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Assessing the Rainfall Water Harvesting Potential Using Geographical Information Systems (GIS)

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Abstract: Water scarcity is a major issue for developing countries due to the continuous increase in population every year, the major environmental challenges faced by developing countries such as Pakistan being the scarcity of water. One proposed solution to meet the requirements is to conserve water from rainfall. The process consists of the collection, storage, and use of rainwater. The rooftop rainwater harvesting systems (RWH) and rainfall harvesting system for artificially recharged water by recharge wells have received increased attention in the recent past as an efficient means of water conservation. In this study, both the systems have been analyzed for the University of Engineering and Technology Taxila (UET Taxila), Pakistan. The objective of this study is to propose a system to harvest water from the rooftops of all of the buildings on the campus and also to propose the most optimum locations of recharge wells for the artificial recharge of groundwater development. Numerous field visits were conducted after every rainfall over the past few months to identify lower elevation areas, which were further validated by the results obtained by Arc GIS. The total area of catchments available for rainwater harvesting in UET Taxila and the amount of water that could be harvested or used for replenishing groundwater reserves were also assessed in the current study. The results show that the harvestable rooftop water per month is 59% of the currently available source for watering trees and plants, and the harvestable water by recharge wells is 761,400 ft^3 per year.

Keywords: rainfall harvesting; Arc GIS; recharge wells; rooftop area

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1. Introduction

Water is the most essential component of life on Earth [1]. About 70% of the Earth's surface consists of water, but less than 1% of this water is easily accessible to fulfill human needs [2]. The demand for water has been increasing worldwide due to demographic changes, socioeconomic factors, changes in agricultural practices, and climatic variations [3,4]. On the other hand, increasing demands for water for irrigation purposes have led to the expansion of groundwater irrigation systems in many countries [5]. Pakistan is a developing country that has been facing water scarcity over the last two decades. Groundwater is the main source of human and agricultural needs, where the annual increase in industrial and domestic water demand is 10% [6–8].

The potential increase in demand from municipal, industrial, and agricultural areas for groundwater has raised questions regarding the sustainability of groundwater [9]. In Pakistan, more than 50% of the irrigation requirement is provided by groundwater [10]. The groundwater abstraction rates have increased to 60 km^3, exceeding the annual recharge rate of 55 km^3 [11]. Khan et al. (2008) showed that if there is no sustainable groundwater development in the region, a 10–20 m decline in groundwater levels is probable in the upper and lower regions of Pakistan [12]. In the recent past, Wada et al. (2010) identified many points of groundwater depletion in different regions of the world, with the highest depletion rates being in North-East Pakistan [13].

Rooftop rainwater harvesting systems (RWHs) are a traditional form of water supply in rural areas, but recently, they have also been applied to supplement urban water supply due to the growing demand for water in many urban regions [14–16]. The typical RWH system provides dual benefits of water supply increase and storm-water retention, which have been widely recognized and analyzed through modeling and empirical studies [17–22]. RWH systems are not only useful for drinking water, but are also an essential component of social, economic, and environmental spheres of user livelihood, communities, and ecosystem generation, and maintenance [23–27]. The performance of site-scale rainwater tank systems and storm-water retention behavior has been assessed by Xu et al. [28]

In the last few decades, RWH has regained importance as a holistic approach for sustainable growth [1,4,23]. Rainfall harvesting increases the availability of groundwater and raises the water levels in wells and tube wells, controls flood and droughts, and supplements the requirement of water for domestic use; reduces soil erosion, silting, and contamination of waterways from polluted surface runoff; and reduces the flow of stormwater and minimizes the chances of overloading of the drainage system [1]. Rainfall harvesting can be done by digging ponds and tanks, building embankments and check dams, constructing concrete underground reservoirs, and constructing recharge bores and recharge pits. GIS is a very effective tool, where layered information from different thematic maps can be integrated for use in identifying the potential zones [29–34].

A study in the United Kingdom showed that without considering the quality of the infiltrated water, it may cause negative effects on human health [35]. In a few countries such as South Africa, rainfall harvesting is illegal due to local constraints [36]. In many other countries, rainfall harvesting has been promoted to achieve the maximum benefit of rooftop and infiltrated water. However, there are few constraints in promoting rainfall the harvesting system, including the absence of rainfall harvesting laws regarding the water policies of many countries, especially underdeveloped countries [37], as it should be part of the national water management plan, as it has already been done in various countries such as Germany and Australia [38]. Underdeveloped countries have serious concerns about financial constraints when developing a rainfall harvesting system at a local level, as it requires a higher installation cost [39]. In addition to all of these factors, lack of awareness in the community is the prime hurdle to overcome when promoting this system [40].

