

Potential of rooftop rainwater harvesting to meet outdoor water demand in arid regions Postprint

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Abstract

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Full Text

Preamble

Potential of rooftop rainwater harvesting to meet outdoor water demand in arid regions

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Abstract: The feasibility of rooftop rainwater harvesting (RRWH) as an alternative source of water to meet outdoor water demand in nine states of the U.S. was evaluated using a system dynamics model developed in Systems Thinking, Experimental Learning Laboratory with Animation. The state of Arizona was selected to evaluate the effects of selected model parameters on the efficacy of RRWH since among the nine states, the arid region of Arizona showed the least potential for meeting outdoor water demand with harvested rainwater. The analyses were conducted on a monthly basis across a 10-year projected period from 2015 to 2024. The results showed that RRWH as a potential source of water was highly sensitive to certain model parameters such as outdoor water demand, the use of desert landscaping, and the percentage of existing houses with RRWH. A significant difference (as high as 37.5%) in rainwater potential was observed between projected wet and dry climate conditions in Arizona. The analysis of storage tank dynamics suggested that a 1.0-2.0 m³ rainwater barrel, on average, can store approximately 80% of the monthly rainwater generated from rooftops in Arizona, even across high seasonal variation. This interactive model can be used as a quick estimator of the amount of water that could be generated, stored, and utilized through RRWH systems in the U.S. under different climate conditions. The findings of such comprehensive analyses may help regional policymakers, especially in arid regions, to develop sustainable water management infrastructure.

Keywords: rooftop rainwater harvesting; rainwater storage tank dynamics; sustainability of outdoor water usage; sustainability of water in arid regions; best management practices in arid regions; variation of rainfall under various climate conditions

1 Introduction

The adverse effects of increasing global population are prevalent worldwide, affecting both the supply and demand of water (WHO, 2009). The rate of increase in water demand is accelerating, and current demand is projected to double by 2035 (Tidwell et al., 2004). Researchers anticipate that in the next several decades, two-thirds of the world's population may experience water scarcity (Rijsberman, 2006). Studies have also found that many river basins around the world face challenges meeting local water quality standards (Shammi et al., 2016). As a result, besides the quantity of accessible water, water quality may severely influence the global water crisis (Khadse et al., 2016). Studies show that changes in climate can significantly influence the hydrologic cycle and hydrologic regimes, even though these effects vary from region to region (Tamaddun et al.,

2017a). Researchers suggest that intensification of water shortage during hot, dry summer seasons could be attributed to shifts in the timing of hydrologic variables (e.g., precipitation, snowmelt, and streamflow patterns), which are subject to climate variability and change (Tamaddun et al., 2017b). Extreme hydrologic events such as floods, droughts, and storms could become more severe and frequent with climate change (Tamaddun et al., 2016). These changes could affect surface and groundwater flow patterns and influence water quality, which in turn could pose serious threats to water resource management (Middelkoop et al., 2001). Optimal allocation and rational use of water resources can potentially reduce costs and enable sustainable water resource development (Chagwiza, 2016).

Rainwater harvesting (RWH) can serve as an alternative water source not only because of the volume it can generate but also because it meets most local water quality standards in terms of maximum contaminant levels (Cain, 2010; Rahman et al., 2014). Rainwater is naturally very soft and can be considered one of the cleanest water sources on Earth (TWDB, 2005). Raindrops can become slightly acidic as they dissolve atmospheric CO₂ and N₂; however, this may not be problematic if the water is primarily used for outdoor purposes (MHLG, 2008). Hence, evaluating the feasibility of RWH as an alternative source for outdoor purposes (e.g., gardening, landscaping, car washing) represents a promising research scope. This study presents a highly adaptable model to evaluate the feasibility of rooftop rainwater harvesting (RRWH) systems for meeting outdoor water demand, applicable to any state, city, or neighborhood through simple modifications and adjustments. The model's interactivity can be used effectively and quickly to estimate the amount of water that can be generated and stored with RRWH systems across seasons under different climate conditions. This study can assist policymakers in obtaining preliminary estimates of harvested rainwater, which can be helpful for implementing regulations regarding sustainable water management.

