Distributed Rainwater Harvesting: Novel Approach to Rainwater Harvesting Systems for Single-Family Households

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Abstract: Communal rainwater harvesting (RWH) systems allow a community to collect rainwater from multiple roofs, store and treat it in a central location, and then distribute it back to the community. This paper proposes a novel distributed rainwater harvesting approach to communal rainwater harvesting in which individual households connect the outflow of their RWH systems to a communal storage from which they can retrieve water when their system is not able to meet their water demands. We simulated the performance of the system in two cities, Houston and Jacksonville, for multiple private and communal storage combinations. We measure the performance of the system using the volumetric reliability (VR) metric, which is the ratio of rainwater that the communal system is able to provide to the total water demand. Results showed that the VR gains over a private system of 1%–6% and 1%–4%, can be achieved for up to 10 and 7 connected households, respectively, for Houston and Jacksonville if the emphasis is on VR gain >1.5%. The system achieved higher VR gains for lower total storage capacity in Houston, whereas the system achieved higher VR gains for higher total storage capacities in Jacksonville. This proposed decentralized rainwater harvesting system is attractive in the face of climate change, increases the resilience of water/stormwater infrastructure, and potentially could decrease the likely effects of flooding and property damage from stormwater. **DOI: 10.1061/(ASCE)WR.1943-5452.0001441.** © *2021 American Society of Civil Engineers.*

Introduction

The aging water infrastructure in the US is becoming a critical issue and investment has not kept up with needs. According to the ASCE, there will be an estimated $84.4 billion annual capital gap for water infrastructure by 2020 (ASCE 2016). Water demand is growing (Sabol 2011) and the rate of urbanization is increasing. The 2010 census indicated that urban areas were outpacing overall national growth by 2.4% (US Census Bureau 2012), and water utility bills are increasing (Walton 2015). City and town managers of growing urban areas are facing increasingly difficult choices with regard to water infrastructure management: should the status quo be maintained, which involves investing in the existing infrastructure, should there be funding for decentralizing the water infrastructure, or should there be some mix thereof? Rainwater harvesting (RWH) systems are situated at the core of the decentralized water structure. RWH systems act as a containment measure for stormwater runoff by storing rainwater, which can be used for irrigation, car washing, nonpotable domestic functions (laundry, toilet flushing, and so forth), and, when treated, as a potable water source. The vital importance of RWH systems is the effect they have on the three water networks (potable, stormwater, and wastewater) in terms of decreasing water demand on the potable water network, decreasing stormwater runoff, and, if coupled with greywater recycling systems, decreasing the wastewater generated (Ghisi and Ferreira 2007).

Communal rainwater harvesting at the individual residential scale preserves excess runoff from multiple roofs, stores it in a communal tank, and then treats and redistributes it as potable water to the community for either potable or nonpotable uses (Cook et al. 2013; Gurung and Sharma 2014; Gurung et al. 2012; Seo et al. 2012, 2015). Variations of communal RWH systems currently exist in multiresidential buildings (Agudelo-Vera et al. 2013; Eroksuz and Rahman 2010; Ghisi and Ferreira 2007; Marinoski et al. 2018; Silva and Ghisi 2016). Communal RWH systems for single-family houses work best in off-grid locations, where access to the municipal water supply is difficult (Cook et al. 2013; Gurung and Sharma 2014). However, the main advantage of communal RWH systems over private RWH systems in urban settings is that they provide a centralized means for adequate maintenance for individual households who could have difficulties sustaining their own system properly. This centralized approach at the heart of a decentralized water infrastructure management ensures better water quality (Gurung and Sharma 2014) and economies of scale for capital costs, reduced land footprint, centralized disinfection, and flexibility in matching supply and demand for different households (Cook et al. 2013). To size the communal system, Gurung and Sharma (2014) estimated the dimensions of the communal tank by gauging the hot potable use for one house in the community (shower, taps, dishwasher, and laundry) using a water balance approach and the software UVQ (Mitchell and Diaper 2010). The design criteria used was a volumetric reliability ratio (VR) of 94%. The VR is the ratio of rainwater that the communal system is able to provide to the total water demand. The next step was to calculate the size of a

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single RWH system based on a VR of 94%. The last step was to multiply the tank size by the number of households in the community to estimate the communal tank size. Hashim et al. (2013) used a simulation-based programming approach to estimate the communal tank size for a community of 200 households in Malaysia by minimizing the cost and optimizing the tank size. They determined a reliability of 60% while saving 58% of the water that otherwise would have been drawn from the municipal supply system for satisfying the daily water demand for nonpotable uses.

Both of the aforementioned communal approaches could be improved by sharing rainwater storage or using a rain barrel sharing network. Seo et al. (2012, 2015) described a network of rainwater sharing that can be a physical or a nonphysical network (such as a community-based sharing program) for using the excess rainwater from one household. They found that a sharing network actually reduces the total storage needed in some cases by up to 61% for a target reliability of 80% for a scenario with four households.

The first communal approach, studied by Gurung et al. and Hashim et al., increases the attractiveness of owning RWH systems for households who do not or cannot handle the maintenance of such systems, whereas the approach described by Seo et al. increases the potential of using the collected rainwater, hence (1) improving the reliability of existing RWH systems; (2) using the same amount of rainwater while using a smaller tank size, which could be an important factor in urban communities; and (3) reducing the peak flows entering the existing stormwater networks (De Paola et al. 2018a, b). Both these systems lack a solution to maximize the capture and reuse from the outflow of RWH systems, in which clean water goes to waste in stormwater drains. Hence, there is a need for a novel way to leverage RWH systems.

The main contribution of this paper is a novel approach to communal RWH systems that is a hybrid of the two approaches described previously that increases the VR per user while reducing overall total storage and increasing user autonomy with regards to water processing. It is a distributed rainwater harvesting system (DRWH) that closely resembles distributed computer systems. Distributed computer systems do not have a unified definition, but they have the following common traits (Ghosh 2014):

1. Distributed computer systems are autonomous, each with their own local memory. Similarly, distributed RWH systems have their own independent usages.
2. Computer systems communicate by message passing. Likewise, a distributed RWH system communicates with water sharing.
3. A distributed computer system has to allow breakdowns in single computers. Similarly, if a single RWH system fails, the entire system is not critically compromised.
4. A distributed computer system has a mutual objective; the combined computers then work as a single entity to attain that objective. Although each computer has particular requirements, the system allows the management of the use of the shared resources. Correspondingly, a distributed RWH system allows single households to use their harvested rainwater as they need, while storing the overflow to be used when needed by that same user or others in the network.

In particular, we considered single-family households, each connected to their own RWH system, but instead of the overflow going to the stormwater system, the overflow of each tank is connected to a communal tank to which multiple other outflows from other single-family households are connected as well (Fig. 1).

The potential advantages of this distributed rainwater harvesting system are as follows:

1. Owners have the freedom to use the disinfection method they choose instead of being forced to use the central disinfection method. They also could opt out of using water treatment, depending on their use of the collected water.
2. A smaller amount of rainwater will be wasted compared with using private RWH systems, and less runoff will go into stormwater systems, thus reducing the load on the stormwater infrastructure.
3. The increased storage in the form of the communal tank will increase the water demand met as well as the reliability of the rainwater harvesting (RWH) system.
4. This distributed system will be more resilient in the face of climate change, especially because, depending on the climate, some adjustments would have to be made to size of the RWH system.

