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The impact of the regularization on the economic analysis of rooftop rainwater harvesting system

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ABSTRACT

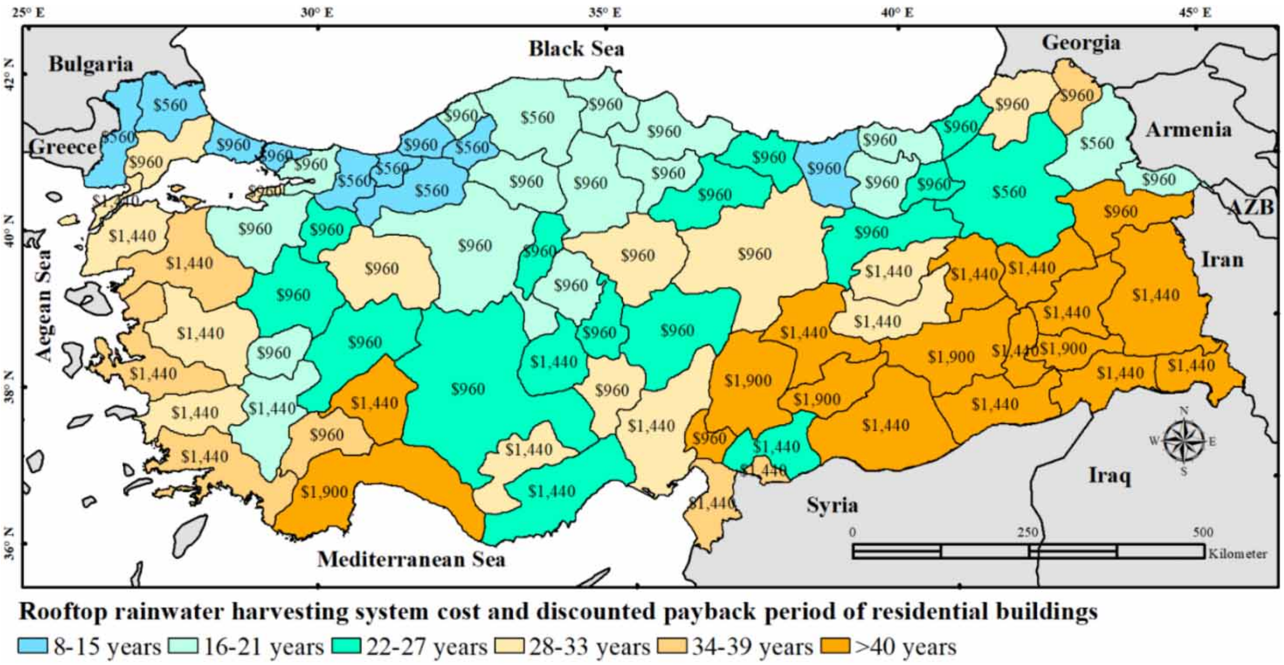
In this study, the economic feasibility of rooftop rainwater harvesting of residential and public/commercial buildings for all 81 provinces of Türkiye is assessed. The Rippl method (RM) is used for optimal storage tank estimation. The net present value (NPV) and the discounted payback period (DPP) are used for economic analysis. Two scenarios were assessed using RM for (I) residential buildings and (II) public buildings. Optimal storage tanks for scenarios I and II were estimated by the selection of minimum roof areas to supply the demand for toilet flushing water for above 90% volumetric reliability. ArcGIS 10.2 was used to illustrate nationwide results of (1) roof areas and storage tank volumes, and (2) the economic analysis. The average DPP of rainwater harvesting system is 36 years for residential buildings and 23 years for public buildings. Based on NPV analysis, 17 out of 81 provinces are economically feasible for residential buildings. The feasibility status in public buildings is 43 economically feasible and 38 infeasible. More savings in public buildings can be obtained in a relatively shorter DPP. Furthermore, regularization is more effective in public buildings than residential buildings.

Key words: rainwater harvesting, regularization, tank sizing, water conservation, water scarcity, water supply

HIGHLIGHTS

- Rooftop rainwater harvesting (RRH) potential is assessed for all 81 provinces of Türkiye.
- Toilet flush water demand for residential and public buildings is assessed.
- 17 out of 81 provinces are feasible for RRH in residential buildings.
- 43 out of 81 provinces are feasible for RRH in public/commercial buildings.
- Regularization has a significant impact on the economic analysis of RRH.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Consumption of existing water resources has been increased due to rapid industrialization and population growth. Approximately 56% of the population currently lives in urban regions globally (WB 2022), which is estimated to increase to 70% by 2050. The average available water in the world is 7,000 m^3/person/year. However, the annual amount of usable water per capita in Türkiye was 1,652 m^3 in 2000, 1,544 m^3 in 2009, and 1,346 m^3 in 2020 (DSI 2022). The water availability per capita for Türkiye is 1/5 of the world average. Water resources become scarcer due to climate change-driven disasters. Annual uncertainty of precipitation producing prolonged droughts creates more stress on water resources.

In areas with annual precipitation between 100 and 1,200 mm, it might be possible to supply demand of 100 L/day with rainwater between 80 and 99% reliability (Gould & Nissen-Petersen 1999). The rainwater collected from the rooftops could be used to fulfill the drinking water requirements. The rainwater can be collected and used for domestic (toilet flushing) and non-domestic (recreational, irrigation, and industrial uses) purposes that do not require drinking water quality. Significant water conservation, especially in public buildings with large roof areas, can be effectively achieved by rainwater harvesting (Teston *et al.* 2018). Harvested water can be utilized in flushing reservoirs where a significant amount of the water is used.

The selection of appropriate methods under convenient conditions is among the most significant preconditions for successful water harvesting systems (Van Steenbergen *et al.* 2011). Water balance models are used widely around the world for tank sizing of rooftop rainwater harvesting system (RHS) (Imteaz *et al.* 2012, 2017; Karim *et al.* 2015; Imteaz & Moniruzzaman 2018). Mathematical models are commonly used around the world (Liaw & Chiang 2014; Lizárraga-Mendiola *et al.* 2015; Musayev *et al.* 2018; Şahin & Manioğlu 2019). Beside the models, simulations are used widely in rooftop rainwater harvesting tank sizing (Lopes *et al.* 2017; Ndiritu *et al.* 2017). The Rippl method (RM) defines the volume of rainwater storage tanks for ensuring a regular flow during the driest periods. Among the most suitable methods to determine the storage volume are the daily simulation with efficiency criteria of 80%, which is the most appropriate rate of economic saving/installation cost, and RM (Santos & Taveira-Pinto 2013). The RM was used for rainwater harvesting tank sizing and efficiency considering various roof areas, demands, and climate (Silva & Maia 2021).

Unreliability occurs due to the inefficient design of the RHS in most cases. The stochastic nature of precipitation, water demand, family size, rooftop area, and the size of storage tanks should be considered while designing the rooftop RHS (Taffere *et al.* 2016). An optimization model has been developed by Okoye *et al.* (2015) on optimal tank size estimation for a single-family house. A comprehensive assessment in rural South Asia using satellite precipitation to prioritize regions for rainwater harvesting projects was investigated by Mahmood & Hossain (2017). Some inputs such as precipitation data, runoff coefficient, roof areas, water demand, and water supply reliability are necessary to design a better system to estimate the storage tank volume and water savings (WS). The storage tank volume may vary between countries according to water consumption habits. In Uganda, a 50 m^2 roof area and a 5 m^3 storage tank are required to meet the household consumption level, which is 5 liters per capita per day (lpcd) (Kisakye & Van der Bruggen 2018).

