Nakhuda	84.01	529	1	4.01	618.02
2	Farrukhabad	41.04	529	35	9.52	614.56
3	Pani Wala Talab	83.01	492	4.02	3.03	582.06
4	Uppar Mall	81	371	109	1.03	562.03
5	Mughalpura	74	386	93.03	0.04	553.07
6	Lakshami Chowk	77.01	446	22.01	2.92	547.94
7	Nishter Town Director Office	97.03	350	89.01	1.52	537.56
8	Airport	75.24	400	51.1	9.03	535.37
9	Gulshan-e-Ravi	109	399	23.02	0.03	531.05
10	Tajpura SDO Office	68.01	396	65	0.04	529.05
11	A.I.T	94.02	398.1	16.02	0.03	508.17
12	Head Office	102	361	28.01	9	500.01
13	Samanabad	87.03	402.1	4	2.04	495.17
14	Jail Road	115.6	341.1	25.8	3.01	485.51
15	Johar Town SDO Office	123	263.1	91.03	1.04	478.17
Average		**87**	**404**	**44**	**3**	**539**

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2019 (IN M.M)



Sr.No	Rain Guage Points	June	July	Aug	Sept	Total
1	Lakshami Chowk	14.02	617	128.04	159.01	918.07
2	Chowk Nakhuda	11.02	553	133.03	149.01	846.06
3	Johar Town SDO Office	34.01	475.02	200.05	112.03	821.11
4	Pani Wala Talab	18.52	562	89.04	99.02	768.58
5	Airport	71.63	424.34	152.41	54	702.38
6	Jail Road	28.54	400.93	106.15	110.56	646.18
7	Mughalpura	9.02	374.51	125.02	116.01	624.56
8	Farrukhabad	17.02	457	74.02	52.02	600.06
9	Uppar Mall	21.01	369.01	134.03	64.01	588.06
10	Head Office	42.52	351.51	137.32	55.02	586.37
11	Samanabad	19.01	273	165.03	103.02	560.06
12	Nishter Town Director Office	18.03	414.01	51.03	76	559.07
13	A.I.T	52.52	303.01	144.01	55.02	554.56
14	Tajpura SDO Office	20.02	371.01	23.04	70.01	484.08
15	Punjab University	47.53	309.51	51.01	53.01	461.06
16	Gulshan-e-Ravi	39.02	237.03	106.02	36	418.07

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2020 (IN M.M)

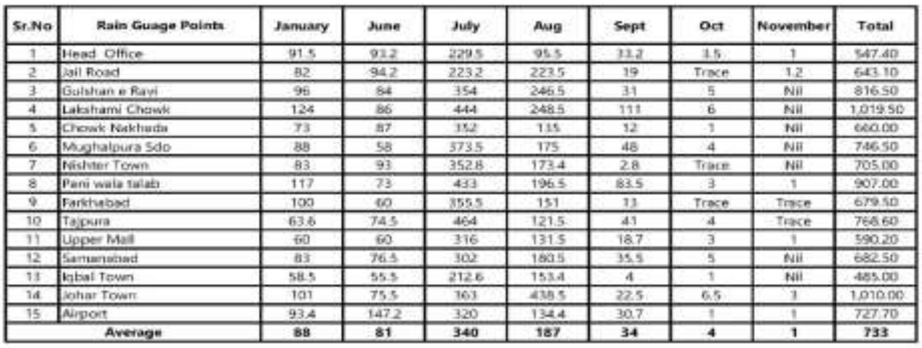


Sr.No	Rain Guage Points	June	July	Aug	Sept	Total
1	Lakshami Chowk	59	164.02	503.03	155.51	881.56
2	Pani Wala Talab	65.51	174.02	457.02	173.01	869.56
3	Tajpura SDO Office	24.53	144.02	527.01	140	835.56
4	Farrukhabad	42.04	135.01	512.01	153.01	842.07
5	Gulshan-e-Ravi	27.03	161.62	419.03	104	711.68
6	Airport	60.23	174.52	368.02	138.61	741.38
7	Nishter Town Director Office	18.53	150	415.02	116	699.55
8	Uppar Mall	16.04	132.02	377.02	112.01	637.09
9	Johar Town SDO Office	16.53	137.52	359.02	124	637.07
10	Jail Road	43.72	151.75	316.37	109.2	621.04
11	Chowk Nakhuda	45.52	118.02	320.02	120.02	603.58
12	Head Office	30.02	143.02	288.02	131.51	592.57
13	Samanabad	16.03	143	269.02	111	539.05
14	Mughalpura	27	77	307.01	153.01	564.02
15	A.I.T	18.51	106.03	263.03	115.51	503.08
Average		**34**	**141**	**380**	**130**	**685**

