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Assessing the Rooftop Rainwater Harvesting Potential in Urban Residential Areas of Pakistan: A Case Study of Model Town, Lahore, Pakistan

Romana Siddiqui[1, 2], Saima Siddiqui[1]*

[1]Department of Geography, University of the Punjab, Lahore, Pakistan
[2]Queen Marry College, Lahore, Pakistan

*****Email: saimagct@gmail.com

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Abstract: Rainwater harvesting (RWH) is widely recognized as an alternative water resource for domestic water supply in different parts of the world, mainly due to water scarcity. Availability of potable water is the major issue in Pakistan due to increase in population density and decrease in permeable surfaces. In this scenario, rainwater can be used as a reliable substitute of fresh water resource. In this study RWH potential in Model Town Lahore is computed for rooftops of buildings by using ArcMap 10.4.1. The RWH model is also proposed at household level with its utilities. Currently, Lahore is going through the phase of rapid population growth; unchecked immigration and reckless urban sprawl followed by undue extraction of groundwater. The water table of Lahore is depleting with an average rate of 55cm (0.55m) per annum, while the recharging water resources of Lahore aquifer are diminishing. With an average annual rainfall i.e. 628.6 millimeters (244.8 inches), Lahore is suitable for rainwater harvesting (RWH). The total estimated rainwater harvesting (RWH) potential of rooftops in Model Town Lahore is 535,756 cubic meters (535,756,000 liters) per year. The methods used in this study prove to be an effective tool for preliminarily estimation of the regional rainwater harvesting potential. RWH is an economic, environmental friendly and easy to install system. It is concluded that RWH is the best functional technique to avert the present and future water crisis in Pakistan.

Keywords: Water scarcity, groundwater, rainwater harvesting (RWH), sustainable water management, Lahore.

Introduction

The world is facing serious water scarcity issue in different regions especially in developing countries like Pakistan. The growing urbanization with high demographic profile is reducing the availability of fresh water in urban areas or cities over the globe. Among all the natural resources water is the most vital natural resource to sustain life of urban units or cities. Therefore, management and supply of freshwater for rapidly growing auspicious urban units become the need of present time (UN-Habitat, 2005). According to Zhe et al. (2010) demand for water supply doubles after every 21 years in the world. There are two options to cope up with the ever growing demand of water especially in the urban world, (1) search for new fresh water resources by traditional methods (2) conserve water by good management and by leaving conservative methods. Unfortunately, more importance is given to the first option and still has, avoiding good governess and management to conserve water for future generations of urban world.

Rainwater harvesting (RWH) is the gathering and storage of rainwater for human consumption from catchment surfaces (rooftops, roads and open spaces) on which rain has directly fallen, by using ordinary and simple scientific methods. It could be a potential alternative source of potable and non-potable water in communities that cannot be served by more centralized water supply system or facing water shortage issue (Lancaster and Marshall, 2008). RWH has become the necessary option for fastest growing population and ever growing demand for water in present era (UN-Habitat, 2005). Rainwater is the best natural resource of freshwater because its pH value is nearly neutral (Texas Manual for Rainwater Harvesting, 2005). Rainwater can be easily harvested at commercial, residential and community levels (Vieira et al., 2014; Belmeziti et al., 2013).

RWH is not a modern technique human beings have been storing rainwater for drinking and non-drinking purposes from the past 4000 years (Boers, 1994; Liaw and Chiang, 2014). Ancient civilizations have developed various runoff control methods and constructed dams and reservoir in urbanized areas (Mays and Antoniou, 2013). RWH technique has become a significant alternative source of water in urban and suburban regions of the developed world (Campisano et al., 2013; Hajani and Rahman, 2014). RWH can be a good replacement of heavily treated drinking water and other uses of water in daily life (Greenman et al., 1967; Bhatti and Nasu, 2010). The rainwater can be harvested for the betterment of human beings as one of best mitigation to flooded roads, to recharge aquifer, to raise water table and to fulfill the water needs of expanding population of Lahore. Rainwater harvesting (RWH) is common and equally popular in western and eastern world. England, Germany and many American countries and states have been practicing RWH techniques. Many people of African countries depend on harvested rainwater for accomplishing their water needs like Botswana. In South Africa and Brazil many projects of rainwater harvesting are being practiced with the assistance of