Pakistan is an agrarian country where almost 70% of the population directly depends on the agricultural yield. As a result of Pakistan's arid and semi-arid climate, agriculture depends greatly on irrigation water supplies from canals and groundwater. However, there has been a gradual decline in surface water supplies, with a 15% decrease over the past two decades. The surface water supply is not only becoming deficient, but it has also become spatiotemporally unavailable in many parts of the Indus Basin. Regarding surface water supplies, the Indus Basin is considered to be the most depleted river basin in the world [41]. While the demand for irrigation is increasing due to agricultural intensification, the supply is unlikely to increase from surface water resources. It is estimated that the domestic and industrial water demand is growing at an annual rate of 10% in Pakistan [42]. Hence, there has been a substantial increase in the utilization of groundwater resources to sustain agricultural productivity as inter-sectoral competition is increasing. Pakistan meets more than 50% of its overall irrigation requirements through groundwater abstractions, which has raised concerns about the sustainability of groundwater resources in the region [43]. Previously, studies have shown that because of climate change conditions, there will be a 10–20 m decline in groundwater levels in the upper and the lower region of Rachna Doab in North-East Pakistan [44]. Research has identified various hot spots of groundwater depletion in different regions of the world, with the highest depletion rates being found in North-East Pakistan and North-West India [45]. Based on the aforementioned evidence, there is an immense requirement to promote and develop rainfall harvesting systems at local and national levels for sustainable surface and subsurface water resources in countries such as Pakistan. The objective of this study is to propose a system to harvest water from the rooftops of all of the buildings at the University of Engineering and Technology Taxila, Punjab, Pakistan. Field surveys were conducted to outline the campus and propose the optimal locations for recharge wells for artificial groundwater recharge development.

2. Materials and Methods

2.1. Study Area

The study area is the UET Taxila, located at 33.7670° N, 72.8235° E, as shown in Figure 1. The entire area is about 160 acres (6,973,330 ft^2), which includes green belts, residential buildings, departments, playgrounds, cafeteria, hostels, and mosques, etc. The rooftop area of 19 different buildings was used to estimate the total harvestable water from the top of the roofs. This harvestable water could be stored in storage tanks for further use for horticulture purposes. The design of the storage tanks depends on the maximum rainfall per day per year and the area of a specific roof. The maximum rainfall per day per year is shown in Figure 2. The schematic diagram of the system is shown in Figure 3.

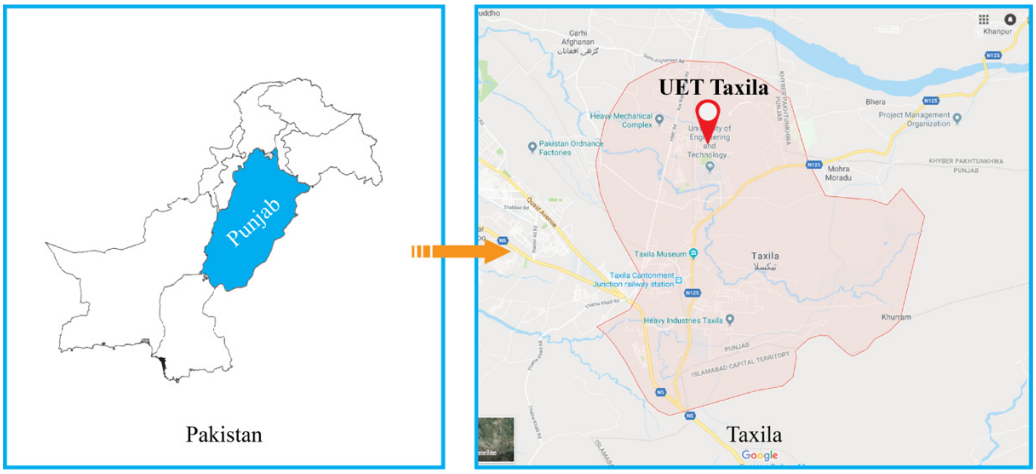


Figure 1. Map of the study area [source: GoogleMaps©].

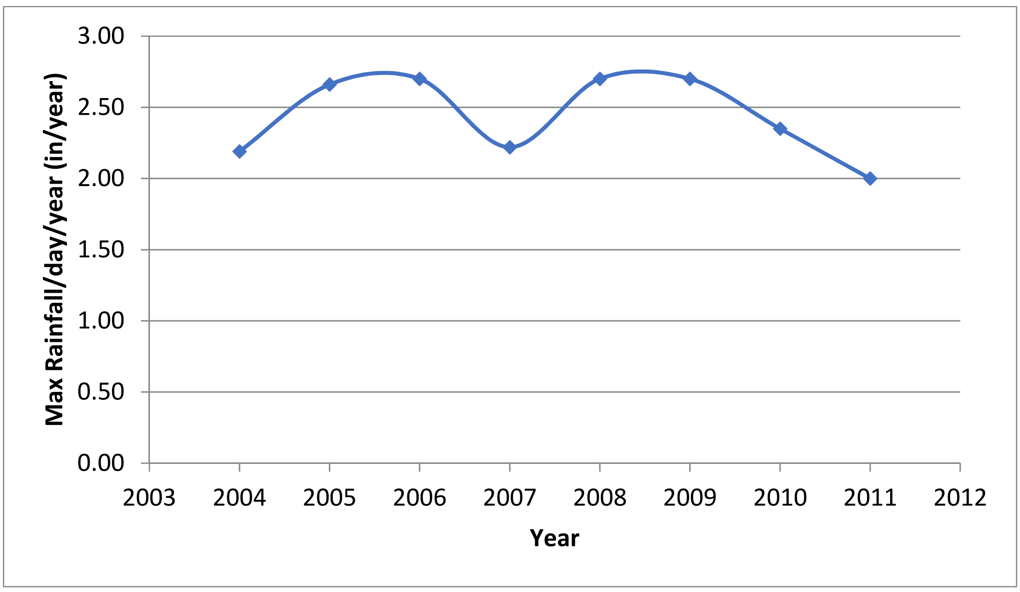


Figure 2. Maximum rainfall per day per year (in/year).