This study determined (1) the impact that a distributed RWH will have on the reliability of the system, (2) the storage (private and communal) required to achieve that reliability, and (3) the optimal number of connected households to the distributed system to perform this study. The optimal number of connected households was determined by the maximum VR increase with the smallest individual tank size. We used simulation tools to build the distributed network, and studied the output of the simulation for feasibility and gain over traditional RWH systems. For validation, we used representative cities from the nine major US climate zones.

Methodology

This study adopted a daily water balance model (Imteaz et al. 2012; Khastagir and Jayasuriya 2011) using publicly available weather and water consumption data (USGS 2017) to estimate the amount of potable municipal water that can be displaced under different tank-size scenarios (private and communal) for each of the nine study cases.

A daily water balance model takes into account daily rainfall, water losses due to leakage, spillage and evaporation, the roof area, the tank volume, water demand, overflow losses, as follows:

$$V_t = \begin{cases} 0 & \text{when } V_t < 0 \\ Q_t + V_{t-1} - D & \text{when } 0 < V_t < S \\ S & \text{when } V_t > S \end{cases} \tag{1}$$

$$O = V_t - S \tag{2}$$

$$C_t = \begin{cases} N \cdot O + C_{t-1} - C & \text{when } D < V_t \\ C_{t-1} - N \cdot (D - V_t) & \text{when } D > V_t \text{ and } N \cdot (D - V_t) < C_{t-1} \\ 0 & \text{when } D > V_t \text{ and } N \cdot (D - V_t) > C_{t-1} \end{cases} \tag{3}$$

$$Y = \begin{cases} D & \text{when } V_t > D \\ D & \text{when } V_t < D \text{ and } N \cdot (D - V_t) < C_{t-1} \\ \dfrac{\{N \cdot (D - V_t) - C_{t-1}\}}{N} & \text{when } D > V_t \text{ and } N \cdot (D - V_t) > C_{t-1} \end{cases} \tag{4}$$

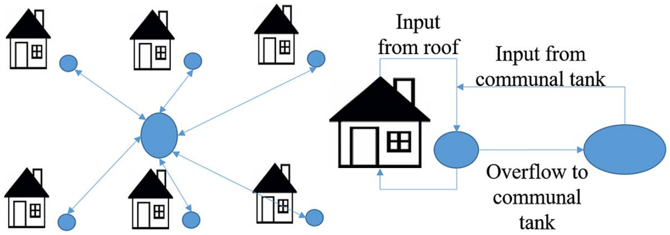

Fig. 1. Distributed RWH and connection at the house level.

where O = outflow from individual RWH tank at time t; N = number of connected households; C_t = storage in communal tank at time t; C = maximum capacity of communal tank; and Y = yield per household.

This study considered daily rainfall data for 10 years (January 2009–January 2019) and average water demand for single-family households. Tank sizes ranged from 3.785 to 75.7 m^3 with a step size of 3.785 m^3. These tanks represented discrete sizes in 1,000-gal. increments commonly available in the US. When the increase in the volumetric reliability VR fell below 1% compared with that of the contiguous smaller size, that change determined the choice of tank size for the private storage scenario. In other words, we used a VR change of less than 1% between adjacent tank sizes to determine the optimal storage tank size. The rationale behind this selection method was that it strikes a meaningful balance for the trade-off between VR gains and tank-size cost increase, which was assumed to be proportional to tank size for storage of this magnitude. For all other sizes above the chosen tank size, although a higher reliability can be achieved, the increase in this reliability is too small to justify the additional investments needed for the larger tank sizes.

For the distributed rainwater harvesting setting, the simulation was designed as shown in Fig. 2, where V_private_tank is the water volume available in an individual tank; and V_common_tank is the water volume available in the common tank.

The overflow of a private tank is stored in the communal tank, and when the water demand is partially met or is not met from a private tank, at the end of the day, just enough water is pumped from the communal tank to the private tank to meet the water demand for that day for that household (Fig. 2). The water level in the communal tank is reduced, and the water level in the private tank is unchanged. The overflow from the communal tank is discarded in the stormwater pipes. If the water demand is not met fully by either private or communal tanks, the municipal water supply is used.

The model derived from the study determines the following:

1. the private tank size before connecting it to the distributed system;
2. the private tank and communal tank sizes after connecting them to the distributed RWH system; and
3. the optimal number of private RWH systems connected to the distributed system and the total storage needed, which is

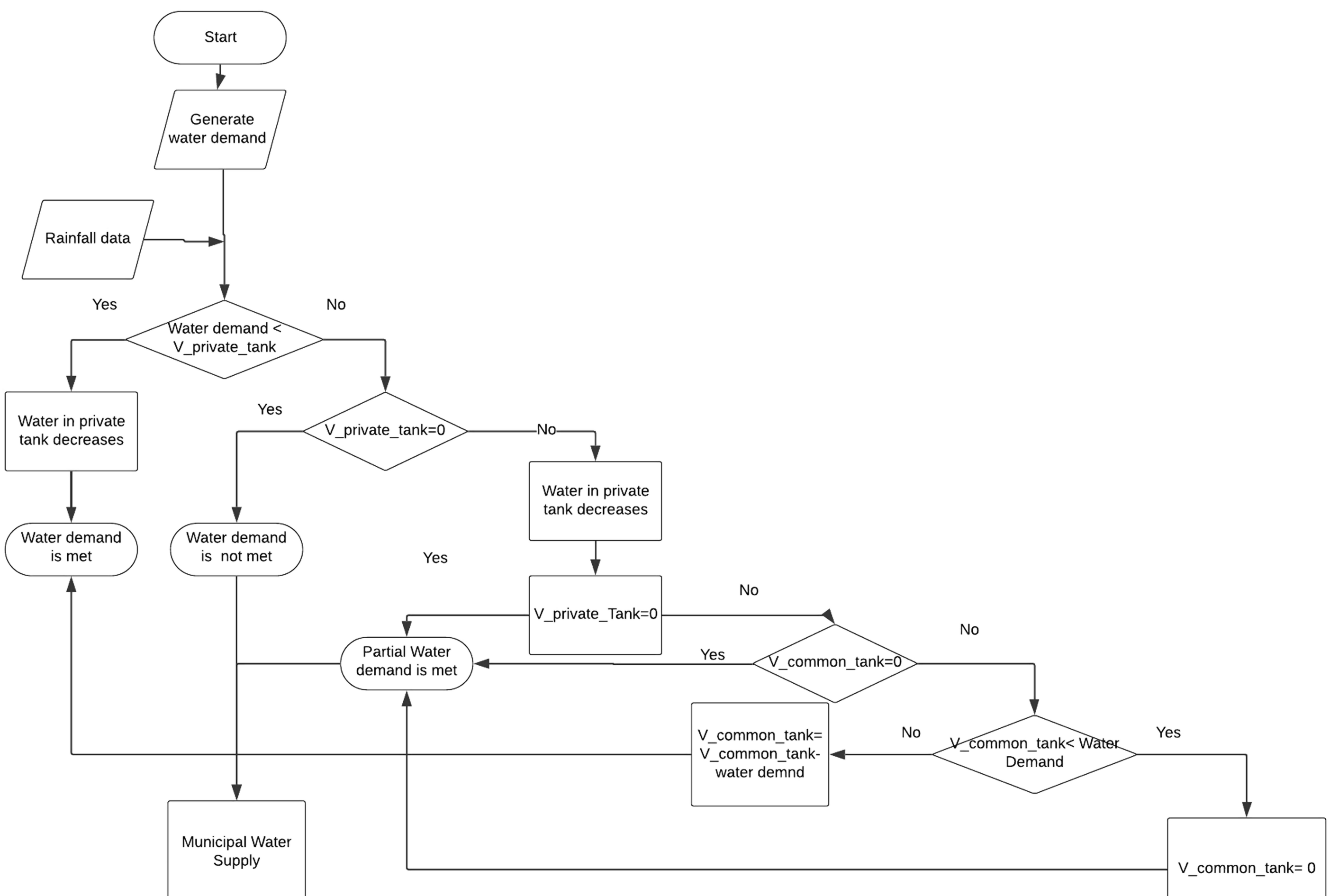

Fig. 2. Flowchart of the logic of the distributed system.

