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Potential Water Balance using Rainwater: An Analysis of Delhi, Megacity in India

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ABSTRACT

Delhi is one of the most water stressed cities in the world. This study aimed to explore the potential of Rainwater Harvesting (RWH) as an alternative source of the water supply for Delhi. Mass curve method has been used to understand the feasibility of RWH, indicating that an average roof of 60 m² in Delhi will collect 3,64,800 L of water in a year for an average family size of five people. The present study assumed that financial constraints, erratic rainfall, unclear legal guidelines, poor public perception, and a lack of commitment from the politicians are possible challenges.

1. Introduction

Water is the prime determinant of sustainability in urban areas [1]. Right from ancient times, civilizations have flourished near water bodies. However, available water supply is now diminishing owing to the population explosion, rapid urbanization, climate change, and pollution, causing a globally acknowledged situation of water scarcity [2]. In the global cities, the municipalities are struggling to provide better water management infrastructure to their growing population.

Most urban growth over the next 5 years will be concentrated in developing nations in Asia and Africa [3]. Due to the increased impact of climate change and population expansion many countries in Asia and the Pacific are emerging as the hot spot for water insecurity. In the year 2016, out of 48 countries, 29 countries in this area fit as water-insecure due to low availability of water and unsustainable groundwater extraction [4]. Because of obsolete water supply systems and insufficient infrastructure to harvest and store rainwater, several large as well as medium-sized cities in these countries face the jeopardy of water shortage [5].

India, the world's largest user of groundwater represents 25 percent of global groundwater withdrawals [6]. Groundwater contributes to almost more than 60% of irrigated agriculture and almost 85% of drinking water supplies across the globe are dependent on groundwater [6]. Correspondingly, agriculture withdraws 89% of available "surface water" too. By 2020, India is foreseen as a water-stressed country and 21 major cities, including the capital, Delhi, are expected to reach zero groundwater levels, affecting access for 100 million people [7].

1.1 Water Scenario in Delhi: Water Supply and Demand Variation

Delhi is one of the 10 largest cities in the world. With the fast-growing rate of urbanization, it is the second most water-stressed city in the world. Through an existing water supply network encompassing of 14,355 km long pipelines and more than 107 underground reservoirs spread across New Delhi, at present water is being supplied to about 18 million populations residing in New Delhi [8]. The growing population, rapid urbanization, and industrialization in Delhi are putting remarkable pressure on water resources availability. The Central Ground Water Board of India assessed the total groundwater potential in Delhi to be 292 million cubic meters (MCM) in 2003 as compared to 428.07 MCM in 1983, showing an overdraft and reduction of around 130 MCM in 20 years [9]. Further, water authorities reported declining groundwater levels in the

year 2018 from 0.5 m to 2 m per year in the last two decades, rating 90% of the city as semi-critical or critical zone [10].

The average annual rainfall in Delhi is 611 mm [10]. However, recharge of groundwater in New Delhi gets restricted due to decreased availability of permeable surfaces which are a subsequent effect of urbanization, the runoff gets diverted into the sewers or stormwater drains. Furthermore, the unplanned and unsustainable withdrawal from the subsoil aquifers due to the irregular supply of water by authorities, have been primarily responsible for the decline in groundwater levels.

Water treatment and supply capacity of Delhi Water Authorities, which was 66 MGD (Million Gallons per Day) in 1956, was raised to 240 MGD in 1979, 437 MGD in 1990, 650 MGD in 2002, and 906 MGD in 2014 [8]. The authorities have been raising concern that the present infrastructure and with existing resources, the projected demand in 2021 of 1380 MGD for the projected increased population of 23 million cannot be met, and there will be a shortfall of about 440 MGD [8].

Thus, the severe water shortages likely to be faced by Delhi require a comprehensive approach to manage both water supply and water demand. While the government has placed a priority on meeting domestic water needs, the importance of the commercial, industrial, and agricultural sectors necessitates a considered approach to improve water security.

Water Policy for Delhi mentions a number of goals and actions to address the water supply-demand imbalance and has recognized the importance of "water harvesting" [1]. As described by Yazar et al. [11], "Water harvesting" is the process of concentrating precipitation through runoff and storage for productive use. The annual rainwater harvesting potential has been assessed at 2500 million liters per day for Delhi [8]. Even if a quarter of this could be reaped it would imply the availability of 625 million liters per day, which would be closely equal to the presently estimated shortage. This will be in addition to the potential for roof water harvesting measured at around 27 million liters per day [8].