Bashar *et al.* (2018) conducted a study on rainwater harvesting reliability and economic analysis for a multi-story building with 50 inhabitants and a 200 m^2 roof area. It is obtained that 500–800 m^3 water conservation between 30 and 40% reliability can be achieved with a payback period between 2 and 6 years. In a study conducted for urban rainwater harvesting in New York City, Chicago, Philadelphia, and Seattle, as a result, it was obtained that a roof area of 100 m^2 and a 5 m^3 storage tank may reduce runoff volume and, consequently the water demand about up to 65–75% in four cities (Rostad *et al.* 2016). In Jordan, using rainwater harvesting cisterns to harvest 88,335 m^3/year of water, it was found that rainwater harvesting at the household level was practical to conserve an average of 24% water demand annually (Assayed *et al.* 2013). In Lebanon, 23 Mm^3/year of rainwater could be harvested, and this amount of water may cover a 70% water deficit in the domestic water supply (Traboulsi & Traboulsi 2017).

Rainwater harvesting is economically practical in regions with humid and semi-humid climates. However, it is not financially practical to install RHS in arid regions (Jing *et al.* 2017). For RHS viability in arid regions, some regularizations should be conducted prior to the system's design. For the residential water harvesting system, the influence of seasonality on rainwater harvesting is considered in the developed optimization model (García-Montoya *et al.* 2015).

Economic analysis might be addressed by various methods. However, net present value (NPV) and discounted payback period (DPP) are the most common performance indicators. The economic/financial performance of the RHS in rural areas of Beijing was assessed by Liang & van Dijk (2011). It has been highlighted that the RHS is economically feasible. RM for tank sizing and, NPV and DPP methods for the economic assessment of RHS were used by Yoshino *et al.* (2014). Economic analysis using NPV and DPP methods for rainwater usage in toilet flushing was carried out in Slovakia and Poland. Possible water saving of 29 and 18% were found for the facilities located in each country (Stec & Zeleňáková 2019). In a study of economic analysis of an RHS in a commercial building in Braga, Portugal, it is stated that the discount rate (DR) used for cost benefits studies is 6% on average not including the inflation rate. The DR of 5 and 10% is used in their study (Matos *et al.* 2015). In a study of economic analysis of RHS conducted in Brazil a DR of 0.0–10% is used and the inflation rate is not considered by Severis *et al.* (2019). Zhang *et al.* (2009) conducted a study for high-rise residential buildings in Australian cities, and in this study, a 6.5% DR not including inflation rate is used for the economic analysis of RHS. Various discount rates of 5, 7, and 10% considering inflation rates of 3, 4, and 5% was used for economic analysis of rainwater harvesting systems in Melbourne, Australia (Khastagir & Jayasuriya 2011). A DR of 5% and the inflation rate of 4.5% are considered by Jurga *et al.* (2020) for the economic analysis of rainwater harvesting in Poland. In Jordan, a 5% DR without considering the inflation rate is used for rainwater harvesting economic analysis (Abdulla 2020).

Previous studies on rainwater harvesting in Türkiye are neither much in quantity nor very comprehensive. These studies are mainly limited to specific university campuses, dormitory buildings, and industrial zones. In a study conducted by İncebel (2012), for an industrial zone in Ankara, it was found that 8,500 m^3/year of rainwater can be harvested from the rooftops of 52 companies. In another study conducted by Dala Ali (2016) for two dormitories in Istanbul, it was found that 20 and 14% of water conservation could be achieved by using a rooftop RHS. In Izmir, it is possible to save 20 m^3/year of water by installing a 1 m^3 storage tank (Tanık *et al.* 2016). As a result of a study conducted on the campus in Türkiye by Harb (2015), rainwater harvesting is practical to supply 41.2% of the irrigation demand of the campus. Şahin & Manioğlu (2019) assessed two different scenarios on rainwater harvesting efficiency and water conservation for two different cities in Türkiye.

In a new regulation in Türkiye under the title of 'Regulation on the Amendment of the Planned Areas' prepared by the Ministry of Environment and Urbanization and enacted on 11 July 2021 (Official Gazette 2021), it is mentioned that a rainwater collection system needs to be installed on new buildings. With this regulation, considering the increasing drought problems, it is obligatory to construct a rainwater collection system to collect the rainwater from the roofs of all buildings to be built on parcels larger than 2,000 m^2. It is stated in the regulation that the collected rainwater should be filtered and stored in the tank for the use of toilet flushing primarily. Excessive collected water can be used for garden irrigation. However, the calculation of the volumes of the storage tanks in the regulation is not very clear, only mentioning that the storage tank volume should be calculated based on the maximum average monthly precipitation of the province and the roof area of the building. By the effectiveness of this regulation, it has been announced that there will be many incentives for RHS in Türkiye. Hence, by the enforcement of this regulation, there will be an increase in RHS applications in Türkiye. This paper may give an idea to decision makers and researchers for these prospective incentive activities and investments at the province level.

The objective of this study is to assess the economic feasibility of RRH for residential and public buildings at the province level in Türkiye and to investigate the influence of precipitation regime on regularization needs that affects economic assessment. Therefore, optimal storage tank estimation for two scenarios (6-member family residential building and 20-employee public building) is evaluated to supply water demand for toilet flushing in all provinces in Türkiye. Various roof areas are selected as minimum area to supply the water demand of toilet flushing for around 90% volumetric reliability. Eight months of regularization is conducted for provinces that have concentrated precipitation index values. Finally, economic analysis is conducted considering water tariff at province level by incorporating two performance indicators, the NPV and the DPP for all provinces to assess the feasibility status of rooftop RHS and the impact of the regularization.

2. MATERIAL AND METHODS

The precipitation data were obtained from the Turkish State Meteorological Services. Total monthly precipitation data from 1960 to 2017 were used in this study. The data from 81 central meteorological stations represent all the provinces of Türkiye.

Precipitation concentration index (PCI) was used for precipitation regime analysis to reflect precipitation concentration in all meteorological stations. PCI results were utilized as a decision tool for determining regularization needs for designing optimal storage tanks. Monthly precipitation data were used while conducting PCI analysis. Various minimum roof areas were selected considering monthly water demand and volumetric reliability to estimate potential precipitation volume. The application of the regularization procedure is to decrease the volume of storage tanks considering only rainy months in the year for rainwater harvesting systems. Based on the precipitation regime analysis part of this study, 8 months of regularization was found appropriate in Türkiye. RM was used for optimal storage tank estimation. Average monthly precipitation data were used for estimating the optimal volume of storage tanks. A conceptual model of the study is illustrated in Figure 1.

The distribution of water use in public buildings and residential buildings varies significantly. In commercial buildings in Portugal and Brazil, 74% of supplied water is used in toilet flushing (Sousa *et al.* 2018) while the amount of water used for toilet flushing in residential buildings in Türkiye is about 30% of all supplied water for those buildings (Şahin 2010). These values should also vary depending on the type of households (low vs. high density, income, etc.) and building types. The figures should also vary across regions/provinces; however, the water demand for toilet flushing in urban can be assumed as 18–24 lpcd, considering the average needs of flushing reservoir volumes (DIN 1989; Belmeziti *et al.* 2013; Okutan & Akkoyunlu 2021).

