Potential of Rainwater Harvesting in meeting the domestic outdoor demand: a study in dry and wet regions of the United States

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Abstract

Feasibility of meeting the outdoor water demand with rainwater harvesting (RWH) was evaluated for the states of Arizona and Florida as representatives of dry and wet regions, respectively, using a system dynamic model. The potential of RWH was found to be highly sensitive to the demand of water, desert landscaping potential, and the percentage of households with RWH systems. The percentage of demand met through RWH and the storage potential of a 50-gallon rainwater barrel was found to be significant even for arid regions. The model can be used to compare among various influencing parameters of RWH systems.

Introduction

The increase in global population has affected the water demand around the world (WHO, 2009) and studies suggest that the demand for water will increase by a factor of two by 2035 (Tidwell et al. 2004). Many watersheds are facing challenge of maintaining environmental needs as well (Vorosmarty et al., 2000). The availability of fresh inland water depends highly on the hydrologic cycle, which has experienced significant change across various spatial scales over the years (Sagarika et al., 2015a; Pathak et al., 2016a). These changes in hydrologic cycle pose challenge to water managers as the long term patterns are likely to change in future by abrupt shifts in the regimes (Sagarika et al., 2014; Tamaddun et al., 2016a). Climate changes is expected to impact both floods and droughts by impacting precipitation (Choubin et al., 2014, Kalra and Ahmad 2011, 2012). The frequency of extreme events is also on a rise due to the changes in oceanic-atmospheric patterns that influence changes in hydrologic variables (Pathak et al., 2016b; Tamaddun et al., 2016b). Studies also show that shift in initiation and recession of seasons, as a result of climate change, have also affected the availability of water (Sagarika et al., 2015b; Carrier et al., 2016).

Rainwater harvesting (RWH) has been used throughout history as an alternate source of water in various parts of the world (Li et al., 2000; Che-Ani et al., 2009). Studies suggest that RWH has significant potential to address water shortages not only in wet regions but also in arid regions (Cain, 2010). In wet regions, RWH can also reduce stormwater and as a result reduce flooding in urban areas (Forsee and Ahmad 2011; Thakali et al., 2016). Rainwater is also considered to be a pure form of water as it meets the majority of the quality standards (US EPA, 2013; Rahman et al., 2014). Studies also suggest that RWH can be effectively used in both domestic and agricultural settings, which can potentially reduce the water withdrawal from the surrounding river basins (Ghimire & Johnson, 2013). In the United States, various states and cities have published guidelines explaining the design and implementation techniques of RWH systems (Kloss, 2008). US EPA has published a report that compiles the common practices of RWH design (US EPA, 2013). This report also referred to the Texas Manual on Rainwater Harvesting (TWDB, 2005) for many design criteria such as the governing equations to capture the rain from rooftops.

System dynamics (SD) is an approach that has been widely used in hydrologic modeling and in developing decision support systems (Mirchi et al., 2012; Zhang et al., 2016; Ahmad & Simonovic, 2006; Wu et al., 2013). Models developed using SD approach have been used to develop conservation policies (Ahmad and Prashar 2010); to plan urban water management policies (Qaiser et al., 2013; Dawadi & Ahmad, 2013; Shrestha et al., 2011; Shrestha et al., 2012); to evaluate water quality (Venkatesan et al., 2011a; Venkatesan et al., 2011b), and to design measures for extreme hydrologic events (Simonovic & Ahmad, 2005).

In this study, an SD model was developed using Stella to evaluate the potential of meeting the outdoor water demand in the states of Arizona and Florida, which represented the dry (arid) and the wet regions of the United States, respectively. The model allows the users to compare between different parameters and climate scenarios that affect the potential of RWH.

Study Area and Data

Continuous rainfall data, on a mean monthly scale, was obtained for 10 calendar years (a total of 120 data points from January 2005 to December 2014) from the National Oceanic and Atmospheric Administration (NOAA) online database for the states of Arizona and Florida (Figure 1). For the projected years (from January 2015 to December 2024), the same raw datasets were used but were adjusted by applying the near-term climate scenarios provided by the US EPA (Rossman, 2013).