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2021 (IN M.M)

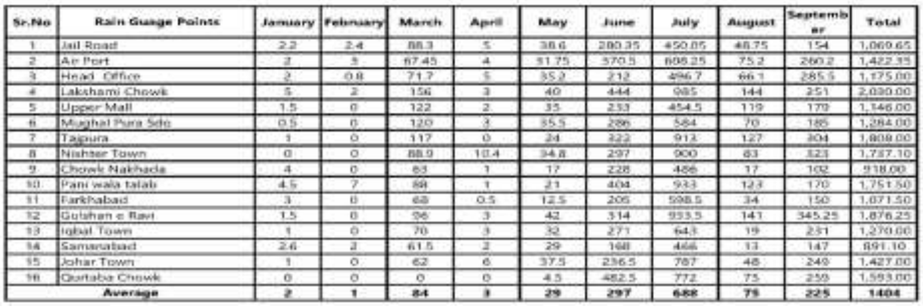
Sr.No	Rain Guage Points	June	July	Aug	Sept	Total
1	Lakshami Chowk	12.5	240	186.5	436	875.00
2	Pani Wala Talab	19.5	302	164.5	364	850.00
3	Tajpura SDO Office	10.51	141.5	247.5	301	700.51
4	Farrukhabad	10.5	323	173.01	432	938.51
5	Gulshan-e-Ravi	3.51	116.5	124.21	276.5	520.72
6	Airport	23	197.8	135.2	166.4	522.40
7	Nishter Town Director Office	41	171	133.01	216	561.01
8	Uppar Mall	9	122.01	97.51	222	450.52
9	Johar Town SDO Office	33	147.3	129.01	195.2	504.51
10	Jail Road	14.9	185.4	82.5	221.4	504.20
11	Chowk Nakhuda	8.01	226	131	293	658.01
12	Head Office	14.8	178.6	103	152.1	448.50
13	Samanabad	9.01	127.5	70.01	168	374.52
14	Mughalpura	13	188.5	151	289.5	642.00
15	A.I.T	10.5	96	84.01	171	361.51
Average		**16**	**184**	**134**	**260**	**594**

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2022 (IN M.M)



Sr.No	Rain Guage Points	January	June	July	Aug	Sept	Oct	November	Total
1	Head Office	91.5	93.2	229.5	95.5	33.2	3.5	1	547.40
2	Jail Road	82	94.2	223.2	223.5	19	Trace	1.2	643.10
3	Gulshan e Ravi	96	84	354	246.5	31	5	Nil	816.50
4	Lakshami Chowk	124	86	444	248.5	111	6	Nil	1,019.50
5	Chowk Nakhuda	73	87	352	135	12	1	Nil	660.00
6	Mughalpura Sdo	88	58	373.5	175	48	4	Nil	746.50
7	Nishter Town	83	93	352.8	173.4	2.8	Trace	Nil	705.00
8	Pani wala talab	117	73	433	196.5	83.5	3	1	907.00
9	Farkhabad	100	60	355.5	151	13	Trace	Trace	679.50
10	Tajpura	63.6	74.5	464	121.5	41	4	Trace	768.60
11	Upper Mall	60	60	316	131.5	18.7	3	1	590.20
12	Samanabad	83	76.5	302	180.5	35.5	5	Nil	682.50
13	Iqbal Town	58.5	55.5	212.6	153.4	4	1	Nil	485.00
14	Johar Town	101	75.5	363	438.5	22.5	6.5	1	1,010.00
15	Airport	93.4	147.2	320	134.4	30.7	1	1	727.70
Average		**88**	**81**	**340**	**187**	**34**	**4**	**1**	**733**