Table 1. Climatic regions, representative cities, and Köppen classification

Climatic area	Representative city	Köppen classification	Average yearly rainfall (mm)
Central	Chicago	Dfa	914
East North Central	Detroit	Dfa	864
Northeast	New York City	Cfa	1,194
Northwest	Seattle	Csb	940
South	Houston	Cfa	1,270
Southeast	Jacksonville, Florida	Cfa	1,270
Southwest	Phoenix	Bwh	229
West	Los Angeles	Csa	381
West North Central	Omaha, Nebraska	Dfa	787

assumed to be proportional to tank size for storage of this magnitude.

The analysis was based on the daily water balance, and the locations of the analysis were chosen based on the climatic regions in the continental US. The National Centers for Environmental Information (NCEI) recognize nine climatically consistent regions in the contiguous US (Karl and Koss 1984)

- Central: Illinois, Indiana, Kentucky, Missouri, Ohio, Tennessee, and West Virginia;
- East North Central: Iowa, Michigan, Minnesota, and Wisconsin;
- Northeast: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont;
- Northwest: Idaho, Oregon, and Washington;
- South: Arkansas, Kansas, Louisiana, Mississippi, Oklahoma, and Texas;
- Southeast: Alabama, Florida, Georgia, North Carolina, South Carolina, and Virginia;
- Southwest: Arizona, Colorado, New Mexico, and Utah;
- West: California, and Nevada; and
- West North Central: Montana, Nebraska, North Dakota, South Dakota, and Wyoming.

Each climatic area was matched with a representative city so that the analysis could be generalized to the entire region. The cities were picked from the most populous cities of the US (US Census Bureau 2017). The cities representing the climatic regions are listed in Table 1.

For this comparative study, we considered a single-family household with two residents in the representative cities from the major climatic zones in the US for a simulation period of 10 years. The house used in the example had a roof area of 68.25 m^2, had two stories, and had a total area of 136.5 m^2, which is the average household size in the US (US Census Bureau 2018). The water demands were extracted from the latest USGS water-use report (USGS 2017) by fitting the average demand across all counties in the US to a normal curve. The histogram of the water demands across all counties the US is shown in Fig. 3. The national average water demand can be represented by a normal curve with mean 0.330 m^3/person/day and standard deviation 0.205 m^3/person/day. The normal curve is an acceptable representation of water demand (Blokker et al. 2010; Schefter and David 1985; Surendran and Tota-Maharaj 2015).

Several factors affect the daily residential water demand of the households. Some of those of factors are (1) socioeconomic factors such as lot size, income, education, employment, and price of water; (2) efficiency of the plumbing features; (3) rainfall, temperature, and evaporation rate; and (4) water prices. A varying daily water demand captures the stochasticity inherent in daily residential water usage. The daily total water demand for the simulation period is shown in Fig. 4.

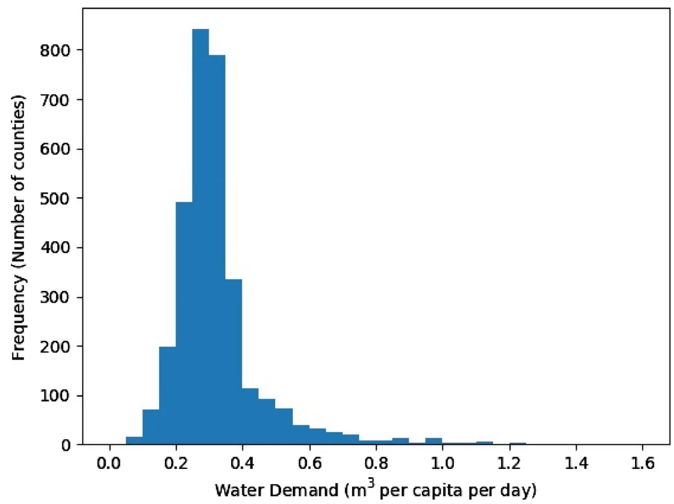

Fig. 3. Histogram of average water demands across all US counties.

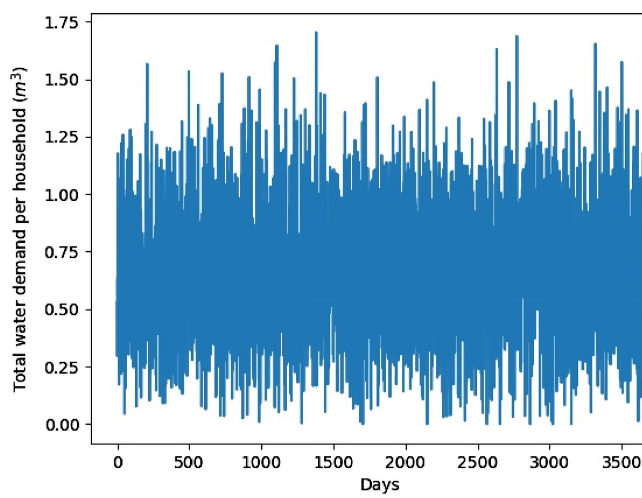

Fig. 4. Daily total water demand per household for the simulation period.

The precipitation data were accessed from the National Centers for Environmental Information for the last 10 years from January 1, 2009 to January 1, 2019. We assumed that the houses were plumbed internally (new constructions) to accommodate the use of rainwater as potable water. The VR was used to evaluate the performance of the different rainwater harvesting tanks. The assumptions related to the considered household are presented in Table 2. The tanks were assumed to be empty at the beginning of the simulation. Tank size referred to mean usable volume. The simulation model was run in Python version 3.7 using rainfall data from January 1, 2009 to January 1, 2019 for multiple cities to determine the feasibility of a distributed RWH systems in different geographical locations in the continental US.

Step 1

The first step of the simulation was to determine which locations would be suitable for distributed RWH systems and the optimal size of the private tank. For that purpose, we ran daily simulations for all nine locations for households with the conditions specified

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Table 2. Assumptions used in model

Parameter	Value
Rainfall	Daily rainfall available from NCEI
House area (m^2)	136.5 [average size household in US (US Census Bureau 2018)]
Roof area (m^2)	68.25
Roof type	Sloped metal roof
Runoff coefficient	0.9
Tank type	Polyethylene [most commonly used at residential scale across US (Thomas et al. 2014)]
Water demand	National average (USGS 2017)

in Table 2. The optimal tank size was chosen based on the change in the VR between two adjacent sizes becoming less than 1%. The simulation results are shown in Fig. 5.

