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# A Comparative Analysis of Rainwater Harvesting System and Conventional Sources of Water

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**Abstract**

Rainwater harvesting systems have been studied in different regions considering their performance, design, and life cycle analysis. However, their performance has not been compared with conventional water sources. The novelty of this study rests in examining the performance and potency of the rainwater harvesting system and the conventional sources of water for potable and non-potable demand. This study has two-fold objectives. Firstly, the challenges and sufficiency of existing water sources for potable and non-potable demand are examined by considering the water gallon delivery at the doorstep, government supply line, tanker-based supply, and extraction of water through bore wells. Secondly, the cost-effectiveness of several water sources is examined using four models. Each model combines water sources for potable and non-potable demand. A comparison is drawn between the cost-effectiveness of current practices and the rainwater harvesting system. The findings suggest that the rainwater harvesting system is more cost-effective than conventional water sources; however, it needs to be coupled with the government supply line to meet the non-potable water demand. On average, five other houses can be covered by the rainwater harvesting system. Implications are drawn to help governments and practitioners consider sustainable social well-being actions and promote rain harvesting through rebates.

**Keywords** Water resource management · Rainwater harvesting · Cost · Mathematical model

## 1 Introduction

Almost 67% of the world population experiences water scarcity for at least a month, and one-fifth of the land in Asia–Pacific will come under severe water stress in the next three decades (Satoh et al. 2017). Thus, there is increased pressure on the water supply side while demand continuously grows. This aspect is more prominent in developing countries where a higher population growth rate, poverty, urbanization, and a growing consumption pattern are observed (Luna et al. 2019).

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Implementing the rainwater harvesting (RWH) system reduces the requirement for potable water and it is effective for non-potable demand (Jing et al. 2017). Several studies have reported that the RWH system is a potential source for saving potable water, and it has a water-saving potency ranging from 12 to 100% in different environmental conditions (Ghisi et al. 2007). Ward et al. (2012) examined the performance of the RWH system and suggested that the RWH system can accomplish almost 87% of water-saving efficiency over eight months.

RWH has been investigated and researched in economically advanced countries such as the USA, Taiwan, and Australia (Semaan et al. 2020); however, there is little focus on developing countries such as Pakistan, which faces acute water shortage, especially in the dry spell. There is an ever-increasing need to provide economic justification and viability of RWH to meet the water requirements of a developing country. As urbanization is rising, a pertinent question of 'Whether the existing water resources are capable enough to cost-effectively meet the requirements of population density?' needs to be addressed.

Several authors have deployed the RWH system, focusing mainly on its initial investment, life cycle analysis, tank size selection, and reliability of the RWH system. However, no study exists comparing the economic effectiveness of the RWH system and the conventional sources of potable and non-potable water. The novelty of this study rests in examining the economic viability of the RWH system, along with its potential to meet potable and non-potable water demand, compared to the existing water sources in Islamabad, Pakistan. The objectives of this study are summarized as follows:

- The existing potable and non-potable water sources in Islamabad are examined for their sufficiency to meet demand. The challenges and sufficiency of water for non-potable demand are examined by considering the government supply line, tanker-based supply, and water extraction through bore wells. The challenges and sufficiency of the existing potable water infrastructure are examined by considering mineral water delivery at the doorstep.
- The cost-effectiveness of several water sources is examined using four models, i.e., Model 1-Model 4. Each model combines water sources (i.e., government supply line, water tankers, bore wells, mineral water, and RWH system) for potable and non-potable demand. A comparison is drawn between the cost-effectiveness of current practices and the rainwater harvesting system.

The remaining study is organized as follows. Section 2 discusses the literature on economic analysis and other critical aspects of the RWH system. Section 3 details the study area of Islamabad, the problem statement, and the challenges related to each water source. Section 4 provides the materials used in this study, i.e., data set and mathematical models, to evaluate the effectiveness of different water sources and the RWH system. Section 5 provides the results and key findings of this study. Section 6 provides a discussion and clear policy implications for practitioners. Section 7 concludes the study and provides future research directions.

## 2 Literature Review

RWH has been primarily researched as an alternative water source for domestic needs. Amos et al. (2020) examined the potency of a village based RWH system to solve water scarcity problems. In another study, Ali and Sang (2023) examined irrigation, flushing, and mixture water demand in four cities in Pakistan. The results suggested that large-size tanks and less water demand results in considerable annual savings for the RWH system.

The water, food, and energy nexus were studied by Stamou and Rutschmann (2017) to optimize the water resources in a basin. The Nile Management Nexus Expert (NIMA-NEX) tool was used for the optimization process. Nanekely and Scholz (2017) studied the demand and supply imbalance in Iraqi Kurdistan and analyzed fifty-five detention ponds with capacities ranging between 49,000 $m^3$ and 250,000 $m^3$. Ferreira et al. (2023) studied the economic and technical feasibility of the RWH system as an alternative source for a retail store in Portugal. The results demonstrated that the RWH system could provide water storage up to 36%, amounting to monthly financial savings of up to € 372. Nachson et al. (2022) used a mass balance model to examine the efficiency of the RWH system for several domestic uses.

Shanmugavel and Rajendran (2022) identified several factors that can lead to adopting the RWH system using the Theory of Planned Behaviour and Norm Activation Model. The findings highlighted the importance of the RWH system and the moderation effect of intention to acquire the RWH system on the relationship between environmental concern, responsibility, and the RWH system. Ndeketeya and Dundu (2022) examined the impact of several socio-economic factors on adopting RWH in Johannesburg. A Multi-Criteria Decision Analysis technique was used for the analysis, and the results indicated that the RWH system influences the institutional, business, and agricultural properties. Ghodsi et al. (2023) identified the optimal RWH locations in almost 900 potential catchments in Buffalo, New York. The Storm Water Management Model (OSTRICH-SWMM) was used by considering the continuous data for one month.

Abd-el-Kader et al. (2023) provided a map of appropriate locations for RWH systems in Saudi Arabia. The authors identified potential areas for RWH systems and dams for harvesting and flood mitigation. In another study, Geographical Information Systems (GIS) and Remote Sensing (RS) were used to select sites for RWH implementation (Matomela and Ikhumhen 2020). The authors used road network, drainage density, runoff potential, slope, and distances for selecting potential locations for the RWH system. Valdez et al. (2016) used a simulation model to compare buildings' greenhouse emissions and energy consumption under several configurations of the RWH system in Mexico City. The results suggested that the RWH system can reduce emissions and help mitigate floods. In another study, Souto et al. (2022) examined the impact of the harvesting system in reducing the runoff and the demand for drinking water in Goiania-GO.

The economic feasibility of an RWH system can be demonstrated by creating a balance between the water supply cost savings and the cost of installing and maintaining an RWH system (e.g., investment, maintenance, and operation costs) (Guizani 2016). The selection of the storage tank size is one of the most critical objectives in the RWH system literature, where cost-optimization has been frequently considered in the selection of tank size (Semaan et al. 2020).

As can be observed from the above-presented literature, more focus is on the initial investment, life cycle financial analysis, optimal tank size selection, and reliability of the RWH system. However, only a few studies have conducted a comparative economic assessment of the RWH system with conventional water supply sources. Okoye et al. (2015) studied whether the RWH system can meet part of the demand or solely rely on the utility water network. The authors noted that the RWH system comprises high initial investment while the utility network costs according to water demand. In another study, Liang and van Dijk (2011) compared the financial aspects of using groundwater and RWH system for agricultural requirements in Beijing. Although these studies provide the financial comparison of the RWH system with the conventional sources of water supply, the focus of all these studies is restricted to the use of non-potable water only. In addition, a consolidated network of non-potable water supply is not presented in any of these studies. Non-potable water supply can be acquired through government supply lines, water tankers, and bore wells. Thus, it is imperative to consider all these sources of non-potable water supply for a fair economic comparison with the RWH system.