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governmental and non-governmental institutions. It is also gaining popularity in the continent of Australia (Fewkes, 1999; Marks et al., 2006; Bhatti and Nasu, 2010). Various studies have been conducted on the application and effectiveness of rainwater harvesting systems in both urban and rural areas of developing countries (Ghisi et al., 2007, 2009; Islam et al., 2010; Mohammad et al., 2013). Rooftop rainwater harvesting is being practiced, to meet potable and non-potable water demand in many areas of China (Li and Gong, 2002; Yuan et al., 2003), India (Goel and Kumar, 2005; Pandey et al., 2006), Namibia (Sturm et al., 2009), Spain (Domènech and Saurí, 2011), Ireland (Li et al., 2010), Singapore (Appan, 1997,1999), South Africa (Kahinda et al., 2007), Taiwan (Chiu et al., 2009; Liaw and Chiang, 2014) and USA (Jones and Hunt, 2010). Rainwater was also harvested by the farmers of Afghanistan, Iran and Pakistan in the third century BC (Fooladman and Sepaskhah; 2004, Marcelo and Enedir, 2011; Rahman et al., 2012).

The present study is conducted to estimate the rainwater harvesting potential for storage and water consumption at household level. This approach is beneficial for reducing the over use of groundwater and conserve it for future generations specifically in Lahore, which is going to be a water scarce city in near future. Geographical Information System (GIS) and tools of ArcMap 10.4.1 have made its presentation possible. Hence, this research work involves careful understanding of the need and use of rainwater harvesting, in an ever growing urban unit and metropolitan city Lahore. The proposed RWH system will motivate readers for installing rainwater harvesting (RWH) system as a source of alternate water supply (potable and non-potable) and to make their urban unit sustainable and environmental friendly. Furthermore, the present study will assist government, water authorities and urban planners to integrate domestic rainwater harvesting systems into water resources planning and management. This paper proposes the steps that can be taken at public level to cope with the issue of water shortage at community and residential level.

Description of the Study Area

Lahore is the capital city of Punjab province and second largest city in Pakistan. It is located between 31^0 $15^/$ - $31^0 45^/$ N latitude and $74\ ^0$ $01^/$-74^0 $39^/$ E longitude. It covers total area of 1772 km^2 while Lahore city covers an area of 404 km^2 which is still growing. It is bounded on the eastern side by India (international border), on the northern and western side by Sheikhupura district and on the southern side by Kasur District. Lahore is located on the left bank of Ravi river. Model Town locality in Lahore is selected as a study area purposefully because it is a fully developed urban residential area. Model Town is a residential suburb of Lahore and it is circumscribed on the western side by Fasial Town, on northern side by Garden Town, on eastern side by Ferozepur road and on southern side by Township. Model Town was established in 1921 as a co-cooperative housing society (Fig. 4). Model Town was a dream society of Dewan Kem Chand and designed by Sir Ganga Ram Agrawal (civil engineer and architect). Model town covers an area of 5.9 km^2 (1463 acres). This area is subdivided into ten blocks (A, B, C, D, E, F, G, H, J and K). While L, M, N, P, Q, R, and S blocks are in the peripheries of Model Town and called as Model Town extension. Although, Q and R blocks of Model Town are not under the administration of Model Town housing society directly, but are included in the case study area for having comparison of small and large catchment area for RWH potential. According to Model Town cooperative housing society office Lahore (2016), the total population of Model Town is about 100,000 persons. Model Town is considered as a posh area of Lahore and it is unique in its design and services. Each block has own mosque, market, playground and a triangular park. This society is rich in greenery with spacious open spaces (parks and play grounds) along with all the requirements of a modern society i.e. community centers, library, clubs, educational institutions and commercial zones.