The water tariff varies by the province. The water price of a cubic meter varies between $0.17 and $1.42 for residential buildings and between $0.49 and $2.34 for the public/commercial buildings depending on the province. The water price for public buildings is higher than the water price for residential buildings in every province of Türkiye. This rate varies significantly depending on the province and might be higher up to six times in some provinces. In Annex 1, water tariff at the province level is provided as supplementary material.

2.1. PCI and RM

Many methods for concentration analysis of precipitation data have been used worldwide. The PCI is often used to determine the temporal distribution of precipitation patterns. In a study conducted in Türkiye to reflect the concentration of precipitation concentration, PCI was found to be more appropriate than Modified Fournier Index (Apaydin *et al.* 2006).

PCI (Oliver 1980) was calculated as an indicator of the concentration of precipitation for each year in the precipitation dataset for 81 provinces of Türkiye. Then, the average values of annual PCIs were calculated for obtaining temporal PCI to reflect each province's precipitation regime. Temporal PCI was calculated by using Equation (1), where Pi represents the monthly precipitation in the ith month.

$$\text{PCI annual} = \frac{\sum_{i=1}^{12} \text{Pi}^2}{\left(\sum_{i=1}^{12} \text{Pi}\right)^2} \times 100 \quad (1)$$

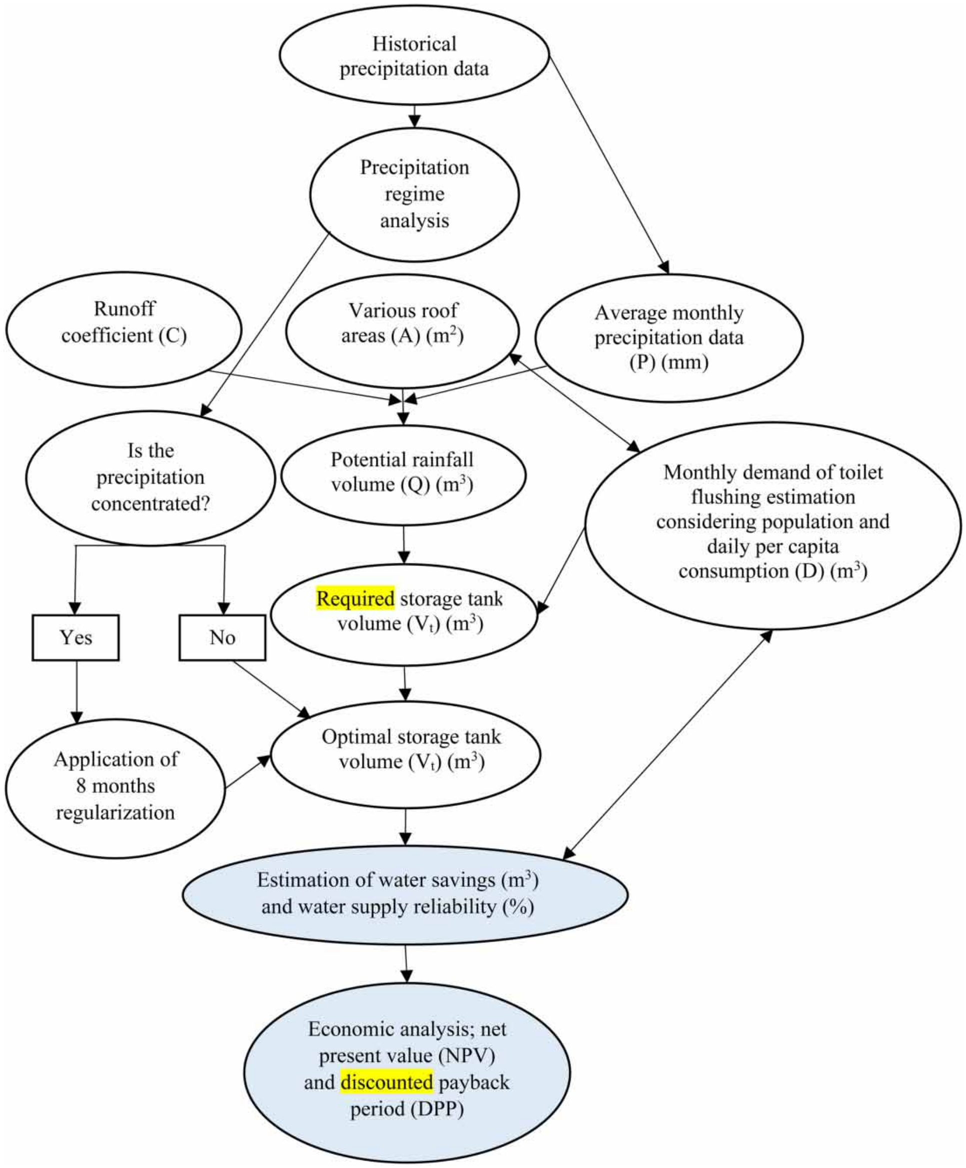


Figure 1 | Conceptual model of the study (modified from Himat (2018)).

The PCI values smaller than 10 indicate the uniform distribution of precipitation throughout the year. The values between 10 and 20 indicate seasonality and, the values greater than 20 indicate that the precipitation is irregular throughout the year. The classification of PCI is given in Table 1.

The RM corresponds to the maximum (positive) accumulated differences between the water demand and the collected rainwater. Some parameters such as average monthly precipitation data, monthly water demand, losses related to leakage/

Table 1 | Classification of precipitation concentration index (Oliver 1980)

PCI	Temporal PCI concentration
<10	Uniform
11–15	Moderate
16–20	Concentrated
>20	Very concentrated

evaporation, and water collection areas are used to estimate storage volume using RM. The list of data required for estimating storage tanks by RM is given by Tomaz (2003).

2.2. Calculation of water demand and potential rainwater harvesting

This study assumes that the water demand for toilet flushing is the same for all urban areas in all provinces in Türkiye. Thus, the water demand for toilet flushing is 24 lpcd in residential buildings (DIN 1989; Okutan & Akkoyunlu 2021). That sums to a daily water demand of 144 L for a family of six members, monthly water demand of 4.32 m^3, and annual water demand of 53 m^3 in the residential buildings. The water demand for toilet flushing in public buildings is 18 lpcd, following Belmeziti *et al.* (2013). Furthermore, assuming 20 employees in each building makes daily water demand of 360 L, monthly water demand of 10.8 m^3, and annual water demand of 131 m^3 in public buildings.

Various minimum roof areas were selected as collecting areas to ensure volumetric reliability of around 90% in each province, considering varying precipitation and a whole number for both roof area and tank size. Roof areas were chosen as multiples of 10 m^2 and standard tank volumes were chosen such as 2, 3, 5, 10, 15, 20, 25, 30, 40 m^3.

Q (the volume of monthly rainwater) was calculated considering losses (EL) and by multiplying P (average monthly precipitation) by A (collecting area) with the coefficient of flow on impermeable areas (C) according to DIN (1989) as seen in the following equation.

$$Q(\mathrm{m}^3) = \frac{(P - \mathrm{EL}) \times C \times A}{1,000} \tag{2}$$

P is the average monthly precipitation,
EL denotes the precipitation losses (0.067 mm/day, 2 mm/month, 24 mm/year) (Martin 1980),
C is the flow coefficient of (80–85%) was recommended by (DIN 1989) for impermeable areas in this study 80% value was selected for tile roofs,
A is the collecting area (m^2).

