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Smart Rainwater Harvesting for Sustainable Potable Water Supply in Arid and Semi-Arid Areas

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Abstract: This paper presents a smart rainwater harvesting (RWH) system to address water scarcity in Palestine. This system aims to improve the water harvesting capacity by using a shared harvesting system at the neighborhood level and digital technology. The presentation of this system is organized as follows: (i) identification of the challenges of the rainwater harvesting at the neighborhood level, (ii) design of the smart RWH system architecture that addresses the challenges identified in the first phase, (iii) realization of a simulation-based reliability analysis for the smart system performance. This methodology was applied to a residential neighborhood in the city of Jenin, Palestine. The main challenges of smart water harvesting included optimizing the shared tank capacity, and the smart control of the water quality and leakage. The smart RWH system architecture design is proposed to imply the crowdsourcing-based and automated-based smart chlorination unit to control and monitor fecal coliform and residual chlorine: screens, filters, and the first flush diverter address RWH turbidity. Water level sensors/meters, water flow sensors/meters, and water leak sensors help detect a water leak and water allocation. The potential time-based reliability (R_e) and volumetric reliability (R_v) for the smart RWH system can reach 38% and 41%, respectively. The implication of the smart RWH system with a dual water supply results in full reliability indices (100%). As a result, a zero potable water shortage could be reached for the dual water supply system, compared to 36% for the municipal water supply and 59% for the smart RWH system. Results show that the smart RWH system is efficient in addressing potable water security, especially when combined with a dual water supply system.

Keywords: dual water supply; Palestine; rainwater harvesting; simulation; smart water; water scarcity

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1. Introduction

This paper introduces smart rainwater harvesting (RWH) and smart dual water supply systems to promote sustainable water security. RWH is an ancient practice that dates back to 2000 years BC [1]. It has been widely adopted in several countries worldwide including India [2], Sri Lanka [3], Kenya [4], Zambia [5], Ghana [6], Pakistan [7], Jordan [8,9], Afghanistan [10], Egypt [11], and Bangladesh [12]. The application of this paper targets water-scarce areas, such as the West Bank in Palestine. Such areas face severe environmental challenges [13], particularly a decrease in freshwater, population growth, and contamination of water resources [14–19]. Moreover, conventional water supply systems have limited capacity to meet water demand [20]. For example, in the West Bank, conventional systems can provide only 60% of the domestic water demand [21]. In addition, scholars highlighted the vulnerability of the water system to contamination [19,22,23].

Several authors presented the advantages of using RWH [15,24–26]. Conventional rooftop RWH systems include a collection catchment, conveyance, and storage tanks [27].

These systems have several strengths, including (i) independency, (ii) proximity of RWH storage tanks to users, (iii) ease of construction and maintenance, (iv) erosion and flood mitigation, and (v) reduction of pressure on water resources [7,28]. However, these conventional systems have some limitations [29], particularly a lack of control of the quality of the harvested water potability [29]. As a result, the RWH is perceived as an undrinkable source of water worldwide [30–32]. In addition, conventional systems don't monitor (i) the filling and emptying process of the storage tanks, or (ii) the water leakage [33]. These processes are governed considering different factors: rainfall volume and intensity, tank storage capacity, and water demand [33].

Scholars proposed smart technologies to enhance the engineering systems' efficiency and overcome their limitations [34–38]. Smart technologies use real-time and historical data to improve the performance and resilience of urban systems [34–37]. They are used in different fields such as health [39,40], transportation, mobility [41,42], indoor risk management [43], energy [44], and environment [45]. They are also used to enhance water supplies [46,47], monitor urban water networks [48,49], detect water leakage [50,51], monitor water quality [52–54], and enhance water resources management [55–58].

Concerning RWH, scholars introduced smart technologies to address the shortcomings of the conventional RWH systems on the household level [33,59] with a focus on a single-aspect upgrade [33,59] on either water quantity or water quality. Ref. [33] discussed using IOT-based sensors to control the water level in RWH tanks. This use secures sufficient spare in the tank to receive the runoff following storm events. It has been found that adopting water-level monitoring in RWH tanks can pointedly mitigate urban flooding and secure non-potable water supply [33]. Ref. [59] discussed using an IOT-based water quality sensor to control the quality of harvested water. The sensor helps in diverting the harvested water (based on its pH value) into two storage tanks: potable and non-potable tanks. Harvested water in the tanks is then directed to the most appropriate uses (e.g., drinking and irrigation). However, the use of pH to control the harvested water potability is controversial [19]. The World Health Organization (WHO) stated the vulnerability of RWH to physical (e.g., turbidity), chemical (e.g., nitrate, lead, and zinc), and biological contamination (e.g., coliform) [60,61]. The type of contamination depends on different factors, including (i) the RWH's surrounding activities (e.g., urban, industrial, and agricultural activities) and (ii) roofs, pipes, and storage tanks materials [60,61]. Scholars proposed several decentralized systems for the treatment of rainwater, such as chlorination [62], pasteurization [63], ultraviolet light (UV) [64], filtration [65], boiling [66], and a combination thereof [67]. The characterization of sources, types, and levels of RWH contamination is of high importance in order to adopt the most suitable treatment units in the smart RWH system.

Considering the challenges of water harvesting and the limitations of the conventional water harvesting system, this paper proposes an innovative smart water harvesting system that combines (i) water tank sharing at the neighborhood level, and (ii) a dual water supply system. The novelty of the proposed system stems from its ability to smartly monitor the water quality, water level, and water leakage, and to increase the harvesting efficiency through enhancing the water sharing capacity at the neighborhood level.

2. Materials and Methods

The methodology adopted in this research involves three phases, as shown in Figure 1. The first phase targets the characterization of the potential causes of RWH contamination and insufficiency. Phase 2 employs the characterization outputs to design the smart RWH system architecture. The last phase aims at performing a reliability analysis of the smart system performance.

2.1. Assessment of Conventional RWH Shortcomings

In order to establish an efficient configuration of the required smart system, the research methodology starts by assessing the challenges of the conventional RWH system.

Although RWH is less vulnerable to contamination than surface and groundwater resources, it could be exposed to contamination sources [68,69]. The first source is the atmosphere, as the rain droplets could absorb air contaminants such as nitrite, carbon dioxide, and sulfate [70]. In addition, it could acquire heavy metals due to industrial emissions (e.g., lead, zinc, copper, and cadmium) [71]. The second source is rooftop materials [70] (e.g., lead-based roofs) which are classified as a hotspot for various toxins [72]. The third source is from wastes (e.g., fecal material and leaves), originating from creatures (e.g., birds) and trees, and settled on roofs [72]. These sources could cause physical, chemical, and biological contamination of RWH [73,74]. The type of RWH contamination differs spatially [74,75]. It depends on the surrounding activities that pollute the roofs and air [74,75]. Monitoring and implementing treatment units for these contaminations are complex, costly, and time-consuming [76,77]. Thus, characterizing the probable contaminants and their sources is a core step in constructing an efficient and financially feasible quality monitoring system. This paper characterizes RWH contamination by considering: (i) the spatial sampling of the RWH from different locations, (ii) the laboratory analysis of the collected samples, and (iii) a review of the literature (see Figure 2).