Need for Rainwater Harvesting in Lahore

Asian Development Bank has placed Pakistan in red zone by declaring it water-stressed region. By international standards Pakistan was a water scarce country with 1600 cubic meter per capita availability of water in 1991. Now, Pakistan becomes water stressed country at about 1000 cubic meter per capita availability of water (Pakistan Statistical Year Book, 2007). This implies that we need to find a solution to the problem at priority especially in growing cities of Pakistan like Lahore. The present study got motivation from the fact that the water table in Lahore has gone down to 61 feet on an average since 1961 (WASA, 2016, Kanwal et al., 2015). Rapid population growth and urbanization are followed by massive burden on the groundwater resources. The rate of groundwater withdrawal has reached to an unsafe level. Undue abstraction of groundwater and decreasing resources of recharging groundwater are the main cause of water table decline in Lahore city (WASA, 2016). Average annual decline in ground water level in Lahore is 2.03 feet per year (Basharat and Rizvi, 2011), however according to WASA currently water level is declining at the rate of about 3 feet per year (Kanwal et al., 2015; Table 1). These threatening groundwater levels are also affecting the quality and taste of water. Rate of ground water abstraction is about 1.45 million cubic meters per day (Gabriel and Khan, 2006). There is the difference of 0.67 million cubic meters per day (MCM/day) or 427 MCM/year between recharge and discharge. This difference is causing 55cm (0.55m) drop per year in water table level of Lahore aquifer (Qureshi and Sayed, 2014). The magnitude of water table depletion varied in different localities of Lahore; however, in urban parts of the city, the water table drop may be higher due to excessive pumping and insignificant recharge.

Table 1 Average annual rate of groundwater decline in Lahore.

Period	Rate of Decline	
	ft/year	*m/year*
1960-1967	0.984	0.30
1967-1973	1.804	0.55
1973-1980	1.969	0.60
1980-2000	2.133	0.65
2007-2011	2.6	0.792
2011-2013	3	0.9144

Source: Kanwal et al., 2015

It is predicted that the population of Lahore will be increased to 22 million by year 2025 and 84% of this population will be residing in urban areas. This will lead to excessive pumping to provide fresh water to this huge number of population. At present, a cone of depression has already been developed at the central part of Lahore and the water table has reached below the level of 40m. Undue withdrawal of water from this level of water table depth will not be technically safe and will put prompt negative impact on hydraulic gradient; due to which the ground water can become saline from the interference of adjacent saline ground water of Raiwind and Pattoki areas. It is also estimated that if extraction of water continues at present rate, the water table depth in many parts of Lahore will drop below 70m by the year 2025 and by the end of year 2040 the water table depth will become even worse (Qureshi and Sayed, 2014).

Over stressed Lahore aquifers are not capable of satisfying the future needs of ever increasing demand of water. Recharge from canal cannot be increased and recharge from Ravi River is not reliable for recharging sustainable aquifer of Lahore (Qureshi and Sayed, 2014). Therefore, exploring the other recharging resources of Lahore aquifer is the need of these days. On the other hand, progressive urbanization has increased land impermeability due to more built up area. Sustainable management of monsoon rainfall is also needed in Lahore city because 80 percent rainfalls occur only within 3 months i.e. June to August in a year with high intensity of rainwater. The amount of peak storm water flow is several times more than the capacity of sewerage system of Lahore because the sewers are normally not designed for the peak storm water flow. During monsoon spell, heavy rain leaves Lahore flooded (Fig. 1). People have to face hardships in flooded streets and roads**.** Traffic jam is the foremost phenomenon associated with flooded roads. Moreover, accumulated water sites have become the home of dengue and other water borne diseases.

Fig. 1 Flooded Mozang Road in Lahore due to monsoon rainfall (source: The News, 2016).

Rainwater harvesting experts recommend that at least 70 mm rainfall is sufficient for positive potential rainwater harvesting. Lahore is suitable for RWH with its average annual rainfall (i.e. 628.8 millimeters). Average annual rainfall data from 1987 to 2016 and mean monthly rainfall of 2016 clearly indicate that Lahore has a significant potential for rainwater harvesting (Figs. 2 and 3). Lahore has serious threats to safe, stable supply of water in its urban areas. Hence, there is a thoughtful requirement to generate substitutes for suitable water sources.

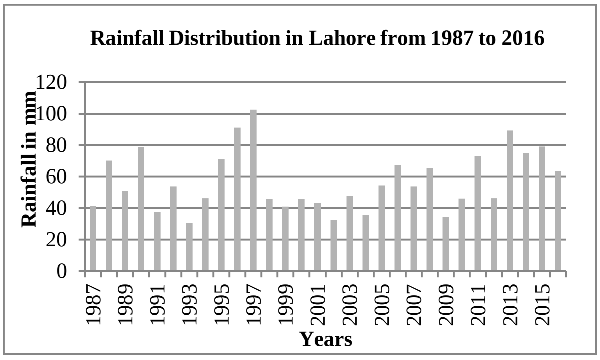

Fig. 2 Average Annual Rainfall Distribution in Lahore from 1987 to 2016 (Source: PMD, 2016).