## 3 Study Area and Problem Statement

### 3.1 Study Area

Islamabad, located at the northern edge of the Potohar Plateau, lies at $32^{o}28^{\prime}$ to $33^{o}48^{\prime}$ N and $72^{o}48^{\prime}$ to $73^{o}22^{\prime}$ E and it has more than 2 million population (Abeer et al. 2020). Surface water and groundwater are the two prominent water sources in Islamabad, and Simli and Khanpur dams are the two major water supply resources/reservoirs (Shabbir and Ahmad 2016). In addition, the development authority in Islamabad supplies the groundwater of around 180 tube wells through supply lines to the residents of Islamabad (Shabbir and Ahmad 2016), as shown in the map in Fig. 1.

### 3.2 Problem Statement

The existing water sources can be classified into potable and non-potable water supplies. Figure 2 illustrates several sources of water in Islamabad. The following sub-sections discuss the.

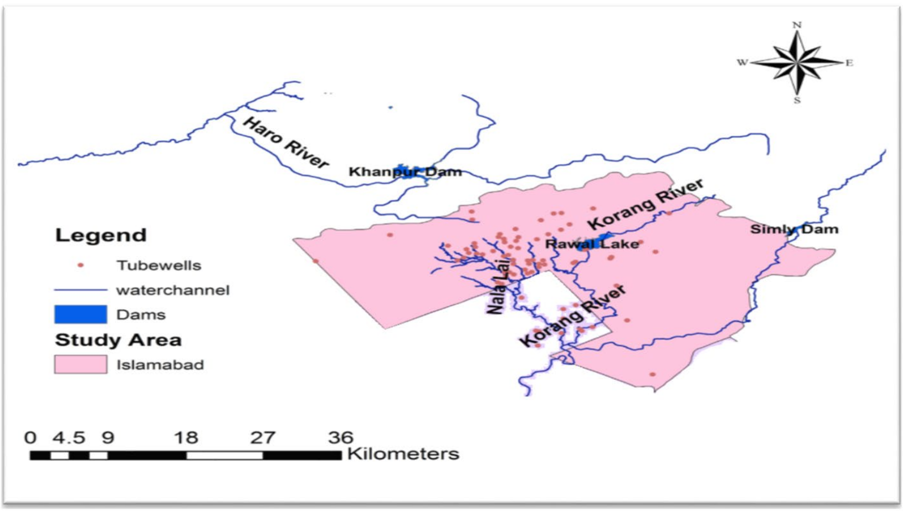


**Fig. 1** Map of water resources in Islamabad (Adapted from (Shabbir and Ahmad 2016))

### 3.2.1 Challenges Related to Non-potable Water Sources

The right side of Fig. 2 details the three sources of non-potable water. There are three dams, i.e., Simli dam, Rawal dam, and Khanpur dam, from where the water flows to the government-owned reservoirs. Water flows to households through the government supply line from this point onwards. Specific dates and times are designated to different sectors/sub-sectors/streets in Islamabad, and water flows into the ground water tank in a household for one hour per week. The population growth, lifestyle, and financial attractiveness have resulted in the construction of a substantially large number of houses, and Islamabad has observed more occupancy over the last 10–15 years. This increase in the number of houses and occupancy has caused water division into many different supply lines. As a result, water flow (discharge quantity) into a household tank has reduced.

The second non-potable water source is a water tanker supplied by the government or private parties. Residents can order a water tanker to cover the water supply deficiency through the government supply line. There are two types of water tanker delivery, i.e., government-managed and private water tankers. Though the government-managed water tanker is cheaper, it is not readily available and is to be requested on a first-come, first-served basis in a specific time window of each day (Monday to Friday). All the requests are compiled, the top 150/200 requests are acknowledged, and the remaining are discarded. On the other hand, the private water tanker is readily available and can be requested through a phone call. However, it is expensive due to inflation, gasoline prices, and price increases as the demand for water increases in the dry/hot season.

Lastly, water extraction from the ground through bore wells is standard in the neighbourhood, where boring is done up to pre-defined feet, and the extracted water is used for domestic purposes. Several issues are associated with this water supply source, such as its high initial investment, high running costs, use of multiple water pumps, and sustainability.

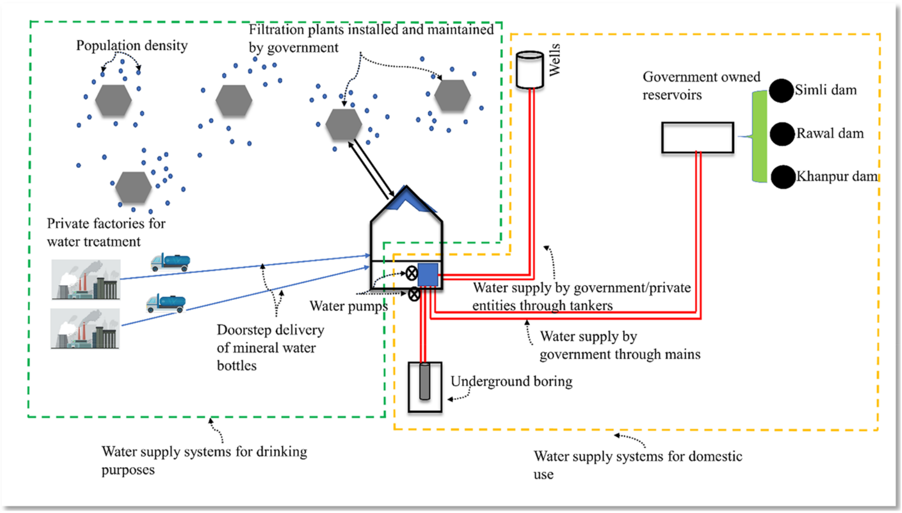


**Fig. 2** Various supply systems for potable and non-potable water in Islamabad

### 3.2.2 Challenges Related to Potable Water Sources

The potable water sources are illustrated on the left side of Fig. 2. There are two potable water sources in Islamabad, i.e., filtration plants and mineral water delivery at the doorstep. It is to be noted that only doorstep delivery of mineral water is examined in this study as a source of potable water.

At each location, a water filtration plant covers the potable demand of the surrounding population density. The water supply is available for 4–6 h twice a day. Residents carry their water gallons and fill them up from the filtration plants. Water filtration plants have been installed at different locations in Islamabad to meet the drinking water demand of the surrounding population.

The second potable water source is the delivery of water gallons by private companies to the doorsteps of households. Consumers are initially charged a security fee (fixed cost) against each empty gallon, to be claimed upon the termination of delivery services. The data on gallon capacity, fixed and variable costs, and the number of visits per week of five prominent mineral water supply companies is provided in Table 1.

# 4 Materials and Methods

## 4.1 Scale and Length of Data

There are two essential aspects of analyzing RWH system-related data, i.e., the length of data (in years) and the scale of rainfall data (monthly or daily data). Several studies have used data of different lengths of the period, such as twenty-four years data (Basinger et al. 2010), forty-two years data (Silva and Ghisi 2016), etc. Although several authors have used monthly rainfall data to examine the efficiency of the RWH system, daily rainfall data provides more accurate results than monthly rainfall data. This study uses Islamabad's average daily rainfall data for the past 30 years, as provided in Fig. 3. A similar data set was used by (Ali et al. 2020) for a hydrology study conducted in Islamabad.