Fig. 5 shows the change in VR for each of the nine cities with the increase of tank size. The largest changes in VR with larger tanks occurred in Houston, Jacksonville, and Omaha. Los Angeles (LA) had a significant VR change between the smaller adjacent sizes, but the VR was small (6%) at the beginning. For the rest of the cities, the VR did not change significantly with larger tank sizes. The cities in which the VR change was significant with larger sizes generally receive more rainfall, and hence households would benefit from increased storage capacity.

The criteria for a location for DRWH systems are as follows:
- the VR increases must be significant enough to increase more than 2% between discrete tank sizes in the range of tank sizes under consideration; and
- the VR changes between adjacent tank sizes also must be significant (>2%).

Applying the selection criteria for the suitability of the available locations for distributed RWH systems and the optimal tank size for the individual tanks, the following observations are made based on Fig. 5:
- among the chosen cities, the only locations suitable for distributed RWH systems were Houston and Jacksonville, as evidenced by the notable increase in reliability with the increase of private storage as well as an important increase in VR change; and
- for those two locations, the optimal private tank size was 15.1 m^3.

We also ran the simulation for a daily average water demand. The averages were extracted from the USGS (2017) for the different counties in which these nine cities are located (Fig. 6).

Comparing Figs. 5 and 6 indicated that Omaha potentially could be a good candidate location for distributed RWH systems, because the difference between the maximum and minimum reliabilities for the average water demand is 1.7% (less than 2%, but competitive) whereas the difference with varying water demand is 1%. The difference between the outputs from varying and average water demands could be due to the fact that the water demand for Douglas County (in which Omaha is located) is 0.216 m^3, whereas the average water demand used in the normal distribution representing the varying water demand in the US is 0.331 m^3. This highlights the need to have more-realistic water-use data in order to accurately assess the potential for distributed RWH systems.

Step 2

The next step was to run the distributed RWH system simulation for the two selected locations. The simulation determined three variables: (1) the number of connected households per higher VR; (2) the optimal/best private tank size; and (3) the optimal communal tank size to determine the highest VR gain. In this case, the optimal solution is a set combining the lowest individual tank volume, the lowest communal tank volume, and the highest VR for every household combination, if available. The optimization model is

$$\mathrm{Max}(\mathrm{VR}) = N \cdot D + N \sum_{\substack{0 \le i \le N \\ 0 < j < N}} (X_{ij} \cdot X_{ji}) - N \cdot W \tag{5}$$

where VR = volumetric reliability of system; N = number of connected households; D = water demand; X_{ij} = water flow between individual systems and communal tank; X_{ji} = water flow between communal tank and individual systems; and W = water demand from municipal water supply system. The following criteria were used as boundaries for the variables:
- The simulation determines the optimal number of households (households) connected to the system. The optimal number of households depends on the maximum VR per household for a given number of households connected. The simulation considers a cluster of 24 households connected to the system to keep the decentralized trait of the system.
- The private tank sizes vary from 3.785 m^3 up to the optimal size determined in the first step.
- The maximum size of the communal tank is the product of the number of households connected and the optimal tank size determined in the first step. The simulation considers multiple communal tank sizes from 3.785 m^3 up to the maximum size (Gurung and Sharma 2014).

The output of the simulation is the optimal combination of number of households, private tank size, and communal tank size which represents the highest VR gain over households not connected to a distributed RWH system.

Results

Simulation of System

We ran simulations to determine the VR gain by having different households connect their RWH systems to a distributed network (Fig. 7). The variables of the simulation were the following:
- Number of households (connected households): we varied the number of connected households between 2 and 24.
- Size of private storage: we varied the size of private storage between 3.785 and 15.14 m^3 in steps of 3.785 m^3. We assumed that all households had the same private tank size per iteration.
- Size of common storage: we varied the size of the public storage between 3.785 m^3 up to number of households in the given simulation multiplied by 15.14 m^3.

As a result, we conducted $2\sum_2^{24} 16x = 9{,}568$ iterations, in which the output of every iteration was the VR gain per user. The next step was to average the VR gains per group of households to determine the average gain per private tank size and public tank size. After running the simulations for two locations (Jacksonville and Houston), we obtained the results in Figs. 8 and 9.

Changes to Communal Storage with Respect to VR

This section evaluates the maximum VR gain and its associated communal storage per group of connected households given the aforementioned four private storage options.

Fig. 8 shows the maximum VR gain for the different simulated scenarios for both cities. We examined the average VR gain for households connected to the distributed RWH network for all the different combinations of private and common tanks

