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WATER SUPPLY AND STORMWATER MANAGEMENT BENEFITS OF RESIDENTIAL RAINWATER HARVESTING IN U.S. CITIES[1]

Jennifer Steffen, Mark Jensen, Christine A. Pomeroy, and Steven J. Burian[2]

ABSTRACT: This article presents an analysis of the projected performance of urban residential rainwater harvesting systems in the United States (U.S.). The objectives are to quantify for 23 cities in seven climatic regions (1) water supply provided from rainwater harvested at a residential parcel and (2) stormwater runoff reduction from a residential drainage catchment. Water-saving efficiency is determined using a water-balance approach applied at a daily time step for a range of rainwater cistern sizes. The results show that performance is a function of cistern size and climatic pattern. A single rain barrel (190 l [50 gal]) installed at a residential parcel is able to provide approximately 50% water-saving efficiency for the nonpotable indoor water demand scenario in cities of the East Coast, Southeast, Midwest, and Pacific Northwest, but <30% water-saving efficiency in cities of the Mountain West, Southwest, and most of California. Stormwater management benefits are quantified using the U.S. Environmental Protection Agency Storm Water Management Model. The results indicate that rainwater harvesting can reduce stormwater runoff volume up to 20% in semiarid regions, and less in regions receiving greater rainfall amounts for a long-term simulation. Overall, the results suggest that U.S. cities and individual residents can benefit from implementing rainwater harvesting as a stormwater control measure and as an alternative source of water.

(KEY TERMS: rainwater harvesting; best management practice; water supply; stormwater management; sustainability.)

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INTRODUCTION

Urban expansion in the United States (U.S.) is overwhelming water supply and stormwater management infrastructure systems. Growing urban areas require additional water supply, more extensive distribution and treatment needs, and larger stormwater drainage networks to achieve expected performance goals. Moreover, the maintenance of the current systems requires as much if not more attention than the addition of new system components (USEPA, 2009; ASCE, 2011). Addressing these problems requires substantial investment in urban water infrastructure now and in the future. Estimates indicate water and wastewater infrastructure face a funding shortfall of more than $500 billion if capital investment, operations, and maintenance remain at current levels

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[2] Graduate Student (Steffen) and Assistant Professor (Pomeroy and Burian), Department of Civil and Environmental Engineering, University of Utah, 110 S. Central Campus Drive, Suite 2000, Salt Lake City, Utah 84112; and Herriman City Engineer (Jensen), Herriman, Utah (E-Mail/Steffen: jenn.steffen2@gmail.com).

(USEPA, 2002). Repairs and maintenance alone on public water supply systems are estimated to require $334 billion from 2007 to 2027 (USEPA, 2009). Given these pressing urban water problems and large funding needs, alternative urban water management solutions are being sought.

Recently, a paradigm shift has been occurring in the approach to manage urban water in the U.S. One alternative approach to traditional urban water supply and stormwater management infrastructure is decentralization of urban water infrastructure systems (Daigger, 2009). Decentralized systems seek to provide water as near to the demand and to manage stormwater as near to the source as possible.

Low-impact development (LID) is a decentralized stormwater management approach that also follows city planning concepts that promote better water management through the use of green infrastructure (GI) best management practices (BMPs). GI implementation at the local to regional scale impacts the hydrologic cycle in an attempt to mimic the natural hydrologic cycle (Burian and Pomeroy, 2010).

Decentralization of water and stormwater systems and the introduction of GI may provide an answer to infrastructure needs, performance challenges, and energy requirements facing urban water systems. Rainwater harvesting (RWH) is a GI stormwater control measure that can serve to decentralize water supply and stormwater management at the same time. Promoted by the green building industry, water conservation proponents, the stormwater management community, and necessitated by recent droughts, RWH has renewed interest in the U.S. (Burian and Jones, 2010; Gleick, 2010; Jones and Hunt, 2010; Lynch and Deborah, 2010). RWH has been used for centuries to meet urban water supply needs (Reid, 1982) and is currently common practice in India, Africa, Asia, Australia, and many other places to meet entirely or supplement water supply needs (Lassaux *et al.*, 2007; Gould and Nissen-Petersen, 2008; Glendenning and Vervoort, 2010; Rahman *et al.*, 2010; Tam *et al.*, 2010; Kahinda and Taigbenu, 2011; Alam *et al.*, 2012). It is commonly used in cities of Japan, and Germany for flood control, stormwater pollution management, and other needs (Herrmann and Schmida, 1999; Nolde, 2007; Furumai, 2008). In addition, RWH is considered an effective adaptation measure for climate change effects for many regions (Pandey *et al.*, 2003; Kahinda *et al.*, 2010).