## 4.2 Types of Households

Several studies have used a fixed catchment area and a pre-defined number of residents for designing the RWH system (Stang et al. 2021). In many practical cases, the house area, catchment area, and the number of people vary across the study area. To consider this

**Table 1** Capacity, cost, and number of visits of selected companies for potable water delivery

| S. No | Company | Gallon capacity (Litres) | Fixed cost (PKR) | Variable cost/ gallon (PKR) | # Of visits per week |
|---|---|---|---|---|---|
| 1 | A | 18L | 800 | 150 | 2 |
| 2 | B | 18.9L | 1000 | 350 | 1 |
| 3 | C | 20L | 1200 | 380 | 2 |
| 4 | D | 8L | 0 | 100 | 1 |
| 5 | E | 15L | 700 | 140 | 2 |

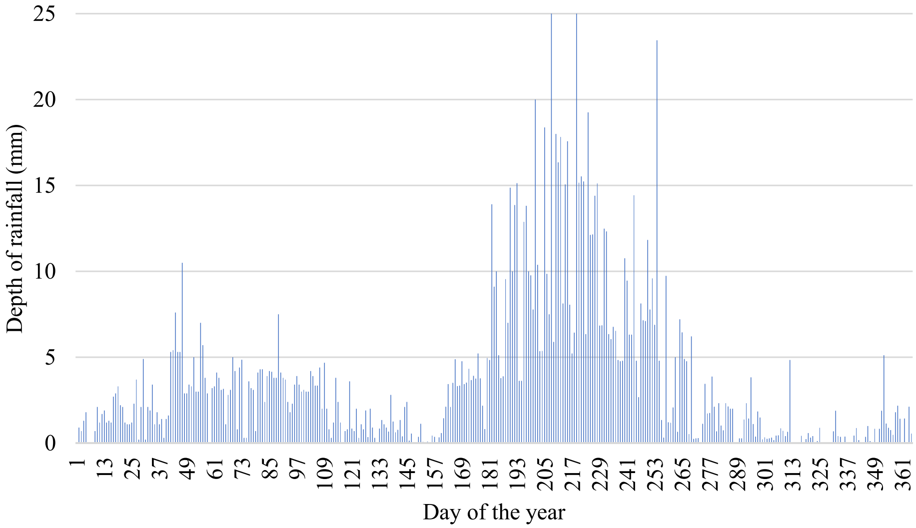


**Fig. 3** Average daily precipitation in Islamabad (past 30 years)

aspect, this study examines the water demand of different size houses (4 Marla, 5 Marla, 7 Marla, and 10 Marla) and the potable and non-potable water demand of 4–15 residents, as shown in Table 2. The non-potable water demand comprises the water used for washing, flushing, and gardening, and its data was taken from the study of Rashid et al. (2018). The potable water demand refers to drinking water; its value is 7.5 L per capita per day (Alim et al. 2020). The bill for government water supply through lines is paid twice a year, depending on the house size. Table 2 lists the government supply line bill per year (in PKR) and the catchment area of each house. It can be noted that most of the data in Table 2 are reported in Litres (L) except for the catchment area (expressed in $m^2$); however, a uniform scale was used in the entire analysis.

### 4.3 Mathematical Models

The cost-effectiveness of several water sources is examined using four models, i.e., Model 1-Model 4. The description of each model is provided in Table 3.

#### 4.3.1 Government Supply Line

The frequency of water supply through the government supply line per week depends on the time of year due to changes in precipitation and water availability in reservoirs. Water is supplied twice a week, eight times a month, and 32 times in September-December. On the other hand, in January-August, water is supplied through lines 32 times (once a week, four times a month).

Equation (1) expresses the quantity of water pouring into the underground tank from the supply lines per year. A parameter of $\omega$ has been introduced in the equation to consider the potential of the supply line to fill the underground tank. For example, if there are no other houses in the street ($\omega$=0), water from the supply line will quickly fill up the tank.

**Table 2** Number of residents, water requirement, supply bill and roof area of different household types

| S. No | House hold Type | # Of residents | Underground water tank size (L) | Non-potable water needs per house per year (L) | Potable water needs per year (L) | Total yearly demand | Govt. supply bill per year (in PKR) | Catchment area ($m^2$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 4 Marla | 4 | 7500 L | 326880 L | 10950 L | 327830 L | 9000 | 80 $m^2$ |
| 2 | 4 Marla | 8 | 7500 L | 653760 L | 21900 L | 675660 L | 9000 | 80 $m^2$ |
| 3 | 5 Marla | 6 | 8700 L | 490320 L | 16425 L | 506745 L | 11500 | 110 $m^2$ |
| 4 | 5 Marla | 10 | 8700 L | 817200 L | 27375 L | 844575 L | 11500 | 110 $m^2$ |
| 5 | 7 Marla | 6 | 9580 L | 490320 L | 16425 L | 506745 L | 15000 | 155 $m^2$ |
| 6 | 7 Marla | 12 | 9580 L | 980640 L | 32850 L | 1013590 L | 15000 | 155 $m^2$ |
| 7 | 10 Marla | 8 | 14356 L | 653760 L | 21900 L | 675660 L | 18000 | 210 $m^2$ |
| 8 | 10 Marla | 15 | 14356 L | 1225800 L | 41062.5 L | 1266862.5 L | 18000 | 210 $m^2$ |

**Table 3** Models and their description

| Model number | Description | |
|---|---|---|
| | **Supply system(s) for non-potable needs** | **Supply system for potable needs** |
| Model 1 | Government supply lines, and government and private tanker supply | Mineral water gallon delivery at the doorstep |
| Model 2 | Water supply through bore wells | Mineral water gallon delivery at the doorstep |
| Model 3 | RWH system | RWH system |
| Model 4 | RWH system and supply through lines | RWH system |

$$W_{lines} = 64(1 - \omega)TAC \tag{1}$$

### 4.3.2 Government-Owned Water Tanker

Since the government-owned water tanker can be ordered at most four times a month, Eq. (2) calculates the maximum number of government water tankers that can be ordered in one year, where $T_{govt}^{cap}$ is the capacity of the government tanker in litres, and its volume is 5000L.

$$W_{govt.tanker} = 48 \times T_{govt}^{cap} \tag{2}$$

### 4.3.3 Private Water Tanker

The excess demand not met by supply lines and government water tankers is met by ordering private water tankers; its expression is provided in Eq. (3).

$$W_{private.tanker} = D_{NP} - (W_{lines} + W_{govt.tanker}) \tag{3}$$

The detailed expression for private water tankers ordered per year is provided in Eq. (4).

$$W_{private.tanker} = D_{NP} - (64(1 - \omega)TAC + 48 \times T_{govt}^{cap}) \tag{4}$$

### 4.3.4 Cost of Model 1- Supply Line and Tankers (Non-potable Demand)

Equation (5) provides the total cost expression of Model 1, combining the cost of government and private water tankers and the yearly cost of government water supply through lines. Equation (6) offers a detailed expression of the total cost of non-potable water.

$$TC_{NP}^{M1} = c_{gt}.W_{govt.tanker} + c_{pt}.W_{private.tanker} + CG_{year} \tag{5}$$

$$TC_{NP}^{M1} = c_{gt}.48 \times T_{govt}^{cap} + c_{pt}.(D_{NP} - (64(1 - \omega)TAC + 48 \times T_{govt}^{cap}) + CG_{year} \tag{6}$$

#### 4.3.5 Cost of Model 2- Bore Wells (Non-potable Demand)

The total cost expression of water extracted through bore wells is provided in Eq. (7). It combines the fixed and variable costs associated with bore wells. The fixed cost expression of bore wells is provided in Eq. (8). It contains the cost of boring per foot ($bc_f$), the number of feet bored ($nf_b$), and the fixed cost of purchasing the motor ($CM$). The variable cost expression of boring is provided in Eq. (9). It includes the information on energy consumed in filling an underground tank of $l$ litres capacity ($ec_l^d$), the size of the underground water tank ($ts$), and the cost of energy consumed by the motor of horsepower $h$ in filling a tank of capacity $l$ ($ce_h^l$).

$$TC_{NP}^{M2} = FC_B + VC_B \tag{7}$$

$$FC_B = bc_f \times nf_b + CM \tag{8}$$

$$VC_B = ec_l^d \times \frac{D_{NP}}{ts} \times ce_h^l \tag{9}$$

#### 4.3.6 Cost of Model 3- RWH System

This model examines the cost-effectiveness of RWH and the sufficiency of harvested water for potable and non-potable demand. The runoff volume generated through the RWH system depends on the catchment area, the intensity of rainfall, and the runoff coefficient (Jing et al. 2017). Its expression is adapted from the study of (Ali et al. 2020) and is provided in Eq. (10).

$$VR_{md} = Q \times CA \times DR_{md}/1000 \tag{10}$$

where $VR_{md}$ is the volume of runoff generated from the catchment area on day $d$ in month $m$ ($m^3$), $Q$ is the runoff coefficient of the catchment area (dimensionless), $CA$ is the catchment area ($m^2$), and $DR_{md}$ is the depth of average rainfall on day $d$ in month $m$ (measured in mm). The runoff coefficient is equal to 0.9, based on the study of (Stang et al. 2021). The first flush (from the first rainwater event) is used to wash away the organic/inorganic contaminations in the rooftop area (Nachson et al. 2022). It is assumed in this study that the first flush (equal to 1 mm) from the first rainfall event of each month is washed away. Alim et al. (2020) and Kus et al. (2010) have also considered the first flush equal to 1 mm.