Volumetric reliability (water saving efficiency) is the ratio between water supply and demand. Reliability shows how much the storage tanks meet the needs of the users. In this study, volumetric reliability, the water demand in toilet flushing, which could be supplied with rainwater, was considered. Volumetric reliability is calculated by using the following equation.

$$\text{Volumetric reliability } (\%) = \frac{\text{Water supply}}{\text{Water demand}} \times 100 \tag{3}$$

Water saving is calculated by using Equation (4), where WS is the saved cost in US$, V_h is the amount of stored rainwater (m^3), and W_t corresponds to the various water prices (Annex 1) for each province with different tariffs ($/$m^3$) depending on the building type.

$$\mathrm{WS} = V_h \times W_t \tag{4}$$

The operational and maintenance costs (OMC) would apply to the time and use of the system. OMC is considered as 1% of the investment cost for each year (Khastagir & Jayasuriya 2011).

Demand and supply difference (DSD) is the difference between D (monthly water demand, explained above as 4.32 and 10.8 m^3 depending on the building type) and Q (the volume of monthly rainwater). Cumulative differences in demand and supply are calculated by ignoring the negative values of DSD in the first months. The maximum positive cumulative differences between demand and supply correspond to the minimum volume of the storage tanks.

2.3. Economic analysis of RRH system

The types of storage tanks were selected based on economic viability and availability in the local market. Polyethylene storage tanks were considered for 1–25 m^3 volume, and polyester storage tanks were considered for larger than 25 m^3 volume. The expected lifespan of these tanks is about 20 years. It is assumed in this study that the storage tank cost is responsible for 50% of all costs (Farreny *et al.* 2011), and accessories cost for the rest 50%.

The net present value (NPV) is evaluated for the feasibility status of the rooftop RHS in this study, following Khastagir & Jayasuriya (2011), Matos *et al.* (2015), Amos *et al.* (2018), and Abdulla (2020). The NPV on Equation (5) is obtained by subtracting the initial investment of the RRH projects (CF_0) from the present value of its cash flows (CF_t) considering the water inflation rate (WIR) with the DR.

$$\mathrm{NPV} = \left[\sum_{t=1}^{n} \mathrm{CF}_t \frac{(1+\mathrm{WIR})^t}{(1+\mathrm{DR})^t}\right] - \mathrm{CF}_0 \tag{5}$$

The evaluation period (n) to assess the NPV is set to 20 years based on the lifespan of the storage tanks and following previous studies (Zhang *et al.* 2009; Matos *et al.* 2015). CF_t is the difference between cash inflow (WS in Equation (4)) and outflow ($OMC = 1\% \times CF_0$) appropriate to the time (t) of the transaction.

In this study, a DR of 20.7% is calculated using the average of effective maximum interest rates for 1 year + deposits given by commercial banks for the last 72 months (2016-12 to 2022-11) in Türkiye (TCMB 2023) which state banks have lower interest rates than this. The WIR based on the water tariff of various provinces in Türkiye for recent years is calculated as 27.5%. As a decision criterion, a RRH project with $NPV > 0$ (zero) is feasible, and this represents the financial amount that exceeds the remuneration of all factors of rooftop RHS.

The payback period is defined as the number of years needed for the investment to pay for itself through WS. The money value over time is considered for the payback period calculation. The DPP of RHS is calculated using the following equation.

$$\mathrm{DPP} = \text{Years until break even} + \frac{\text{Unrecovered amount}}{\text{Recovery year cash flow}} \tag{6}$$

3. RESULTS AND DISCUSSIONS

3.1. PCI results at the province level

PCI analyses were conducted at the province level to determine the precipitation regime and its impacts on rainwater harvesting tank sizing. As a result, any temporally uniform series of precipitation was not observed in all provinces of Türkiye. The precipitation concentration of the provinces was divided into three categories as moderately concentrated, concentrated, and very concentrated.

The obtained results of PCI at the province level are illustrated in Figure 2. It has been found that the Black Sea, Central Anatolia, Eastern Anatolia, and Marmara Regions have moderately concentrated precipitation. Moreover, Southeast Anatolia, Mediterranean, and Aegean Regions have concentrated precipitation (Figure 2). Among 81 provinces of Türkiye, Antalya,

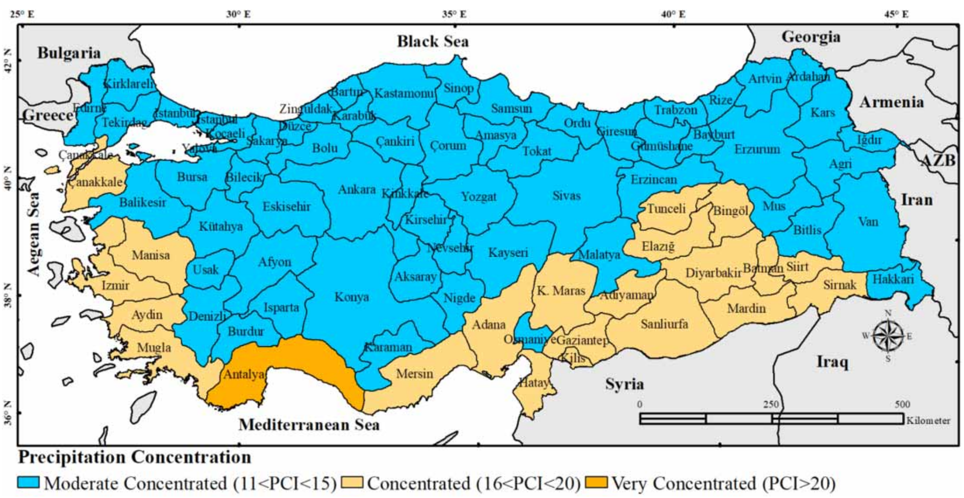


Figure 2 | Precipitation concentration index (PCI) at province level.

located in the Mediterranean Region, is considered the sole province with a very concentrated precipitation pattern (Figure 2).

Regions with a uniform/homogenous distribution of precipitation are the most suitable regions for rainwater harvesting. Precipitation distribution directly affects the RHS efficiency. In provinces with regular precipitation, it is practical to supply the water demand with small storage tanks. In provinces where precipitation is irregular, large storage tanks are required to supply. The RHS would become more feasible when the precipitation series is uniform. As the concentration of precipitation increases, large storage tanks are required for RHS. Thus, the cost of rainwater harvesting will increase due to the large storage tank requirement (Figure 2).

PCI can be used as a decision-support tool for RRH optimal tank volume estimation. For a more feasible RHS, 8 months of regularizations is recommended in provinces that have concentrated and very concentrated precipitation (Figure 2).

3.2. Storage tank volume at the province level

In this section, required storage tank volumes to supply the flushing water demand for residential and public buildings at the province level are discussed. Determination of optimal storage tanks in rainwater harvesting is crucial for designing the system economically. Small rainwater storage tanks are needed in provinces with low fluctuations in the precipitation distribution. Large storage tanks are required in provinces with high fluctuations in the monthly precipitation distribution.

Required roof areas (m^2) and storage tank volumes (m^3) for residential buildings (6-member family toilet flushing water demand, 24 lpcd) are illustrated in Figure 3, while required roof areas (m^2) and storage tank volumes (m^3) for public buildings (20 employees, toilet flushing water demand, 18 lpcd) are illustrated in Figure 4.