1.2 Rainwater Harvesting for Megacities

Rainwater Harvesting (RWH) has drawn the interest of researchers and policymakers as a sustainable source to meet the increasing water demand and one of the most suitable sustainable solutions to be included in the urban water management system [12]. Multiple paybacks of the RWH systems include mitigation of the water crisis issues, reduce the load on traditional water sources, lighten non-point source pollutant loads, control water logging problems, prevent flash-floods, mitigate climate change impacts, contribute to stormwater management, and so forth [12]. The RWH system has been utilized all around the world locally and commercially for securing water demand as in large public institution [13]; domestic; irrigation, industries, etc., [13-15]. Hence, evaluating the

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feasibility of RWH as an alternative source for securing water demand for megacities is potential scope for research.

The economic and environmental benefits associated with rainwater harvesting systems as possible sustainable solutions towards the water scarcity issues in the urban areas of Colombo, Sri Lanka [16]. The potential for rainwater harvesting in the major ecological zones of Nigeria and furthermore, classified residential buildings into different classes with different amounts of water consumption in order to focus on flood mitigation and domestic water supply [17]. It was inferred from the results that the rainwater harvesting potential was a power function of rainfall coefficient of variation as the reliability of the system was over 80 % for the rainforest and guinea savanna zone. The potential for potable water savings by using rainwater for the residential sector of 62 cities in the state of Santa Catarina, Brazil. They found that it ranges from 34% to 92% depending on the potable water demand in the cities, with an average potential for potable water savings of 69% [18].

A study conducted by Mehrabadi and Motevali in 2012, modeled different tank volumes to collect rooftop runoff from residential rooftops to control urban floods in Tehran, Iran, and concluded that with increasing tank size and subsequently the volume of collected water, the frequency of the urban flood decreased [19]. A study conducted by Dwivedi et al in 2013 estimated the rooftop harvesting potential of the buildings which also described the planning and scheming of the Rain water harvesting systems as well as their delivery system, and the groundwater recharge system for a town in India called as Dhule. The study found that the unit cost of water appeared to be high in comparison to the market price, however, the environmental benefits of the groundwater recharging with good quality water validates such projects [20]. Clark et al. in 2015 simulated runoff, recharge, and recovery for different rainfall, catchment, and aquifer conditions, and working scenarios for Salisbury, South Australia estimating that the annual demand associating to 12.8% of catchment rainfall could be met with 99.5% volumetric reliability [21]. Adguna et al. through their study showed that there is a high potential contribution of rooftop RWH from large public institutions which can supplement the potable water demand. He also described the relation among the rainwater harvest to city level consumption and consumption at the individual institution for the water-stressed city of Addis Ababa in Ethiopia [2].

With this background of clear evidence of dwindling water resources in the Megacity of Delhi and escalating water demand, though this paper we aim to evaluate the potential for water balance in the city of Delhi through the technique of rainwater harvesting.

2. Experimental Methods

The present study evaluates the reliability of rainwater as an alternative water supply for the Megacity of Delhi. The methods that have been widely investigated to understand the performance and design of RWH systems worldwide, include water balance simulation analyses, mass curve analyses [22, 23]; probabilistic method; and economic optimization [22–25]. The unequal distribution and seasonal concentration of rainfall is so great in Delhi that even a small demand can't be met during dry periods and storage facilities must be built to save water during wetter periods. The reservoir should be large enough to provide dependable supply but should not be unnecessarily large covering unnecessarily more space, more investment, and more pressure on underlying slope forming materials. So the rational calculation for reservoir size has to be made.

In the present study, proper reservoir size has been estimated using the mass curve method, which calculates the difference between the total water flowing in and the water demanded to estimate the quantity that the reservoir must hold if the demand is to be met. Further, the feasibility has been assessed through understanding construction-materials of roofs and calculating the monthly yield of water-discharge from the rooftop of average size in relation to average monthly rainfall. The amount of water yield from a rooftop and that of demand are then plotted to construct mass curve for calculating the reservoir size for a family of modal constituents of 5 members to meet average demand in the dry period.