According to the U.S. Environmental Protection Agency (EPA), RWH has drawn interest from researchers and policymakers as a sustainable source to meet increasing water demand since the technique can conserve both water and energy (Kloss, 2008). Throughout history, RWH has been used as an alternative water source, especially in regions where water resources are either scarce or difficult to access. Cain (2010) found that small-scale RWH systems can be effectively applied in both rural and urban settings in India and suggested that RWH should be more widely used to address the global water crisis. Che-Ani et al. (2009) found that RWH may be the most suitable solution for meeting future water demand in Malaysia as accessibility to clean surface and groundwater becomes scarce both qualitatively and quantitatively. Studies show that RWH is feasible not only in wet regions but also in relatively dry or arid regions. Li et al. (2000), studying semi-arid regions of China, found that in-situ RWH systems can significantly improve rain-fed farming systems. Bitterman et al. (2016), in a study in Tamil Nadu, India (which has a tropical climate with fairly hot temperatures year-round), proposed a conceptual framework to

measure water security as a causal response to rainwater harvesting tanks to mitigate risks caused by water shortage. Examining the application of domestic and agricultural RWH systems in U.S. river basins, Ghimire and Johnston (2013) found significant reductions in average monthly withdrawal (water yield) among surrounding watersheds. Several studies have also provided cost-benefit analyses of applying RWH in urban and industrial setups based on optimized design and policy guidelines (Jothiprakash and Sathe, 2009; Temesgen et al., 2016).

Angrill et al. (2012) analyzed different scenarios and identified the most suitable strategies for designing environmentally friendly RWH systems in urban settings. The study also suggested that RRWH has the potential to function as a thermal regulator if designed and located properly on roofs, which can contribute to energy conservation. EPA (2013) discusses different types of RWH systems, such as active cisterns with treatment facilities, passive systems as complements to existing stormwater systems, rain barrels used for outdoor purposes, check dams, and fog/moisture collectors. Details on installation costs, energy savings, carbon emission reductions, distribution system design, and treatment facilities for different RWH systems can be found in Kloss (2008) and EPA (2013).

EPA (2013) compiled current scenarios of RWH systems in the United States. The Texas Manual on Rainwater Harvesting, published by the Texas Water Development Board in 2005, provides necessary guidelines for designing RWH systems. The Building Codes Division of Oregon's Department of Consumer and Business Services published a handbook (ODCBS, 2014) on designing RWH systems. Kloss (2008) discussed design methods for different RWH systems along with environmental benefits and included information regarding energy savings due to RWH. Basinger et al. (2010) developed a nonparametric stochastic model to evaluate RWH potential in multi-family residential buildings in New York City and determined the reliability of rain-harvested water through rooftop facilities for meeting demands for toilet flushing, garden irrigation, and air-conditioner topping. The study found that RWH can significantly reduce potable water demand and rooftop runoff inputs to sewer systems. Ward et al. (2010) developed evaluation models to design storage tanks based on demand level and catchment size for both commercial and domestic buildings and found considerable potential for water conservation. The study also emphasized the use of simulation models instead of traditional models since complex, continuous simulation models have higher stakeholder involvement.

The current study developed a system dynamics simulation (SDS) model using Systems Thinking, Experimental Learning Laboratory with Animation (STELLA), based on regional demographics and historical records to evaluate the feasibility of RRWH systems across nine states within the conterminous United States. The model evaluates RRWH potential under various climate conditions and calculates the volume of water generated to meet increasing demand. The dynamics of storage tanks, as they are recharged and drained based on seasonal demand variation, were also evaluated. The absence of a

comprehensive study on RRWH potential under various climate conditions in the U.S. served as the primary motivation for this research. Consequently, based on information gathered from literature, the key objective was to present a single interactive model that would allow policymakers and end users to evaluate RRWH system potential under various controlled scenarios.