Required storage tank volumes vary between 4 and 21 m^3 for residential and 9–52 m^3 for public buildings. Required roof areas vary between 30 and 270 m^2 with an average of 120 m^2 to supply flushing water demand (144 L/day) with 96% average volumetric reliability (varies between 88 and 100%) in residential buildings (Figure 3). And in public buildings, required roof areas vary between 70 and 670 m^2 with an average of 303 m^2 to supply flushing water demand (360 L/day) with 98% average volumetric reliability (varies between 94 and 100%) (Figure 4).

Storage tank cost has half the share of the overall costs of the RHS. According to the obtained results, provinces that require large storage tanks have irregularity and deficiency in the precipitation distribution due to the monthly precipitation (<20 mm), especially during the summer season (June, July, August, and September). Regularization is necessary for provinces that require large storage tank volumes to make the RHS more feasible.

3.3. Economic analysis of RRH system

The cost and DPP besides the feasibility status of rooftop RHS of residential buildings are shown in Figure 5.

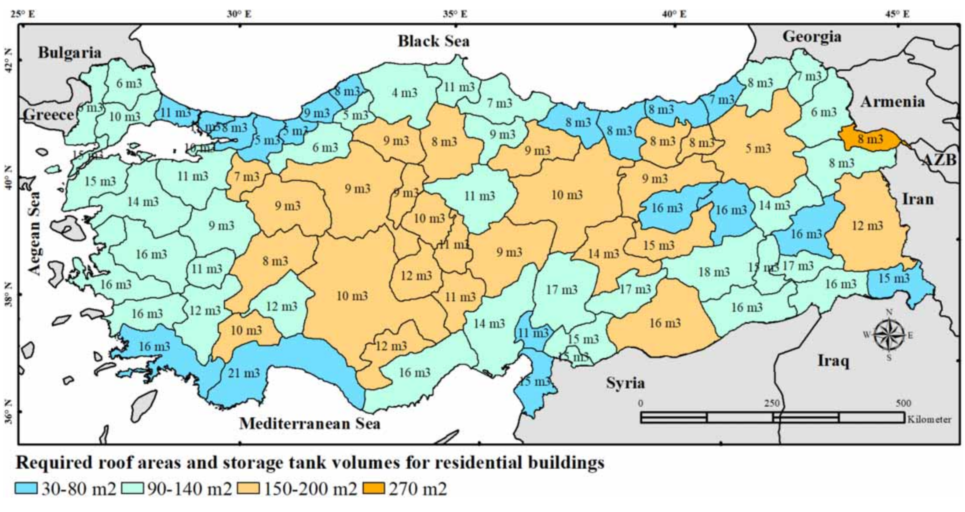


Figure 3 | Required roof areas (m^2, as shown in legend) and storage tank volumes (m^3, as shown on each province) for residential buildings (water demand of 144 L/day) with 96% average volumetric reliability.

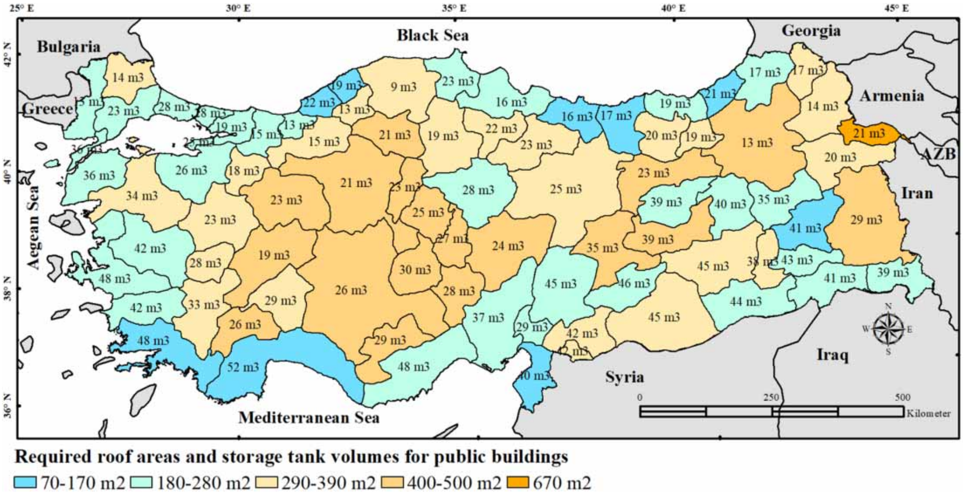


Figure 4 | Required roof areas (m^2, as shown in legend) and storage tank volumes (m^3, as shown on each province) for public buildings (water demand of 360 L/day) with 98% average volumetric reliability.

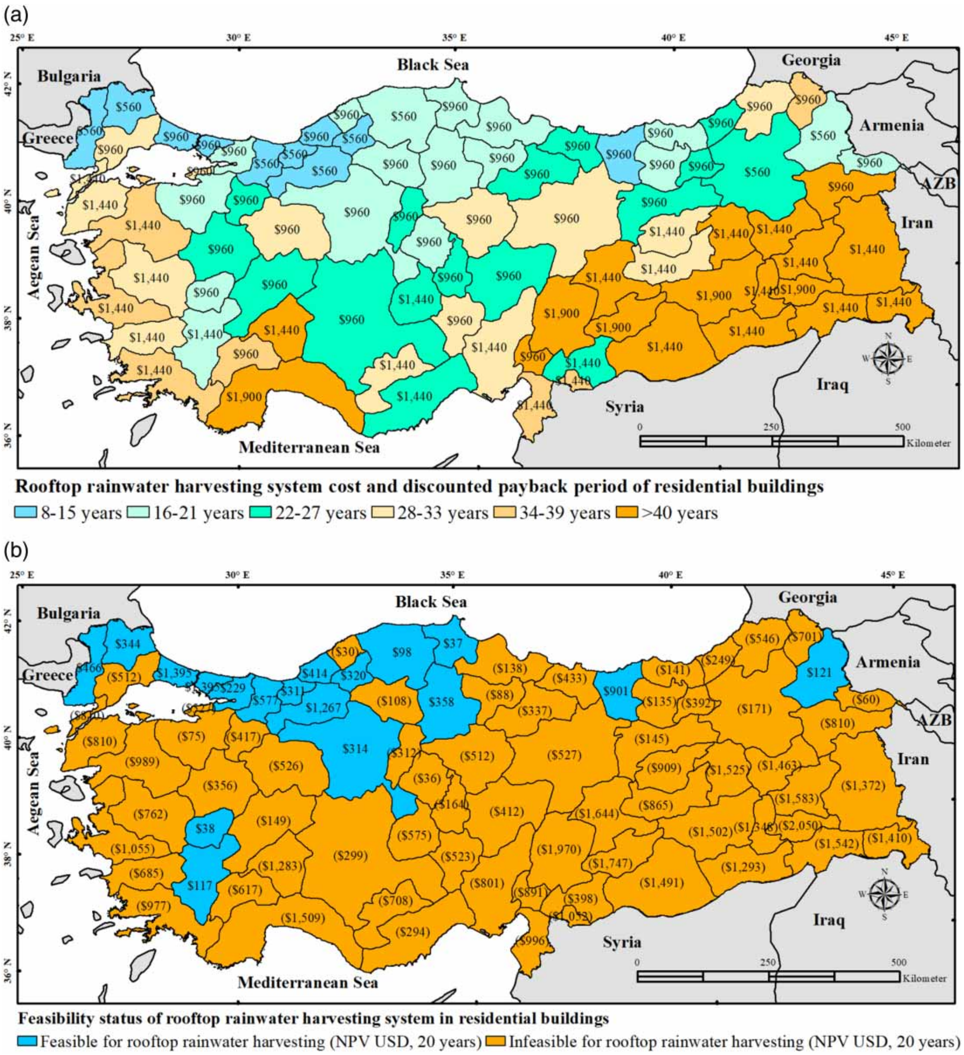


Figure 5 | (a) The cost and DPP and (b) feasibility status, of RHS in residential buildings.