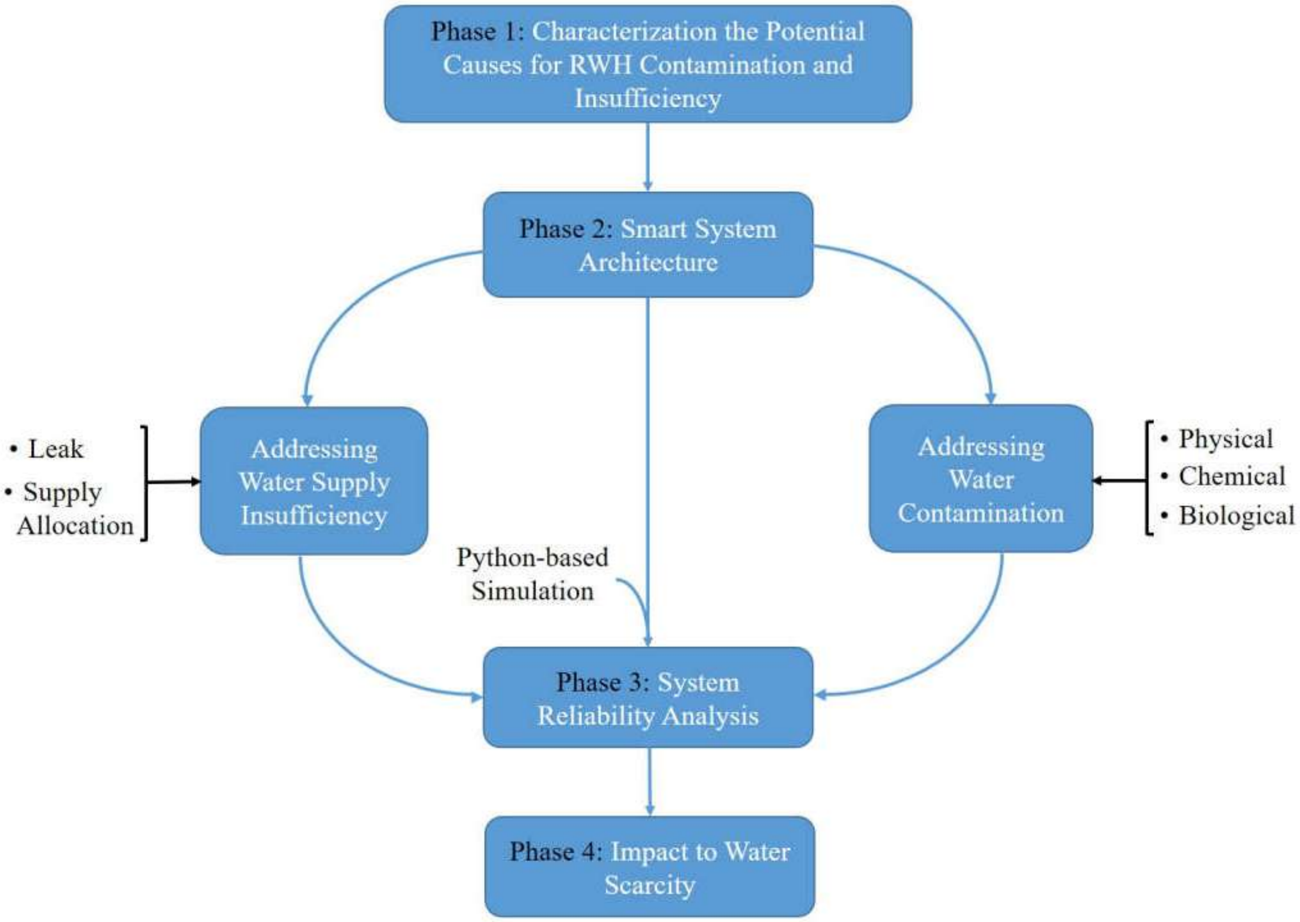


Figure 1. The research methodology used in this research.

The inefficiency of RWH systems in providing a reasonable water supply volume could be attributed to uncontrollable and controllable factors [9,78]. The uncontrollable factors include the rainfall volumes and patterns and the roof area [25]. The controllable ones include the proper sizing of the RWH storage tank, leaks in the RWH system, the efficiency of the RWH system components (e.g., pumps and valves), and the roof type [9,25,78]. Therefore, controlling and monitoring these controllable components is the key to an efficient RWH system.

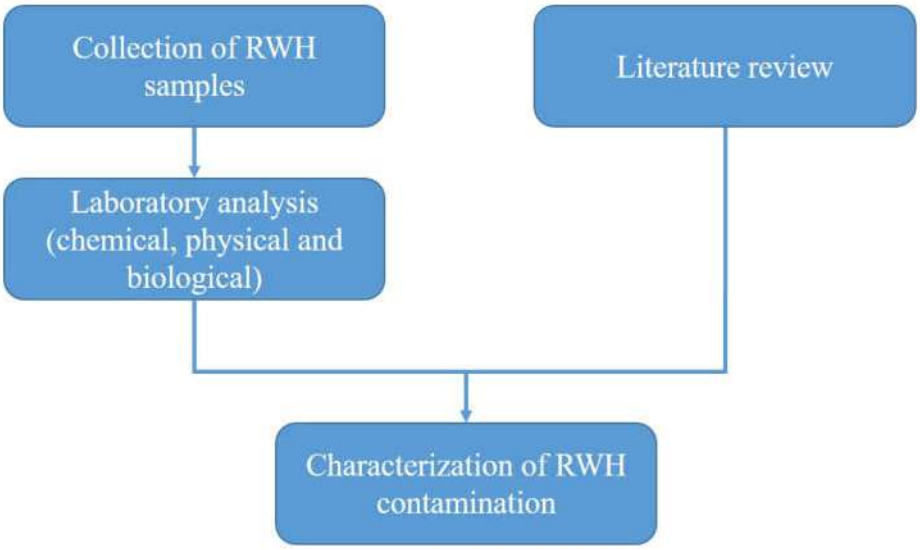


Figure 2. Characterization of RWH contamination.

2.2. Smart RWH System Architecture

The smart RWH system is used to ensure (i) early detection of water contamination and water leak, (ii) the control of water contamination and water leak, (iii) satisfying the needed domestic water demand, and (iv) the wise and sustainable use of available water resources/supply. In addition, the system ensures (i) data collection, (ii) interaction with users, and (iii) the control of the smart system's equipment, such as valves and pumps.

The architecture of the smart RWH system involves six layers, as illustrated in Figure 3. The physical layer includes the physical components of the water harvesting system, the municipal water supply, and the users. The monitoring layer includes sensors used to monitor the water quality, water flow, and the water level in the water tank. The data transfer layer uses wireless technology for data transmission from the monitoring system to the server. The data processing layer operates data cleaning, storage, analysis, and visualization. The control layer includes actuators that control the water flow, such as pumps and valves. Finally, the smart services include the detection of water contamination or water leak, and the optimal tank filling.

2.2.1. The Physical Layer

The water supply, leak, and contamination are influenced by the building's distribution, citizens' density, and the water distribution systems [79,80]. Therefore, the smart water supply system is designed to consider the physical components (See Figure 4), which could be organized into three groups. The first one, "RWH quantity group" is responsible for facilitating the collection of RWH. It involves the building roofs, gutters, shared RWH tank, household water tank, RWH distribution network (from roofs to shared RWH tank and from shared RWH tank to household water tanks), valves, overflow pipe, pump, backflow preventer, municipal water supply, and control panel. The second group, "RWH quality group" is responsible for mitigating/avoiding the contamination of harvested water. It involves the inlet filter, first flush diverter, RWH tank screen, overflow pipe screen, treatment unit, discharge pipe, and flushing unit. The third group, "Beneficiaries group" concerns the users, public authorities, service providers, and policymakers.

The building roofs are considered the catchment area for receiving the falling rainfall droplets. Such droplets are transported through the gutters (channels located around the edge of a sloping roof) to the RWH distribution network. The latter is used to transport the rainwater from the roofs to the shared RWH tank. Valves are used to regulate the water supply. They have three main functions: stopping and starting the water flow, throttling the water flow, and directing the water flow. Pumps transport the harvested rainwater from the shared tank to the household water tank installed on the top of the house. The house tank is also connected to the municipal water system. Backflow preventers are installed to protect the pump.