The guidelines, along with the underlying equations and the model parameters, were selected based on the manual by Texas Water Development Board (TWDB, 2005) on RWH. The manual has also been recommended by the US EPA (US EPA, 2013) to design RWH systems in domestic facilities.

The per capita water usage (measured in gallons per capita per day or GPCD) for each state were calculated based on the work of Maupin et al. (2010) using the population of 2014. Statistical and demographic data used in the model were obtained from the online databases of the U.S. Census Bureau (USCB), National Center for Health Statistics (NCHS), and the U.S. Bureau of Labor Statistics (USBLS) (Table 1). The methodology section discusses all the model parameters and the usage of data in greater detail.

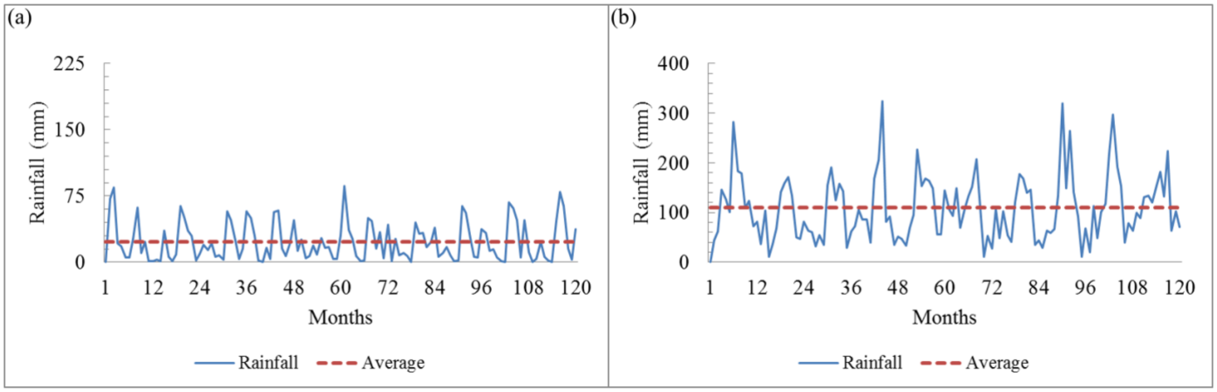

Figure 1: Rainfall data for (a) Arizona and (b) Florida from January 2005 to December 2014. The dotted lines represent the long-term average over the study period.

Methodology

The feasibility of installing RWH systems on the rooftops of residential households to meet the domestic outdoor water demand was evaluated using an SD simulation model developed in Stella. A major advantage of using a simulation model representing a system is that it allows the users to evaluate the effects of desired modifications of the model parameters; this feature has made system dynamic approach popular in resource management problems (Stave, 2003). The theory and application of systems thinking and modeling has been discussed by Forrester (1994) and Sterman (2000). Interested readers may also refer to Ford (1999) for more details on SD modeling of environmental systems.

The following sub-section named the Modeling Approach discusses the components of the model along with the assumptions made during the model development process. The sub-section named the Model Dynamics discusses the evaluation of the dynamics of the model and the calibration techniques used in the study.

Table 1: Demographic data used in the study (based on 2014 data).

Average Birth rate	1.04/1000 per month
Average Death rate	0.68/1000 per month
Average number of people per household	2.54
Average area per household	250 m^2 (2700 sft)
Average roof area/household area	0.5

Modeling Approach

The primary sectors of the model were the Climate Scenario Sector, the Outdoor Demand Sector, the Household Sector and the RWH Sector (details of each of these sectors have been discussed separately under their respective names in the following paragraphs). The Rainfall Sector and the GPCD Sector provided the rainfall data and the per capita usage of water, respectively, for the two states. The Population Sector estimated the population of the two states for each month over the projected years. The monthly rates were determined from the annual birth and death rates provided by NCHS.

Climate Scenario Sector

For this study, the near-term climate projection scenarios for rainfall, based on the U.S. EPA (Rossman, 2013), were selected, which included: No Change scenario, Hot or Dry scenario, Median Change scenario, and Warm or Wet scenario. A comparative analysis of the different scenarios was conducted in the study to observe the effect of climate change on the potential of RWH.