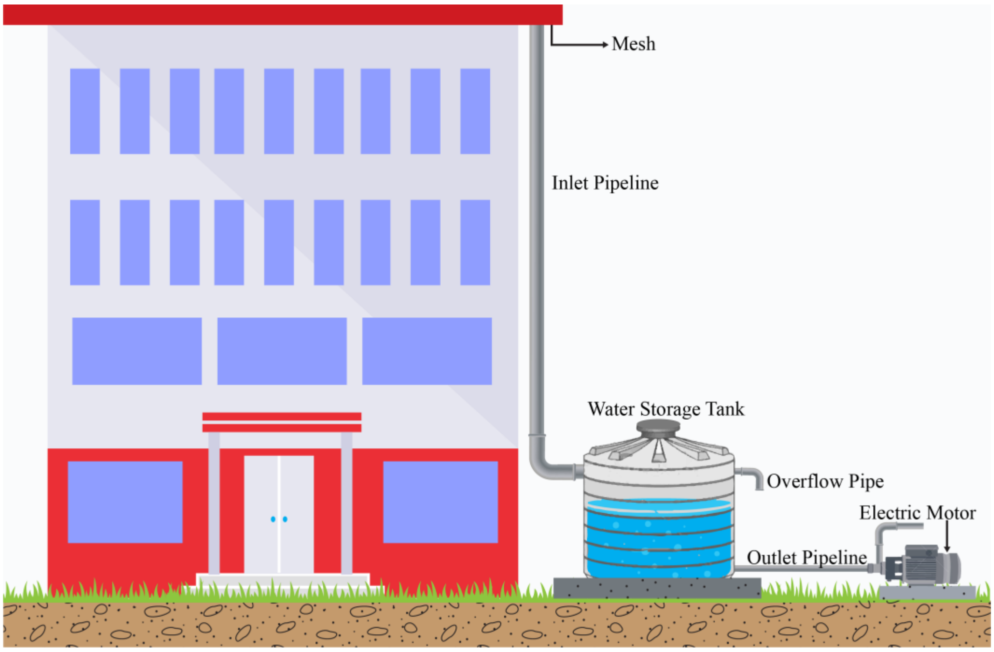


Figure 3. Schematic diagram of a rooftop harvesting system.

The groundwater is depleting every year due to land-use change and climatic variations. Hence there is a need to design a rainfall harvesting system in order to raise groundwater by installing an artificial groundwater recharge system. There are twenty depression points in the study area where water accumulates during rainfall. These points are observed by field visits after every rainfall event during the past few months as shown in Figure 4.

Figure 4. Water accumulation points observed during and after the rainfall events.

The groundwater recharge and rising of water table phenomena are shown in Figure 5a. The surface runoff is received in a filter to filtrate water before going to recharge well. The components of the filter are shown in Figure 5b. Recharge wells are proposed for groundwater recharge at these depression points for recharge water to the underground layers which tend to become the part of groundwater table and the level of the groundwater table will rise within few years. The design of recharge wells for water harvesting is based on the amount of water accumulating in the recharge well. The recharge borehole should be at a depth close to the water table. The water will percolate in deeper soil layers in a downward direction which tends to raise the existing groundwater table. The percolation rate depends upon the coefficient of permeability, different coefficients for soil type are shown in Table 1.