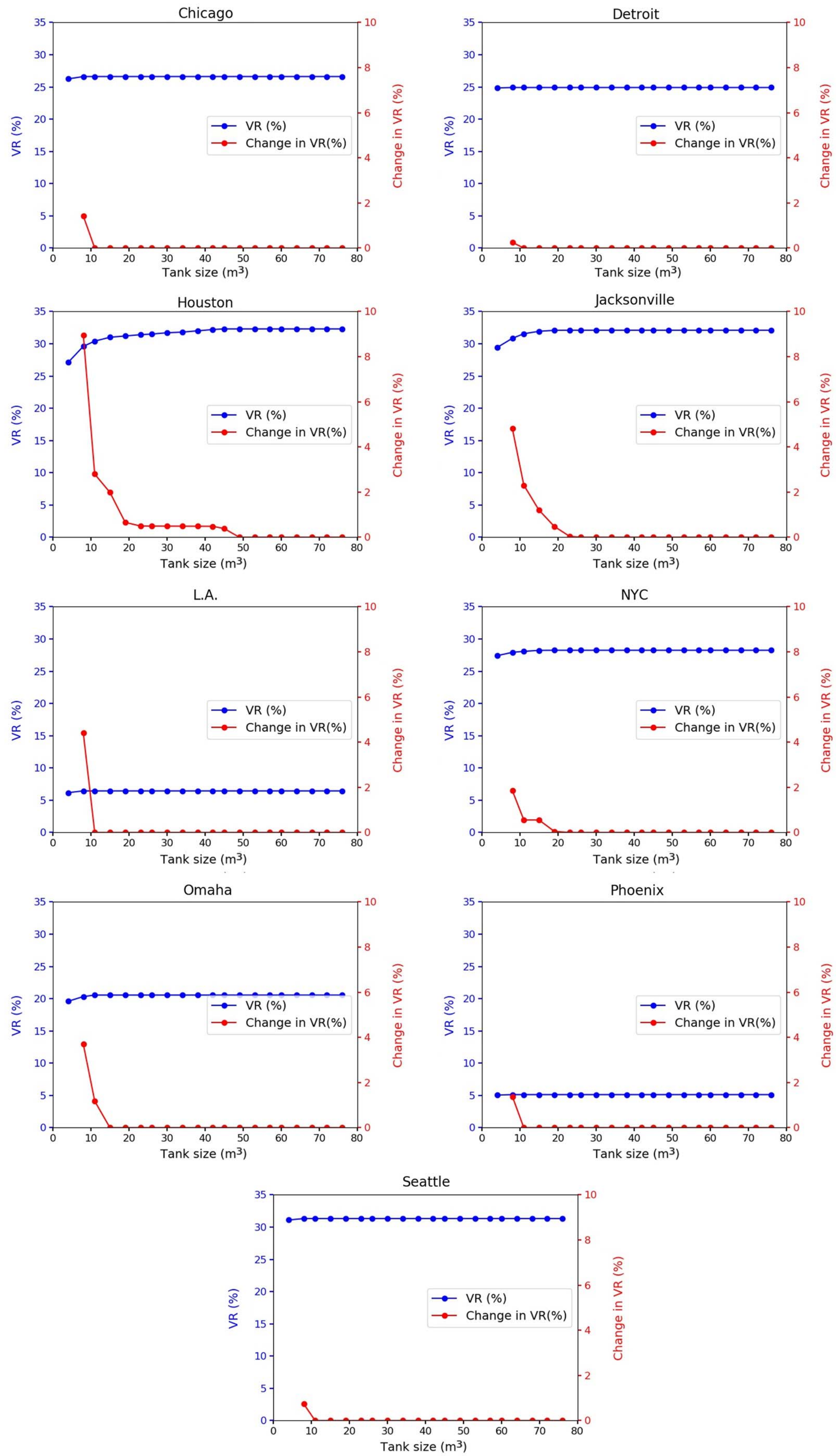

Fig. 5. Private tank sizes and volumetric reliabilities for nine US cities using varying water demands.

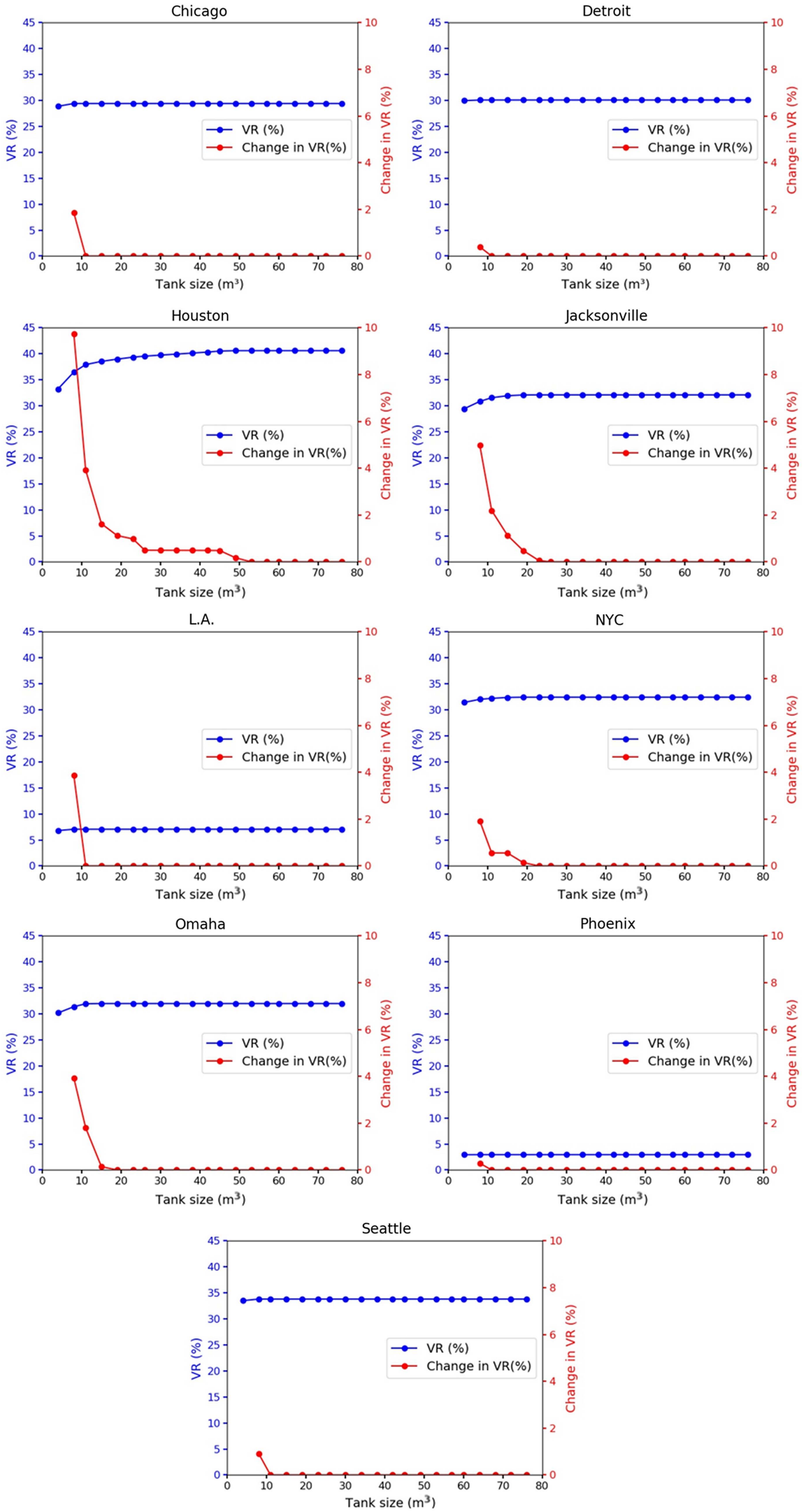

Fig. 6. Private tank sizes and volumetric reliabilities for nine US cities using average water demands.

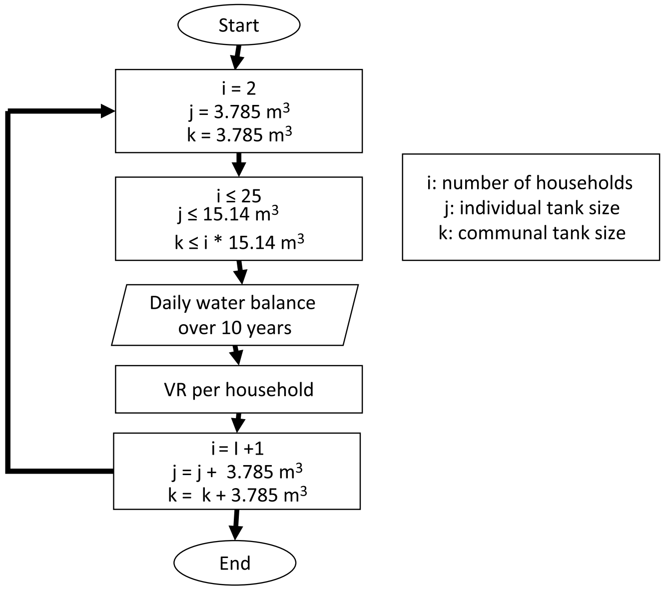

Fig. 7. Simulation of the distributed RWH network.