Annual water conservation of 53 m^3 and 10–80 US$ savings/year (depending on the water tariff for each province, given in Annex 1) can be obtained in a 6-member family residential building that uses rooftop RHS to supply water demand for the toilet flushing. The costs of RHS in residential buildings vary between 560 and 1,900 US$ with an average of 1,134 US$, and the discounted payback periods vary between 8 and 100 years with an average of 36 years (Figure 5(a)). The significant difference in the discounted payback periods mainly depends on the size of storage tanks and local water tariffs that vary in each province. Rooftop RHS for residential buildings in 17 out of 81 provinces is found economically feasible while in 64 provinces is infeasible based on the NPV analysis. (Figure 5(b)).

In some provinces, such as Bingöl, Bitlis, Kahramanmaraş, Malatya, Muş, Şanlıurfa, Siirt, and Şırnak in eastern Türkiye, DPPs are found as 100 years which is the limit year for the analysis. These higher DPPs are found due to the very low water tariff. RHS would not be economically feasible for these provinces since the WS are not significant considering the low water price in southeastern Türkiye.

Economic analysis of rooftop RHS for public buildings is shown in Figure 6. Annual water conservation of 131 m^3 and 64–306 US$ savings/year can be obtained using a rooftop RHS for supplying the toilet flushing water of a public building with 20 employees. The costs of RHS for public buildings vary between 960 and 8,000 US$ with an average of 4,154 US$, and the discounted payback periods vary between 4 and 78 years with an average of 23 years (Figure 6(a)). The significant difference

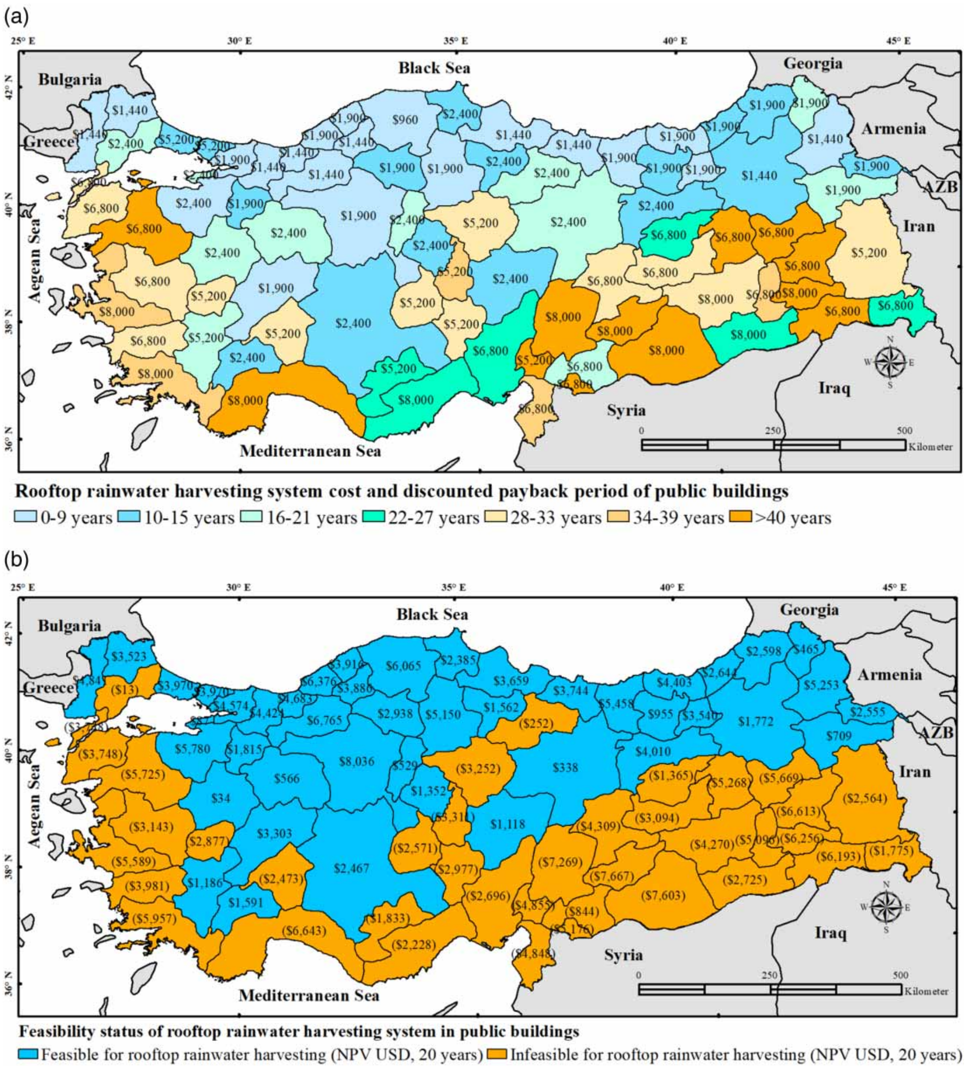


Figure 6 | (a) The cost and DPP and (b) feasibility status, of RHS in public buildings.

in the DPP is mainly due to the size and type of storage tanks and local water tariffs that vary across the provinces. The feasibility status in public buildings as shown in Figure 6(b), RHS in 43 provinces is found as economically feasible and in 38 provinces is as infeasible. Hence, compared with residential buildings, the use of rainwater harvesting in public buildings is more advantageous than in residential buildings in terms of the NPV and DPP.

3.4. Economic assessment of rooftop RHS after 8 months of regularization

The costs of RHS were re-analyzed after making 8 months of regularization for the provinces where large storage tanks were required due to concentrated precipitation found by PCI analysis. The costs and the discounted payback periods, and the feasibility status of rooftop RHS in residential buildings after 8 months of regularization are illustrated in Figure 7. Using harvested rainwater for toilet flushing in a 6-member family residential building, 35 m^3 of water conservation and 6–31 US$ savings in 8 months can be achieved. After 8 months of regularization in the provinces where large storage tanks are required, the cost of RHS in residential buildings varies between 280 and 960 US$ with an average of 597 US$, and the DPP varies between 12 and 52 years with an average of 30 years.