2 Study Area and Data

The U.S. Census Bureau divided the continental U.S. into nine divisions, each consisting of several states. Since only residential households were considered to evaluate RRWH potential for meeting domestic outdoor demand, the states with the highest population in each division were deemed appropriate for the study (Fig. 1 [Figure 1: see original paper]). Ten years of continuous precipitation data (referred to as rainfall in later sections since other precipitation forms eventually melt and can be considered rainfall volume) from January 2005 to December 2014 were obtained on a monthly basis from the online database of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce (Fig. 2 [Figure 2: see original paper]). Rainfall patterns were assumed to remain the same for the upcoming 10 years (projected years: January 2015 to December 2024) but were adjusted based on near-term climate projections suggested by EPA (Rossman, 2013). Guidelines for RRWH systems were obtained from EPA (2013). Governing equations and conversion factors were obtained from the Texas Manual on Rainwater Harvesting, published by the Texas Water Development Board (TWDB, 2005), which EPA also recommends as a guideline for designing RRWH systems in the United States.

Water usage data, measured in cubic meters per capita per day (CMPCD)—the most commonly used unit for reporting water usage in the U.S.—were calculated from Maupin et al. (2014) using 2014 population data. To maintain consistency with SI units, subsequent sections report water usage in cubic meters per capita per day. Demographic data such as birth and death rates, initial (2014) state populations, number of people per household, average household area, and average household-area-to-roof-area ratio were obtained from survey results conducted by the Centers for Disease Control and Prevention National Center for Health Statistics (CDC-NCHS), U.S. Census Bureau, and Bureau of Labor Statistics, United States Department of Labor. Table 1 lists the demographic data and statistics used in this study.

3 Methodology

System dynamics simulation (SDS) models have been used extensively in hydrology and water resource management problems (Chen et al., 2017). Applications of SDS models can be found in river basin planning (Zhang et al., 2016), municipal water conservation policy development (Qaiser et al., 2013), city-based water resources planning (Venkatesan et al., 2011), determination of river/river basin system sustainability and water reusability (Elshorbagy et al., 2005), eval-

uation of water quality parameters (Rusuli et al., 2015), examination of reservoir performance (Ahmad and Simonovic, 2000), design of flood management and emergency evacuation systems (Simonovic and Ahmad, 2005), and development of support systems and accounting tools (Gastélum et al., 2009; Turner et al., 2010). Considering the advantages of SDS models in simulating complex systems, this study developed an SDS model using STELLA to evaluate RRWH potential in residential households throughout the nine selected states (Fig. 1). Once a simulation model representing a system has been developed, it can be replicated to observe the effects of proposed modifications—a significantly helpful feature for water resource management problems (Stave, 2003). Detailed descriptions of how SDS models capture system dynamics can be found in Forrester (1994), Ford (1999), and Sterman (2000).

3.1 Model Structure

The model was built with seven sectors: rainfall (S1), climate (S2), RRWH (S3), demand (S4), CMPCD (S5), housing (S6), and population (S7). S1 and S5 provided regional data for each state. S7 provided information regarding total state populations based on monthly birth and death rates (monthly rates were calculated from annual rates provided by CDC-NCHS). Although each state's population varied, birth and death rates were considered identical across all selected states (Table 1).

3.1.1 Climate Sector (S2) EPA suggested four climate conditions for both near- and far-term projections (Rossman, 2013): (1) no change, (2) hot or dry, (3) median change, and (4) warm or wet (Fig. 3a [Figure 3: see original paper]). For the analyses, near-term (2020-2049) projected values were used. In baseline scenarios (BLSs; explained in section 4.1), against which controlled/modified scenarios were compared, no climate change was considered. However, for further analysis, median climate change was selected for comparison purposes.