Outdoor Demand Sector

The outdoor water demand was calculated as a function of GPCD for the two states based on the work of Maupin et al. (2010). Since the demands vary across the seasons, a seasonality index was introduced based on the work of Griffin and Chang (1991). The model also considered the effect of desert landscaping in this sector, as desert landscaping influences the outdoor water demand.

Household Sector

The total number of residential households was calculated in this sector based on the number of people living in the state. Using the average household area, the average roof area was calculated, which acted as the catchment area for each house. Table 1 lists the numbers and conversion factors used in this study based on USCB, NCHS, and USBLS.

Rain Water Harvesting (RWH) Sector

This sector calculated the volume of water generated from RWH systems installed at rooftops. The volume was calculated based on the equation provided by TWDB (2005) and US EPA (2013).

Total volume of rainwater (in gallons) = rainfall (in inch) * roof area (in sq. ft.) * 0.62 (gallons/inch/sq. ft.) * 0.85 (capture ratio)

The users of the model can choose the capture ratio of the roofs based on the material used. A reduction factor (not shown in the above equation) was also introduced to incorporate the effect of antecedent dry period on the collection efficiency based on the concept of SCS curve number (NRCS, 1986; Yuan et al., 2014).

Model Dynamics

Four assessment techniques followed by a sensitivity analysis were used to evaluate the model. The four assessment techniques were a) maintaining dimensional consistency; b) testing for extreme conditions; c) testing for integration error i.e., application of Euler's expansion and Runge-Kutta two and four as the integration methods and obtaining comparable results; and d) comparing the change in rainfall amount under various US EPA climate scenarios. Figure 2a shows the variation of rainfall pattern in Arizona under various climate scenarios.

The users of the model can control two set of parameters. The first set, known as the primary set, included the percentage of GPCD used to meet outdoor water demand, the percentage of existing houses with RWH, the percentage of future houses (to be built) with RWH, and the percentage of the population using desert landscaping. The desert landscaping parameter was introduced to complement the reduction of outdoor water use in arid areas. The second set of parameters, known as the secondary set, included the capture ratio of the roof (depends on the roof material), the reduction factor due to the effect of antecedent dry period (based on the concept of SCS curve number), and the parameters of the governing equation. Both primary and secondary sets of parameters allow the user to perform sensitivity analyses and evaluate different scenarios. In the results section, a sensitivity analysis of the primary set has been presented. The values chosen for the parameters in the secondary set have also been discussed in the following sections.