A typical RWH system comprises six components, i.e., filtration arrangement, catchment area, storage system, gutter with rainwater spout, treatment system, and delivery system. The catchment area and delivery system costs are not considered part of RWH system implementation as these aspects are covered during the construction of a house. Thus, this study only considers the cost of filtration arrangements, storage system, and treatment system for harvested rainwater. The total cost of the RWH system (Model 3) is provided in Eq. (11). It is the sum of the potable and non-potable cost of harvested water.

$$TC^{M3} = TC_{NP}^{M3} + TC_P^{M3} \tag{11}$$

The cost of harvested water used for non-potable demand is provided in Eq. (12). It combines the cost of a non-potable water storage tank ($C_{Ntank}^L$) and the cost of treatment (chlorination, etc.) ($Ct_{NP}$).

$$TC_{NP}^{M3} = C_{Ntank}^{L} + Ct_{NP} \tag{12}$$

The cost of a potable water tank (Eq. 13) combines the costs of a potable water storage tank ($C_{PNtank}^{L}$), the treatment cost of potable water ($Ct_P$), and the filtration system cost ($FC$). Water is made fit for drinking purposes through treatment and filtration by treating it with Chlorine so that the pathogens contaminations can be removed from it (Hayder et al. 2022).

$$TC_{P}^{M3} = C_{PNtank}^{L} + Ct_P + FC \tag{13}$$

#### 4.3.7 Cost of Model 4- RWH System and Supply Through Line

Model 4 combines the RWH system and water supply through the government supply line. The total cost of Model 4 is provided in Eq. (14), combining the costs of potable and non-potable uses. The potable cost is the same as in Model 3, while the non-potable cost includes the cost of the RWH system and the government supply line cost per year, as provided in Eq. (15).

$$TC^{M4} = TC_{NP}^{M4} + TC_{P}^{M4} \tag{14}$$

$$TC_{NP}^{M4} = C_{Ntank}^{L} + Ct_{NP} + CG_{year} \tag{15}$$

### 4.4 Storage Tank Selection

Two separate storage tanks are proposed to store potable and non-potable water. The output of the potable water storage tank is connected to only one water tap in the kitchen, while the output/discharge of the non-potable water tank is connected to several taps in washrooms. The schematic connections of potable and non-potable storage tanks (RWH systems) and storage tanks for conventional water sources are provided in Fig. 4.

The next task is to select an optimal-size RWH storage tank. The run-off coefficient, rainfall pattern, and roof size must be considered in deciding the water storage tank size (Nachson et al. 2022). The following steps are considered in selecting a storage tank:

1. The average daily precipitation in Islamabad is computed from the data given in Fig. 2.
2. Several house types are considered with different catchment areas, residents, and water demand.
3. The harvested water first serves the potable water demand, and the remaining water is used for non-potable demand.
4. The average daily potable water demand is added for all the days in one month. This monthly demand is used for calculating the potable water storage tank size.
5. The difference between the average monthly harvested water (sum of daily precipitation each month) and the average monthly potable water demand is used to calculate the non-potable water storage tank capacity.
6. The water-efficient solution costs can be more accurately derived through market research and consulting the local vendors (Sousa et al. 2019). Several water tank types and materials are available in the local market to store harvested water, such as concrete-based storage tanks and Polyvinyl Chloride (PVC) water storage tanks. Concrete tanks are more

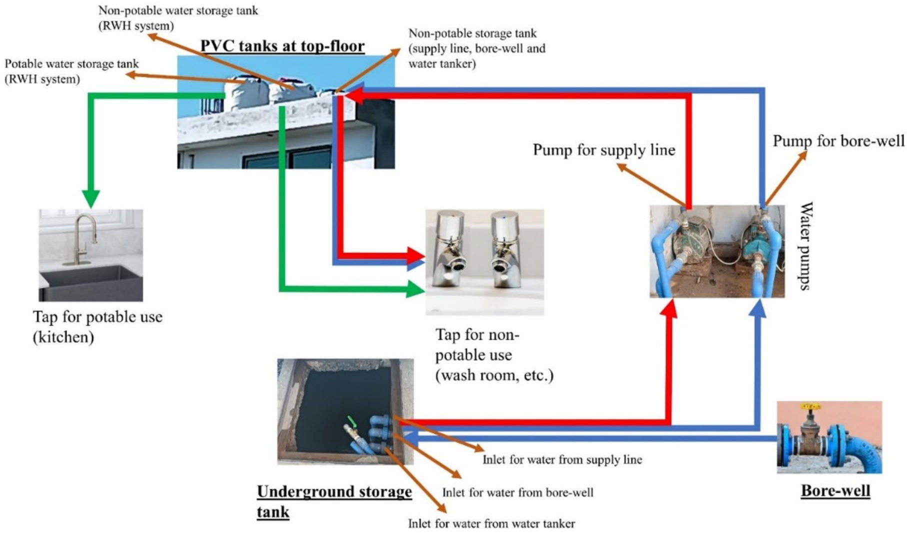


**Fig. 4** Schematic connections of PVC water storage tanks

durable but are much more expensive. Since two storage tanks are needed to store potable and non-potable harvested water, the regulatory body may not allow the construction of multiple tanks on the top floor. Thus, PVC water storage tanks were preferred due to their portability, ease of availability, cost-effectiveness, and everyday use in Islamabad. Once the tank size was computed, quotations were acquired from the local vendors concerning the costs of plastic water tanks, treatment systems, and filtration systems.

# 5 Results

## 5.1 Analysis of Demand and Supply

The demand and supply analysis (government water supply lines and government water tanker supply) for all types of households (#1 to #8) is provided in Fig. 5 and 6. It can be observed that water from supply lines and government water tankers is sufficient, in most cases, to meet the non-potable water demand of households type #1, #3, #5, and #7. On the other hand, these two water supply sources are insufficient to meet the non-potable demand of households type #2, #4, #6, and #8, especially when the number of houses increases in the neighbourhood. Thus, an increased number of private water tankers will be ordered by these households to meet the excessive water demand.

The number of private water tankers ordered by each household type is provided in Fig. 7. The analysis is presented for an increasing number of houses in the street. As the number of houses in a street increase, the potential of the supply line to meet demand decreases. As a result, more private water tankers are ordered to fulfill the excessive demand. A household with a significant number of residents (#4, #6, and #8) ends up ordering more private tankers compared to a house with a smaller number of residents (#1, #3, #5, and #7).