3.1.2 RRWH Sector (S3) This sector considered rainfall from selected states and calculated water generation through RRWH using the governing equation below (TWDB, 2005; EPA, 2013). where V is the total volume of water generated (m^3); R is rainfall (mm); CA is catchment (roof) area (m^2); C is the unit conversion factor of 0.001 (m/mm); and CE is the collection efficiency equals to $V=R \times CA \times C \times CE$. Equation 1 was modified from its original form to express it in terms consistent with the Système International (SI). CE depends on roof material, which users can modify as required. This sector also considered the effect of antecedent dry period on total runoff generation using a reduction factor (not included in Eq. 1), introduced based on the Soil Conservation Service (SCS) curve number concept (Lim et al., 2006; Yuan et al., 2014), which measures rainfall excess considering surface moisture and infiltration.

3.1.3 Demand Sector (S4) This sector calculated total outdoor demand as a percentage of monthly water demand for selected states. Annual average

CMPCD values for states were calculated from Maupin et al. (2014) using 2014 population data (Table 2). Table 2 reports water usage in CMPCD. Griffin and Chang (1991) studied seasonal effects on community water demand, and their results were used as an approximate seasonal variability index to consider water demand changes across a year (Fig. 3b). The effect of desert landscaping was also considered in this sector as it affects overall water demand.

3.1.4 Housing Sector (S6) This sector calculated the number of households based on total state populations. Factors such as average household area, average number of people per household, and average household-area-to-roof-area ratio (Table 1) were obtained from sources mentioned in Section 2.

3.2 Assessment of Model Dynamics

A set of assessment techniques (Forrester and Senge, 1980; Shreckengost, 1985) were applied to test model dynamics and build confidence. First, dimensional consistency was maintained throughout the modeling process. Indices and multipliers were chosen (or converted if necessary) to avoid influencing units and dimensions. Second, to test dynamic relations, three extreme conditions—zero rainfall, zero current population, and zero CMPCD—were set to observe results. The model simulated these extreme conditions as expected. Third, to observe model behavior, three different integration methods (Euler's method, Runge-Kutta 2, and Runge-Kutta 4) were used while reducing the interval fraction from 1/4 to 1/132 unit of time. Under all settings, the model generated comparable results. Fourth, to test whether the model could replicate expected behaviors, different climate conditions were applied to Arizona rainfall data (for the last 12 months: January–December 2014) (Fig. 3c). Results indicated that reduced rainfall due to hot or dry climate could significantly decrease rainfall amounts, particularly from May to September. Warm or wet conditions showed maximum rainfall increases from June to August. These pattern changes were consistent with EPA climate condition suggestions (Fig. 3a). Finally, sensitivity analyses were run to observe how outcomes responded to various model parameters. Comparative responses of these parameters are discussed in the Results section below.

4 Results

4.1 Baseline Scenarios

A set of parameters were chosen as most influential for determining RRWH feasibility in a state (Table 2). In baseline scenarios (BLSs), climate condition was set to no change for all states. The percentage of existing houses with RRWH was considered 5%, while the percentage of new houses (to be built in the next 10 projected years) with RRWH was kept at 25%. These percentages were reasonably assumed since the study objective was to present a relative comparison between BLSs and controlled scenarios and to evaluate RRWH potential.

The percentage of CMPCD used to meet outdoor demand, the percentage of population living in households with desert landscaping, and the reduction factor due to antecedent dry period had unique values for each state. The EPA WaterSense program (www.epa.gov/watersense) suggests that, on average, 30% of per capita water demand is used for outdoor purposes across the U.S., which can be as high as 60% in southwestern arid regions (e.g., Arizona, California, and Texas). The percentage of population living in households with desert landscaping was set to zero in BLSs for all states except arid states, since remaining states had more than 100 mm of long-term average precipitation per month (Fig. 2). The reduction factor due to antecedent dry period was close to 1.0 (suggesting no reduction) for states with sufficient, frequent rainfall (Table 2). Values were set according to state location and climate based on the SCS curve number (Yuan et al., 2014). Graphical BLS outcomes are presented in Figure 4 [Figure 4: see original paper].