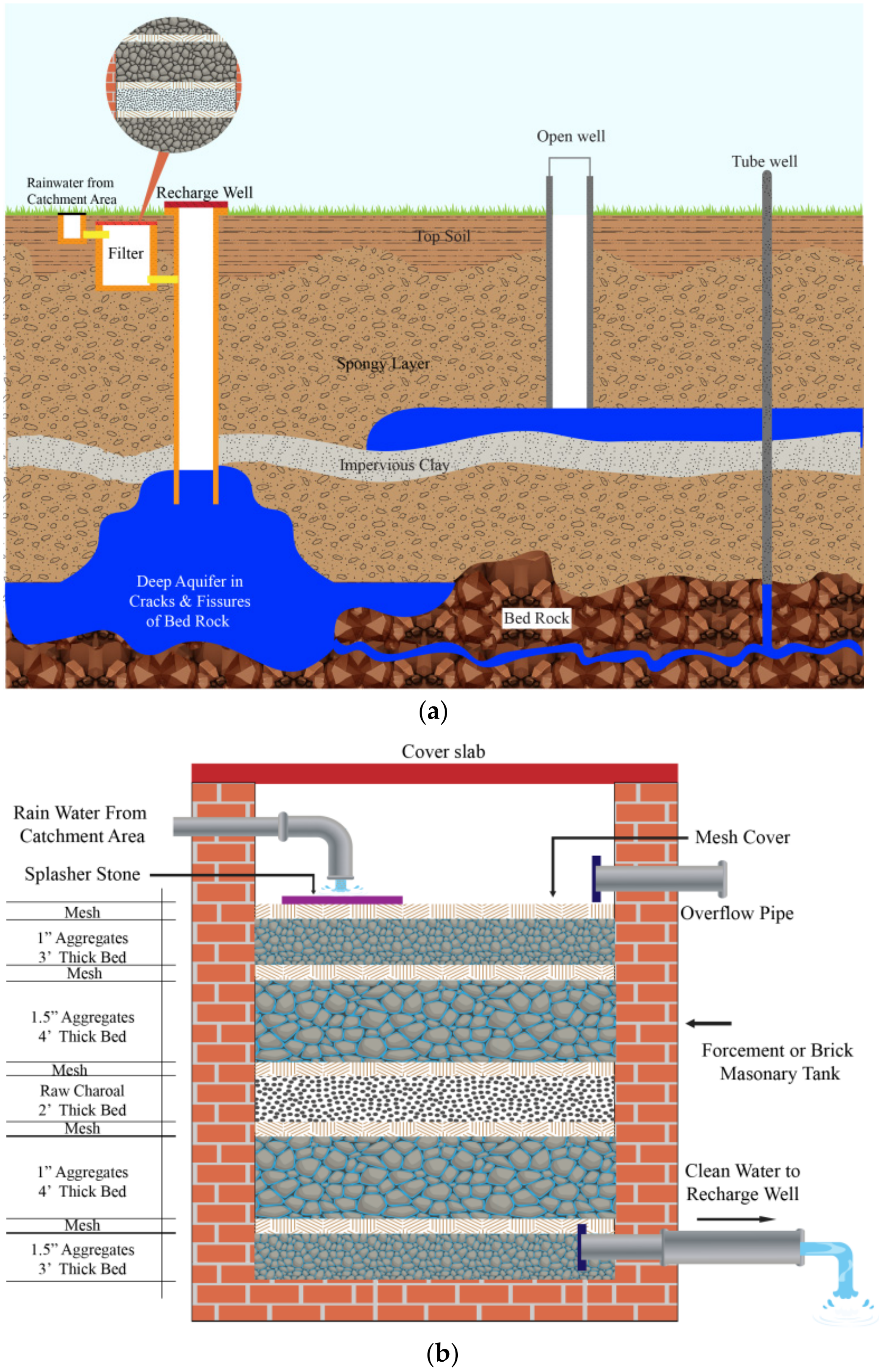


Figure 5. (**a**) Groundwater level rises by recharge well, and (**b**) Schematic diagram of filter.

Table 1. Typical ranges of permeability coefficients for different soil types [45].

Sr. No	Soil Type	Coefficient of Permeability (mm/s)
1	Clean gravel	10^{+1}–10^{+2}
2	Coarse and medium sands	10^{-2}–10^{+1}
3	Fine sand, loose silt	10^{-4}–10^{-2}
4	Dense silt, clayey silts	10^{-5}–10^{-4}
5	Silty clay	10^{-8}–10^{-5}

The residential area of the University is excluded for rooftop harvesting but included for groundwater recharge. The annual rainfall data of the study area is obtained from the Pakistan Metrological Department which consists of monthly data from 2004–2011 as shown in Figure 6.

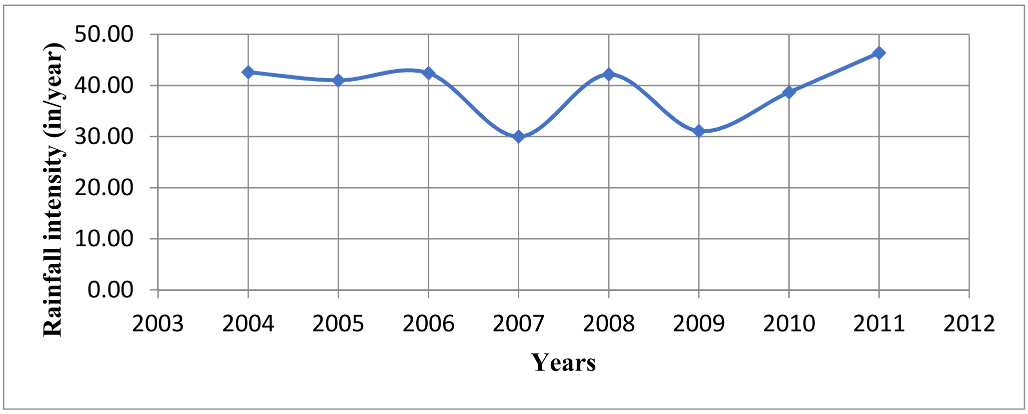


Figure 6. Annual rainfall (2004–2011) in/year.

2.2. Methodology

The proposed harvesting scheme is divided into two parts, i.e., water harvesting from the rooftop, which can be used for horticulture requirements, and runoff water accumulation in the recharge wells in different locations of the study area.