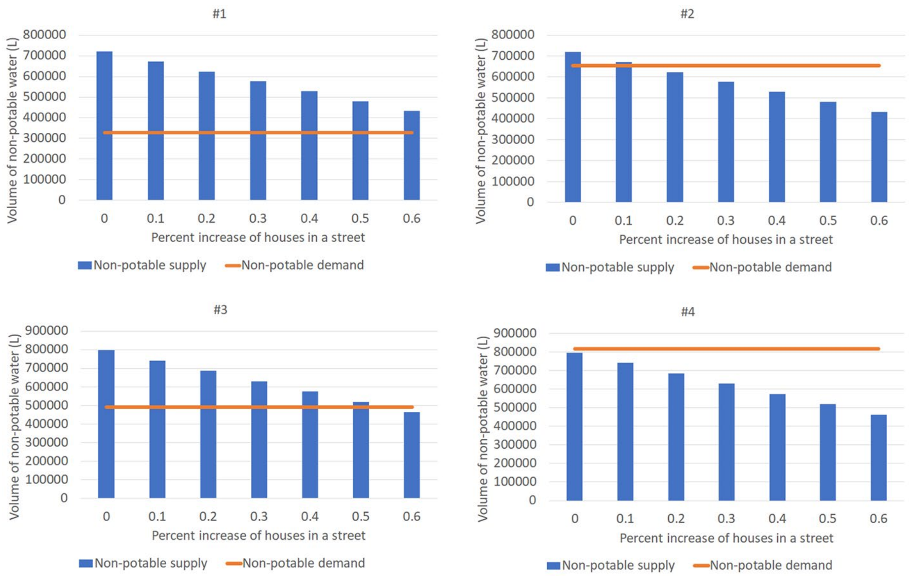


**Fig. 5** Demand and supply analysis of water through government supply line and government water tanker (non-potable use) for household types 1–4

## 5.2 Cost of Existing Sources of Water

The cost of Model 1 for an increasing number of houses in the street is provided in Fig. 8. The water-related cost of household types 1, 3, 5, and 7 is least affected by the increase in houses in the street, as the non-potable demand for such houses is below the supply

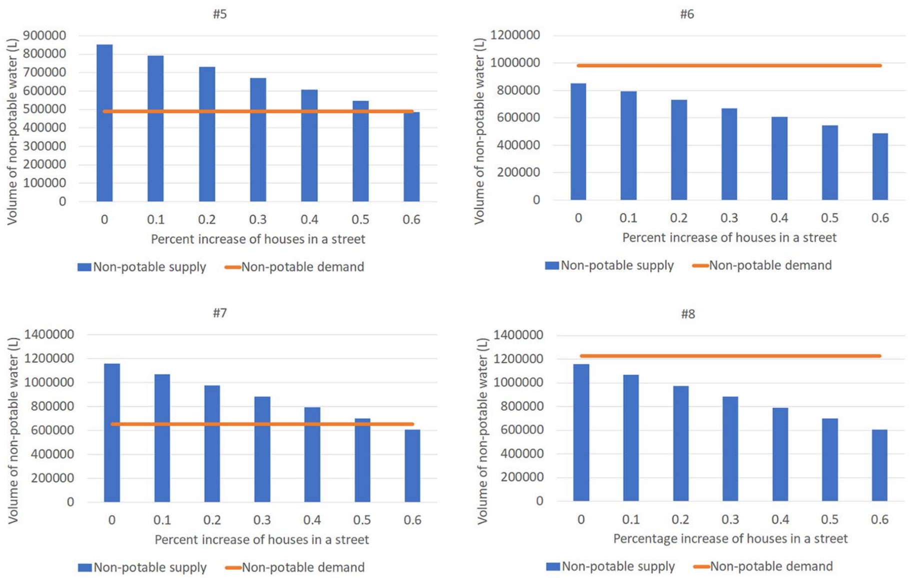


**Fig. 6** Demand and supply analysis of water through government supply line and government water tanker (non-potable use) for household types 5–8

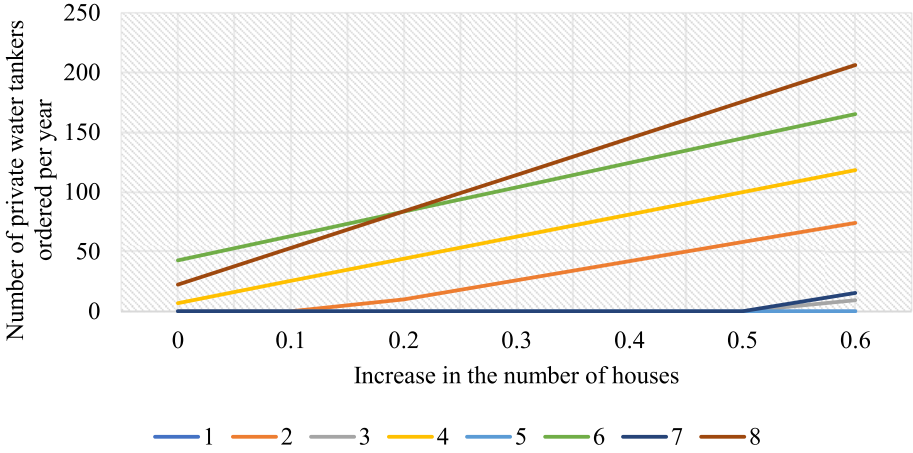


**Fig. 7** Number of private water tankers ordered per year for different household types (for non-potable use)

capacity of the existing water sources. The cost of household types 2, 4, 6, and 8 are affected mainly by the construction of new houses due to decreased water supply through lines. As a result, many private tankers are ordered to meet non-potable water demand, which results in an increased cost.

A comparison was drawn between the potable water costs of type A and type E water gallon delivery companies. The variable cost and the total cost of type A and type E water gallon delivery companies are provided in Fig. 9. There is a difference of up to 5% between the total cost of potable water delivery made by type E and type A companies. The total cost of potable water delivery per year by company A to household types 1 and 8 is 100000 PKR and 400000 PKR, respectively.

The combined analysis of different cost factors related to drinking, supply through lines, water tankers, and bore wells is provided in Fig. 10 and Table 4. The fixed cost related to

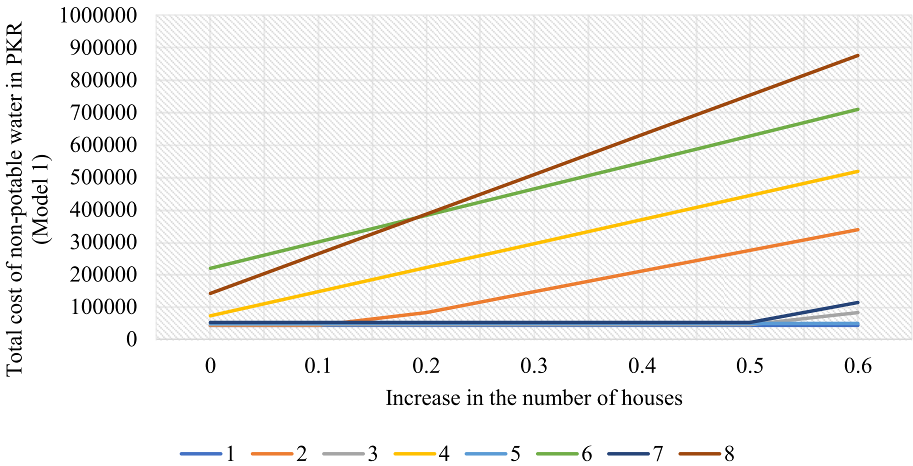


**Fig. 8** Total cost of non-potable water (Model 1, i.e., supply through lines, government, and private tankers) for different types of households

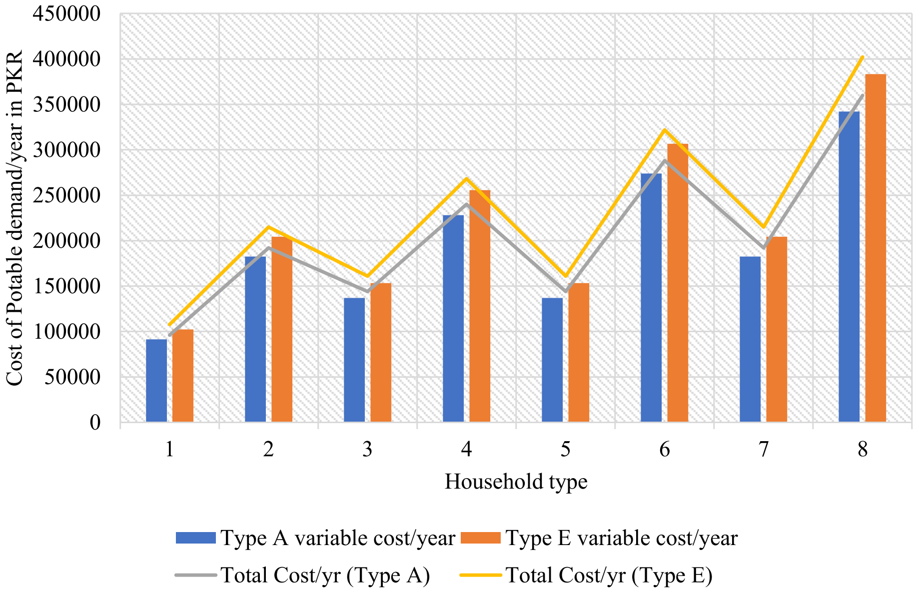


**Fig. 9** Fixed and variable cost of mineral water gallon delivery by Type A and Type E company

drinking is negligible compared to the variable cost of drinking and the costs related to non-potable sources of water. The cost of a bore well has a maximum value for household types 1–7, whereas the cost of private water tankers exceeds the bore well cost for household type 8. The variable cost of drinking is also considerably high for all household types.