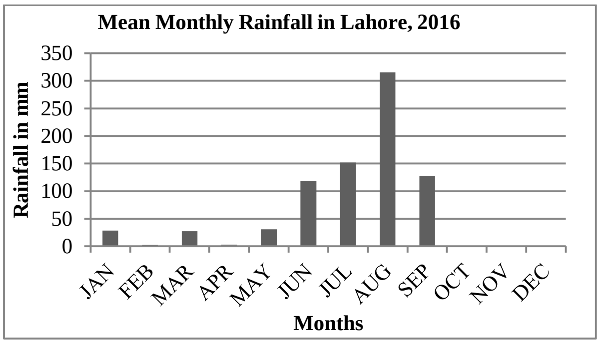

Fig. 3 Mean monthly rainfall in Lahore, 2016 (Source: PMD, 2016).

Materials and Methods

Implementation of rainwater harvesting system is dependent upon harvestable quantity of rainwater. RWH potential is calculated from the Rooftop Catchment Method described by Gould and Nissan (1999). This is the most common, easy and economical

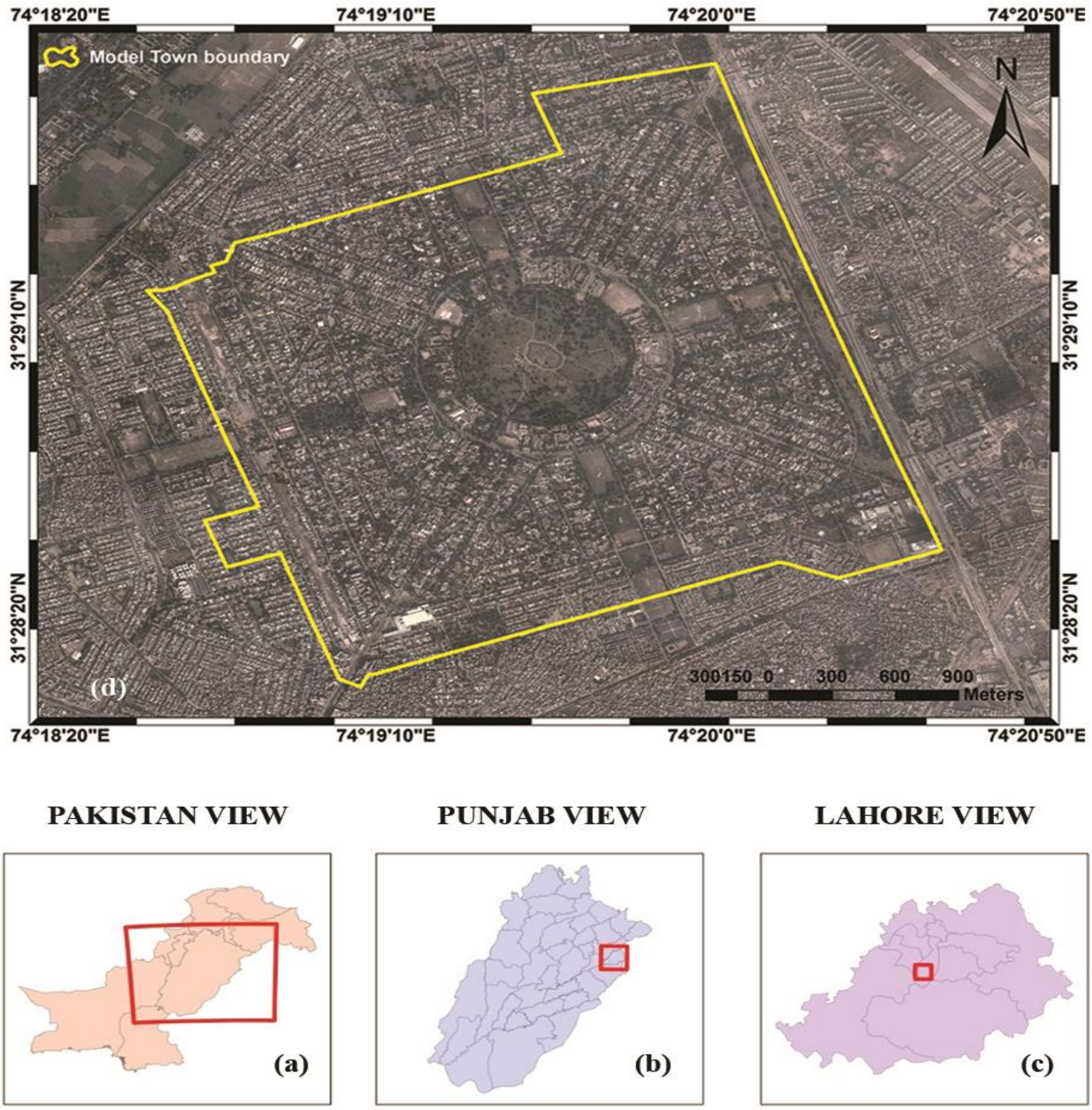

Fig. 4 Map showing spatial location of study area. (a) Location of Punjab province in Pakistan (b) Location of Lahore district in Punjab (c) District map of Lahore showing location of study area (d) Map of Model Town, Lahore.

method to estimate RWH potential, in any particular catchment surface.

Following equation is used for RWH estimation.

S = A× R× Cr (Eq. 1)

Where: S is rainwater harvesting potential, A is catchment area, R is mean annual rainfall in mm, and Cr is coefficient of runoff.

Runoff Catchment Area (A)

An area of any type of surface from where rainwater can be collected is called catchment area. The rooftops of all domestic, commercial, governmental and non-governmental buildings, of the Cooperative Model Town Society, have been digitized for the computation of RWH potential. Quick bird satellite image of 0.65m resolution of year 2013 was obtained from Urban Unit Lahore, as a primary data source for digitization of rooftop area (Fig. 4d). For calculation of area, rooftops were manually digitized from the satellite image using ArcMap 10.4.1 (Fig. 5). Then in GIS data base the corresponding area of each polygon was calculated in square meter (m^2), by using area calculation tool. Catchment area calculation using satellite imagery depends on precise knowledge of ground data. Absence of ground information might result in an incorrect value. For assuring accuracy, areas of some rooftops of selected houses were manually measured in the field verification survey. To create realistic approach, detailed information about houses and other required elements were also collected by the Cooperative Model Town Society, Lahore. Formula for runoff catchment area calculation is:

Area (A) = Length (m) × breadth (m) (Eq. 2)

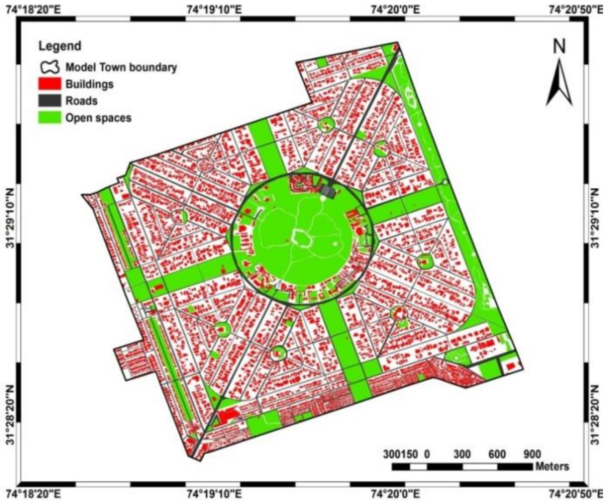

Fig. 5 Map showing digitized rooftops of buildings, roads and open spaces of Model Town, Lahore

Coefficient of Runoff (Cr)

Runoff coefficient is a ratio between rainfall and runoff rate. It is a dimensionless factor. It is a factor which is determined by considering the fact that all the rainfall runoff from a catchment surface cannot be captured. There is always a handsome amount of runoff lost from the catchment surface due to evaporation or retaining on the surface itself. It is a combined effect of catchment losses. It can be calculated as (Gould and Nissan, 2005):

Cr = Vr/Vt (Eq. 3)

Where: Vr is volume of run off and Vt is total volume of rainfall on the surface. A field experiment was conducted in Model Town to determine more precisely, the runoff coefficients (Cr) for the study area. According to broad analysis of District Census Report of Lahore (1998) the main constructing material used for rooftops in Lahore includes cement, concrete and bricks. The most commonly used roofs in study area are level cement or brick roofs, as shown in Fig. 6. The values of runoff coefficient for different types of catchments are given in Table 2. The value of runoff coefficient increases as the amount of rainfall increases. However, it turns into a constant value after a certain amount of rainfall for all types of roof. The roof types in study area showed similar average Cr values. Therefore, a single value of Cr (0.6) is used for RWH potential estimation following Pacey and Cullis, (1996).