MONTH WISE SUMMARY OF RAIN RECORDED FOR THE YEAR OF 2023 (IN M.M)



Sr.No	Rain Guage Points	January	February	March	April	May	June	July	August	September	Total
1	Jail Road	2.2	2.4	88.3	5	38.6	280.35	450.05	48.75	154	1,069.65
2	Air Port	2	3	67.45	4	31.75	370.5	608.25	75.2	260.2	1,422.35
3	Head Office	2	0.8	71.7	5	35.2	212	496.7	66.1	285.5	1,175.00
4	Lakshami Chowk	5	2	156	3	40	444	985	144	251	2,030.00
5	Upper Mall	1.5	0	122	2	35	233	454.5	119	179	1,146.00
6	Mughal Pura Sdo	0.5	0	120	3	35.5	286	584	70	185	1,284.00
7	Tajpura	1	0	117	0	24	322	913	127	304	1,808.00
8	Nishter Town	0	0	88.9	10.4	34.8	297	900	83	323	1,737.10
9	Chowk Nakhada	4	0	83	1	17	228	486	17	102	918.00
10	Pani wala talab	4.5	7	88	1	21	404	933	123	170	1,751.50
11	Farkhabad	3	0	68	0.5	12.5	205	598.5	34	150	1,071.50
12	Gulshan e Ravi	1.5	0	56	3	42	314	933.5	141	345.25	1,876.25
13	Iqbal Town	1	0	70	3	32	271	643	19	231	1,270.00
14	Samanabad	2.6	2	61.5	2	29	168	466	13	147	891.10
15	Johar Town	1	0	62	6	37.5	236.5	787	48	249	1,427.00
16	Qurtaba Chowk	0	0	0	0	4.5	482.5	772	75	259	1,593.00
Average		**2**	**1**	**84**	**3**	**29**	**297**	**688**	**75**	**225**	**1404**

Data Analysis

Analyzing Collected Data Using GIS Techniques

GIS techniques have been applied, ensuring the spatial relationships between several factors are accurately examined. The Rainfall data has been simulated on the stations based on their respective UTM locations that have been recorded while collecting Rainfall Data.

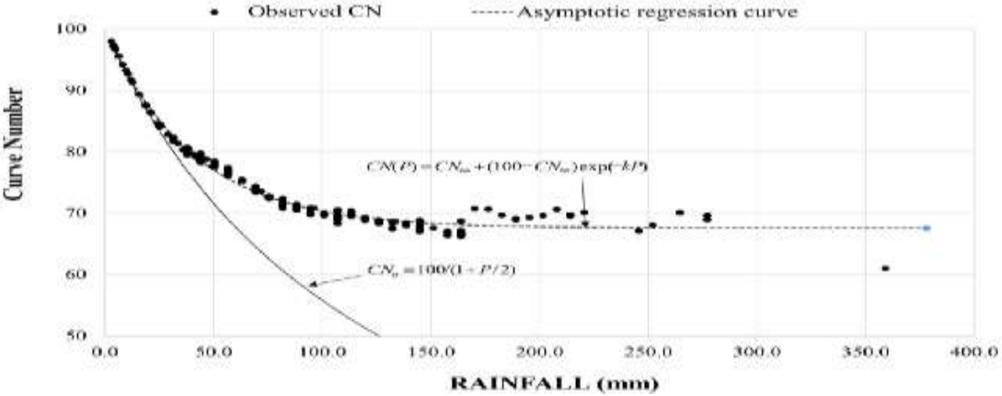
Applying the Soil Conservation Service - Curve Number (SCS-CN) Method

The SCS-CN method, based on USDA Natural Resources Conservation Service guidelines, is used for evaluating hydrological characteristics, allowing for a comprehensive analysis of water runoff potential.

Weighing Curve Numbers with Respect to Using Appropriate Equations

The equations like those provided by Hawkins (1993) have been utilized in calculation and weighing of curve numbers based on watershed area for a more refined assessment of rainwater harvesting potential.