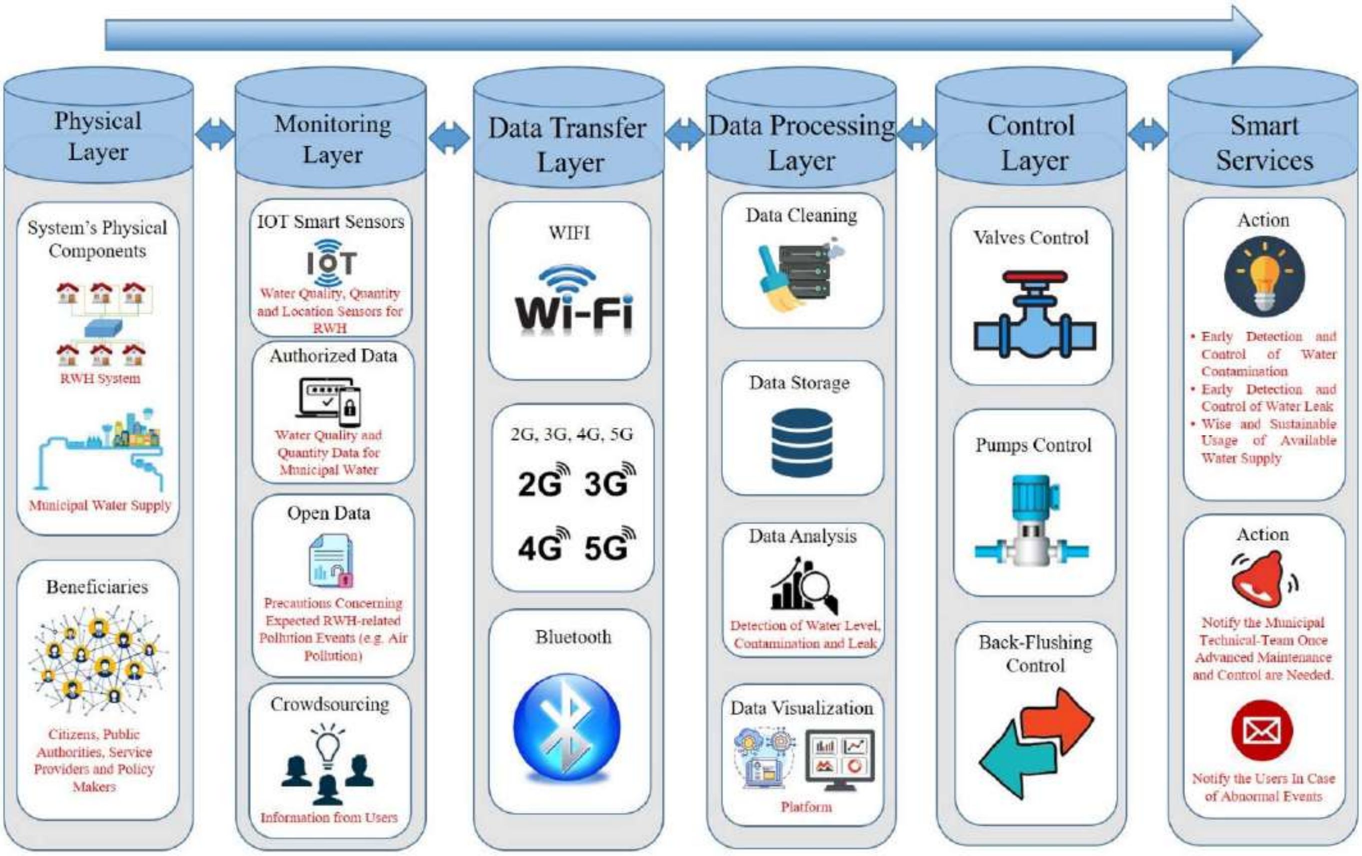
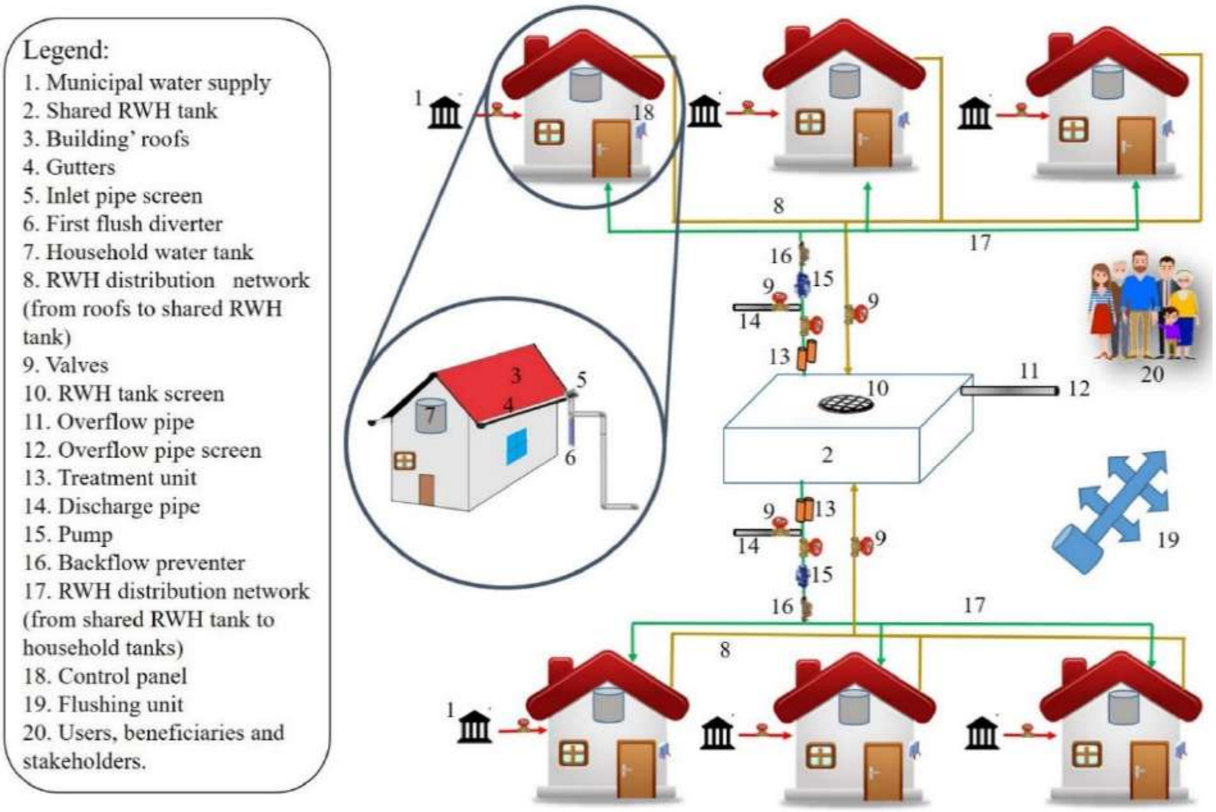


Figure 3. The architecture of the smart RWH system.

An inlet filter is installed to catch the large debris and prevent them from entering the pipe of the RWH distribution network. A first flush diverter is used to capture and divert the contaminated harvested water during the first rain because different substances and deposits could contaminate it on the roof. However, this diverter forms the second defense line since it captures the contaminants not captured by the inlet filter. The RWH tank screen is located at the entry point of the RWH storage tank. It has two main roles: filtering the harvested water before reaching the storage tank, and preventing pests and mosquitos from entering the tank. The overflow pipe screen (filter) is installed at the end of the overflow pipe. It also prevents pests and mosquitos from entering the RWH system. A treatment unit is added to convert the non-potable water into potable water. This unit will be based on the characterization of the probable RWH contamination in the study area. A discharge pipe is installed to discharge the non-potable water away from the distribution network and prevent it from reaching the household water tank. Finally, a flushing unit is added for cleaning, disinfecting, and flushing the RWH system.

The features of the system components depend on the design criteria, cost, and social preference [8,25,81]. Several roofing materials could be used; concrete and the bricks are the most common [25]. Scholars confirmed the impact of roof material on the RWH's collection efficiency [25]. Tow shapes of gutters (based on their cross-section) can be used which are K-style and half-round gutters. They can be made of aluminum, copper, steel, zinc, and fiber-reinforced plastic [81]. Several shapes of storage tanks can be used including rounded, cube-shaped, pear-shaped, or rectangular [8]. They could be made of concrete, steel, or plastic [8]. Installing the properly sized first flush diverter is of high importance to protect the harvested water quality [8].



First group "RWH quantity group": 1, 2, 3, 4, 7, 8, 9, 11, 15, 16, 17, and 18.
Second group "RWH quality group": 5, 6, 10, 12, 13, 14, and 19.
Third group "Beneficiaries group": 20.

Figure 4. Physical components of the smart RWH system.

2.2.2. The Monitoring and Data Transfer Layer

This layer ensures the collection, monitoring, and transfer of data through three groups. The first group, "Collection of RWH quantity data" facilitates the monitoring of water flow, levels, and leak. It involves (i) smart water flow meter to monitor the water flow in the distribution network, (ii) water level sensor to monitor the water level in the shared RWH tank and the household's tanks, and (iii) leak detection sensor: these sensors can detect an indoor water leak for different household equipment. The second group, "Collection of RWH quality data" employs smart water quality devices to monitor the water quality in the RWH system (See Figure 5).

The system also uses crowdsourcing, open data, and authorized data to collect the water supply agenda from the water provider, the weather and air quality forecasting from the relevant authorities, and information from users about the water quality or water shortage in the RWH service [82,83].