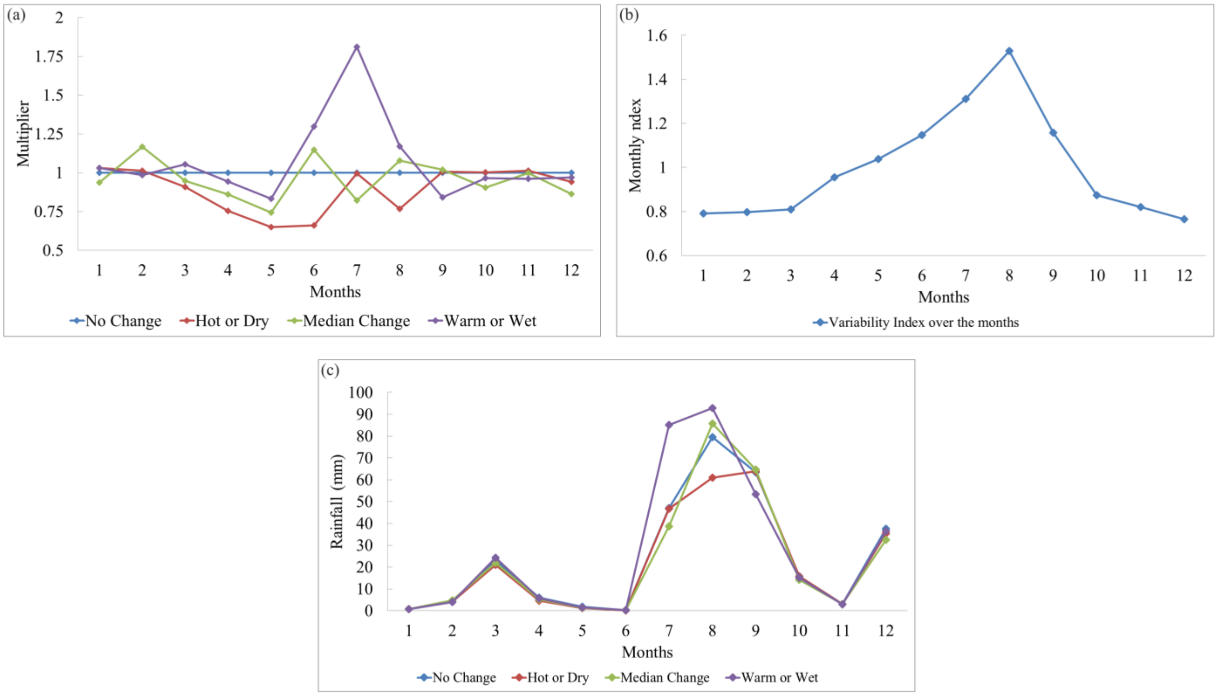

Figure 2: (a) Multiplication indices of the rainfall amount in the state of Arizona under various climate scenarios suggested by US EPA (Rossman, 2013). (b) Seasonality indices along a typical year based on Griffin and Chang (1991). (c) Change in rainfall pattern in the state of Arizona under various climate scenarios based on US EPA (applied on Arizona 2014 rainfall data).

Results

For both the states, an initial scenario named the baseline scenario (BLS), was developed, which was later used to compare against the controlled scenarios (CS). The parameters chosen for the BLS have been listed in Table 2. The results obtained under BLS have been illustrated in Figure 3 and tabulated in Table 3. The effects of various climate scenarios and the parameters of the primary set for the state of Arizona are illustrated in Figures 4 and 5, respectively. A suggested scenario (SS), based on the parameters selected as in Table 4, and the effectiveness of a 50-gallon rainwater barrel in storing rainwater for the state of Arizona are shown in Figures 6a and 6b, respectively.

Baseline Scenarios

The parameters chosen for the BLS, against which the CSs were compared, have been listed in Table 2. In the BLS, a no change climate scenario was selected for both the states. The Percentage of existing houses with RWH systems was selected to be 5% and the percentage of future houses to be built with RWH systems was selected to be 25% for both the states. The percentage of the population using desert landscaping was selected to be 0% and 20% for the states of Florida and Arizona, respectively. According to US EPA WaterSense program (www.epa.gov/watersense), the average percentage of per capita demand used for outdoor purposes is 30% across the United States. For the dry climate such as the southwest, this percentage can be as high as 60%. In this study, the percentage of GPCD used to meet the outdoor water demand was selected to be 25% for Florida and 50% for Arizona.

Table 2: Parameters of the Baseline Scenarios for each state.

	Regions (States)	
	Florida	Arizona
Parameters	Settings	
Climate scenario	No Change	No Change
GPCD	96	140
% of GPCD used for outdoor use	25	50
% of Population with desert landscaping	0	20
Percentage of existing houses with RWH	5	5
Percentage of new houses with RWH	25	25
Reduction factor due to antecedent dry period	0.98	0.7