Figure 9: Asymptotic CN regressions obtained in the study by Hawkins



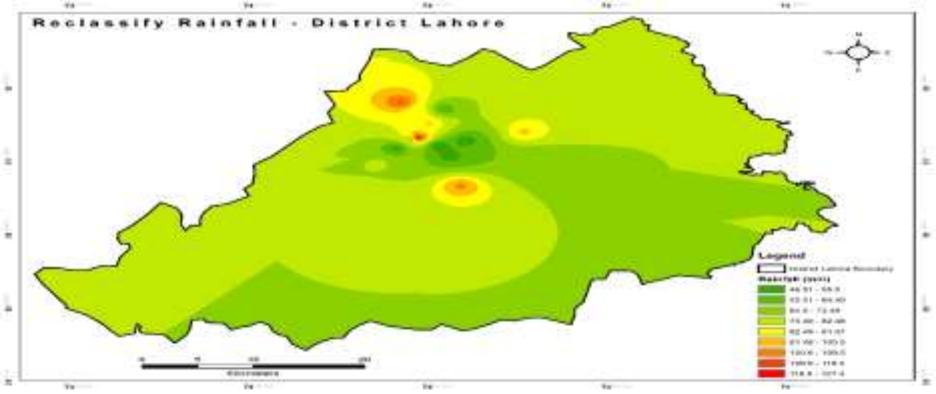
CN(P) is the Curve Number as a function of rainfall, and $CN_0 = 100/(1 + P/2)$ defines a threshold below which no runoff occurs until the rainfall P in mm exceeds an initial abstraction of 20% of the maximum potential retention.

Identification of Suitable Locations

Analyzing Data to Identify Suitable Locations

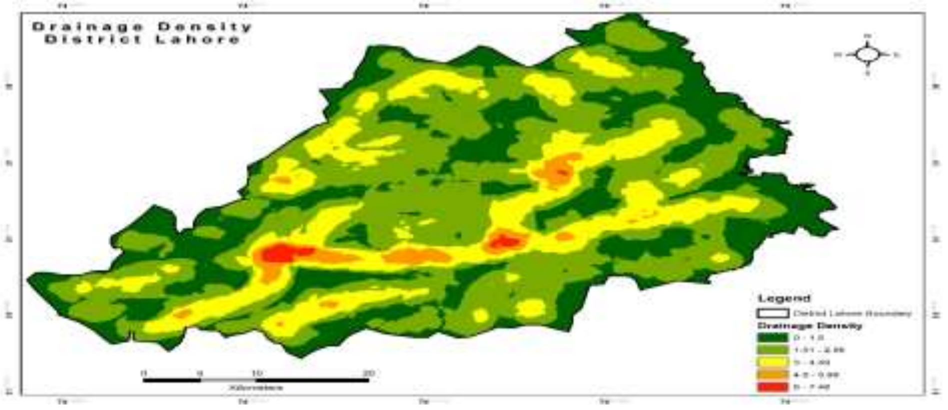
The GIS analysis results are employed to identify optimal rainwater harvesting locations based on predefined criteria, ensuring a systematic and data-driven approach. A rainwater intensity model of Lahore based on the collected data is provided as below:

Figure 10: Rainwater Intensity Model of Lahore based on the collected data



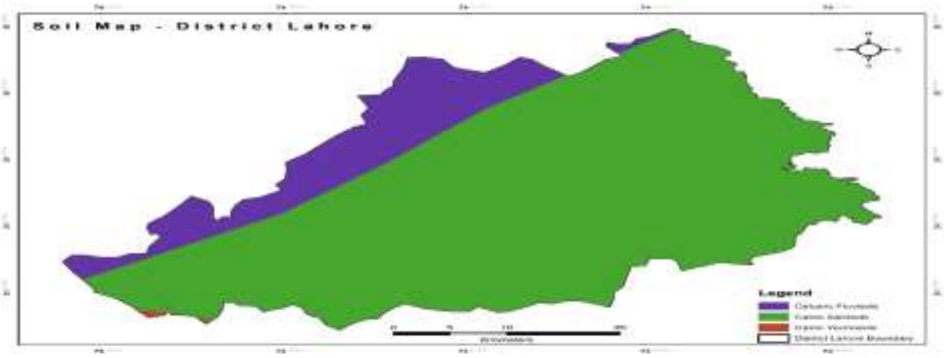
Further, Drainage Density has also been kept a key determining factor for analysis and classification of Suitable locations. A Drainage Density Map of the project Area is attached below:

Figure 11: Drainage Density Map of Lahore



The type of soil surrounding various parts of the project area is also a keen factor in determining the RWH Potential as the surface runoff is directly proportional to the soil properties. In this regard, soil classification data for the project site is attached below:

Figure 12: Soil Classification Map of Lahore



Using Proposed Criteria to Classify Locations as Excellent, Good, or Not Suitable for Rainwater Harvesting

Based on the above data and Land availability, the categories have been classified as excellent, good, or not suitable, inspired by studies like Tiwari and Joshi (2013), facilitating practical implementation. The classification map (rainwater intensity) is attached below:

Figure 13: Classification Map (Rainwater Intensity) of Lahore

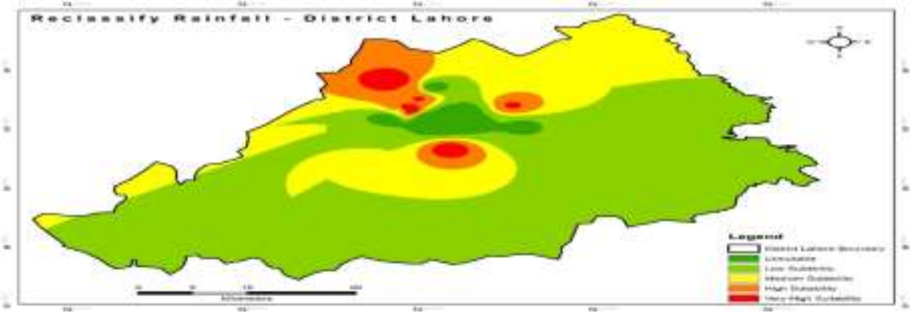


Figure 14: Classification Map (Drainage Density) of Lahore

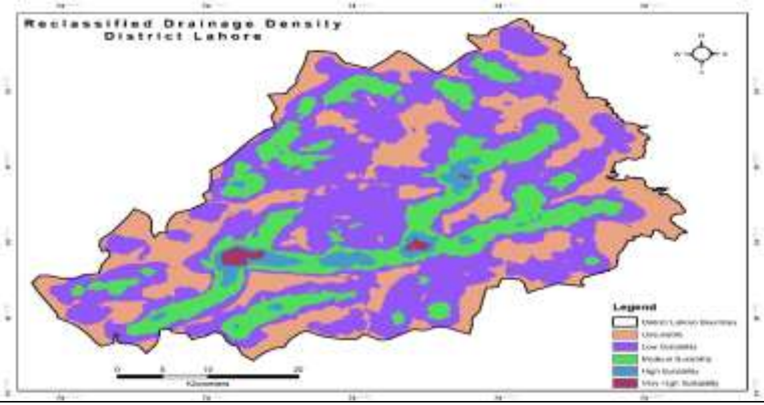
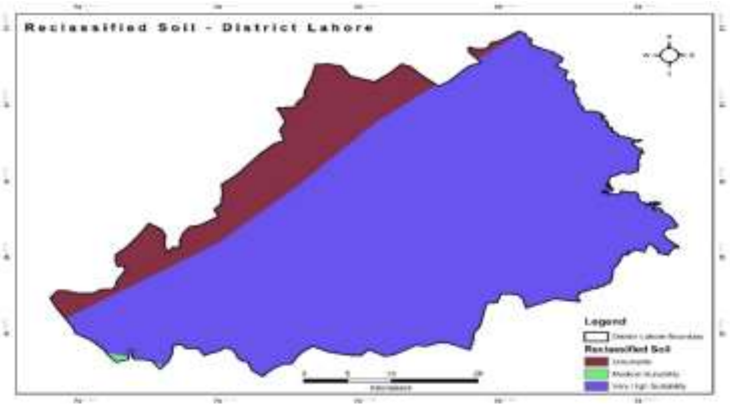


Figure 15: Classification Map (Stream Order) of Lahore

Figure 16: Classification Map (Soil Type) of Lahore



Choosing the Critical Locations & Values for RWH

Based on the above attached maps, suitable locations for RWH are selected. Locations No. 2, 4, 8 & 9 are the most critical based on the Rainwater intensity Map and Rainwater Harvesting Potential is calculated as described in sub-head 7. The critical values of Precipitation are listed below:

Table 4: Monthly Critical Precipitation Values in different areas of Lahore

Location No	Rain Gauge Points	01. 2023	02. 2023	03. 2023	04. 2023	05. 2023	06. 2023	07. 2023	08. 2023	09. 2023	Total
2	Nishter Town	0	0	89	10	35	297	900	83	323	1,737
4	Qurtaba Chowk	0	0	0	0	5	483	772	75	259	1,593
8	Gulshan e Ravi	2	0	96	3	42	314	934	141	345	1,876
9	Tajpura	1	0	117	0	24	322	913	127	304	1,808
Most Critical		2	0	117	10	42	483	**934**	141	345	**1876**

The most critical value in the monsoon of 2023 was 934 mm/month for the location Gulshan e Ravi. In order to calculate the most effective rainwater harvesting, we need to take the maximum rain in one day value and consider it for our design. The detailed data for rainy days in Gulshan e Ravi for the Month of July 2023 is attached below:

Table 5: Precipitation in Gulshan e Ravi for the Month of July 2023

Day	Precipitation (mm/day)
03.07.2023	14
05.07.2023	268
06.07.2023	59
08.07.2023	50
15.07.2023	32
19.07.2023	13
22.07.2023	203
24.07.2023	zero
26.07.2023	137
27.07.2023	trace
28.07.2023	1.5
29.07.2023	156

Most critical value from the above data is found to be 268 mm/day. This rainfall intensity has been considered for 2 consecutive days for the capacity design of UGWT.

Estimation of Rainwater Harvesting Potential

Calculating Total Rainwater Harvesting Potential of Lahore

With the help of GIS, the catchment area has been marked for each collection point. The data for water ponding has been obtained from field surveys provided by WASA. The total critical catchment area has been calculated with the help of GIS as presented below:

Figure 17: GIS Classification Map (Rainwater Intensity) of Lahore

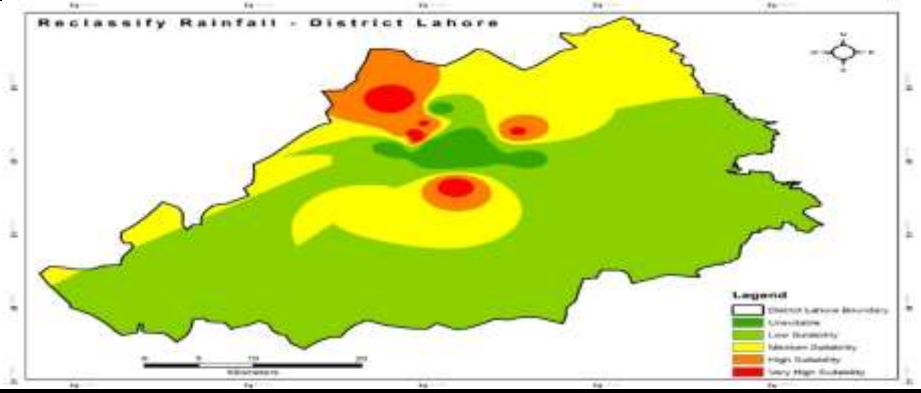


Table 6: Total Critical Catchment Area calculated with the help of GIS

Suitability	**Area sq.km**	**Coverage %**
Unsuitable	49.19	2.92
Low Suitability	1,101.28	65.44
Medium Suitability	413.03	24.54
High Suitability	95.43	5.67
Very High Suitability	24.21	1.44

The total area is considered for those catchment areas having Very High Suitability (i.e., 24.21 sq.km). The total volume after accounting for Evaporation, Surface runoff has been calculated as below:

Total Volume = Area x Rainfall Depth
$= 24.21 \times 0.268 \times 10^6$
Total Flow = 6,497,717 cu.m/day (Say 6.5×10^6 cu.m/day)

$$Q_{evaporation} + Q_{runoff} + Q_{RWH} = Q_{total} \quad (1)$$

$$Q_{RWH} = Q_{total} \times 0.6 \quad (2)$$

40% of Rainwater accounts for the total evaporation, Runoff, and sub-surface drainage.
Q_{RWH} = 3,892,630 cu.m/day