After 8 months of regularization, considering the NPV analysis, residential rooftop RHS is found in 16 out of 28 provinces with concentrated precipitation that are economically feasible while 12 provinces are still infeasible (Figure 7(b)). Furthermore, because of comparing Figures 5 and 7, there is only 1 province (Mersin) out of 16 provinces which was already

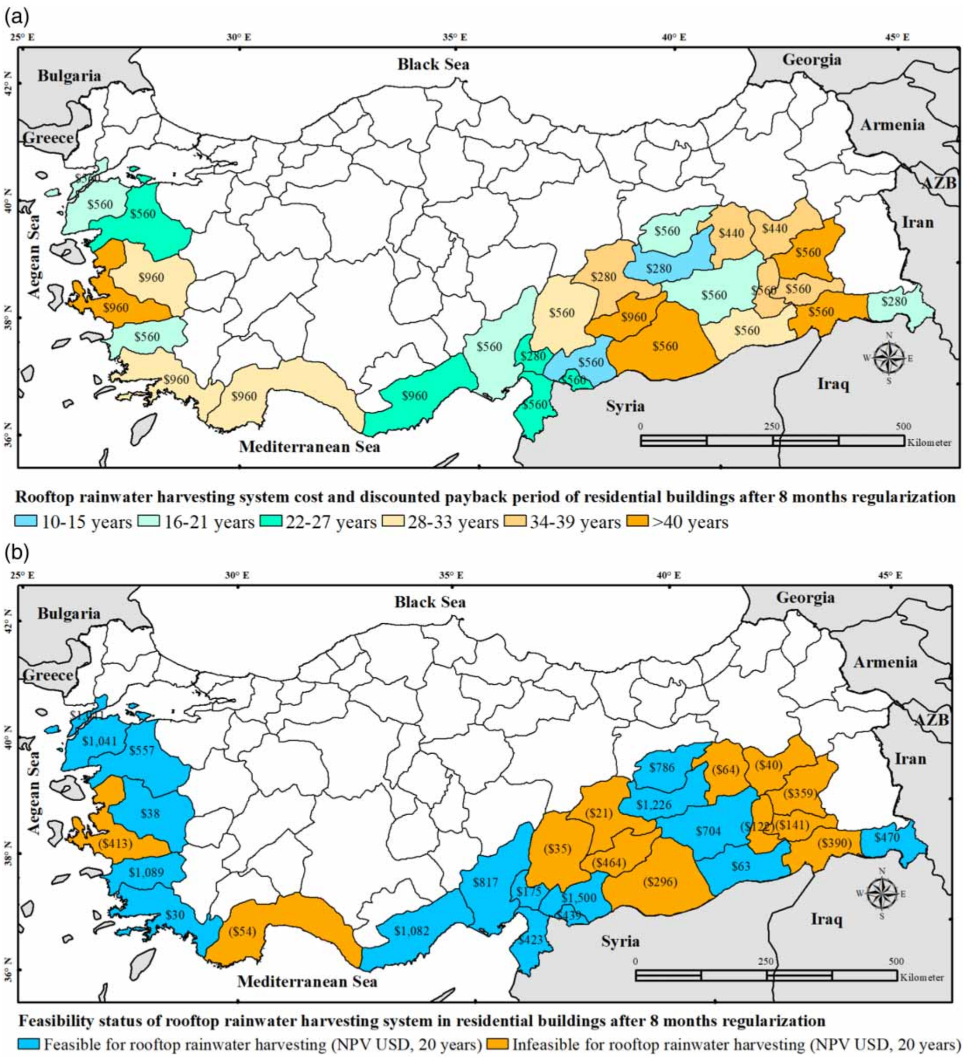


Figure 7 | (a) The cost and DPP and (b) feasibility status, of RHS in residential buildings after 8 months regularization.

economically feasible before the regularization process. After regularization, 15 provinces with concentrated precipitation have become economically feasible for residential rooftop RHS. Furthermore, the average cost decreased by 60% considering the cost of RHS in residential buildings in 28 provinces after 8 months of regularization.

The cost and DPP, and feasibility status of rooftop RHS in public buildings after 8 months of regularization are shown in Figure 8. Water conservation of 88 m^3 and 40–160 US$ savings in 8 months can be achieved using harvested rainwater for toilet flushing in a public building with 20 employees. After 8 months of regularization in the provinces where large storage tanks are required, the costs of RHS in public buildings vary between 440 and 2,400 US$ with an average of 1,249 US$, and the discounted payback periods vary between 3 and 22 years with an average of 11 years. The economic analysis showed that the average cost decreased by 83% considering the cost of RHS in public buildings in 28 provinces after 8 months of regularization.

After 8 months of regularization, rooftop RHS for public buildings in 27 out of 28 provinces with concentrated precipitation isfeasible (Figure 8(b)) as indicated by the NPV analysis. Furthermore, as a result of comparing Figures 6 and 8, the rooftop RHS in public buildings in 28 provinces with concentrated precipitation, 12 provinces which were infeasible before regularization have become economically feasible after 8 months of regularization. Only 1 province (Antalya) still remains economically infeasible after regularization which was already economically infeasible before the regularization process.

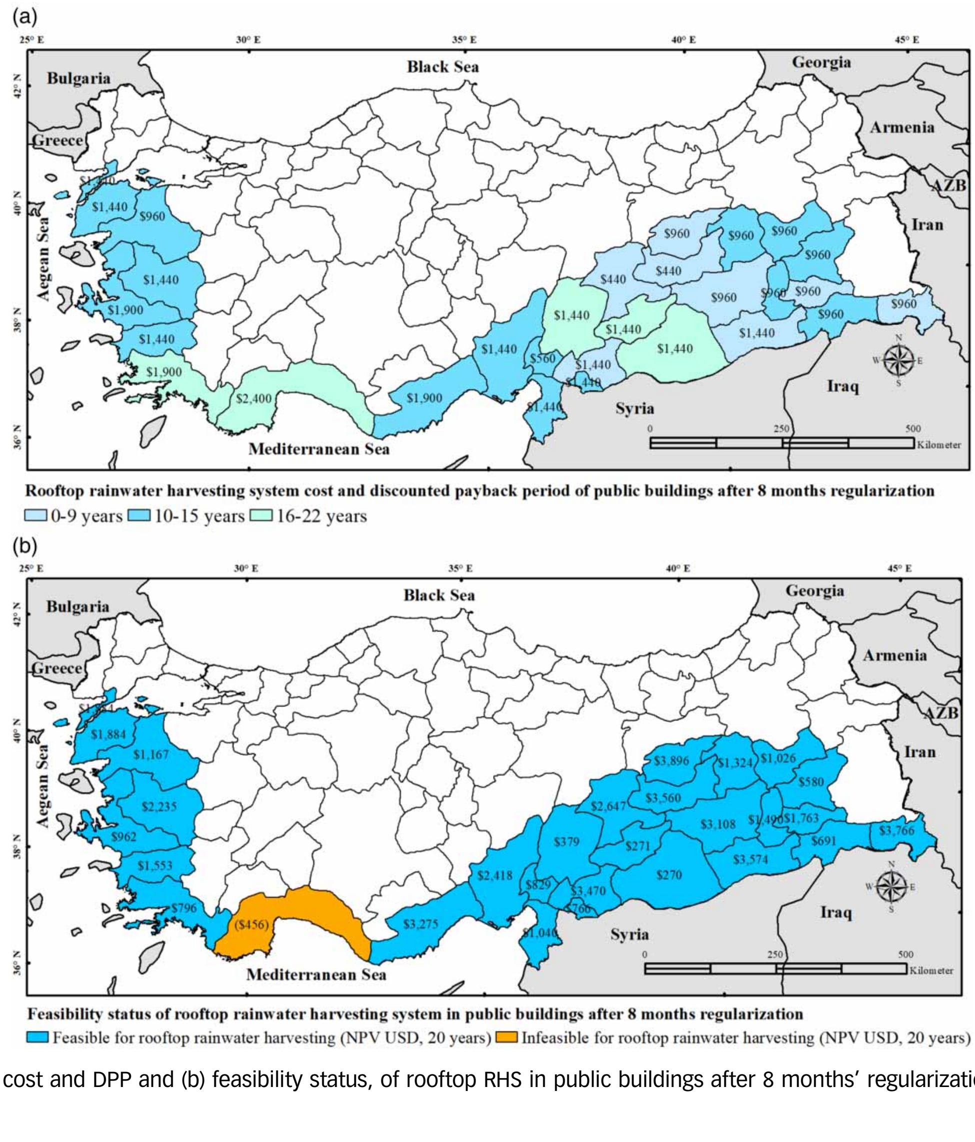


Figure 8 | (a) The cost and DPP and (b) feasibility status, of rooftop RHS in public buildings after 8 months' regularization.