In BLSs, many states—especially those with sufficient, frequent rainfall—could meet outdoor water demand quite effectively through RRWH (Table 3). Although four of nine states met total outdoor water demand from RRWH in terms of total volume over projected years (Table 3), none could meet demand year-round on a monthly basis since seasonal effects influenced both rainfall and outdoor water demand (Fig. 4). Florida, Massachusetts, and Tennessee showed good responses; RRWH met outdoor water demand during most months in these states. Demand was met during some months for Illinois, New York, and Missouri; however, these states fell short of target demand during a few summer months. Arizona, California, and Texas showed poorest performance in meeting water demand. California and Texas had only a few monthly instances where RRWH met outdoor water demand; Arizona showed no instances of meeting demand during the entire projected period in BLSs.

The study did not provide a unique solution for each state since it depends on users changing model parameters and observing outcome effects. Arizona was selected as the sample state to analyze model parameter effects since it had the least potential for meeting outdoor water demand with RRWH compared to other states. Subsequent subsections discuss the dynamics of each model parameter in detail for Arizona.

4.2 Effect of Climate Conditions

Figure 5 [Figure 5: see original paper] shows variation in rain-harvested water (monthly average) for each projected year for Arizona under various climate conditions. All parameters except climate conditions were fixed as in BLS (Table 2). Results show that hot or dry climate significantly decreased rainfall and therefore reduced water volume generated from RRWH. Conversely, maximum water production from RRWH occurred under warm or wet climate in almost all months during projected years. The difference in water volume produced from RRWH under warm/wet versus hot/dry conditions reached as high as 37.5% in a single month. The average monthly difference in rainwater generated

through RRWH between warm/wet and hot/dry scenarios was 4.3% across the study period. Annual variation (Fig. 5) also showed that warm or wet climate produced more water via RRWH than hot or dry climate in each projected year.

4.3 Effect of CMPCD

A reduction in the percentage of CMPCD available for outdoor water usage can increase the chances of meeting demand via RRWH. The EPA WaterSense program (www.epa.gov/watersense) suggests that water-efficient best management practices (BMPs) can reduce outdoor water usage by 15% if regulated properly. For Arizona, the percentage of CMPCD used to meet outdoor water demand was reduced to 40%, compared to 50% in BLS. As shown in Figure 6a [Figure 6: see original paper], reducing outdoor water usage caused a linear reduction in total outdoor water demand, which significantly narrowed the gap between total outdoor demand and water generated through RRWH.

4.4 Effect of Desert Landscaping

The relationship between the percentage of population living in households with desert landscaping and total outdoor water demand was built based on water smart landscape guidelines (www.snwa.com/rebates) by the Southern Nevada Water Authority (SNWA). According to SNWA, total lawn area (turf) should not exceed 50% of side and rear yard areas in Southern Nevada to receive additional credit as a lawn owner. Water smart landscape guidelines suggest that 0.21 m³ of water per year can be saved per 0.093 m² (1.0 ft²) of grass replaced by water-smart landscapes. Based on these guidelines, a function was built into the model. For Arizona, the percentage of lawn area converted to desert landscapes was kept at 50%, but the percentage of population living in households with desert landscaping was varied. The percentage of population with desert landscaping was increased to 50%, compared to 20% in BLS, which reduced outdoor water demand by 14.2% (Fig. 6b). Such reduction can be quite significant in arid states where desert landscaping is a viable option.

4.5 Effect of Households with RRWH Systems

Increasing existing households with RRWH systems from 5% (BLS) to 15% showed a 200% increase in water volume generated through RRWH (Fig. 6c). For the first time in Arizona, there were a few monthly instances where demand was met from RRWH. As expected, water generated through RRWH was highly sensitive to the existing number of households with RRWH.

The percentage of new households with RRWH systems increased from 25% (BLS) to 100% (Fig. 6d), causing a 0.54% average increase in total water volume generated through RRWH over projected years. The difference between results was not visually noticeable since the number of new households to be built over the next 10 projected years was quite insignificant (only 0.04%) compared to the number of existing households.