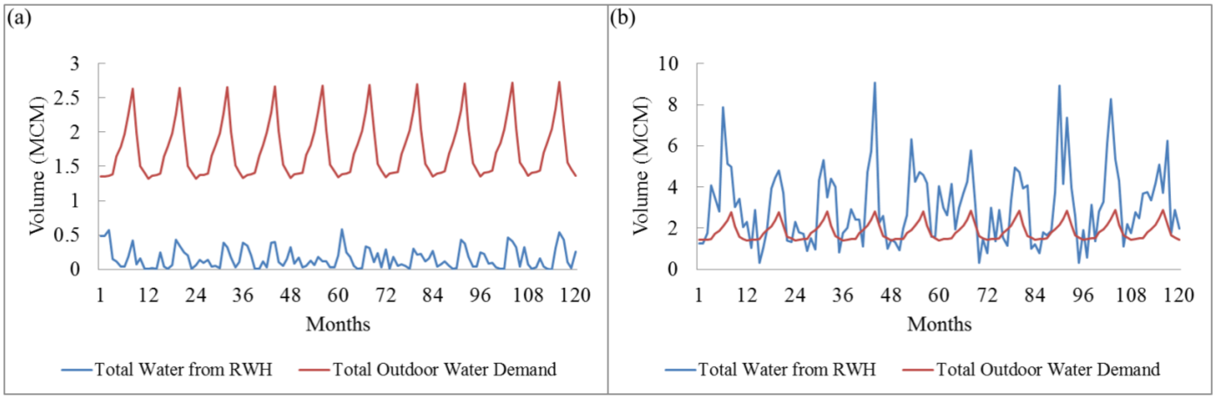

Figure 3: Comparison between the volume of total water demand and the total rain harvested water in (a) Arizona and (b) Florida under the Baseline Scenarios.

Table 3: Comparison between the volume of total water demand and the total rain harvested water in the projected years under the baseline scenarios.

States	Total Outdoor Water Demand (MCM)	Total Water from RWH (MCM)	Percentage Demand Met
Florida	223.24	367.71	100%
Arizona	211.5	19.25	9%

The per capita demands for the states were obtained from Maupin et al. (2010). The reduction due to antecedent dry period was selected to be 0.98 and 0.7 for Florida and Arizona, respectively, based on the concept of SCS curve number (Lim et al., 2006; Yuan et al., 2014). The results showed that the state of Florida was able to meet the outdoor water demand quite satisfactorily along the projected years with RWH (Figure 3). In fact, Florida met 100% of the outdoor water demand for the projected years (Table 3). On the other hand, only 9% of the outdoor water demand was met in the state of Arizona (Table 3). Since Florida already met the outdoor water demand under the BLS, the effects of changing the selected parameters were analyzed for the state of Arizona only in the following sections.

Effect of Climate Scenarios

The climate scenarios suggested by US EPA (Rossman, 2013) were tested for the potential of RWH in the state of Arizona. The parameters were set to the BLS except for the climate scenarios that were changed between the four suggested scenarios. The results showed that the hot or dry scenario had the least potential of meeting the demand, while the warm or wet scenario had relatively the highest potential (Figure 4). The highest difference in a month in terms of the volume of water produced from RWH between warm or wet and the hot or dry scenario was found to be 96%, while the average difference over the projected years on a monthly basis was found to be 27%.