2.2.1. Water Harvesting from Rooftop

The harvestable water from rooftops can be collected in storage tanks. The amount of discharge that can be harvested is calculated by the following rational formula (Equation (1)):

$$Q = C \cdot I \cdot A \tag{1}$$

where "Q" is the runoff (cusecs), "I" is the average rainfall intensity (inch per unit time), "A" is the drainage area (ft^2) calculated by Arc GIS, and "C" is the runoff coefficient (no units) depending on the catchment characteristics. This factor accounts for the fact that some of the rainfall cannot be collected due to the loss of water during evaporation and retention on the surface itself [37,38]. The value of "C" is taken as 0.75.

2.2.2. Water Harvesting from Rooftop

Elevation raster is pixel-based elevation data that can be classified to assess the flow path of rainwater. This raster is generated by using contour lines that represent the geometry of physical features on the topographical maps. For the study area of UET Taxila, a handheld Garmin Etrex 10 in combination with a GeoMax total station was utilized. Initial coordinates of the start-up station were assessed using a handheld GPS. After setting it up with certain parameters in its configuration, i.e., indexing vertical and horizontal reference directions, heights of the instrument (HI), and target prism (HR), not only the horizontal but also the vertical angles, sloping distances, and three-dimensional coordinates were also computed. Working with this machine, prism points were recorded using the complete survey information and were stored in its electronic notebook. Later on, the surveyed data were retrieved from a computer for the purpose of raster elevation rendering. To achieve higher accuracy of the raster data model for elevations, a total of 1892 prism points were taken in the study area. The 3D elevation map of the university is shown in Figure 7.

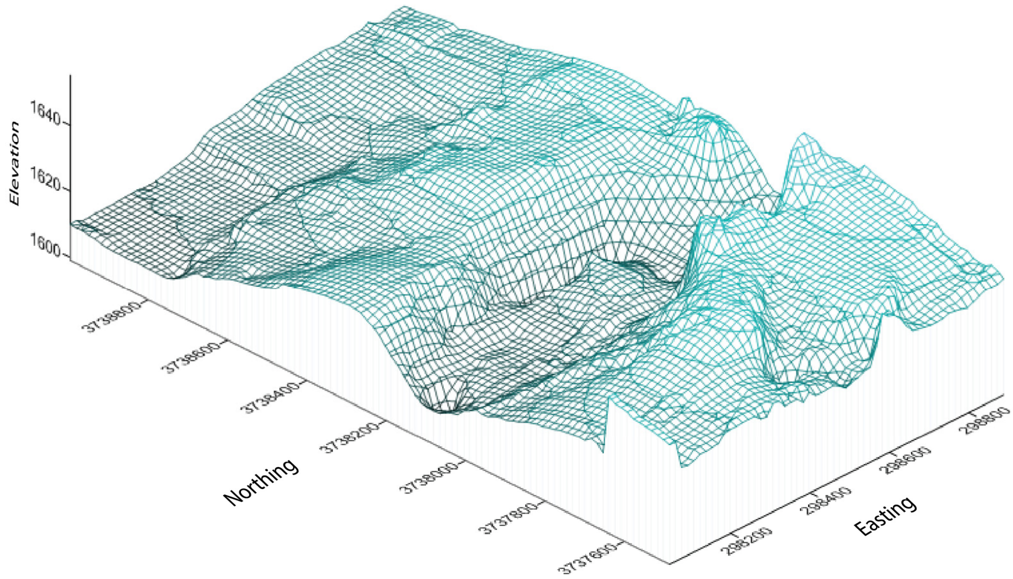


Figure 7. The 3D elevation map of UET Taxila.

Contours were generated with the help of ArcGIS using the IDW analyst tool at an interval of three feet. The flow directions were found, and layered symbology of raster pixels was assigned. A total of eight classes of elevation raster were made to find out the flow path of rainfall. The contours and flow direction map is shown in Figure 8. This direction map highlighting the direction of flow indicates water movement from cell to cell. In most of northern zone, water flow direction was found in northwest whereas on southern region waterflow was predominantly in southeastern direction. This flow may be associated with the fact that spatially connected cells contribute to the flow direction based on slope of each cell resulting from the field survey. As a result, most of the pixels residing on top, will yield the flow direction towards low lying areas. Likewise, if the direction of steepest pixel is towards the left, the water flow will also receive the direction code (indicated with corresponding arrow) towards left. Also, resulting pixels with high flow directions kept on accumulating the water resulted in concentrated flow points as shown in Figure 8. On the other hand, all the pixels where flow direction do not indicate any accumulation were indication of the ridges where the potential recharge was zero.

Geo-referencing and map digitization was carried out to overlay the buildings' orientation roof areas. The elevation raster was superimposed on the digitized map and a 3D TIN surface was generated. In addition to building polygons and road polylines, boreholes were also pin-pointed based on their geographical location. 3D elevation raster was also counter-checked with the help of photographs taken during the rainfall at UET Taxila. Finally, 19 major locations of water accumulation points were reflected for rainwater accumulation. Rooftop areas and water accumulation points are highlighted in Figures 9 and 10 respectively. Analysis showed that, if natural resources are to preserve, accumulation points should be considered. Knowing the resulting points prior to designing the potential recharge wells majority of the flow pathways would be reserved and the corresponding volume of water loss would be prevented.