Transportation and Storage to Rainwater Storage Tanks

As, Q_{RWH} = 3,892,630 cu.m/day
For 100% of Very High Suitability, the locations 4 occupies 19% of this area, the location 8 occupies 35% of this area, the location 2 occupies 30% of this area and the location 9 occupies 16% of this area.
Q_{RWH2} = 1,167,790 cu.m/day
Q_{RWH4} = 739,600 cu.m/day
Q_{RWH8} = 1,362,420 cu.m/day
Q_{RWH9} = 622,820 cu.m/day
After analyzing the quantum of rainwater potential to undergo harvesting and defining the suitable locations, the storage of rainwater at each individual site is the main objective. This problem is proposed to be addressed as follows:

1. The accumulated Rainwater at each site is to be transported in Downpipes.
2. The Downpipes size calculated based on Equation of Continuity.
3. The downpipes will carry the water to the storage tank or in this case UGWT which will be designed based on the quantum of water at each individual site.
4. The location of UGWT will be based on several factors such as Distance Relevance, type of facility/ open land availability.
5. The Collected Water in the UGWT will then be filtered and made fit for use.

For the Water to be evacuated in 6 hours, the Value of Q RWH shall be divided by 6 x 3600 for Cu.m/s.
$Q = A.v$ (Eq. of Continuity)
(3)
Q_{RWH} = 180.214 cu.m/s
Velocity kept as 4.5 ft/s; the diameter of pipe has been selected as 2 ft.
Based on their respective locations, the nearest suitable locations for the UGWTs (Underground Water Tanks) have been marked with distances from accumulation site in the below maps:

Figure 18: Locations for the UGWTs (Underground Water Tanks) marked with distances from accumulation site (Fig on Next Page)


438 M
Location 4
145 M


Location 2


334 M
105 M
309 M
Location 9


Location 8
75.4 M

Table 7: Comprehensive Overview of UGWTs (Underground Water Tanks) across various Locations, including Length and Diameter Specifications of Pipes

Location No.	No. of UGWT	Size of UGWT (m)	Total Length of Pipes (m)	Dia. of Pipes (ft)
2	2	60 x 50 x 4	77	2
4	2	60 x 50 x 4	583	2
8	2	60 x 50 x 4	565	2
9	3	60 x 50 x 4	748	2

Conclusion

In this study, a critical issue was identified related to the escalating water demand and the concurrent decline in the water table within urban populations. A multifaceted problem statement under-utilization of a valuable natural resource.

The observed surge in urban water demand, coupled with the concerning decline in the water table, prompted the identification of a pressing issue. Additionally, the inefficient utilization of accumulated rainwater in various locations emerged as a key concern. The inefficiency in managing rainwater not only contributes to water scarcity but also underscores the need for a comprehensive solution. The problem at hand, therefore, encompasses both the quantitative imbalance in water supply and the qualitative mismanagement of available water resources. It was established, shedding light on the significant wastage of rainwater at various locations. In response, the proposed solution takes the form of rainwater harvesting techniques, aiming to address both the surge in water demand and the geographical regions in the future. The scalability and adaptability of this solution presents opportunities for implementation in diverse urban landscapes, fostering sustainable water resource management practices. Summarizing, the integration of rainwater harvesting techniques offers a holistic and sustainable solution to the identified challenges associated with increasing water demand and diminishing water tables in urban areas. By addressing the inefficiencies in rainwater utilization, this approach not only caters to immediate water supply needs but also lays the groundwork for scalable and impactful solutions that can be applied to broader geographic contexts in the future.

To mitigate the identified problems, a pragmatic solution is proposed through the implementation of rainwater harvesting techniques. This involves the introduction of a specialized drainage system designed explicitly for the purpose of collecting and harnessing rainwater. The collected rainwater is then strategically stored in underground water tanks strategically positioned at suitable locations, ensuring optimal storage capacity and accessibility from the collection points.