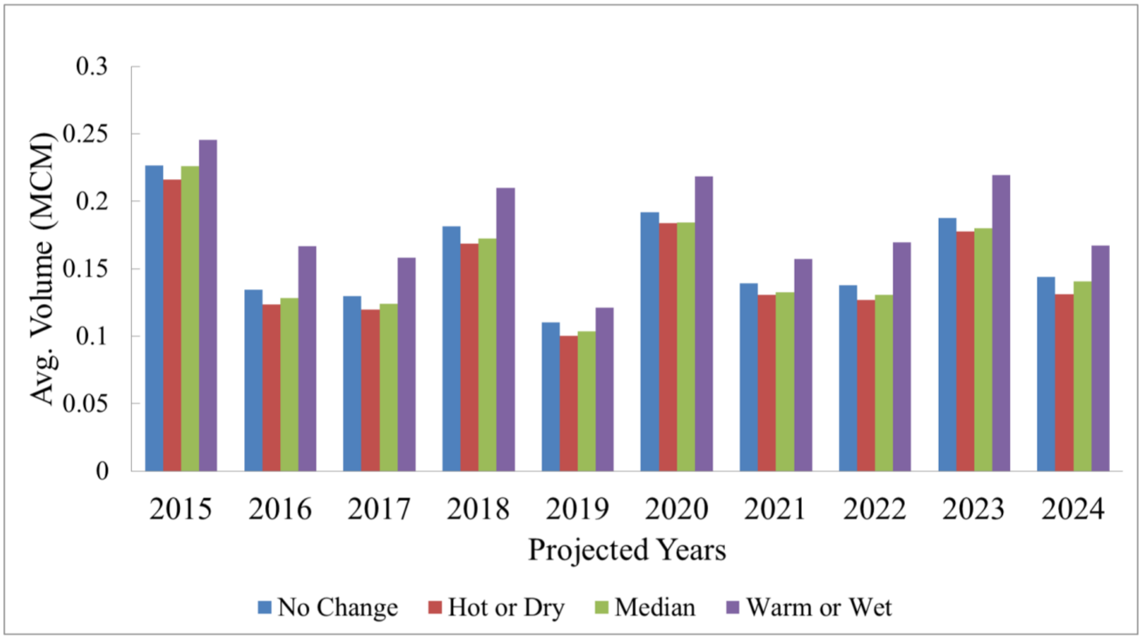

Figure 4: Average volume of water produced per year under BLS from RWH using the US EPA climate scenarios for the projected years in Arizona.

Effect of Primary Set Parameters

The first parameter of the primary set, which was modified to reduce the gap between the outdoor water demand and the water produced by RWH, was the percentage of per capita water usage to meet the outdoor demand. In the BLS, the percentage was set to be 50% for the state of Arizona. A 20% reduction (reduction to 40% from 50%) in the outdoor usage reduced the gap by 20%, as the relation was linear (Figure 5a). Outdoor water use may be reduced, for example, by using regulated drip irrigation. As a complement to the reduction of outdoor water usage, the percentage of the population with desert landscaping was increased.

The relation between the outdoor water demand met and the percentage of the population with desert landscaping was developed using a graphical function. The graphical function was designed in such a way (with a down-swept convex curve) that it estimated the potential of reducing the demand by increasing the percentage of the population with desert landscaping. In the BLS, the percentage of the population with desert landscaping was kept at 20%. A 13% decrease in the outdoor water demand was observed when the percentage of the population with desert landscaping was increased to 50% (Figure 5b). If half of the household implement desert landscaping on at least 50% of yard area, then based on the Southern Nevada Water Authority's (SNWA) Water Smart Landscape (www.snwa.com/rebates) guideline, conversion to desert landscapes can potentially reduce the outdoor water usage by 14.2%. This is comparable to the model estimated reduction potential. If all homes had desert landscaping on 100 % of the yard area, the potential reduction in outdoor demand can be 56.8%.

Out of all the parameters of the primary set, the percentage of existing houses with RWH systems was found to be the most influential. A 200% increase in the rain harvested water generation was observed when the percentage of existing houses with RWH was increased by 3 fold (from 5% at the BLS to 15%. Even though this increase resulted in a few instances where the demand was met with rain harvested water, still it was not enough as the majority of the months along the projected years did not meet the demand (Figure 5c).

The increase in the percentage of the new houses that would be built in the projected years did not have significant influence in meeting the demand from rain harvested water. The percentage of future houses with RWH was increased to 100% from 25% (as in the BLS), which resulted in a 0.54% increase in the average generation of rain harvested water over the projected years (Figure 5d). The effect of new houses with RWH was not found to be significant since, at the end of the projected years, the percentage of new houses to be built out of the total number of houses in Arizona was found to be only 0.04%.