The third group, "Data transfer" is responsible for transmitting the real-time data from the meters, IoT sensors, devices, crowdsourcing, open data, and authorized data to the RWH server in order to be processed and analyzed. This is carried out using wireless networks (e.g., WIFI, Bluetooth, and 4G).

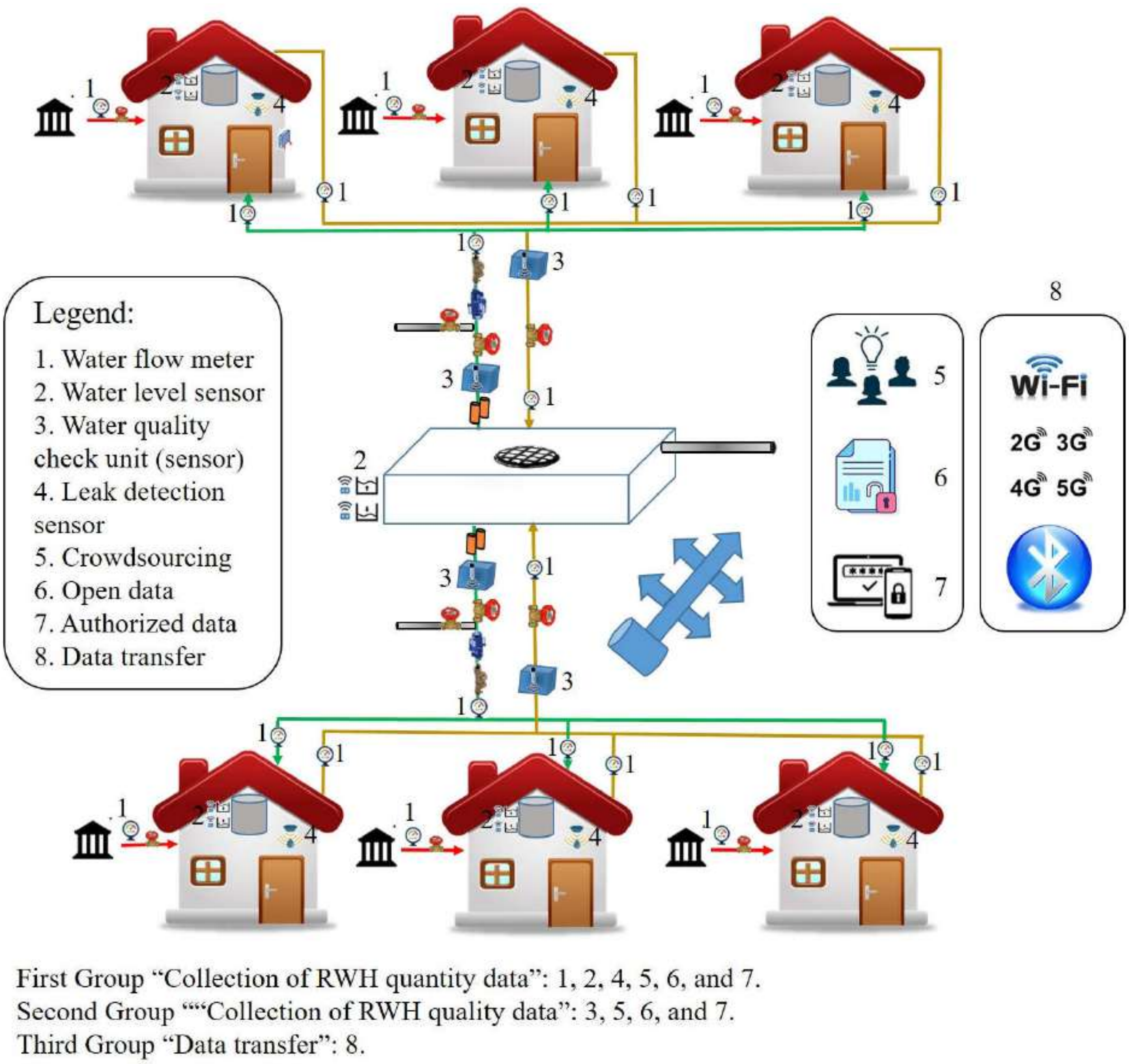


Figure 5. Monitoring components of the smart RWH system.

2.2.3. Data Processing Layer

The data processing layer operates the following tasks: data cleaning, data storage, analysis, and visualization. Data cleaning is the process of guaranteeing data correctness, consistency, and usability [84,85]. It involves detecting and removing/replacing/correcting inaccurate records from the database [43]. The smart system's actions depend highly on the input data [86]. Therefore, cleaning collecting data could significantly help the smart systems avoid inappropriate actions. Data storage includes the containment and integration of collected data in a specific location (database) [87]. The access, calling, and manipulation of stored data should be secured (e.g., using XQuery) [88]. XQuery is a functional language that is employed to retrieve the stored data in XML format [88]. Data analysis converts the collected, cleaned, and stored data into helpful information [89,90], which is then used to conduct suitable actions [89,90]. In this research, data is statistically analyzed. Water quality statistics (minimum, 1st quartile, median, mean 3rd quartile, and maximum) are compared to the drinking water standards stated by the WHO [60]. Statistics concerning water flow, volumes, and levels in the RWH system are analyzed and compared. ArcGIS is also used to facilitate the spatial analysis of data. This analysis helps detect a water leak and allocate water resources to users. Data visualization is the graphical representation of the analyzed data [91,92]. It forms an effective way of communication, especially where the input data is big data (e.g., temporal, spatial, and spatiotemporal data) [90].

Data cleaning, storage, analysis, and visualization are connected to the smart platform. The platform receives real-time data from the water level sensors, water flow meters, and leak detection sensors. It can then detect a water leak in (i) the RWH system, (ii) the municipal water system, (iii) indoor household equipment, and in an (iv) indoor water network. The platform also receives water quality records concerning the treated RWH from the water quality check unit. These real-time records will be available for the users on the platform.

2.2.4. Control Layer and the Provided Smart Services

Following data analysis, the smart system operates control actions of pumps and valves (e.g., via automated system and/or user interface module). Such a module enables the end users to control the system components remotely. For example, pumps will be automatically shut down in case of water contamination to avoid a non-potable water supply. Valves will be used to discharge the contaminated water through the discharge pipes. Moreover, backflushing will be automatically operated to clean and disinfect the RWH system from the contaminants. In a case when a water leak is detected, pumps and valves will be temporally turned off to minimize water losses.

The smart system provides several services, including (i) the early detection of water contamination, (ii) the early detection of a water leak, (iii) the smart control and elimination of water contamination to secure potable water supply, (iv) the optimal use of available water resources (e.g., RWH and municipal water supply), and (v) incidents notification to users.

2.3. Smart System Reliability Analysis

The smart water system's reliability aims to assess the efficiency and capability of the system to supply the water demand [93,94]. Scholars introduced two indices for the estimation of the systems reliability: (i) time-based reliability (R_e), which designates the ratio of days with a fully met water demand in one year, (ii) and the volumetric reliability (R_v), which denotes the ratio of the annual supplied water to the annual volume of water demand [15,95–97].

This research is based on a simulation-based R_e and R_v dataset obtained using a Python code on the Kaggle platform. The simulation was carried out in three steps. The first step consists of estimating the daily water demand (D_t) and the daily captured volume of RWH at the roofs (S_t). The second step targets the quantification of the daily volume of rainwater in the RWH tank (V_t), the daily overflow from the RWH tank (O_t), and the daily shortage in covering the needed water demand (X_t). Finally, the last step targets the estimation of both R_e and R_v.