A mass curve of inflow is plotted between cumulative inflow values against time. Similarly, the mass curve of demand is plotted between accumulated demand and time. Ultimately, the capacity of a storage reservoir required for a specified yield or demand is determined by using the mass curve of inflow and mass curve of demand or demand curve. The demand lines which are drawn tangent to the tall points of the mass curve characterize the rate of withdrawal from the reservoir [26].

2.1 Rainfall Variability

Two decades of data related to the daily rainfall was obtained from the Indian Meteorological Department and was analyzed to estimate the

average monthly rainfall for Delhi city (Fig. 1). The figure shows that heavy rainfall is concentrated in the months from May to September. The precipitation received from October to April is in-adequate to meet the demand during this period. Thus, the storage of rainwater during the rainy season is a necessity for the rest of the year.

Fig. 1 Average monthly rainfall distribution for Delhi calculated from the year 1997 to 2017

2.2 Household Size

Household size is one of the crucial parameters in designing an RWH system specifically by using the mass curve analysis method [27]. The calculation for finding RWH potential is based on the total water demand, storage volume, and catchment area. The average size of a household is 4.55 persons according to the Directorate of Economics & Statistics, Government of NCT of Delhi [28]. The average household size is taken as 5 for the calculation of design storage capacity in the present study.

2.3 Roofing Material

The roofing materials used in Delhi include brick, wood, iron sheets, cement concrete, and roofing tiles. There are about 99.10% of proper 'pucca' houses (solid and permanent houses), 0.68 % of 'semi - pucca' (either roof or wall is not made up of solid material like burnt bricks, stone, cement, concrete or timber) and rest only 0.22 % of 'kutcha' houses (houses made from mud, thatch, or other low-quality materials) [29]. Thus the roofing materials of these houses specifically 'pucca' are suitable for rainwater catchment to be used for non-potable purposes.

2.4 Roofing Size

Of the dwellings located in the urban area of Delhi, 51.1% on average are individual houses and 46.5% are flats [29]. Therefore, as there are no official data on Rooftop Area (RA), an area of 83.6 m² has been assumed for houses and 6.00 m² per person for flats in the urban area (this gives approximately 30.00 m² of Rooftop area per flat) [30]. In the next step, a weighted average rooftop area per dwelling was then determined by using Eq. (1) [31].

$$RA = (H \times 83.6 + F \times 30.00) / 100 \quad (1)$$

In the above formula, 'RA' stands for the weighted average of Rooftop area per dwelling in the city (m²), H represents the percentage of houses in the city (non-dimensional) whereas F signifies the percentage of flats in the city (non-dimensional). By applying Eq. (1), the average RA obtained for the city was 56.68 m² which is about 60 m².

2.5 Catchment Surface

The runoff coefficient specific to various types of surfaces of rooftops is shown in Table 1 [32] derived from the Eq.(2). A runoff coefficient 0.8 was used for this study since the houses in New Delhi are mostly 'Pucca' houses and the rooftops are made up of concrete [33].

$$\text{Runoff} = CiA \quad (2)$$

where C is the coefficient of runoff, i is the rainfall intensity, and A is the roof area.

Table 1 Runoff coefficients for different catchment surfaces

Surface	Co-efficient
Tiles	0.8 - 0.9
Corrugated metal sheets	0.7 - 0.9
Concrete	0.6 - 0.8
Brick pavement	0.5 - 0.6
The soil on slopes less than 10 percent	0.0 - 0.3
Rocky natural catchments	0.2 - 0.5
Green area	0.05 - 0.10

3. Results and Discussion

3.1 Mass Curve to Derive the Storage Tank Capacity

To evaluate the potential of rainwater as an alternative water supply in Delhi, the mass curve approach has been used in this study. The mass curve has been prepared by calculating cumulated rainwater harvested using the average monthly rainfall, assumed rooftop area of 60 m², and a runoff coefficient of 0.8 to estimate the monthly runoff harvested (Table 2). The mass curve has been prepared by plotting cumulative runoff harvested and considering the constant withdrawal for a whole year. The maximum gap between these two determines the rational reservoir size to meet the demand for water for the concerned year (Fig. 2).