4.6 Effect of Antecedent Dry Period

The antecedent dry period reduces runoff generation potential of a rainfall event since atmospheric moisture content varies greatly between wet and dry seasons and across states due to climate variation. For Arizona—a state with little rainfall and high temperatures (common in arid or semi-arid regions)—the reduction factor was set to 0.70, which rationalized water generation potential of RRWH. This model parameter controls the effect of moisture content and potential evaporation with a single number, introduced based on the SCS curve number concept (Yuan et al., 2014). Moreover, the model allows users to choose different reduction factors at different times of year during the study period.

4.7 Achievable Scenario

Analyses of previous cases suggested that no single model parameter could solve the entire problem of meeting outdoor demand using RRWH. Comprehensive measures are required to generate more water from such systems while simultaneously addressing the demand side by reducing outdoor water demand and implementing BMPs such as desert landscaping. Several scenarios with different parameter combinations provided realistic solutions. One scenario, shown in Table 4, was selected as an achievable scenario (AS). Although this scenario did not meet demands year-round for a state like Arizona with very little rainfall, it provided an example of how the problem could be tackled by controlling several system parameters.

To attain the AS, the demand side was reduced by decreasing the percentage of CMPCD used for outdoor purposes from 50% (BLS) to 40% (Tables 2 and 4); desert landscaping use was increased from 20% (BLS) to 75%; the percentage of existing households with RRWH was increased from 5% (BLS) to 25%; and the percentage of new houses with RRWH systems was increased from 25% (BLS) to 100% (Tables 2 and 4). In Arizona, under the AS, generated water through RRWH increased by up to 400% and outdoor demand decreased by up to 41% compared to BLS. Total water generated from rooftops was observed to meet 0.85% to 56% of total monthly water demands.

4.8 Dynamics of Storage Tanks

Storing, draining, and refilling rainwater tanks are critical for evaluating RWH efficacy since available tanks have specific storage capacities. A passive harvesting system (rain barrel) typically stores 0.2–0.4 m³ of water, whereas an active harvesting system (cistern with treatment facilities) stores 4.0–40.0 m³ (EPA, 2013). Depending on size, these tanks can be placed on rooftops or on the ground. During projected years under median climate conditions, Arizona experienced 22.3 mm of rainfall per month. This rainfall generated up to 2.4 m³ of water per month per household with a roof area of 125 m².

A 4.0-m³ tank was chosen to evaluate RWH tank dynamics, which was large enough to store average monthly water generated from rooftops in Arizona. If a

particular month experienced sufficient rainfall to meet outdoor water demand (i.e., if total water volume generated in lawn areas exceeded total outdoor water demand), no water was drawn from tanks. During months when rainfall was insufficient to meet outdoor demand, the required amount (the gap/difference between demand and rainfall water) was drawn from tanks, sometimes emptying them.

During the projected 10 years (120 months), 37 instances (30%) were found where no water was required from tanks, suggesting that monthly total rainfall alone was sufficient to meet monthly outdoor water demand (Fig. 7a [Figure 7: see original paper]). For remaining months when a gap existed, water from storage tanks was drawn. The percentage gap filled by tank water varied from 0.86% to 100% (on 15 of 120 months). Average monthly gap filled by tank water was 27% over projected years (Fig. 7b). Several tank sizes were tested to suggest feasible options. Tank sizes ranging from 1.0-2.0 m³ were found to store close to 80% of water generated from rooftops each month under various climate conditions in Arizona.

5 Discussion

From BLSs (Table 2), Florida, Massachusetts, and Tennessee showed highest potential for meeting outdoor water demand using RRWH during projected years (Fig. 4). Illinois, New York, and Missouri also showed significant potential for meeting demand across many monthly instances. Arizona, California, and Texas showed poor potential in BLSs, as none could consistently meet demand using RRWH. EPA (2013) also suggests that RWH benefits are generally higher on the U.S. east coast compared to southwestern regions where rainfall occurs for limited times each year. Although the current study indicates that six of nine states can effectively meet significant portions of demand through RRWH, many states lack relevant regulations and codes for local standards and guidelines (Kloss, 2008). States such as Georgia, North Carolina, Texas, and Virginia have published guidance manuals with design criteria and water quality standards for RWH systems based on their rainfall potential (EPA, 2013). Among study states, Arizona showed least potential for meeting outdoor demand; hence, it was selected as the sample state and model parameters from both demand and supply sides were adjusted, considering climate conditions and seasonal variations, to produce an AS that could bring satisfactory balance between demand and supply sides.