- The system achieved equilibrium, i.e., a steady state, after a certain number of households were added to the system. That equilibrium corresponded to 9–10 households for the Houston system and 6–7 households for the Jacksonville system for all private tank sizes used in the simulation. Common sense predicts that given an unlimited storage capacity, the average VR gains would be the same no matter how many households were added to the system because, even though the water demand increases by adding more households to the system, that demand is offset by the addition of common storage capacity. In reality, above a certain number of households, the balance of water inflows and outflows between the households and the common storage tank becomes negligible. This is interesting, because after reaching equilibrium, the communal storage capacity does not increase with the addition of households. This could imply that the multiple water demands do not occur at once, nor for the same amounts, especially because the water demand was simulated according to a normal distribution.
- The largest VR gains for the four private tank scenarios were for the smallest tank size of 3.785 m^3 and for about 9–10 households in the system for Houston and about 6–7 households for Jacksonville, reaching the equilibrium point. Beyond that point, for the four private tank sizes, the average VR gains reach steady-state around 1%. The system achieved equilibrium regardless of the input increase.
- The average VR gains followed a log function distribution (Fig. 9), and it is clear that a DRWH system works best with private storage sizes of 3.785 and 7.57 m^3 for both cities.

The impact of the DRWH system is twofold: VR and the total water storage capacity of the system both increase compared with an individual RWH systems. To examine further both those impacts, we studied a DRWH system of two, three, and four households, each with a 3.785 m^3 tank and variable communal storage for both cities.

The peaks in the storage capacity (Fig. 8) can be attributed to the variable water demands that we used in the simulation instead of average water demands. For example, for the peak in Fig. 8 for a private tank of 3.785 m^3, the highest VR is at 72 m^3 for a VR of 29.9%, whereas for the previous and following storage capacities, the maximum VR was 29.8%, which occurred for a communal storage capacity of 53 m^3. The difference between both VR outputs was minimal, and the higher VR can be attributed to lower water demands in that particular simulation.

Changes to VR with Respect to Storage Capacity (Private and Communal Storage)

This section focuses on reducing the total storage capacity (private and communal storage) and its effect on the VR.

In both cities, an addition of a small communal storage connected to the existing private storage per household (3.785 m^3) produced a VR gain compared with the total storage capacity (Fig. 10). For example, for two households for the city of Houston, the distributed RWH system produced an average gain of 1.3%/user for two connected households for the same total storage capacity as for two traditional, unconnected RWH systems. For a total capacity storage of 22.5 m^3, the DRWH system averaged a VR gain of 2%/household. For the DRWH system with four households, the traditional rainwater harvesting system produced better gains for a total storage capacity of about 40 m^3.

In the case of Jacksonville, two connected households produced average VR gains compared with a traditional rainwater harvesting system with no exchange between systems for all storage capacities, whereas for three households and four households, the larger the communal tank, the closer the VR gains to the VR of an individual RWH system.

VR of DRWH System and RWH System with No Exchanges and No Communal Storage

For the city of Houston, Fig. 11 compares the VR resulting from the DRWH system of multiple households, each using a private storage of 3.785 m^3, with the VR of a single household with the same storage tank capacity that is not connected to a communal tank. The average VR for each user from the three DRWH systems was higher than for a comparable household with the same storage capacity rainwater harvesting system (3.785 m^3). For the city of Jacksonville, in the case of two connected households, the average VR was higher than that of a single user, and for the case of three and four connected households, the average VR increased when the total storage capacity (private and communal storage) increased, with the highest gains for private storage of 3.785 m^3.

Discussion

The purpose of this research was to determine (1) the impact of a distributed RWH on the reliability of the system, (2) the storage (private and communal) required to achieve that reliability, and (3) the optimal number of connected households to the distributed system.

In Houston's case, connecting 7–10 households can produce average VR gains above 1.5% (Fig. 7) compared with the VR expected from a traditional, unconnected rainwater harvesting system, with the highest gains for 6–7 households connected with private tanks of 3.785 m^3. As the number of households increases beyond 24 households, the communal storage needed to sustain a VR gain does not increase above a certain storage capacity, which means that the system achieves saturation.

For Jacksonville, connecting up to 7 households can produce average VR gains above 1.5% (Fig. 7), with the highest gain for the use of private tanks of 3.785 m^3. As the number of households increases, there are no notable gains in VR; hence, in Jacksonville

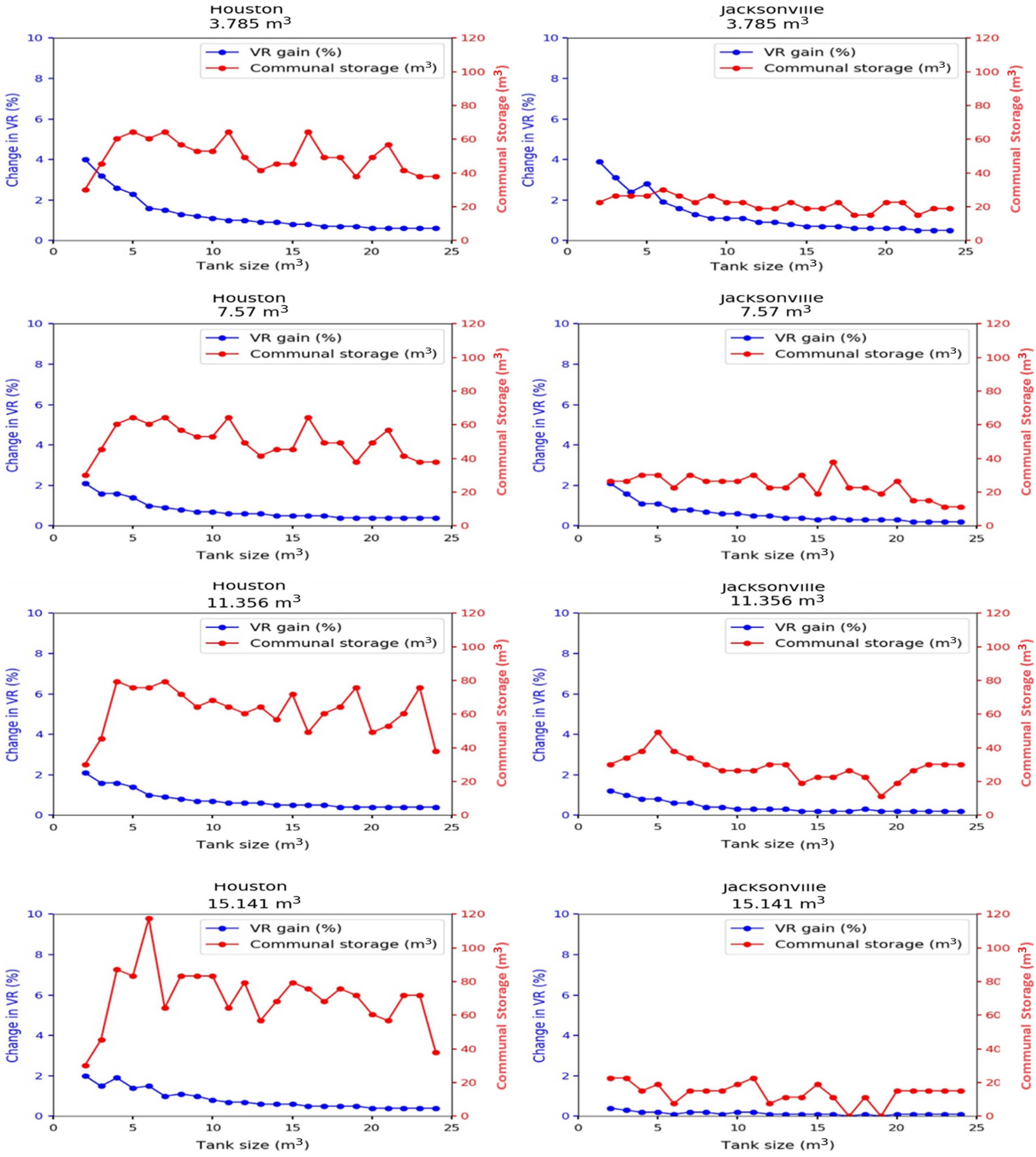

Fig. 8. Maximum volumetric reliability gains for each group of households for four private storage options.

the ultimate number of connected households should not be more than four.