First step: Estimation of D_t and S_t

The daily per capita water consumption rate (DWCR) is identified in view of the WHO recommendation [60]. Such rates, along with the residents' statistics, are employed to estimate D_t:

$$D_t = \frac{DWCR_t * POP}{1000} \tag{1}$$

where

D_t: the water demand on the t-th day (m^3/day)
DWCR: the daily per capita water consumption rate in liter/capita/day (L/c/d)
POP: the resident's statistics (capita)

S_t is estimated using Gould and Nissen-Petersen's Equation (1):

$$S_t = \sum_{j=1}^{n} RF_t * A_j * RC_j \tag{2}$$

where

S_t: the potential daily RRWH volume for the shared system in the t-th day (m^3/day)
RF_t: daily RF for the t-th day (m/day)
A_j: area for the j-th rooftop (m^2)
RC: runoff and collection efficiency coefficient for the j-th rooftop [25]
t: the day (1 to 365)
j: the building number
n: total number of buildings

Second step: Estimation of V_t, O_t, and X_t

The estimation of V_t, O_t, and X_t is conducted using the following formulas [94]:

$$O_t = \mathrm{Max}(0, V_{t-1} + S_t - D_t - C) \tag{3}$$

$$V_t = \sum_{t=1}^{365} \mathrm{Max}(0, V_{t-1} + S_t - D_t - O_t) \tag{4}$$

$$X_t = \mathrm{Min}(0, V_{t-1} + S_t - D_t) \tag{5}$$

where

O_t: daily overflow from the RWH tank (m^3)
V_t: daily water volume in the RWH tank in the current day
$V_{t-1:}$ daily water volume in the RWH tank in the previous day
S_t: daily captured volume of rainwater at the roof (m^3)
D_t: daily water demand (m^3)
C: tank size/capacity (m^3)
X_t: daily shortage in covering the needed water demand (m^3)
t: day (1 to 365)

Third step: Estimation of R_e and R_v

R_e and R_v are estimated using the following formulas [15,95–97]:

$$R_e = \frac{N - U}{N} * 100 \tag{6}$$

$$R_v = \frac{AWS}{AWD} * 100 \tag{7}$$

where:

N: total days in a year (365 days)
U: number of days with water shortage each year ($X_t > 0$) (in days)
AWS: annual water supply from the system (in m^3)
AWD: annual water demand (in m^3)

3. Case Study

The application of the proposed methodology was carried out in a small neighborhood in the city of Jenin, which is located in the north of the West Bank, Palestine (See Figure 6). Table 1 summarizes the characteristics of the six buildings in the neighborhood.

However, the water supply continuity is vulnerable and ranges between 2–3 days/week [98]. Each of the high-altitude, moderate-altitude, and low-altitude locations in the study area are separately supplied (7 days every 3 weeks). Therefore, supply volumes vary considering the altitude of the community and the season (See Table 2). DWCR of about 100 L/c/d is specified for the study area, according to the WHO and Palestinian Water Authority (PWA) recommendations [25,99].

Figure 6. BIM representation for the case study.

Table 1. Characteristics of the buildings in the case study.

Parameter	**Building Number**					
	Building 1	**Building 2**	**Building 3**	**Building 4**	**Building 5**	**Building 6**
Roof area (m^2)	125.6	188.3	160.9	134.6	208.9	148.6
Roof material	bricks	concrete	concrete	bricks	concrete	bricks
RC	0.85	0.9	0.9	0.85	0.9	0.85
Residents' number	7	6	4	8	4	5

Table 2. Municipal supply capacity at the neighborhood level.

Altitude	**Supply Rate (m^3/Day of Supply/Neighborhood) ***	
	Dry Season (May to October)	**Rainy Season (November to April)**
High-altitude	7	15
Moderate-altitude	10	25
Low-altitude	22	35

* neighborhood is adjacent houses in the study area (mainly 5–15 houses).

The community receives an average annual rainfall of around 590 mm/year, while the maximum annual daily rainfall is about 62.3 mm/day [100]. Therefore, the number of rainy days (with rainfall depth of more than 1 mm/day) is around 50 days [100]. The temporal distribution of the daily rainfall in the study area is shown in Figure 7. It is noticed that most of the rainfall falls between October and April.

Spatially distributed RWH samples were collected from 35 residential units in the city of Jenin (See Figure 8). The sampling process was carried out between October and December 2021. RWH samples were analyzed at the laboratory for various physiochemical and biological water quality parameters, including pH, turbidity, chloride, alkalinity, total dissolved solids (TDS), FC, and residual chlorine. The sampling and analysis processes were carried out considering the regulations and procedures stated by the WHO [60]. Analysis results were then compared to the WHO drinking water standards [60].

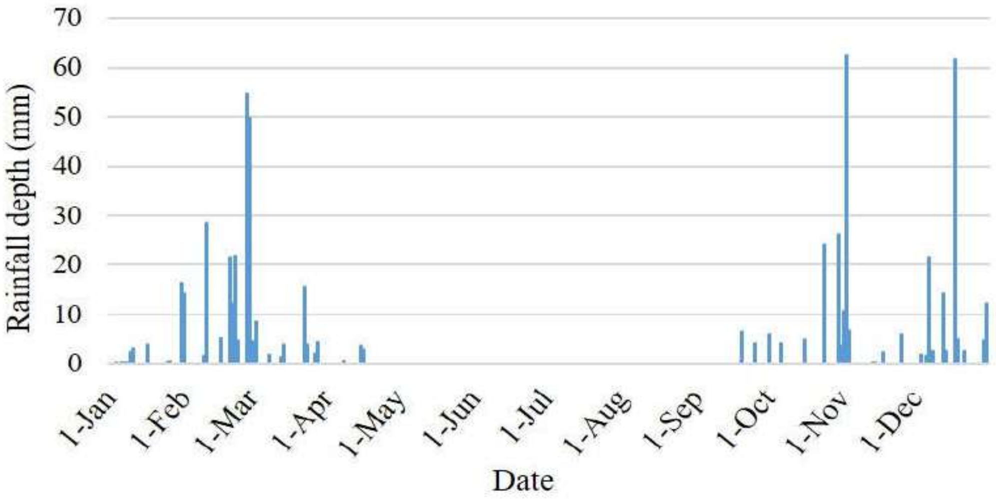


Figure 7. Temporal distribution of the daily rainfall in the study area.

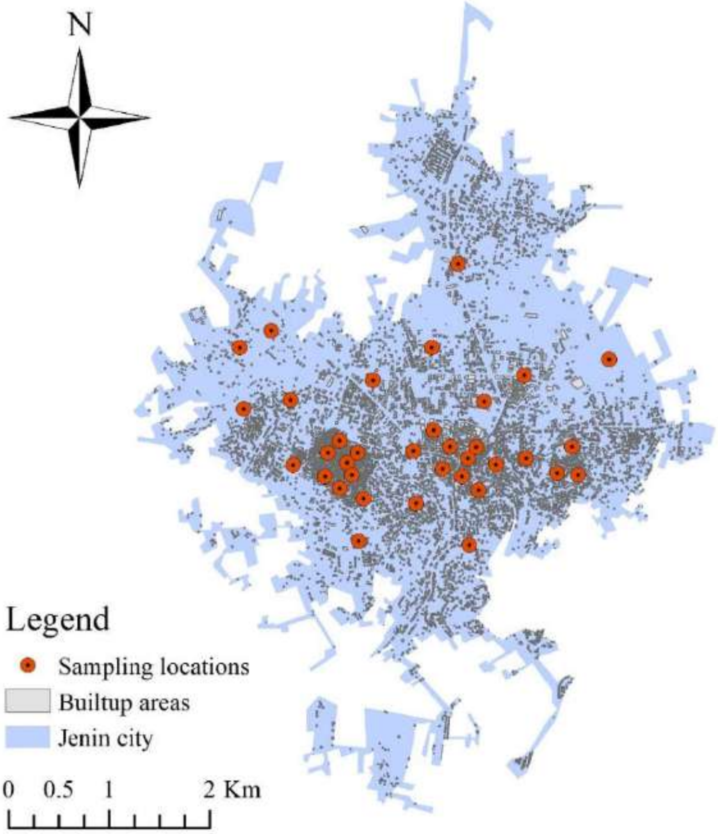


Figure 8. RWH sampling locations.

4. Results

4.1. Smart RWH Quality Assessment and Control

This section assesses the probable physiochemical and biological contamination in the collected RWH samples (Table 3). Accordingly, it proposes the most suitable and feasible smart quality control options.

Table 3 shows that pH, chloride, alkalinity, and TDS are within the acceptable limits of the WHO standards for all the samples. In contrast, 20% of the samples exceed the thresholds of the WHO turbidity standards. Measured turbidity could reach 29 nephelometric turbidity units (NTU), about six times higher than the maximum allowable limit (5 NTU). This could be related to the absence of screens and filters in the RWH systems present in the study area [101]. High turbidity protects the organisms (e.g., bacteria and pathogens) in the drinking water [102–104]; therefore, disinfecting the water (e.g., through chlorination) becomes less efficient. Thus, consuming such water could cause nausea and headaches to users [102–104].