Implementation Strategy

The proposed drainage system is envisioned to efficiently channel rainwater to designated storage points, ensuring minimal wastage. Subsequently, the accumulated rainwater undergoes a thorough filtration process to render it fit for various purposes. The utilization of underground water tanks guarantees a sustainable and accessible reservoir of rainwater that can be effectively harnessed to meet the escalating water demand within the urban setting.

References

- Abhijit, M. (2018). *Overview of the Groundwater of South Asia, Part I: Groundwater Systems of South Asia*, Chapter 1: Overview of the Groundwater of South Asia, Abstract, p3
- Bhowmik, T., Sarkar, S., Bhattacharya, A., & Mukherjee, A. (2022). A review of arsenic mitigation strategies in community water supplies with insights from South Asia: options,

opportunities and constraints. *Environmental Science: Water Research & Technology*, *8*(11), 2491-2520.

- Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., & Breyer, C. (2021). Low- Cost Renewable Electricity As The Key Driver Of The Global Energy Transition Towards Sustainability. *Energy*, *227*, 120467.
- Bouramdane, A. A. (2023). Optimal Water Management Strategies: Paving The Way For Sustainability In Smart Cities. *Smart Cities*, *6*(5), 2849-2882
- Croce, S., & Vettorato, D. (2021). Urban surface uses for climate resilient and sustainable cities: A catalogue of solutions. *Sustainable Cities and Society*, *75*, 103313.
- de Oliveira, J. A. P., Bellezoni, R. A., Shih, W. Y., & Bayulken, B. (2022). Innovations in Urban Green and Blue Infrastructure: Tackling local and global challenges in cities. *Journal of Cleaner Production*, *362*, 132355.
- Groundwater Depletion-A Review of Aquifer Susceptibility to Degradation and its Consequences, *Technical Journal UET Taxila Pakistan,20*(1), I-2015, p32.
- Hawkins, R.H. Asymptotic determination of runoff curve numbers from data. *J. Irrig. Drain. Eng.* 1993, p119, 334–345.
- Huang, Z., Nya, E. L., Rahman, M. A., Mwamila, T. B., Cao, V., Gwenzi, W., & Noubactep, C. (2021). *Integrated Water Resource Management: Rethinking The Contribution Of Rainwater Harvesting. Sustainability, 13*(15), 8338.
- Kanwal, S., Gabriel, H. F., & Mahmood, K. (2019). *"Lahore's Groundwater Depletion-A Review of the Aquifer Susceptibility to Degradation and its Consequences.* Retrieved from, https://www.academia.edu/12000803/Lahores_Groundwater_Depletion_A_Review_of_the_Aquifer_Susceptibility_to_Degradation_and_its_ConsequencesR
- King, R. (2021). *Rainwater Harvesting To Meet The Portable Water Supply Of Residential Buildings In Tayi Village Minna*, Niger State (Doctoral Dissertation).
- Musz-Pomorska, A., Widomski, M. K., & Gołębiowska, J. (2020). Financial Sustainability Of Selected Rain Water Harvesting Systems For Single-Family House Under Conditions Of Eastern Poland. *Sustainability*, *12*(12), 4853.
- Rammal, M., & Berthier, E. (2020). Runoff Losses On Urban Surfaces During Frequent Rainfall Events: A Review Of Observations And Modeling Attempts. *Water*, *12*(10), 2777.
- State Bank of Pakistan's Annual Report (2017). *Water Sustainability in Pakistan – Key Issues and Challenges, 7*.3 Issues in Water Management, Groundwater resource depleting rapidly due to over-pumping, p98-99
- Supangat, A. B., Agus, C., Wahyuningrum, N., Indrawati, D. R., & Purwanto. (2021). *Soil And Water Conservation Planning Toward Sustainable Management Of Upstream Watershed In Indonesia. In Sustainability In Natural Resources Management And Land Planning (Pp. 77-91).* Cham: Springer International Publishing.
- Tiwari, K. N., & Joshi, M. P. (2013). Identification of potential sites for artificial recharge in Rabi watershed of Gujarat state, India using remote sensing and GIS. *Journal of the Geological Society of India*, *81*(6), p765-772.
- Vinagre, V., Fidélis, T., & Luís, A. (2023). How Can We Adapt Together? Bridging Water Management and City Planning Approaches to Climate Change. *Water*, *15*(4), 715.