The importance of connecting the overflow of RWH systems and hence the existence of DRWH systems serves multiple purposes:

1. It reduces potential flooding and property damage. Excessive stormwater can enhance the potential for flooding, erosion and potentially hazardous events. Reducing the overflow from the storage tank by diverting it to a communal tank reduces the likelihood of such events.
2. It reduces impacts on the stormwater infrastructure. Collecting the overflow from one individual rainwater harvesting system, storing it, then repurposing that stored overflow for that same household or another household reduces the amount of rainfall going to waste in the stormwater pipes. The risk of exceeding

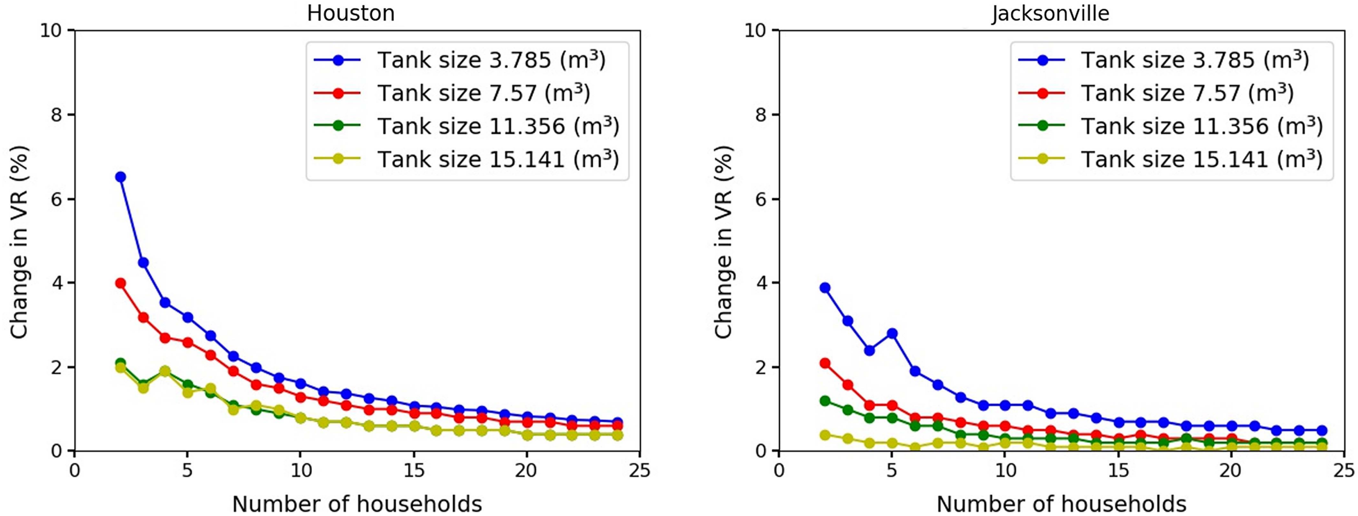

Fig. 9. Maximum volumetric reliability gains for Houston and Jacksonville.

the stormwater infrastructure's capacity is reduced, hence minimizing potential infrastructure breakdown or malfunction.

3. It decreases the pressure on the municipal water supply network. The presence of a communal storage system increases the volumetric reliability of RWH systems [which could be as high as 25% increased reliability (Fig. 10, Houston)], which means an increase in meeting water demands from rainfall, which means a decrease in the water supply from the municipal water supply, which could translate to financial gain to the household (reducing the water bill) and freeing resources on the municipality's side to upgrading the existing infrastructure.
4. It increases the resilience of the water and stormwater infrastructures in the face of climate change. One of the potential impacts of climate change is the change in rainfall patterns. Areas that used to receive a certain amount of rainfall could receive more or less, which in turn will affect the storage capacity of a single rainwater harvesting system, especially because planners use data from previous years to determine the storage capacity of a given system. Backup storage could alleviate that problem, which in turn directly would impact the water and stormwater infrastructure in the event of greater or lesser water demand or more or less rainfall runoff.

The two candidate cities chosen both have a Köppen classification of Cfa and an average yearly precipitation of 1,270 mm. Interestingly, those climates make stormwater management of paramount importance, mainly because of (1) frequent and heavy rainfall, and (2) the increase in impervious surfaces in urban areas. Hence, a distributed rainwater harvesting system is especially attractive in such climates where there is a need to save space. New York City has almost the same characteristics as the two selected cities, but was not chosen for further analysis based on the criteria set previously. Hence, more research should focus on what makes an area suitable for DRWH systems.

Figs. 7 and 10 differentiate between designing the system for a high VR or for a balance between higher VR and total storage capacity. The former can be the case for an expected increase in rainfall due to climate change and a lack of funds from town managers to update the stormwater infrastructure quickly enough or critically enough to mitigate those effects. In that case, the system can become part of the town's stormwater management plan. Therefore, Fig. 7 can be a valuable resource in determining the target private and total storage for a maximum increase in VR with respect to the number of households.

When the emphasis is on maximizing VR without exceeding the total storage capacity of individual RWH systems, the resource for planners is Fig. 10, which minimizes the increase cost of unlimited communal storage while at the same time increasing the VR of the individual system per household. This system could work in a communal-type development such as cohousing communities, which consist of private homes and shared resources, or in a community of tiny homes in which storage and roof area are limited and the pooling of water resources truly can make a difference.

This work studied identical single-family households with two residents. Based on the criteria discussed in the first section, two cities were selected to validate the simulation. Future work should consider different households, with more or fewer residents, and a mixture of building types (residential and office/commercial buildings). This DRWH system could be effective in more areas, hence increasing the resilience of water and stormwater infrastructures, especially in the face of climate change, and especially with the use of modular water tanks. More granularity with respect to water demand is needed; the increased use of smart water meters will help accurately gauge the amount of water needed per building type, thus improving the inputs to the system, especially as we move toward cities based on the Internet of Everything (IoE).

Conclusion

A mix of centralized/decentralized water infrastructure is becoming more appealing in the face of the amount of resources needed to upgrade or improve the existing infrastructure. Communal and individual RWH systems are at the core of the decentralized solution because they impact both the water and stormwater infrastructures. This paper examined a novel approach to communal RWH systems, which is distributed rainwater harvesting systems, in which individual households connect the outflow of their RWH system to a communal storage from which they can retrieve water when their system is not able to meet all water demands. This approach is based on distributed computer systems, which are autonomous, communicate by message passing, are robust against component failure, and work toward a mutual objective.