Table 3. Physiochemical and biological analysis of RWH samples.

Parameter	**Min**	**Mean**	**Median**	**Max**	**WHO Standards**	**Number of Contaminated Samples (%)**
pH	6.92	7.32	7.31	7.75	6.5–8.5	0 (0%)
Turbidity (NTU)	0.18	3.37	0.95	28.50	$\leq$5.00	7 (20%)
Chloride (mg/L)	15.00	37.66	37.00	76.00	$\leq$250.00	0 (0%)
Alkalinity (mg/L $CaCO_3$)	65.00	169.74	145.00	325.00	$\leq$400.00	0 (0%)
TDS (mg/L)	72.00	185.49	175.00	302.00	$\leq$600.00	0 (0%)
FC (CFU/100 mL)	0.00	92.23	9.00	545.00	$\leq$10.00	17 (48.6%)
Residual Chlorine (mg/L)	0.00	0.27	0.17	2.10	0.2–0.8	20 (57.1%)

Around 49% of the samples recorded FC levels higher than the WHO standards. The maximum presence of FC in the sampled water reaches 545 CFU/100 mL (around 55 times the maximum allowable limit by the WHO). This could be attributed to the extensive use of cesspits for wastewater disposal [19]. Leaching from these cesspits could contaminate the underground RWH tank [101,105,106]. Birds, animals, and other creatures' fecal waste (on the roof or next to the storage tank) form a main source of FC in the harvested rainwater [101,105,106]. Elevated numbers of FC in drinking water are linked to stomach infections, and intestinal diseases such as diarrhea and nausea [107,108]. The severity of such health problems might be higher and could be life-threatening for people suffering from immune deficiencies [107,108].

In total, 51% of the samples recorded a residual chlorine concentration lower than the minimum recommended concentration. Securing the minimum recommended chlorine concentration in drinking water is important [109,110] to eliminate bacteria's harmful effects and prevent water recontamination during the storage phase [109,110]. On the other hand, around 6% of the samples exceeded the maximum allowable residual chlorine concentration. High residual chlorine concentrations can react to form hypochlorous acid and hypochlorites [111,112]. Therefore, consuming water with high chlorine concentrations could cause human health problems such as diarrhea, vomiting, stomachaches, poisoning, and bladder cancer [111–114]. In addition, high chlorine levels affect the water palatability since it becomes of unpleasant taste and odor [115,116].

Results of the physiochemical and biological assessment are compatible with what was found by other scholars for the southern [105,117,118], middle [101], and northern [106] parts of the West Bank.

Figure 9 indicates the negative relationship between residual chlorine and FC among the 35 samples. Such a relationship is in line with other researchers' findings [119–121]. It was found that 16 out of the 17 samples contaminated by FC were also over the stated limits of residual chlorine. They almost fall below the minimum threshold of residual chlorine (0.2 mg/L). Therefore, controlling the levels of residual chlorine in RWH will relatively secure the control of FC as well.

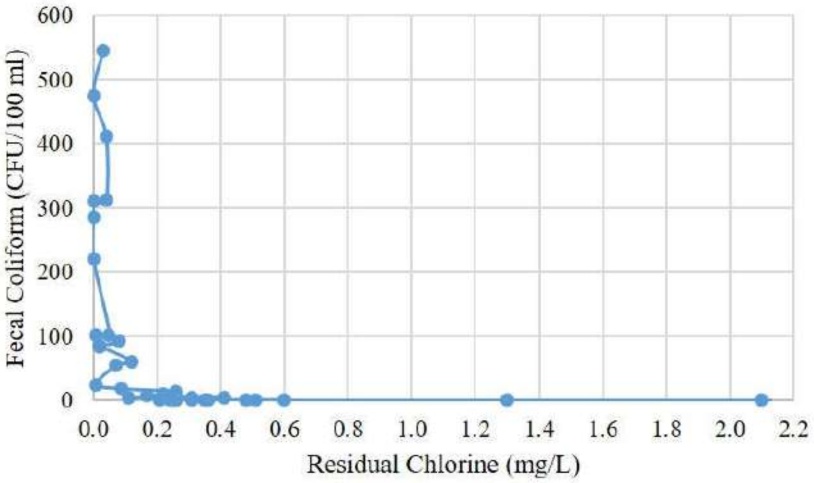


Figure 9. Residual chlorine VS. FC among the RWH samples.

The physiochemical and biological analysis shows that the control of the RWH turbidity is the first defense line for securing RWH potability in the study area. Such control could be performed by installing the inlet pipe screen, first flush diverter, filter, and overflow pipe screen. The smart monitoring of turbidity could be conducted by assessing the performance of such a defense line. This could be achieved by using (i) smart turbidity sensors and/or (ii) conventional turbidity meters and crowdsourcing.

Controlling the FC levels is the most important part of the RWH quality control. Due to its efficiency, scholars recommend the use of UV filtration for the control of FC in rainwater water [64]. However, the high cost of this filtration restricts its suitability for decentralized water systems, particularly in developing countries [122]. Boiling is another option for water disinfection [123]. However, it has limited suitability to the smart shred system, and it is more suitable for individual household practices. Moreover, the boiling and cooling of water is energy dependent, time-consuming, and restricts the direct use of water [123].

Chlorination is proposed for the disinfection of rainwater in the smart systems due to several factors including its efficiency [122], low cost [122], and the abundance and experience to deal with the disinfectant materials in the West Bank [98]. According to the WHO, RWH requires 2 mg/L of chlorine to be disinfected (to inactive the organisms, including FC) [99]. Thus, the WHO recommended an optimal chlorination rate of about 2.5 mg/L to ensure the disinfection of existing FC [99]. Such disinfection maintains a residual chlorine concentration of around 0.5 mg/L in the harvested water. This will secure the re-disinfection of future FC contamination during the storage and pumping phases [99]. Thus, the use and calibration of the chlorination unit are of high importance in the smart RWH system. In addition, residual chlorine sensors/meters are noticeably cheaper than other water quality sensors (including FC sensors/meters) [60,99]. Therefore, this research proposes the use of these feasible sensors to control FC and residual chlorine levels through the RWH system in the study area.

New do-it-yourself (DIY) systems are proposed by a non-governmental organization (NGO), Aqueous Solutions, for the biological treatment of water (based on biochar and metallic iron) [66]. Such cost-effective systems showed their efficiency for water disinfection in Thailand [66]. Up to now, these DIY systems are not available in the West Bank. Therefore, they are highly recommended in the future.

4.2. Smart RWH System Reliability

This section discusses the reliability of the smart RWH system in supplying the residents with their potable water needs. The potential annual RWH volume on the roofs is around 507 m^3. However, the actual annual RWH volume that could be stored and utilized is dependent to the size of the RWH storage tank. Figure 10 shows the effect of RWH tank size on the annual RWH and overflow volumes. It is found that the annual storage of the

RWH increases with the tank size to attain a maximum of about 500 m^3 for a tank size of 112 m^3. This size guarantees no overflow from the tank. Errors in the volumes of RWH and tank overflow could be caused by two main sources: (i) partial exploitation of the roofs for RWH, and (ii) temporal variation in rainfall volumes. Since there is no available data concerning the exploitation rates of each roof, this error analysis neglects the effect of such rates, but they are highly recommended to be considered in future work (e.g., using surveys). The furnished error analysis in this paper focuses on the temporal variation in rainfall volumes (by comparing the dry and wet years to the adopted average rainfall year). Figure 10 shows that the higher tank size was, the higher the error in RWH volumes were. In contrast, it was found that the higher the tank size was, the lower the error in overflow volumes were.