As, shown in Figure 9, this study utilizing the data derived from field survey was not limited to the topographic analysis, but also roof tops' areas for all the buildings were measured. After geographically locating the regions, potential roof tops were mapped for better accuracy. Not only, this approach was effective to visualize the areas graphically but also it helped discovering the area information of each unit of the settlement. Importantly, it also helped visualizing the neighboring structures near to those of the predicted points of water accumulation. Predominantly building structures covered a total of 394,935.3 ft^2. Excluding other man-made features such as cafeterias and parking zones, these building units were almost covering a total of 6% of the gross area of the university. Moreover, it was observed that building patterns were mainly land-use dependent, following similar hierarchy for academic buildings whereas residential units were geospatially based on social interaction. Symbolically associating the settlements based on topographic pattern also help identifying the structures contributing to or altering the flow of water.

The soil types are investigated by boreholes data at different locations of the study area with the collaboration of Soil Mechanics Lab, UET Taxila. These location points are highlighted in Figure 10. The soil classification of each borehole is shown in Table 2.

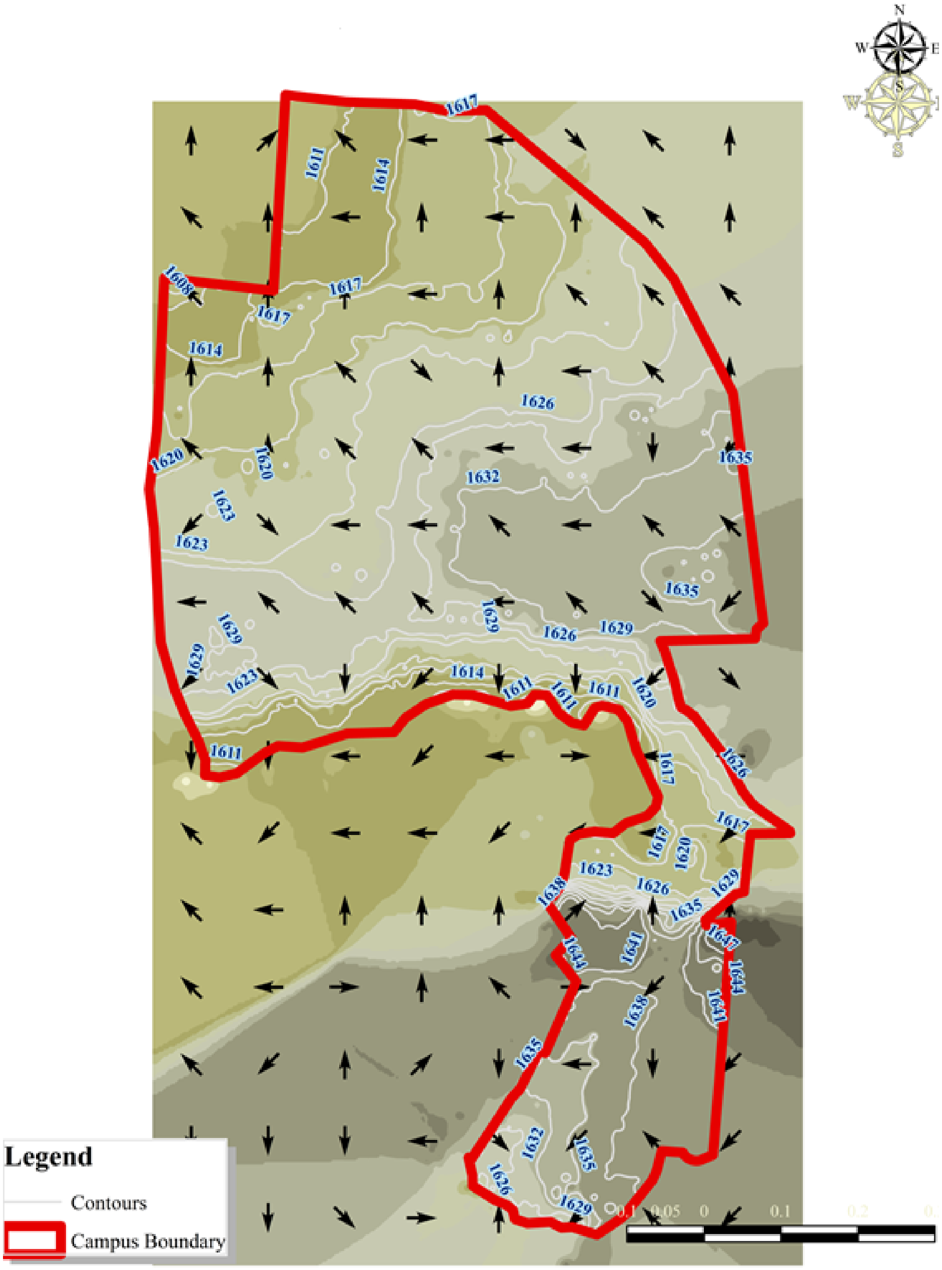
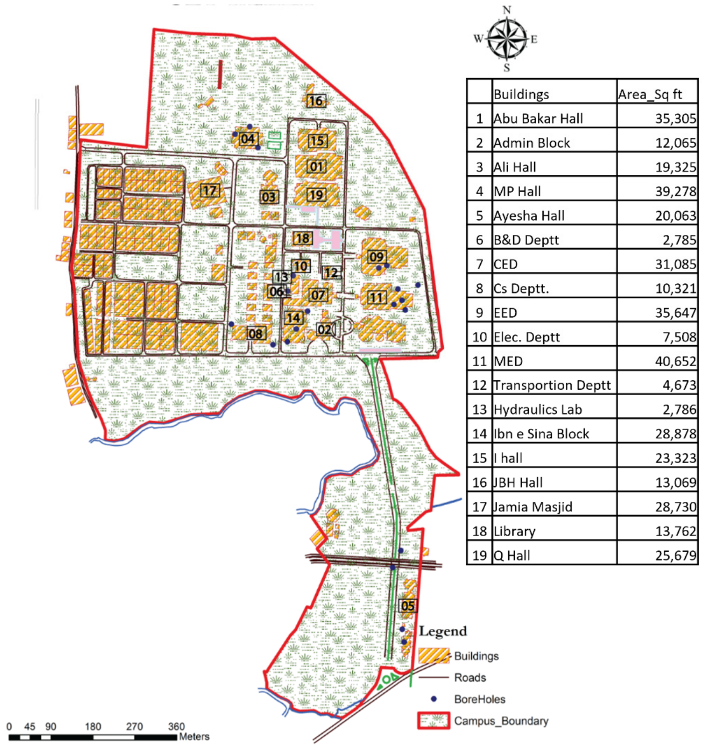