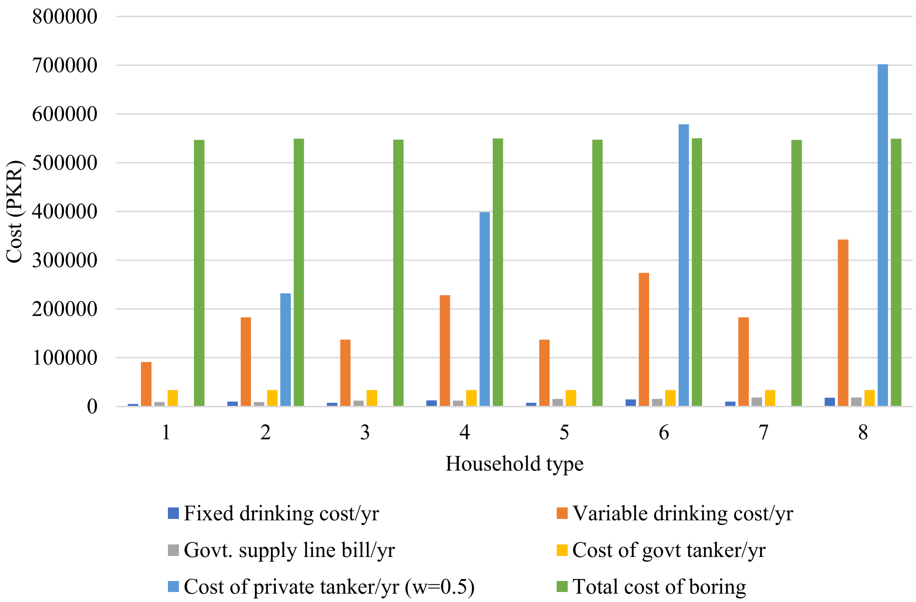


**Fig. 10** Cost of drinking, supply line, tankers and boring for different household types

**Table 4** Cost breakdown of potable and non-potable supply to different household types

| Cost (PKR) | Household type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Fixed drinking cost/year (Type A) | 4800 | 9600 | 7200 | 12000 | 7200 | 14400 | 9600 | 17600 |
| Variable drinking cost/year (Type A) | 91250 | 182500 | 136875 | 228125 | 136875 | 273750 | 182500 | 342187.5 |
| Govt. supply line bill/year | 9000 | 9000 | 11500 | 11500 | 15000 | 15000 | 18000 | 18000 |
| Cost of govt tanker/year | 33600 | 33600 | 33600 | 33600 | 33600 | 33600 | 33600 | 33600 |
| Cost of private tanker/year ($\omega$ =0.5) | 0 | 231680 | 0 | 398400 | 0 | 578773.3 | 0 | 701877.3 |
| Total cost of bore wells | 546580 | 549280 | 547420 | 549640 | 547120 | 550180 | 546760 | 549160 |

Thus, the potential of an RWH system as a replacement for potable water gallons delivery, private water tankers, and bore wells needs to be thoroughly examined.

#### 5.2.1 Cost of RWH System

As discussed earlier, priority is given to potable water demand, and the remaining water serves non-potable water demand. The cost of the RWH system to meet the potable and non-potable demand is provided in Fig. 11. It can be observed that the RWH system can meet the potable water demand of all household types while the non-potable water demand remains unfulfilled to a more significant extent.

As the rainfall precipitation changes from day to day/month to month, Fig. 12 provides the monthly non-potable water demand of household type 6 and the potential of harvested water extracted from the precipitation in each month to meet such demand.

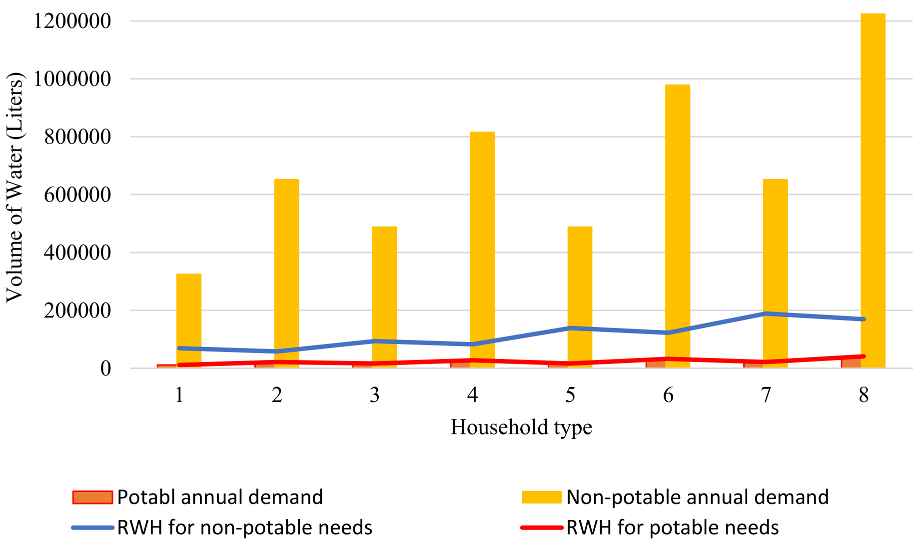


**Fig. 11** RWH system supply and demand for annual potable and non-potable needs

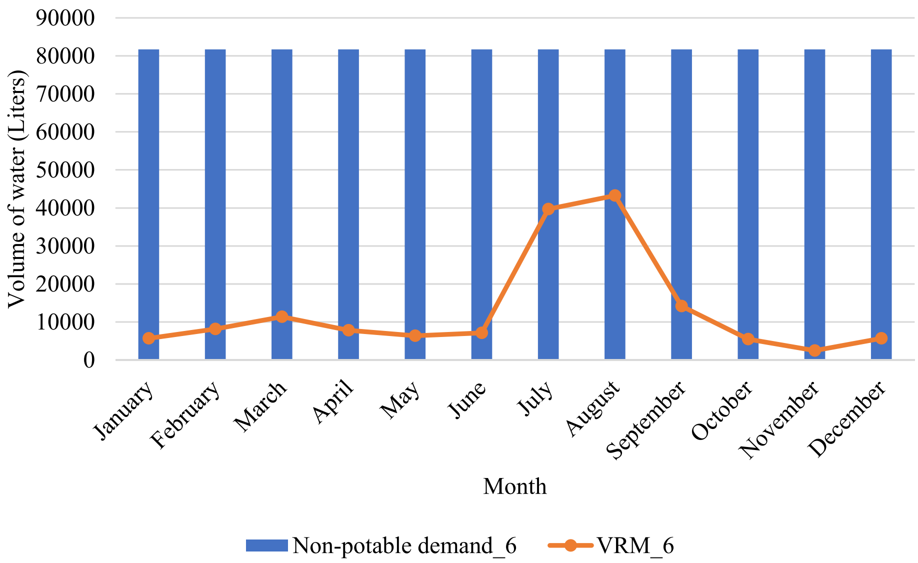


**Fig. 12** Monthly demand and RWH supply for household type 6

The supply and demand gaps are relatively small in July and August, while there is a maximum gap in November. Thus, though the RWH system can partially meet demand in certain months, another non-potable water must be coupled to cater to the untapped demand. The analysis so far informs that the RWH system can replace the water gallon delivery service, and another cost-effective source of non-potable water needs to complement the RWH so that 100% demand can be met.