Table 2 Factor of runoff coefficient for various types of catchments

Type of Catchment	Coefficients
Tiles and bricks Corrugated metal sheets	0.8 – 0.9 0.7 - 0.9
Concrete Brick pavement	0.6 - 0.8 0.5 - 0.6
Untreated ground catchments Soil on slopes less than 10% Rocky natural catchments	0.0 – 0.3 0.2 – 0.5

Source: Pacey and Cullis, 1989

Fig. 6 Rainwater catchment surface of building rooftop in Model Town, Lahore

Mean annual rainfall (R)

Magnitude of rainwater is an essential component to adopt rainwater harvesting (RWH) system. First of all, the rainfall data of last 30 years (1987-2016) is obtained from Pakistan Metrological Department (PMD), Lahore. This data is used to show rainfall trend in Lahore district. The mean annual rainfall data of 2016 is analyzed and used to calculate rainwater harvesting potential.

Data Analysis

All the building's rooftops were digitized and converted into polygons. The area of each polygon was calculated in ArcMap database. Later calculation of rainwater harvesting (RWH) potential was done by adding another fields of mean annual rainfall and runoff coefficient. GIS data base findings are represented in thematic maps comprehensively. A model house with rainwater harvesting (RWH) system is also proposed. This model house is generated by using AutoCAD and 3-D Max.

Results and Discussion

Rooftop rainwater harvesting (RWH) is the modest way of supplying potable and non-potable water at domestic level. Rooftops of buildings are digitized to calculate the RWH potential in cubic meter (m^3). Assistance from Google Erath was also taken to attain accuracy. Four thousands nine hundred and thirteen (4913) polygons were digitized in order to calculate the area of almost all the rooftops of the buildings in Model Town. The results vary according to the size of each rooftop catchment area, but there is an opportunity in each of the rooftop evaluated to capture hundreds and thousands of cubic meters of rainwater each year. This quantity of water can reduce the burden on the central water supply system. The total area of building rooftops is 1,336,270 square meters (Fig. 7). Maximum size available area for RWH is 6,537 square meters i.e. building of Metro shopping mall. Areas of buildings are further classified into six classes with natural breaks to understand the available area visually.

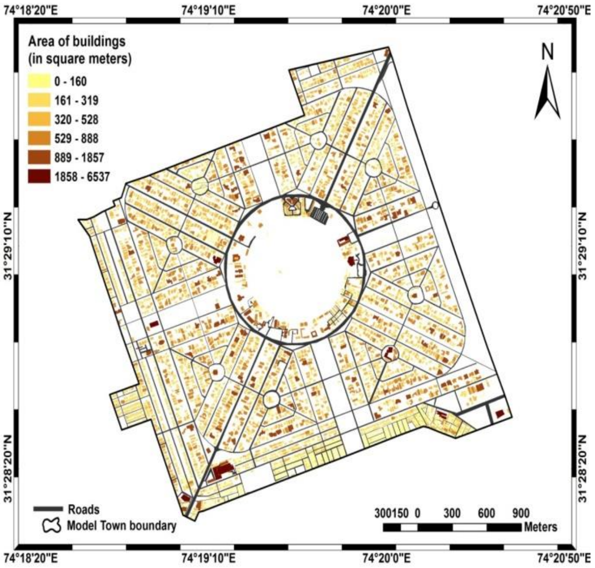

Fig. 7 Map showing area of building rooftops in Model Town, Lahore.

The estimated RWH potential on rooftops in volume is presented in Fig. 8. The results for potential of RWH are varied according to the size of each catchment area (rooftop). The Runoff co-efficient is taken as 0.6. To study the potential for rainwater harvesting from rooftop areas, the average annual rainfall of 2016 is taken. The total estimated potential of RWH is 535,756 cubic meters (535,756,000 L) for the year 2016 with an average annual rainfall of 616.82 mm (0.61682 m). 535,756,000 liters rainwater is a significant volume of harvestable rainwater potential, which can be utilized for domestic purposes. According to Water and Sanitation Agency (WASA) Lahore, the estimated consumption of water is 227-454 (average=340.5) liters per capita per day (LPCD). Therefore approximately 100,000 population of Model Town could consume 34,050,000 liters per day (12,258,000,000 liters per year). 4.37 % consumption could be covered by harvested rainwater. The maximum estimated potential of RWH from the largest available building rooftop is 2,620 cubic meters. Fig. 8 is showing estimated potential of building rooftops in six classes which efficiently present the potential with lowest to highest intensity. The simple practice of rooftop rainwater capture offers the potential to improve the sustainability of urban areas of Lahore for instance Model Town. The RWH potential in volume is directly proportional to catchment area of rooftop. There is steady increase in the volume of RWH potential with increase in area of the rooftops of buildings.