Figure 8. Contours and surface runoff flow direction map.



	Buildings	Area_Sq ft
1	Abu Bakar Hall	35,305
2	Admin Block	12,065
3	Ali Hall	19,325
4	MP Hall	39,278
5	Ayesha Hall	20,063
6	B&D Deptt	2,785
7	CED	31,085
8	Cs Deptt.	10,321
9	EED	35,647
10	Elec. Deptt	7,508
11	MED	40,652
12	Transportion Deptt	4,673
13	Hydraulics Lab	2,786
14	Ibn e Sina Block	28,878
15	I hall	23,323
16	JBH Hall	13,069
17	Jamia Masjid	28,730
18	Library	13,762
19	Q Hall	25,679

Figure 9. Demonstration of the roof tops considered and the respective area estimation for each building.

Figure 10. Water accumulation points where recharge wells are proposed.

Table 2. Soil classification of boreholes.

Depth Upto	Bore Hole No.	Location near by	Type of Soil
30′	1	Telecom Department	Sandy Silt
30′	2	Telecom Department	Sandy Silt
30′	3	Combined Academic Block	Clay
30′	4	Combined Academic Block	Clay
30′	5	Combined Academic Block	Clay
15′	6	Girls Hostel	Silt
15′	7	Girls Hostel	Silt
30′	8	Overhead Bridge	Silt
30′	9	Overhead Bridge	Silt
30′	10	Industrial Department	Silt
30′	11	Industrial Department	Silt
30′	12	Industrial Department	Silt
30′	13	Industrial Department	Silt
30′	14	Industrial Department	Silt
20′	15	Electrical Department.	Clay
20′	16	Electrical Department	Clay
60′	17	MP Hall	Sillty Clay
30′	18	MP Hall	Silty Clay
50′	19	MP Hall	Silty Clay
20′	20	Hydraulics Lab	Silt
20′	21	Hydraulics Lab	Silt

3. Results and Discussion

Previously, rainfall harvesting systems were only adopted for flushing. However, the advancement in the research field has resulted in harvesting rainwater for irrigation and groundwater recharge [46]. Therefore, the current research results align with the previous research showing similar results for sustainability of rainfall water by utilizing rooftop water, and that this water that can be infiltrated as a subsurface flow [47,48].

The maintenance of rainfall harvesting tanks and wells should be properly managed; otherwise, the system's performance may be reduced [49]. This system collects rainwater and stores its runoff, which comprises the collection, storage, treatment, and distribution of rainwater from roofs and impermeable surfaces [50]. Hence, rainwater utilization depends highly on the local water supply and demand conditions [51]. In some countries, rainwater is allowed for non-drinking purposes only, e.g., Australia, Germany, Japan, and the United States [52]. However, in France, rainfall-harvested water is not allowed for general purposes [53].

Previously, many researchers have calculated the percentage of water that can be saved within their study areas to check the efficiency of the proposed harvesting system. For example, in Jordan, 12 different cities have been studied for harvesting drinking water rainfall, and the system's resulting efficiency is 0 to 20% [54]. Similarly, this resulted in a study of 22 cities in Egypt that showed that the amount of water that could be saved from the RHW system was 0 to 12% [55]. Finally, a study was conducted in Germany to investigate the effectiveness of the RWH system for household usage. The results indicated that 30 to 60% of water could be saved by applying the system [56].