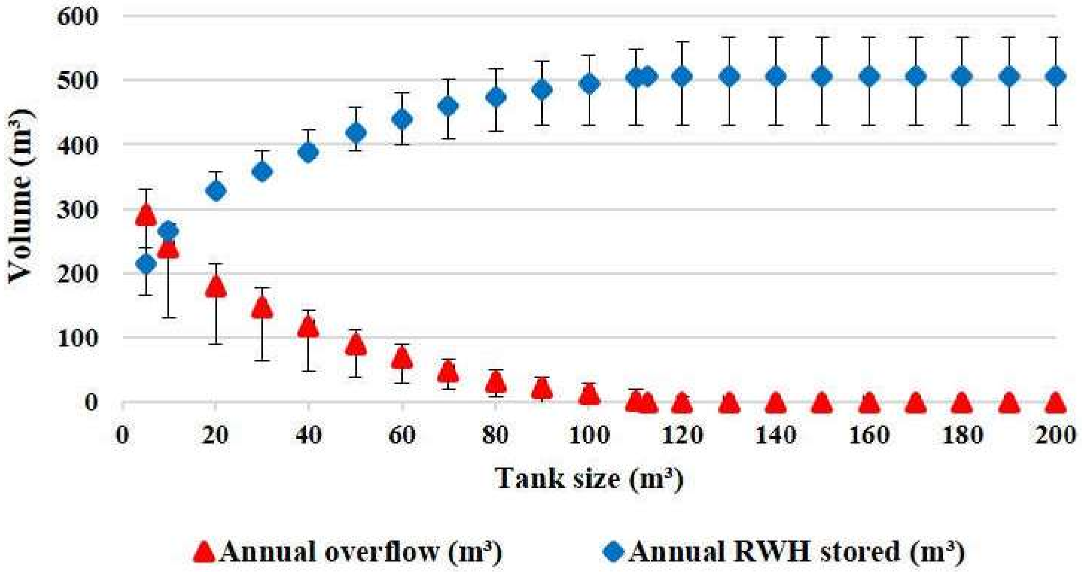


Figure 10. Effect of tank size on the annual utilized RWH volumes and the annual overflow.

According to Equation (1), the annual water demand for the study area is around 1240 m^3/year. The lowest shortage (59%) in water supply could be reached by using the optimal tank size (112.5 m^3) (See Figure 11). However, using lower sizes is associated with a higher shortage rate. For instance, the tank of 5 m^3 size has 83% shortage in providing the needed water demand.

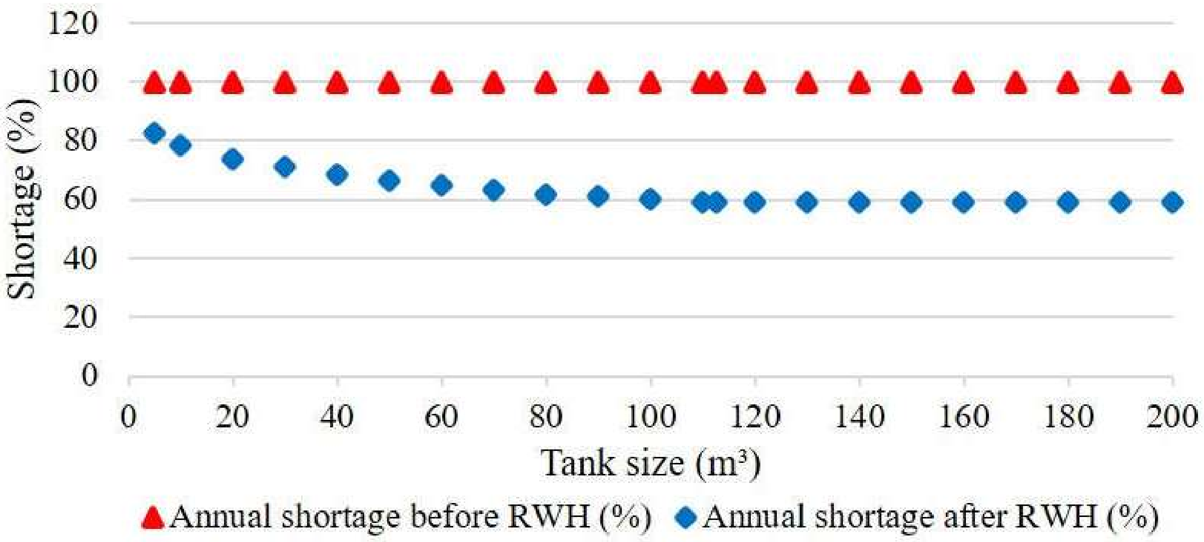


Figure 11. Effect of tank size on the annual shortage through the smart RWH system.

Figure 12 displays the influence of the tank size on R_e and R_v of the smart RWH system. R_e is around 12.6% for the 5 m^3 tank. Such a rate covers the water demand for 46 days. The maximum R_e (37.5%) is recorded for the 112.5 m^3 tank, which means that the residents' water demand is covered for 137 days. Concerning R_v, the maximum recorded rate is 41%. This implies providing the residents with an average daily supply of (41 L/c/d).

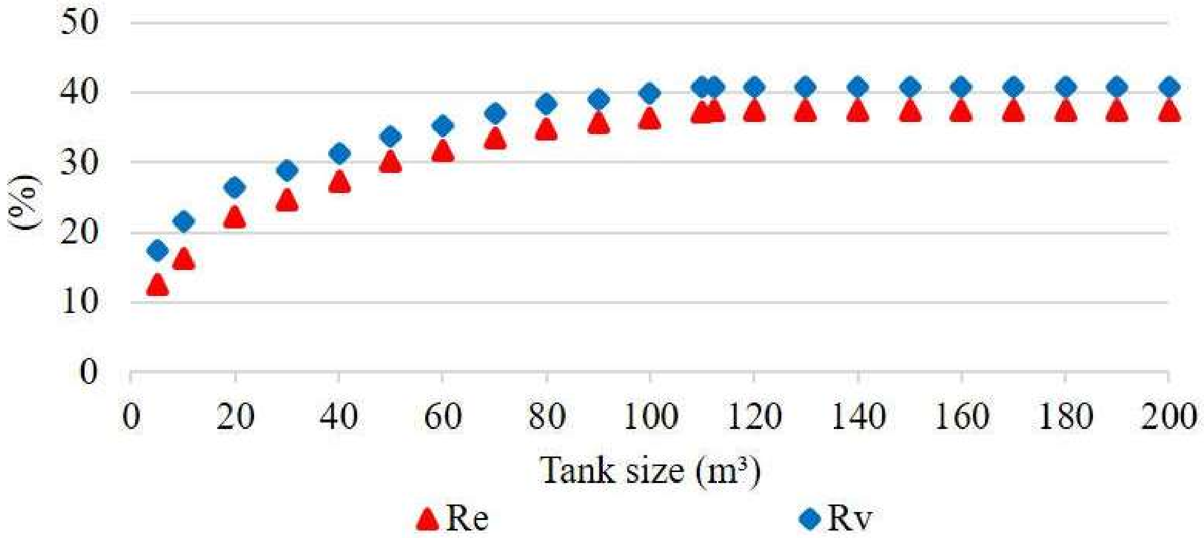
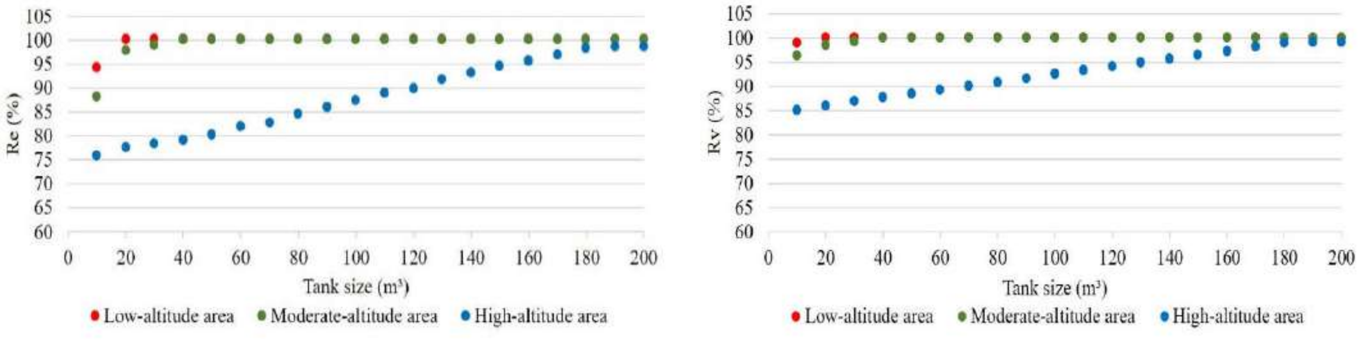


Figure 12. Effect of tank size to the Re and Rv, through the smart RWH system.