The RWH system was combined with the supply lines (Model 4) due to the least added cost of the latter (Table 4). The combined analysis of the RWH system and supply through lines for non-potable demand is provided in Fig. 13. The potential of the water supply line for a dynamic range of houses was considered in the analysis. It can be observed that for $\omega \leq 0.3$, water acquired through RWH and supply line is sufficient to meet the non-potable demand of household types 1, 3, 5, and 7, while for a very low occupancy in a street ($\omega \leq 0$), water supplied through both systems can meet the non-potable demand of household types 2, 4 and 6. The non-potable demand of household type 8 partly remains unfulfilled, and it can be met by ordering private tankers.

## 5.3 Cost of Models 1–4

The total cost of each model is provided in Fig. 14. Model 3 has the lowest cost value for each household type, followed by the cost of Model 4. Thus, the RWH system is more economically viable for potable and non-potable demand. This is primarily due to the selection of PVC water storage tanks which are readily available and cost-effective. Selecting any other type of storage tank (concrete reinforced tanks, etc.) may not guarantee the cost-effectiveness of the RWH system. The combination of the supply line and RWH system (Model 4) does not elevate the total cost value considerably and is more viable compared to the total cost values of Model 1 and Model 2. A trade-off between demand fulfilment and cost optimality can easily be achieved through Model 4.

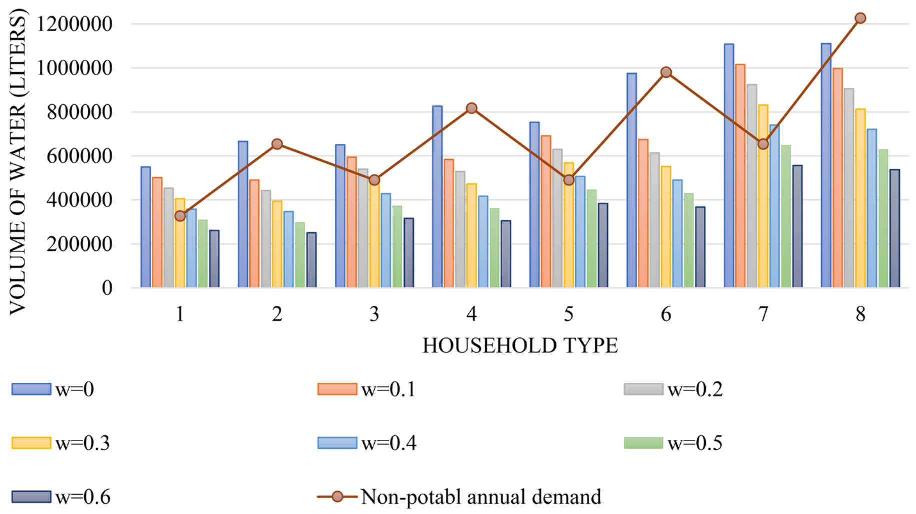


**Fig. 13** Water supply through supply lines and RWH for different household types (after subtracting the potable water needs from RWH)

### 5.4 Cost of Potable Demand

Figure 15 provides the cost of potable water for all models. Model 1 and Model 2 use the exact source of potable water (doorstep delivery of gallons), while Model 3 and Model 4 use the exact source of potable water (RWH system). The cost of potable water from the RWH system is much less for all household types compared to the cost of doorstep delivery of water

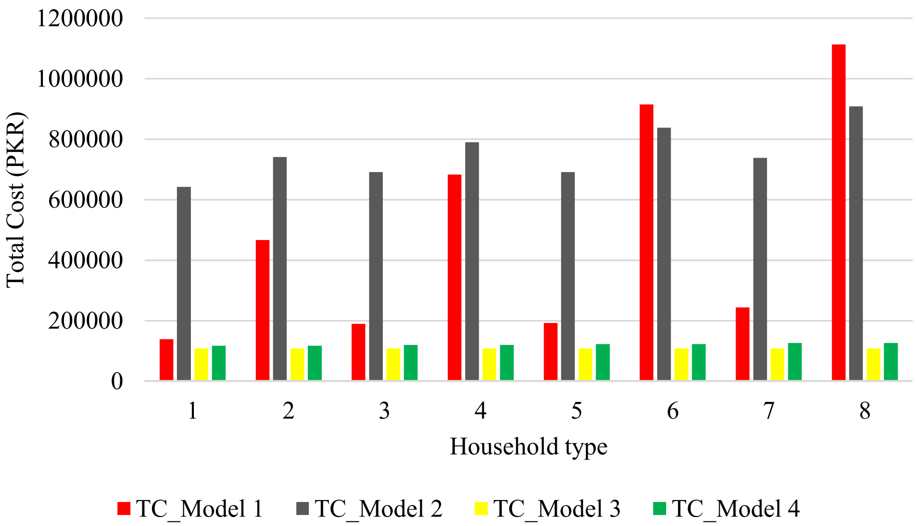


**Fig. 14** Total Cost of Models 1–4 for several types of households

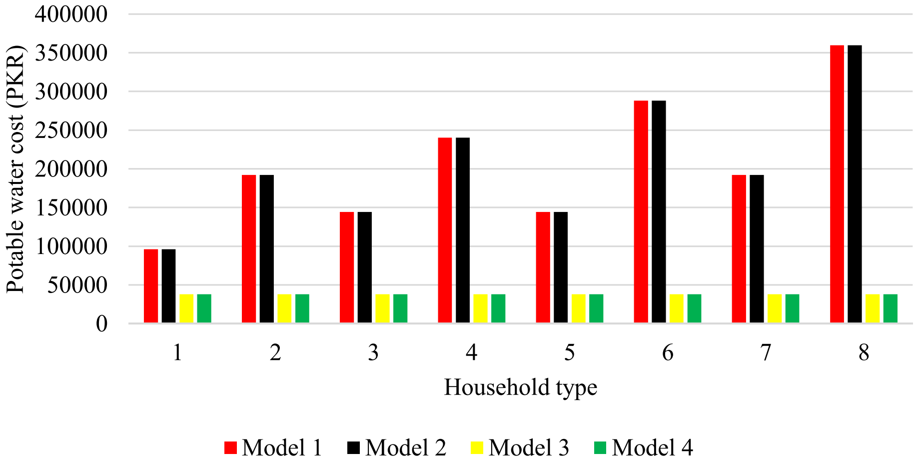


**Fig. 15** Potable water cost of Models 1–4 for several types of households

gallons. Thus, even if the water extracted through RWH is insufficient to meet the household's non-potable demand, it can still be preferred as a source of potable water due to its cost-effectiveness.

## 6 Discussion

### 6.1 Generating Profit Through RWH System

Few existing supply sources are cost-effective but insufficient to meet the demand (government supply lines and water tankers), while other sources can fulfill the demand; however, they are much more expensive (private tankers, bore wells, and mineral water delivery). The findings suggested that the RWH system can meet the potable demand of all types of households and must be coupled with the government supply line to meet the non-potable water demand cost-effectively. If the RWH system is designed only for potable demand, the excessive harvested water can be sold to neighbouring houses. Let us consider the case when the RWH system is designed only to serve potable needs. Figure 16 provides the distribution of harvested water into potable demand and excessive potable water. On average, almost 87% of the harvested water is excessive and can be sold to neighbouring houses in case the harvested water is not used for non-potable use.

We benchmarked the price of potable water charged by mineral water delivery company A as it has the minimum cost of water per litre equal to 8.33 PKR (150 PKR per gallon/18 L). Let us consider that a house with RWH sells the additional harvested water for a cost of 4 PKR per litre (more than 50% less compared to the cost/litter of company A). Figure 17 analyzes households where several other houses are covered through the harvested system installed in one house and the profit associated with it. For example, household type 1 can cover the potable needs of six other houses and generate a profit of 277118. 4 PKR. The data shows that, on average, five other houses can be covered (minimum = 3 and maximum = 9) with a mean profit of 462149 PKR (minimum = 233318 PKR and maximum = 754810 PKR).