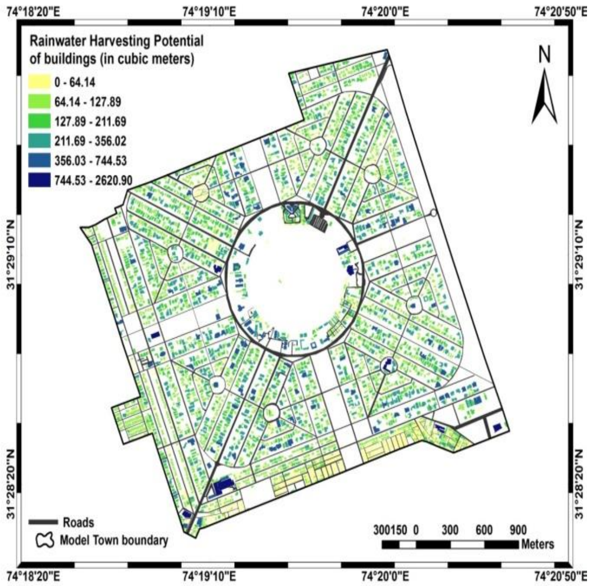

Fig. 8 Map showing estimated RWH potential on rooftops in Model Town, Lahore.

A Proposed RWH Model at Household Level

A model is a scheme that represents an estimation of field situation or a thing to be used as an example to follow or copy. It is a presentation of a structure for thinking through the problem. To harvest rainwater at household level, a rainwater harvesting system is needed. Such system helps to fulfill the gap between the demand and supply of water in urban areas for instance, Lahore. RWH storage and utilization model at household level is designed to show catchment area (rooftop) of 300 square meters (Fig. 9). The runoff water is shown on the rooftop catchment area with the help of arrows. Runoff flow and direction is also shown elaborately with the help of valley line and ridge line on surface of catchment area i.e. rooftop. Basically, this is an architect phenomenon to design the roof or floor for the convenience of runoff flow towards the direction of the gutter. The national roofing contractors association (2010) defines ridge as highest point on a roof, represented by a horizontal line and valley line as the lowest point on roof which is also horizontal line to show the flow of runoff towards the gutter drainage pipes. Whenever rain falls the rainwater is collected by Plasticized Polyvinyl Chloride (PVC) pipes of 4 inches diameter which are shown as white color pipes in given model. Green pipes are for central water supply system which receives water from overhead water tank. Both the water supply systems are running side by side in given model of house with rainwater harvesting (RWH) system. Rainwater flows in the form of runoff on the catchment surface of the house and then it is directed towards the roof gutters. From there, it passes through a special type of filter (mesh filter) and is stored as harvested rainwater in the storage tank. The selection of rainwater harvesting tank depends upon the amount of average annual rainfall and catchment area (e.g. roof size) of the residence. For an average house of Model

Town Lahore, the estimated average roof catchment area is 300 m^2. The average annual rainfall of 616.82 mm on 300 m^2 catchment area will deliver 185,046 liters of water into the tank. Therefore, large rainwater tanks with water harvesting capacity of greater than 10,000 liters are suitable for the study area. Harvested rainwater is pumped out from the tank and can be utilized by the consumers easily. RWH storage tank can be placed underground which reduces the impact on the space of the garden and does not get in the way while moving in lawn. There should be a warning sign on each water tap to inform the consumers that the water is non-drinkable. It is an important precaution in using RWH system at household level.