Similarly, the RWH system for household use was also implemented in Spain, which resulted in a 16% potential saving of water within the study area [57]. In Brazil, the RWH system was studied at a large scale, and involved 195 cities, with the results finding that the potential that could be saved in big cities was 12% to 79% [58], and it was 22 to 64% in low-income houses [59]. In Brazil, a study was also conducted for multistorey buildings, and it was calculated that potable water efficiency saved 39% to 43% of water. However, the use of rainwater could generate 15 to 18% more water [60]. The potential of RWH systems for storing a percentage of floodwater volumes can also be quantified using flood modeling software, such as FLO-2D, and can be used for planning effective flood risk mitigation options, as demonstrated for an urban area in Southern Italy [61].

In the current study, the RWH system was studied at the University of Engineering and Technology (UET), Taxila, Punjab, Pakistan, to calculate the amount of water (in percentage) that could be harvested. The UI GreenMetric World University Ranking shows that the UET Taxila stands at 735 [62]. Therefore, a huge amount of water is required for horticultural purposes within the campus. Currently, the horticulture requirement of the university is fulfilled by extracting water from a tubewell specified only for irrigating plants and trees inside the campus. The survey from the horticultural department of the campus revealed that the total requirement for watering the green area of the campus is 125,125 ft^3 per month, which exceeds the availability. The total rooftop area of 19 different buildings on the campus is 394,935.3 ft^2, as calculated by Arc GIS. The water from the outlets of the rooftops could be collected in storage tanks. The total harvestable water from the rooftops was calculated using the rational formula (Equation (1)), where the value of "C" is taken at 0.75 and the average rainfall intensity (ft/year) is used. The total harvestable water from the rooftop is 74,050.34 ft^3 per month, which is 59% of the total water used per month for irrigating plants and trees. Hence, we can provide 59% additional water for irrigation purposes by harvesting.

The discharge of water from catchments to the recharge wells' location is calculated by the rational formula (Equation (1)), where the value of "C" is taken as 0.75 and the average rainfall intensity (ft/year) is used. All of the proposed recharge wells will contribute to harvesting water for groundwater recharge. The amount of water harvestable from each recharge well is shown in Figure 11. The total harvestable discharge for groundwater recharge is 761,400 ft^3/year. Hence, applying the RWH on the campus will save the groundwater, and the deficiency in water availability can also be fulfilled.

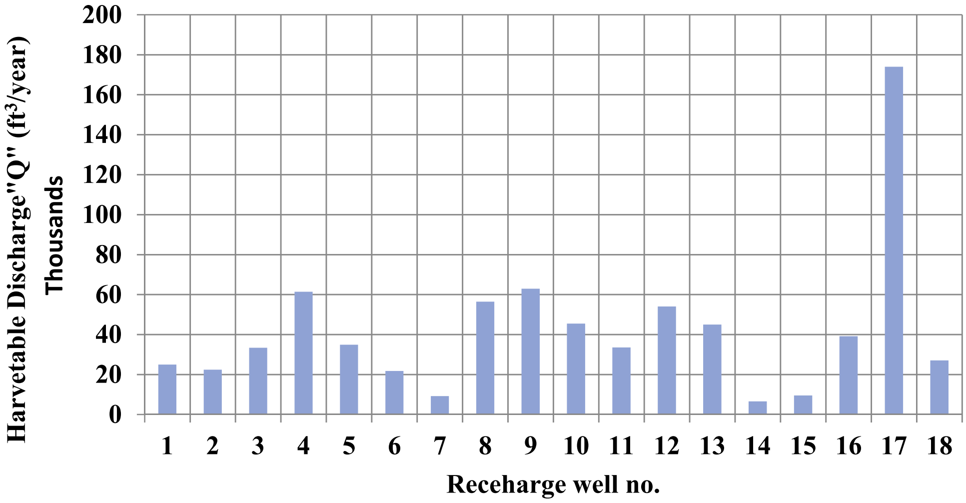


Figure 11. Harvestable water from each recharge well "Q" (ft^3/year).

4. Conclusions

At the end of this study, the following is concluded:

a. A significant amount of highly valued water is usually lost from rooftops and direct runoff after each rainfall event.

b. The water required to irrigate trees and plants on the campus is 125,125 ft^3 per month, which exceeds the irrigation requirements. Water can be conserved by proper planning to harvest rainfall from rooftop areas and this water can be used for agriculture, domestic, or drinking purposes. In this study, it was calculated that we could save 74,050.34 ft^3 of water per month by using a rooftop harvesting system on the campus, which can be used as an additional source of water for irrigation purposes. In this way, 59% of the current water used for this purpose could be harvested.

c. Water can also be conserved by installing recharge wells at proper locations in the area, and after recharging water to the deeper layers, the groundwater table will rise. In this study, it is calculated that by installing recharge wells at suitable locations, we can use 761,400 ft^3/year of water for groundwater development.

This research can be extended through a detailed study of the groundwater response to recharge water if the proper amount of soil classification data up to the water table are available.

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