Seasonal variations (Fig. 3b) indicated highest demand from May to September in a typical year. Climate effects on rainfall also showed highest variation during these months (Fig. 3a). Various climate conditions showed that warm or wet climate could generate maximum rainfall (7.2% increase from long-term average), while hot or dry climate would significantly reduce rainwater volume (10.5% reduction from long-term average; Fig. 3c). Rossman (2013) suggested similar rainfall variations across the U.S. due to various climate conditions. Ford (2011) discusses the importance of incorporating climate change in SDS models result-

ing from global carbon cycle changes, showing how SDS models can improve understanding of interdisciplinary analyses involving climate change. In this study, median climate change was considered for Arizona throughout the study period; however, model users can modify these settings to observe effects of other climate conditions. Figure 5 showed that warm/wet (hot/dry) climate produced maximum (minimum) water from RRWH as expected from rainfall patterns under different climate conditions (Fig. 3c). Woodhouse et al. (2010), studying 21st-century drought in the southwestern U.S., suggested that drought conditions in southwestern regions (e.g., Arizona and New Mexico) were highly susceptible to summer rainfall dictated by the North American monsoon. Climate conditions used in this study also suggest highest variation during summer months (Fig. 3a). A wet summer month showed as much as 81% more rainfall compared to a dry summer month in Arizona during projected years. According to the Arizona Department of Water Resources (ADWR) (www.azwater.gov/azdwr), a 25% reduction in rainfall from long-term average can cause abnormally dry conditions in central and western Arizona during summer. ADWR (2016) suggested that in 2016, all major basins in Arizona's mountainous regions experienced 6%-18% precipitation reduction compared to the 30-year average. ADWR also indicated that based on 30-year records, at any given month, Arizona has a 2% (exceptional drought) to 30% (abnormally dry) chance of facing drought. Multiple climate models suggest the 21st-century southwestern U.S. will become increasingly arid and experience severe, prolonged droughts due to high temperatures from increased greenhouse gases (MacDonald, 2010). In this study, average monthly difference in rainfall amount between wet and dry climate was 17.7%, which can be significant for arid regions like Arizona. Although the AS used median climate change, results suggest dry climate conditions will reduce storage potential even more due to reduced rainfall. Hence, a sustainable approach that conserves both water and energy, as presented in this study, should draw more attention for dealing with extreme conditions.

Reducing the percentage of CMPCD used for outdoor purposes can significantly affect the water demand side (Fig. 6a). Outdoor water demand can be reduced by installing water-conservative facilities, using water-efficient irrigation techniques, and implementing BMPs (Rossman, 2013). EPA WaterSense and SNWA water smart landscape program (www.epa.gov/watersense; www.snwa.com/rebates) provide details on water conservation practices and guidelines for arid and semi-arid regions. Desert landscaping is a viable BMP for residential setups, especially in arid regions. In this study, implementing desert landscaping (Fig. 6b) along with reducing the percentage of CMPCD for outdoor purposes significantly reduced the gap between supply and demand curves. The percentage of existing houses with RRWH and the percentage of new houses to be built in projected years with RRWH determined total water volume generated through RRWH (Figs. 6c and d). Among these parameters, the percentage of existing houses with RRWH was most influential, as the system was highly sensitive to this parameter.

In the AS, increased water generation (400% increase compared to BLS) from

installing RRWH systems across Arizona was much higher than reduced water demand (41% reduction compared to BLS) from conservation practices (Fig. 7a). Although detailed analysis was conducted only for Arizona, obtained relationships can easily apply to other regions with similar climate conditions. Policies adopted in various states are discussed in Forasté and Hirschman (2010), who analyzed benefits and practice credits from implementing RWH as a BMP.