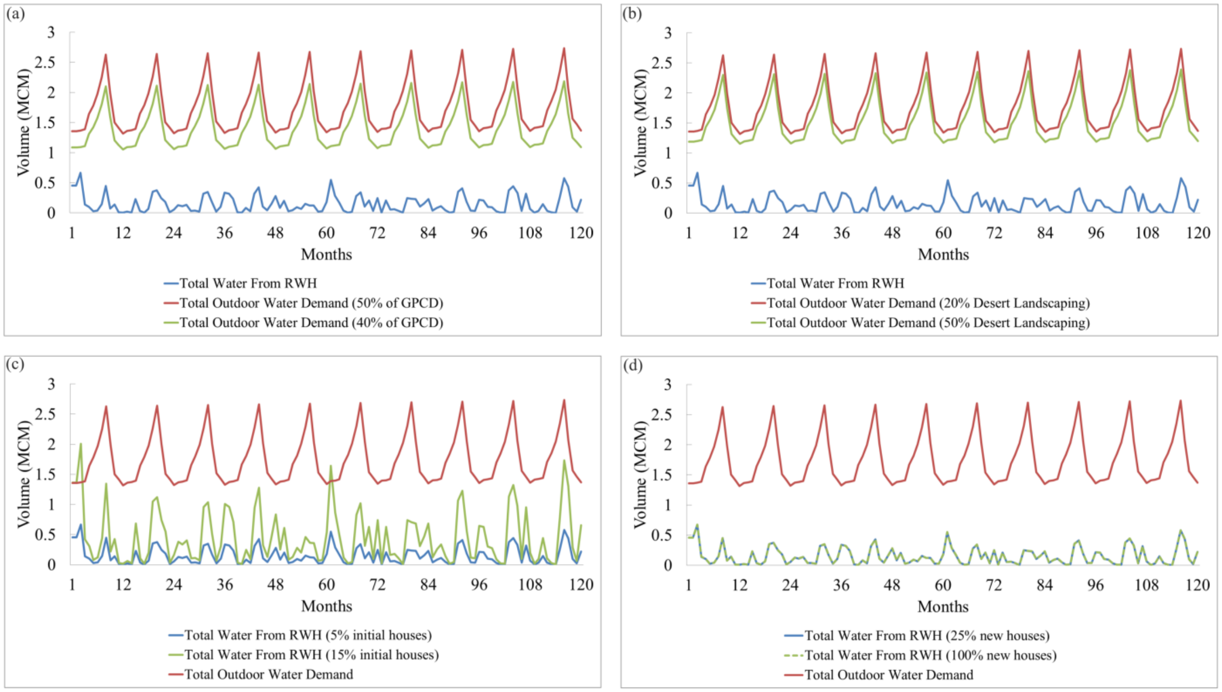

Figure 5: The responses of (a) reduction of percentage of GPCD used to meet outdoor water demand, (b) increment of percentage of population with desert landscaping, (c) increment of the percentage of the existing houses with RWH, and (d) increment of the percentage of the future houses with RWH in Arizona.

Suggested Scenario

The CSs showed that none of the parameters of the primary set were effective enough to reduce the gap between the outdoor water demand and the water generated from RWH. The results of the sensitivity analyses suggested that a comprehensive modification of the chosen parameters was required to produce a significant change. Hence, an SS was developed where all the parameters were altered together, which not only reduced the gap between the demand and supply but also was pragmatic. Table 4 shows the values of the parameters chosen in SS.

Table 4: Parameters of the Suggested Scenario (SS) to meet the outdoor water demand with RWH systems in Arizona

Parameters	Settings
Climate scenario	Median
% of GPCD used for outdoor use	40
% of Population with desert landscaping	75
Percentage of existing houses with RWH	25
Percentage of new houses with RWH	100
Reduction factor due to antecedent dry period	0.7

Under SS, the percentage of per capita water usage for outdoor purposes was set to 40%, the percentage of the population with desert landscaping was increased to 75%, the percentage of the existing houses with RWH was increased to 25%, and the percentage of future houses with RWH was increased to 100%. These resulted in a scenario where on an average, 60% of the total outdoor demand in the state of Arizona was met with rain harvested water (Figure 6a). A total of 42 months out of the 120 projected months (35%) were observed to meet the outdoor water demand from rain harvested water.

Storage of Rainwater

The US EPA (US EPA 2013) has provided design details regarding various types of rainwater barrels and rainwater cisterns (with treatment facilities) that come in a variety of storage capacities. In this study, only the potential of rain barrels was evaluated. A 50-gallon rain barrel was chosen as the storage tank at a single household. The results showed that this tank, on an average, can store 42% of the water generated from the rooftop of a single household facility (Figure 6b).