To overcome the water shortage with the RWH system, it is necessary to use the dual water system that combines RWH and municipal water supply [124]. Various researchers discussed the concept and performance of the dual supply system [124–128]. Scholars agreed on adopting two independent distribution networks: centralized and decentralized [124–128]. This section discusses the dynamic management of the proposed dual water supply system. Such management considers the various spatial levels in the study area (e.g., high-altitude, moderate-altitude, and low-altitude locations).

Figure 13 shows the effect of the tank size on R_e and R_v for the smart dual water supply system, in light of the existing municipal water supply agenda. Both reliability indices hit 100% for the low-altitude (using tank sizes of 20 m^3) and moderate-altitude locations (using tank sizes of 40 m^3). This implies fully addressing water scarcity (0% of water shortage). Concerning high-altitude locations, R_e ranges between 76% (for 10 m^3 tank) and 98% (for 190 m^3 tank). In addition, R_v ranges between 85% (for 10 m^3 tank) and 99% (for 190 m^3 tank).

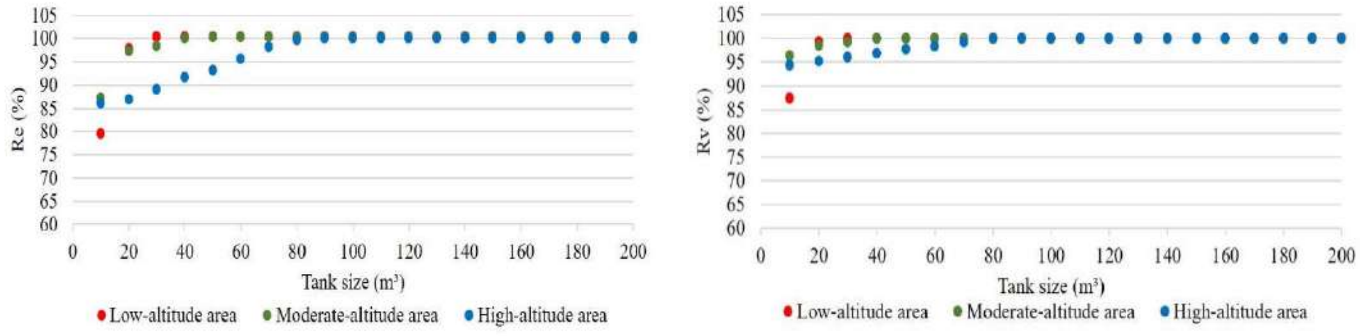


(**a**) (**b**)

Figure 13. Impact of tank size on (**a**) R_e; (**b**) R_v of the dual supply system considering the existing municipal water supply agenda.

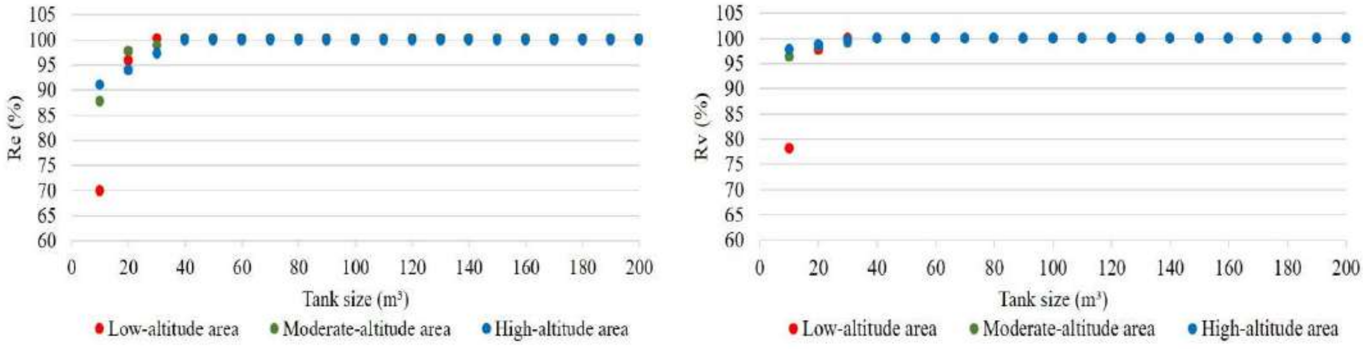
Such results urge the need to propose and examine other municipal water supply agendas in order to achieve 100% reliability for all altitude levels. Thus, two agendas are introduced: (i) agenda A (9, 7, and 5 days of water supply per 3 weeks for high-altitude, moderate-altitude, and low-altitude locations, respectively), and agenda B (10, 7, and 4 days of water supply per 3 weeks for high-altitude, moderate-altitude, and low-altitude locations, respectively).

Figure 14 shows that agenda A could assist in reaching the full reliability (both R_e and R_v) at all altitude levels in the study area. This could be realized by utilizing tank sizes of 30, 40, and 80 m^3 for the low-altitude, moderate-altitude, and high-altitude regions, respectively. On the other hand, it was found that agenda B achieves the same reliability records (100%) by utilizing smaller tank sizes. Tank sizes of 30 m^3 could be used in low-altitude areas, and 40 m^3 could be used in moderate-altitude and high-altitude areas (See Figure 15). These results indicate the efficiency and reliability of the dual water system in addressing the water demand compared to the smart RWH system solely. It also shows the need for rescheduling the existing municipal water supply agenda.



(**a**) (**b**)

Figure 14. Impact of tank size on (**a**) R_e; (**b**) R_v of the dual supply system considering agenda A.



(**a**) (**b**)

Figure 15. Impact of tank size on (**a**) R_e; (**b**) R_v of the dual supply system considering agenda B.

5. Discussion

This section compares the findings of the proposed smart RWH and dual systems to what was found by other scholars. The smart RWH system attained a potential annual RWH capacity in the study area of about 0.6 m^3 of rainfall per 1 m^2 of roof, which is slightly higher than the 0.5 m^3 of rainfall per 1 m^2 of roof found by Alawna and Shadeed, 2021 [129]. The slight variation could be due to the different sources of rainfall data. Our study used daily rainfall data while Alawna and Shadeed, 2021, relied on long-term annual rainfall data [129].

The success and efficiency of RWH in addressing 41% of the needed water demand supports what was found by Shadeed et al., 2019 [130], which highlighted Jenin Governorate as an optimal location for implementing the rooftop RWH systems.

According to Shadeed and Alawna, 2021 [131], a 60 m^3 storage tank is needed to entail a 39% of Rv for a five-member family living in a 150 m^2 house in Jenin Governorate. On the other hand, the smart RWH system proposed in this paper entailed a 41% Rv using a 112 m^3 shared storage tank for 34 persons living in five houses (with total roof areas of about 840 m^2). More efficiently, the dynamically managed dual water system hits a 100% Rv for the five houses using a 40 m^3 shared storage tank, given the rescheduling of the municipal water supply agenda (Agenda B). The higher reliability of the shared systems with respect to the individual ones could be referred to the swap in harvesting and utilization of the rainwater among the five houses. Thus, adopting either the 112 m^3 or the 40 m^3 shared tanks instead of using five individual tanks (60 m^3 each) could significantly promote the socioeconomic development of the study area.

6. Conclusions

This paper introduced and assessed the reliability of a smart RWH/dual water supply system to address the potable water shortage in the water-scarce areas. First, assessing the potential challenges of the conventional roof RWH systems was followed by proposing a smart RWH system architecture to cope with such challenges. Next, the smart system architecture was introduced, in light of the collection and utilization of shared RWH. A Python-based simulation followed this to assess the reliability of the smart RWH system.

Results indicated the need for a crowdsourcing-based, and automation-based treatment and check units in the smart system to control the elevated turbidity, fecal coliform, and residual chlorine in the harvested rainwater in Jenin. The smart RWH system showed the capability to cover 41% of the domestic water needs of citizens.

Results indicated the efficiency and reliability of the dual water system in addressing the water demand compared to the smart RWH system solely. The dynamic management of the system (including the storage) enabled the best reliability by using smaller storage tank sizes. This could have a significant positive effect on the city's socio-economic development. Results also showed the need for rescheduling the existing municipal water supply agenda. By adopting the dynamic management and a new supply agenda, the smart dual system showed its ability to cover the water demand at all altitude levels in the study area.

Future research could improve the work achieved by targeting (i) the cost-benefit analysis for the smart RWH system and (ii) the social acceptance investigation for the adoption of the proposed system.

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