A 4-m³ tank was chosen to capture storage tank dynamics, which was large enough to store mean monthly water generated from rooftops in Arizona. TCEQ (2007) provides detailed descriptions of RRWH system design, including tank sizing, conduit piping, and contaminant treatment. Results indicated that water stored in tanks can meet up to 27% of monthly outdoor demand not met by rainfall alone, potentially reducing overall water usage. In eastern regions with sufficient rainfall, water demand can be reduced up to 53% using RRWH systems (Basinger et al., 2010). Smaller tank sizes (1-2 m³) can also store significant amounts of water generated from rooftops in Arizona depending on climate conditions. During months when rooftop water generation exceeded selected tank capacity, surplus water could be conveyed to drainage disposal facilities (EPA, 2013). Although smaller tanks might not store all system-generated volume each month, they could still play important roles in reducing surface runoff, especially in urban areas with minimal infiltration. Runoff reduction could potentially decrease water treatment costs and infrastructure maintenance (i.e., roadways, paved parking lots, and other water disposal facilities). Basinger et al. (2010) observed 28% reduction in runoff volume into sewer systems from implementing RRWH systems in New York City. Further discussions on benefits of rain-harvested water, including cost and energy consumption reductions, can be found in Kloss (2008) and EPA (2013).

This study showed that RRWH could be used effectively as an alternative water source even in arid or semi-arid regions where rainfall is scarce, though this requires demand-side reductions. The study suggested several options that can effectively reduce water consumption at the user end. RRWH system potential could be extended by adding treatment facilities. Although such systems would be more expensive, stored water would not be limited to outdoor purposes only. Several major cities, including Los Angeles, San Francisco, Tucson, and Portland, have published municipal-level guidelines and policy documents addressing treatment and permit requirements for RWH systems (EPA, 2013). Regions struggling to meet water quality standards may greatly benefit from such facilities. Implementing RWH may require legislative changes as water right issues are involved for larger-scale use. Regional water managers and policymakers may use simulation models, such as the one presented here, to evaluate holistic benefits of retrofitting RWH systems.

A model extension could serve as a tool for cost-benefit analysis of implementing RRWH systems, especially in urban setups, since RWH can potentially reduce water treatment and maintenance costs. Some factors such as average single household size and birth/death rates were considered uniform across all states

and may not represent actual scenarios. Certain assumptions were made to simplify model development; however, these simplifications also broadened model scope by allowing users to compare among several states. For higher accuracy, the model can be adjusted accordingly if region-specific analysis is required for future applications.

6 Conclusions

Demographic data and historical records were used as inputs in a system dynamics simulation model to determine RRWH efficacy across nine U.S. states. As a special case, Arizona was selected since it had the lowest historical rainfall records among selected states and the least potential to meet outdoor water demand with RRWH. Model parameter sensitivity was evaluated to determine the most influential factors affecting RRWH efficacy. Rainfall anomalies under different climate conditions were tested along with seasonal demand variations. Storage tank dynamics based on variable demand and supply were also determined. The major findings are:

1. RRWH has significant potential to meet outdoor water demand, even in arid regions such as Arizona, as long as the demand side is also addressed.
2. RRWH system efficacy is highly sensitive to climate conditions, the number of existing households with RRWH systems, and seasonal variation of outdoor water demand.
3. BMPs such as desert landscaping can significantly reduce outdoor water demand in arid regions.
4. In arid regions, small rooftop rainwater barrels (e.g., 1.0–2.0 m³) can potentially store a significant percentage of monthly rainwater, which can be effectively used in following months with less rainfall and higher demands.

This study developed a model based on existing RRWH system knowledge and combined it into a tool that can be easily adjusted and modified by users based on their needs to promptly evaluate change effects. The model's versatility and interactivity could be helpful to policymakers, especially those facing challenges meeting increasing water demand under changing climate conditions. The model is also available in a web-based interactive format that can be easily utilized by interested parties.

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