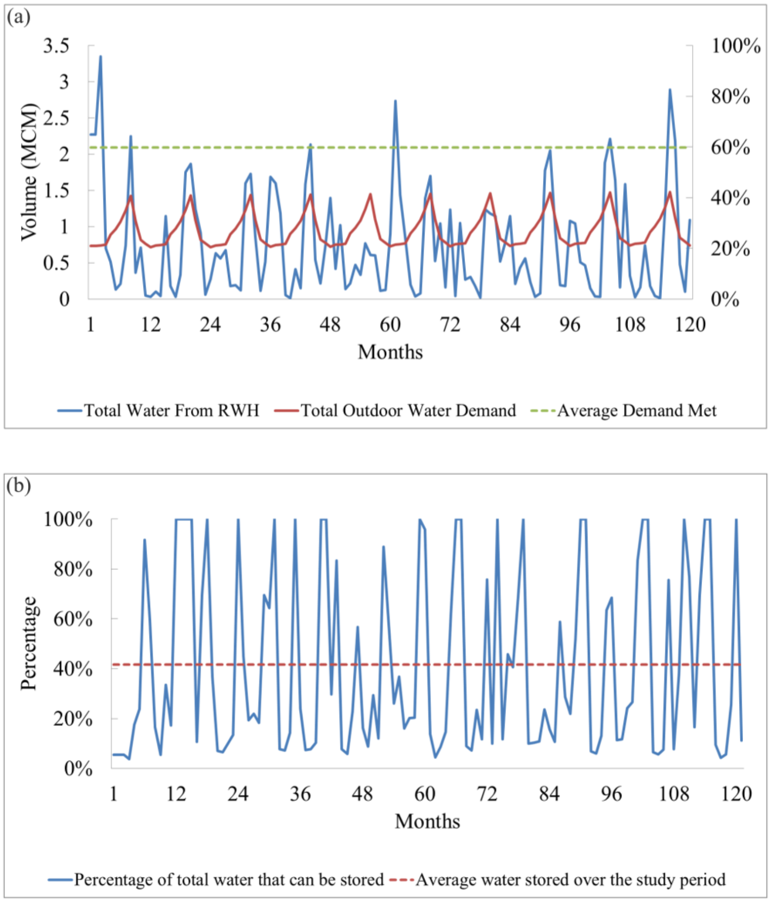

Figure 6: (a) Effect of the suggested scenario on meeting the outdoor water demand by RWH in Arizona. (b) Storage potential of 50-gallon rain barrel in Arizona.

Discussion and Conclusion

The study evaluated the potential of RWH based on a system dynamics model in the states of Arizona and Florida as the representatives of dry and wet regions, respectively. Demographic information was obtained for both the states along with their historic rainfall records. Various near-term climate projections were used to modify the rainfall data to incorporate the effects of climate change. The results indicated that wet regions, such as Florida, can fully meet the outdoor water demand using RWH systems under the BLS (the scenario against which the CSs were compared). For, dry regions, such as Arizona, comprehensive measure were required to meet a portion of the demand, where all the controlling parameters were adjusted accordingly to develop a feasible scenario.

The results indicated that the potential of RWH in meeting the outdoor demand is highly sensitive to the percentage of existing houses with RWH systems. Installing RWH systems in the future houses to be built in the projected years, would not produce a significant change. Reduction in the percentage of per capita water demand used for outdoor purposes was found to be an effective parameter that influences the potential of RWH systems. Water demand for outdoor usage can be reduced by implementing various management practices. In this study, desert landscaping was chosen for Arizona, which yielded in a significant reduction in the outdoor water demand.

The major contributions of the study are:

- Development of an interactive model that can estimate the potential of RWH at various locations i.e., model can be applied to other states with appropriate adjustments.
- Determination of most important parameters that influence the potential of RWH.
- Sensitivity analysis of the most influential parameters that may be helpful to policy makers.

The model was developed to provide the policy makers a tool that can be used to obtain an estimate of the rain harvested water in the wet and dry regions of the United States. The model allows the user to select and adjust region-specific parameters as well. Harvested rainwater can not only be an alternate source to meet the outdoor water demand, it can also help reduce surface runoff generated from stormwater, thus reducing urban flooding potential.

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