Table 2 The cumulative harvested water calculated for the city of Delhi

Month	Average Rainfall [i] (mm)	Roof Area [RA] (m ²)	Runoff Coefficient [C]	Monthly Runoff Harvested [i x RA x C] (m ³)	Cumulative runoff Harvested (m ³)
January	16	60	0.8	7.68	7.68
February	24	60	0.8	11.52	19.2
March	18	60	0.8	8.64	27.84
April	14	60	0.8	6.72	34.56
May	46	60	0.8	22.08	56.64
June	89	60	0.8	42.72	99.36
July	178	60	0.8	85.44	184.8
August	209	60	0.8	100.32	285.12
September	143	60	0.8	68.64	353.76
October	17	60	0.8	8.16	361.92
November	3	60	0.8	1.44	363.36
December	3	60	0.8	1.44	364.8

The analysis of the result of mass curve derivation revealed that the rooftop with an area of 60 m² can collect 3,64,800 L runoff every year. Thus, assuming a constant withdrawal throughout the year, the volume of water collected will be 999.45 L/day. For a family of five people, this means 200 L/person/day, which is quite a substantial amount of water in urban areas like Delhi, provided there is sufficient storage infrastructure. Furthermore, Fig. 2 presents that the maximum storage is required in September with an additional storage capacity of 94 m³ (94,000 L).

Fig. 2 Mass curve of cumulative demand vs. cumulative rainwater harvested for Delhi

Comparing the present study with another similar study, it was observed that a 4,000 L concrete tank installed with a roof area of 40 m² was adequate to take care of the water demands of a household consisting of four members [34, 35]. Similarly, a study conducted by Woltersdorf et al. in 2015 recommended that a rooftop of 100 m² should have a tank size of 30 m³, while according to Ndiritu et al. a storage tank size of 40 m³ optimum for a roof size area range between 75 m² and 150 m² [36,37]. According to Imteaz et al., a tank size of 7,000 L is required to achieve 100% reliability for toilet flushing and laundry [38].

The present study recommends that the rooftop RWH should be considered as one of the alternative sources of the water supply system for the water scarce Delhi megacity and for the megacities of the future. The application of RWH is technically feasible based on the prevailing rainfall pattern. According to the data available, over 90% of households have a rooftop constructed from technically appropriate materials like concrete. Results of the research performed in New Delhi indicate that an average roof of 60 m² will collect 3,64,800 L/yr (999.45 L/person/day) for an average family size of five people. This amount of water can be used to easily used to fulfill the demand for drinking and cooking purposes. Thus, domestic rainwater harvesting is highly encouraged as a supplementary water source and also a means for groundwater recharge especially in

urban and peri-urban areas to reduce the vulnerability of the acute shortage of water resources. Therefore, the objective of this study was to estimate the potential contribution of rooftop RWH from Residential areas to supplement the potable water demand and relate the rainwater harvest to city level consumption.

Rainwater harvesting being widely practiced across the globe but there are still some major concerns and barriers that exists in its wide scale implementation. The concerns of RWH especially in the developing world could be financed, followed by the volume of water depending on erratic rainfall, calling for large water storages, the inability to link with the present water system, no clear legal guidelines, poor public perception, and a lack of commitment from the politicians. Although RWH in Delhi is being encouraged by Delhi Master Plan 2021 and Delhi Water Policy 2017 guidelines but practiced only at an insignificant level with few, small-scale traditional practices at household levels and mandatory for new residential and commercial building usage is for some non-potable applications.

4. Conclusion

Using Delhi as a case to represent rapidly developing cities in South Asia struggling with water scarcity, the idea of this study was to estimate the potential of RWH for water balance in the city of Delhi through the technique of rainwater harvesting. Results of the present research indicated that an average roof of 60 m² in Delhi will collect 3, 64, 800 liters of water in a year (999.45 L/person/day) for an average family size of five people. This amount of water is sufficient to fulfill the demand for all domestic purposes and also a means for groundwater recharge especially in urban and peri-urban areas to reduce the vulnerability of acute shortage of water resources in dry seasons. Thus, to narrow the water supply gap, considering RWH as an alternative water supply source is recommended through this study. It was also analyzed during the study that various aspects such as the high investment costs for rainwater harvesting facilities, short-term tenancy arrangements, and the perception among the users that rainwater is not clean have emerged as limiting factors for the domestic use of rainwater. However, the present study assumed that financial constraints, erratic rainfall calling for large water storages, the inability to link with the present water system, with no clear legal guidelines, poor public perception, and a lack of commitment from the politicians are considered as possible challenges.

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