In this section, 8 months of regularization has been conducted to investigate the impacts of the precipitation regime on tank sizing and RHS cost. For the optimal design of a domestic RHS, a dimensionless methodology is assessed by Campisano & Modica (2012). It has been reported that the economic suitability of large storage tanks decreases as rainwater availability decreases. For tank sizing and economic analysis of rainwater harvesting, 7 months of regularizations were conducted for three scenarios in a commercial building located in Braga city of Portugal. After the regularization, the RHS cost decreased significantly (Matos *et al.* 2013, 2015). In Portugal, for single-family residences, technical feasibility and economic viability of the RHS were assessed, and it has been reported that water fees influenced the economic viability (Silva *et al.* 2015).

In this study for Türkiye, the average cost of RHS decreased about 60% in residential buildings and 83% in public buildings after 8 months of regularization. Therefore, at a first glance at the costs, it might be assumed that regularization is not strongly effective in residential buildings compared to public buildings. However, it is not true once the number of feasible provinces is considered after regularization. For residential rooftop RHS, 15 provinces out of 28 with concentrated precipitation have become economically feasible after regularization while this number is 12 in public buildings.

4. CONCLUSION AND RECOMMENDATIONS

A significant amount of water conservation and savings can be obtained effectively by using an RHS in buildings with large roof areas, such as public and residential buildings. The RHS efficiency is directly influenced by the precipitation concentration. Therefore, precipitation regime analysis should be investigated prior to the RHS design. PCI can be used as a decision-support tool for the optimal tank design. Large storage tanks are required in provinces with higher PCI values. Rainwater harvesting is economical due to the small storage tank requirements in provinces with moderate PCI. Moreover, there is not much need for regularization in provinces with moderate PCI. In general, provinces with dry summers require larger storage tanks for rainwater harvesting. 90% of the total precipitation occurs in 8 months of the year in most provinces of Türkiye. Larger storage tanks are required in the Aegean, Mediterranean, and Southeastern Anatolia Regions than in other regions due to the high seasonality in the precipitation. Hence, in these provinces during June, July, August, and September, rainwater harvesting is not effectively applicable due to the deficiency of precipitation. The priority for RRH incentive projects might be given to the provinces due to precipitation amount or concentration. However, the feasibility of RHS does not solely depend on the precipitation amount or concentration. Furthermore, this study has shown that some provinces that require similar or even larger tank volumes might be more feasible considering water tariffs.

Using the RHS in residential buildings to supply the demand of toilet flushing of a 6-member family, annual water conservation of 53 m^3 between 88 and 100% volumetric reliability and 10–80 US$ savings/year can be achieved. The cost of RHS for residential buildings varies between 560 and 1,900 US$ with an average of 1,134 US$, and the discounted payback periods vary between 8 and 100 years with an average of 36 years. After 8 months of regularization for the provinces with concentrated precipitation, 35 m^3 of water conservation between 89 and 100% reliability and 6–31 US$ savings in 8 months can be achieved. The cost of RHS in residential buildings may decrease to 280–960 US$ with an average of 597 US$, and the discounted payback periods may vary between 12 and 52 years with an average of 30 years after 8 months of regularization.

Annual water conservation of 131 m^3 between 94 and 100% volumetric reliability and 64–306 US$ savings/year can be achieved using the RHS to supply the demand for toilet flushing in public buildings with 20 employees. The cost of RHS for public buildings varies between 960 and 8,000 US$ with an average of 4,154 US$, and the discounted payback periods vary between 4 and 78 years with an average of 23 years. Accordingly, rainwater harvesting in public buildings is more advantageous than in residential buildings. After 8 months of regularization, 88 m^3 of water conservation between 94 and 100% volumetric reliability and 40–160 US$ savings can be achieved in public buildings. The cost of RHS may decrease to an average of 1,249 US$ (440–2,400 US$), and the discounted payback periods decrease to an average of 11 years (3–22 years).

Eight months of regularization in 28 provinces leads to a decrease in the average costs of RHS by 83 and 60% in public and residential buildings, respectively.

As a result of the NPV analysis, it is found that 17 out of 81 provinces are economically feasible and 64 provinces are infeasible for residential rooftop RHS. The feasibility status in public buildings is more than half in terms of being feasible and infeasible compared to all 81 provinces. The NPV analysis showed that 43 provinces are economically feasible while 38 provinces are infeasible for public buildings. After 8 months of regularization, it is found that 16 out of 28 provinces with concentrated precipitation are economically feasible and 12 are still infeasible for residential rooftop RHS. After 8 months of regularization for public buildings, 27 out of 28 provinces with concentrated precipitation are feasible for rooftop RHS.

Hence, even in provinces with concentrated precipitation with 8 months of regularization the rooftop RHS in public buildings is economically feasible. The NPV analysis showed that regularization has a significant impact on the economic analysis of rainwater harvesting.

The installation of a rooftop RHS is mandatory in new buildings with roof areas larger than 2,000 m^2 in Türkiye by the new regulation enacted in 2021. City administrations may also impose obligations on the rainwater collection system to be built in smaller parcels, the collecting tank volume calculation method, and additional usage areas (Official Gazette 2021). Many countries suffer from drought and water scarcity. These countries might also enact their regulations on rainwater harvesting. This study might be helpful to understand the feasibility status, costs, and payback periods of the RHS better and would be scalable for both Türkiye in terms of various scenarios and other countries.

4.1. Recommendations

- It is recommended to perform regularizations to ensure that the RHS is practical and economical in provinces where precipitation falls in certain months.
- The implementation of rainwater harvesting projects in the Aegean, Mediterranean, and South-eastern Anatolia Regions in Türkiye provides the beneficial use of water. On the other hand, the effects of floods can be mitigated.
- Due to the seasonality in precipitation in the Aegean, Mediterranean, and Southeast Anatolia Regions in Türkiye. In other regions with similar seasonality, rooftop RHS should be regularized to make them more feasible.
- Considering the higher share of toilet flushing in water demand in public buildings and its higher water tariff compared to residential buildings, the installation of RHS in public buildings should be prioritized, especially in provinces that suffer from water scarcity.
- The priority should be given to rainwater harvesting projects in the regions where it is economically feasible and floods occur frequently, not only for water conservation and savings purposes but also to mitigate floods.
- Application of an RHS should become mandatory in new building constructions, especially in regions that suffer from water scarcity. Enforcement of the regulation may decrease the stress on water resources and water supply demands.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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