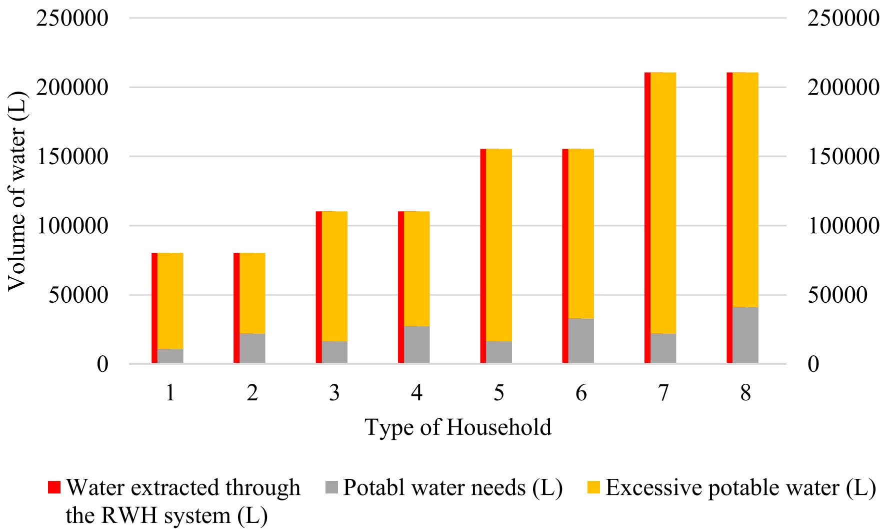


**Fig. 16** The requirement of RWH for potable needs and excessive water for different types of houses

## 6.2 Social Well-being

Pakistan recently observed disastrous flood events and is also combatting the spread of dengue disease. RWH system can help mitigate disastrous events such as flooding (Alim et al. 2020). The cause of the spread of dengue disease is the presence of still water on roads/parks and other surroundings of households. Rainwater harvesting systems can reduce water drainage outside a house's premises. Thus, besides demand fulfilment and cost optimization, there is a social well-being advantage of the RWH system. Implementing

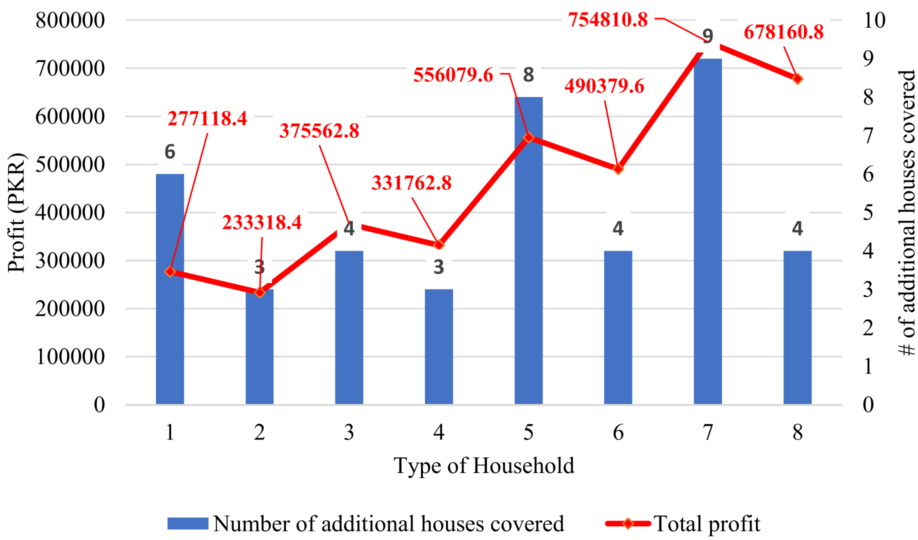


**Fig. 17** The number of houses covered, and profit generated through excessive harvested water

the RWH system at a mass level can help reduce social issues and medical concerns, relax the pressure on underground water strata, and ensure water resource management.

### 6.3 Anchoring Role of Government

The government's role is vital in the broader applicability of the RWH system. Government can offer incentives or rebates on installing the RWH system so that more people can afford such systems. For example, Chen et al. (2020) studied the water supply and demand mapping in China to develop a sustainable ecosystem. The findings suggested that government can anchor a role in water conservation, constructing lifestyles conducive to water saving and improving the utilization of water resources. Rahman et al. (2012) stated that the benefit–cost ratio of the RWH system is less than one if there is no rebate. Thus, the government cannot only relax the construction by-laws by allowing the construction of multiple water storage tanks on the top floor of houses in Islamabad but can also offer incentives to construct concrete-based storage tanks that are expansive but long-lasting. This will encourage the residents to adapt the water harvesting systems sustainably.

## 7 Conclusion

This study examined the challenges and cost-effectiveness of existing water sources for potable and non-potable use in Islamabad. A comparison was drawn between the existing water sources and the RWH system's implementation. Four models were proposed to assess the cost-effectiveness of different water sources for various demand values.

The findings suggest that few existing supply sources are cost-effective but insufficient to meet demand, while other sources can meet demand; however, they are much more expensive. RWH system can cost-effectively meet the potable demand; however, it needs to be coupled with the government supply line to meet the non-potable demand. RWH system is more economically viable for potable and non-potable uses. Adding a government supply line with the RWH system (Model 4) does not considerably elevate the total cost value and is more viable than Model 1 and Model 2. A trade-off between demand fulfillment and cost optimality can easily be achieved through Model 4.

The following comprise the limitations of this study and suggestions for future research. The capacity of the harvested water storage tank was calculated by considering the average precipitation. Future studies may design the RWH storage capacity by considering the dynamic precipitation of different seasons/months. The literature suggests that the storage tank needs to be designed to conserve water in dry periods in water-stressed regions (Nguyen and Han 2017). If only used for drinking purposes, the proposed RWH system can store water for potable needs in the dry season. This study only considered mineral water delivery as a conventional source of meeting potable demand. Future research can also model the distribution of filtration plants and water collection through transportation/vehicle routing problems. The selection of size and material of the storage tank impacts the cost-effectiveness of the RWH system. The cost-effectiveness of the RWH system reported in this study is primarily due to the selection of PVC water storage tanks which are readily available and cost-effective. Selecting any other type of storage tank (concrete reinforced tanks, etc.) may not guarantee the cost-effectiveness of the RWH system.

**Nomenclature** $TAC$ : Tanker capacity (Litres); $\omega$ : Fraction of additional houses in the street (dimensionless); $c_{gt}$ : Cost of government tanker/order (PKR/tanker); $c_{pt}$ : Cost of private tanker/order (PKR/tanker); $CG_{year}$ : Cost of government supply through lines per year (PKR/year); $D$ : Yearly water demand of a household ($D = D_{NP} + D_P$; Litres); $D_{NP}$ : Yearly non-potable water demand of a household (Litres); $D_P$ : Yearly potable water demand of a household (Litres); $TC_{NP}^{M1}$ : The Total cost of non-potable water of Model 1 (supply through lines, government tanker, private tanker) (PKR); $TC_{NP}^{M2}$ : The Total cost of non-potable water of Model 2 (total cost of boring (PKR)); $TC_{NP}^{M3}$ : The Total cost of non-potable water of Model 3 (cost of RWH system (PKR)); $TC_{NP}^{M4}$ : The Total cost of non-potable water of Model 4 (cost of RWH system and supply through lines (PKR)); $FC_B$ : Fixed cost of boring (PKR); $VC_B$ : The Variable cost of boring (PKR)

**Availability of Data and Material** Data will be made available upon request.

**Code Availability** Not applicable.

## Declarations

**Ethics Approval** Not applicable.

**Consent to Participate** Not applicable.

**Consent for Publication** All authors consent for publications.

**Competing interests** The authors have no relevant financial or non-financial interests to disclose.

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