We simulated the performance of the system in two cities (Houston and Jacksonville) based on our selection criteria, which initially comprised nine representative cities from the nine climatic regions in the United States, for multiple private and communal

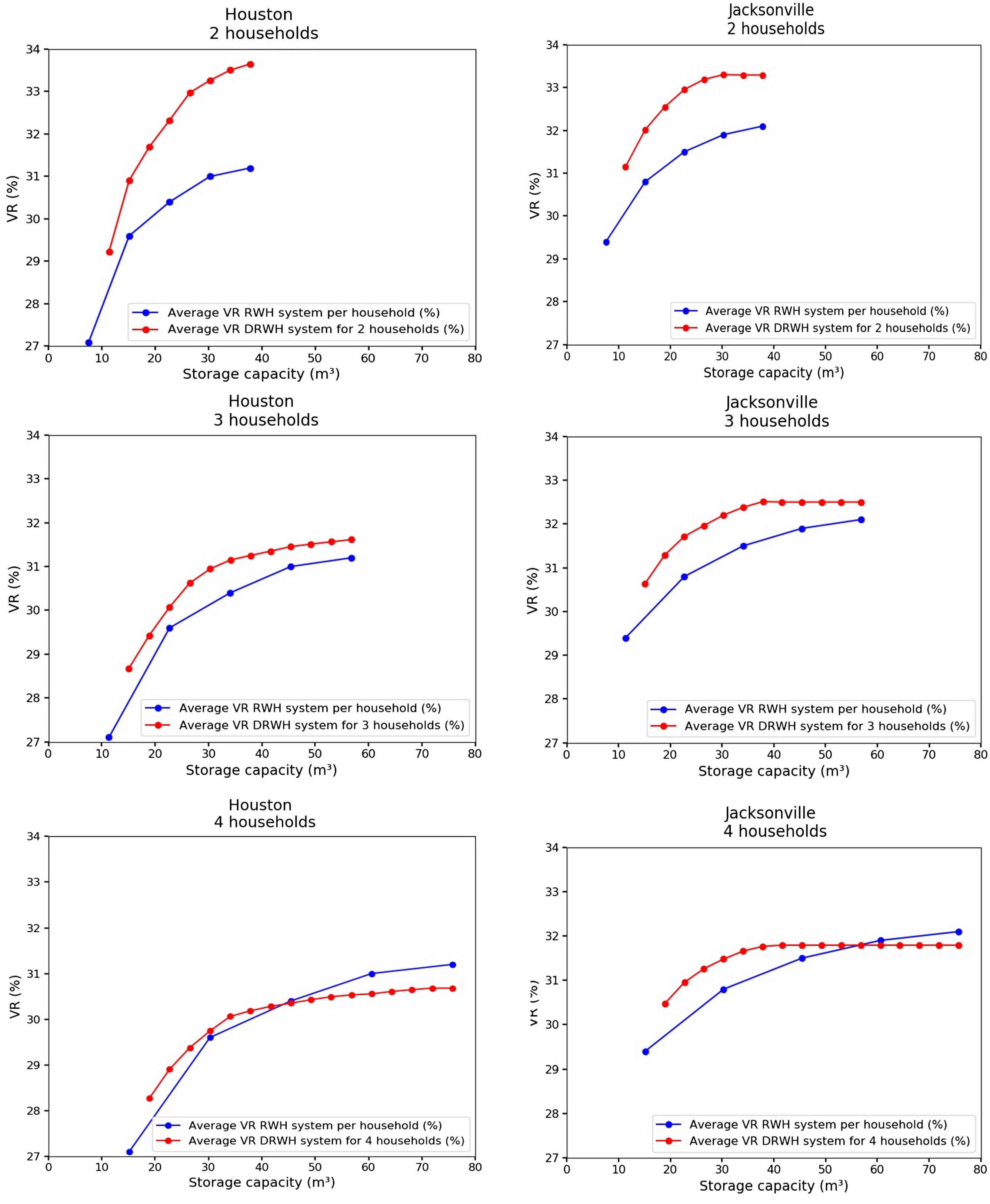

Fig. 10. Average volumetric reliability per total storage capacity for Houston and Jacksonville.

storage capacities combination. Volumetric reliability gains (1.5%–6% and 1.5%–4%) can be achieved for up to 10 and 7 connected households, respectively, for Houston and Jacksonville if the emphasis is on VR gain greater than 1.5%. In terms of total storage capacity, the system achieved higher VR gains for lower total storage capacity in Houston, whereas the system achieved higher VR gains for higher total storage capacities in Jacksonville.

This proposed decentralized rainwater harvesting system is attractive in the face of climate change, increases the resilience of water/stormwater infrastructures, and potentially could decrease

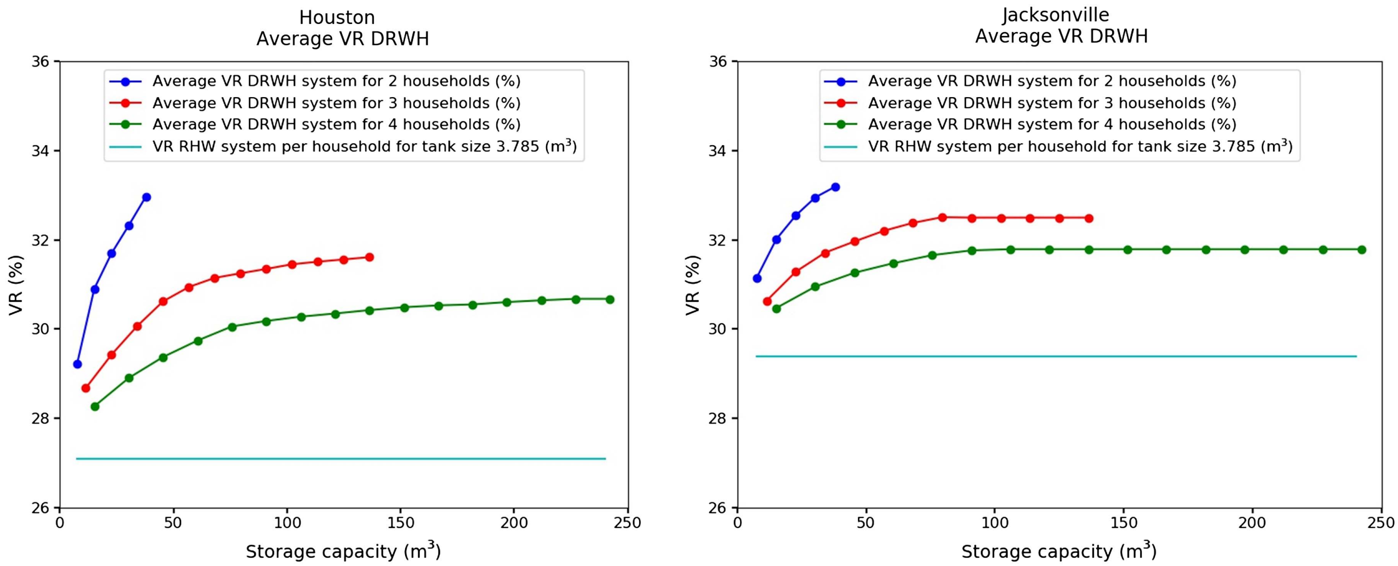

Fig. 11. Average VR for DRWH system and RWH system for Houston and Jacksonville.

the potential effects of flooding and property damage from stormwater. This research focused on two cities; more exploration is needed to (1) determine which areas are suitable for this distributed communal rainwater harvesting system, and (2) understand the effect of mixing different types of buildings in the communal mix.

Data Availability Statement

The code that supports the findings of this study is available from the corresponding author upon reasonable request.

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