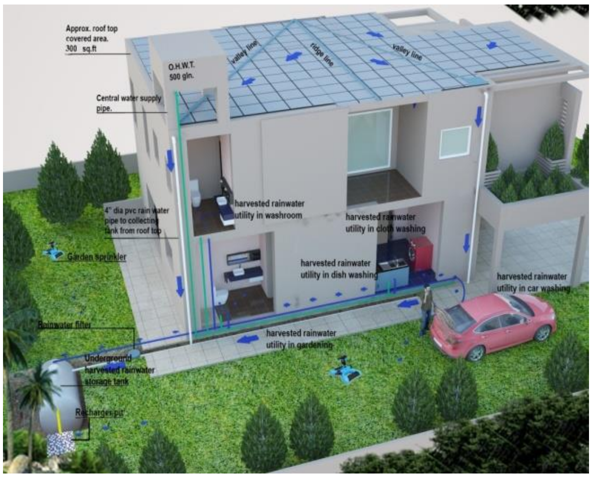

Fig. 9 A Proposed rainwater harvesting (RWH) model along with its possible uses at household level

Advantages of Domestic Rainwater Harvesting

The domestic per capita water consumption in Pakistan varies vividly from 30 liter per capita per day to 350 liter per capita per day (Bhatti and Nasu, 2010). Rainwater can be consumed for potable and non-potable purposes. It can be used as drinking water after proper filtration. Where the rainwater cannot be ingested, there are many other uses of harvested rainwater (RWH).

- Consuming harvested rainwater is extremely simple and similar to normal tap water use.
- It lessens the burden on the central water supply system by saving up to 50% water usage.
- Harvested rainwater system is a low maintenance system and reduces water bills.
- It progresses the sustainability of water.
- Below ground tank has low visual impact and no algae growth.
- It can be consumed for non-drinking purposes like flushing toilet, in washing machine, washing utensils, watering plants, washing floor and washing vehicles etc.
- Main supply system of water contains chlorine (Cl). Many people get allergies from the chlorine water therefore rainwater is safe for such consumers.
- Rainwater is a soft water without any salt. Cleaning detergents show good result in soft water. Soft water is best suitable for washing clothes. Rainwater does not contain magnesium (Mg) and calcium (Ca). Due to this trait, using rainwater completely safeguards clothes and washing machines.
- Rainwater without calcium and magnesium also gives long service life to toilet cistern.
- Rainwater can be used for mopping and washing floors.
- It can be effectively used for creating cooling effects.
- It can be used in water heaters.
- Rainwater is best for watering gardens.
- Rainwater is the most decentralized supply of water at household level. Utilization of rainwater reduce the burden on central water supply system by at least 50% while reducing the negative impact on the environment.
- According to the utility directory (2012) 30% harvested rainwater can be used for body care. 30% in WC flushing, 20% in dishwashing, 10% for drinking and cooking, 25% clothes washing, 15% in car washing, 10% in garden watering.
- Rainwater can be reused by having an over-head tap on toilet flush storage tank. An average flush tank has a capacity of 6 liters of water. The daily use of flush water per person per day is almost 34 liters. By implementing such ideas water can be conserved.

Conclusion

The present study strongly advocates and concludes that there is a need of a sensible, effective and integrated water management system to meet the present and future water challenges of Lahore. Lahore is facing water challenges like increasing demands of water, lowering of water table, deceasing recharging resources of aquifer, chaos of inundated streets and roads in monsoon spell. Hence, there is a need for some strategic planning to develop better economic, social and environmental future of Lahore to compete in the global urban world. The rainwater harvesting (RWH) experts recommended that 70 mm (minimum) rainfall is required for doing rainwater harvesting. Therefore, Lahore is suitable for RWH with 628.8 mm average rainfall. Lahore is also suitable for doing rainwater harvesting with an extensive catchment area for instance rainwater can be captured on rooftops, on roads and even on open spaces. It has been proved by this research that only a single housing society (Model Town) has vast catchment area for harvesting rainwater. Therefore, creating self-sustainable rainwater harvesting (RWH) system is the need of an hour in the present scenario of water shortage in Lahore.

Domestic rainwater harvesting (DRWH) is need of the time to solve the emerging water issues in Lahore. Furthermore, the proposed RWH system will provide support to water supply authorities and urban designers. There is also a need to estimate RWH potential at national and regional level to do water resource planning for future. This study is significant to promote RWH at public level to bring them out of this critical situation of water crisis. Responsible government departments have to make laws to facilitates and install DRWH system. Also, pilot project should be launched and monitor in selected urban areas (e.g. new and old housing schemes) and successful projects should be advertised by electronic media.

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