RWH in urban areas is accomplished by diverting precipitation runoff to a location where it can be used or stored for later use or release. In its simplest form, RWH is designed to convey runoff from a catchment (e.g., rooftop) to a landscaped area for infiltration to support plant growth. RWH in this manner follows LID-based stormwater management concepts seeking to recreate the natural hydrologic cycle (Dietz, 2007). In more complicated systems, harvested rainwater can be used for other indoor uses–occasionally for laundry washing but more commonly for toilet flushing (Anand and Apul, 2010; Rahman *et al.*, 2010). In these systems, rain is harvested from the roof of the building (or occasionally from pavement) (Gomez Ullate *et al.*, 2011), then it is filtered and stored in a cistern prior to being pumped for use in toilet flushing as needed. These systems may also be equipped with backup connections to the locally supplied potable water for times when harvested rainwater may not be enough to meet the demand. The technological performance of RWH systems has been studied and is not a concern (Fewkes, 1999a,b).

Many studies showed the effectiveness of RWH for meeting water supply and stormwater management goals. In South Carolina, results showed that although smaller cisterns could be used for water supply, larger cisterns were needed for adequate stormwater control (Jones and Hunt, 2010). Water supply has been the more common benefit cited for RWH, but precipitation variability has been found to be a limitation because of longer periods of dry weather or reduced cumulative precipitation (Karpiscak *et al.*, 1990; Heaney *et al.*, 2000). Studies have found that the use of RWH for water supply reduces the imported potable water demand by 50% and more depending on site characteristics (e.g., roof/lot size ratio, landscape type) (Mitchell *et al.*, 1996; Jensen, 2008).

Controlling stormwater runoff volume, peak discharge, and pollutant loading have emerged as additional benefits of RWH. In a study using the Virginia Tech BMP Decision Support Tool, Young *et al.* (2009) found that the benefit of RWH was comparable to sand filters, vegetate roofs, porous pavement, and manufactured BMPs in a subarea with an imperviousness >67%. Crowley (2005) determined that installation of a 17,034 l (4,500 gal) tank at houses in a Portland, Oregon, neighborhood could reduce the average annual runoff volume by 68%. Gilroy and McCuen (2009) calculated a reduction of peak runoff rate and volume of more than 30% for the one-year recurrence interval storm for a single hypothetical single-family residential lot served by four cisterns with the dimensions of 0.75 m diameter and 0.91 m height. Less than 10% reduction was found for the two-year event. They concluded the effectiveness of cisterns for controlling runoff decreases as the size of the storm event increases. Reducing stormwater runoff volume and peak discharges logically leads to reduced downstream drainage infrastructure needs. Jensen *et al.* (2010) determined that water supply and stormwater management benefits for four cities in the U.S. are dependent on water demand and precipitation and benefits vary for the four cities. These studies have quantified in different ways the performance of RWH systems for water supply and in a few cases stormwater management at the lot scale and in isolated cities. However, there remains a lack of studies from the U.S. investigating water supply and stormwater management simultaneously at the municipal scale. Further, there is limited regional intercomparison of performance and limited guidance for projecting municipal RWH program effectiveness at the residential parcel and neighborhood scale. There is a need for a national assessment to provide preliminary guidance for local government water supply and stormwater management entities to help them coordinate their integrated efforts to address their goals with a mutually beneficial RWH solution. This article addresses this need by presenting a national study of the potential benefits of residential RWH for water supply and stormwater management, and highlighting the regional differences and impact of rainfall pattern and storage cistern size on estimated benefits.

METHODS

TABLE 1. Characteristics of 23 Cities and Seven Regions Used in the Study.

Region	Cities	Population	Population Density (per 260 ha [sq. mile])
Mountain West	Salt Lake City	181,700	825
	Denver	598,700	304
Southwest	Albuquerque	521,999	120
	Phoenix	1,567,900	223
	Las Vegas	558,400	40
Southeast	Atlanta	538,000	672
	Miami	413,200	1,158
	Savannah	132,400	216
	Tampa	340,900	938
	Memphis	669,700	378
East Coast	Baltimore	636,900	979
	Norfolk	234,200	668
	Richmond	202,000	338
	Boston	609,000	1,685
	Philadelphia	1,447,400	1,323
	Providence	171,600	1,042
Midwest	Milwaukee	604,400	1,028
	Columbus	754,900	490
West Coast	Los Angeles	3,834,000	2,344
	Sacramento	463,800	399
	San Diego	1,279,300	670
Pacific Northwest	Portland	557,700	326
	Seattle	598,500	492

Daily precipitation and water demand patterns for 23 cities representing seven regions of the U.S. (Figure 1 and Table 1) were analyzed using a water-balance approach to quantify the effect of single residential building RWH on urban water supply, water-saving efficiency (E_T) is the percent reduction of urban water due to RWH. For stormwater reduction analysis, hourly precipitation and continuous water demand patterns for the seven selected cities representing the seven regions were used to drive the U.S. Environmental Protection Agency (USEPA) Storm Water Management Model (SWMM) (Rossman, 2010) to determine stormwater management benefits at a neighborhood scale. The cities range in size from small cities with low densities such as Savannah, Georgia, with a population of <150,000 to large cities with populations of more than one million. The cities were selected to cover different climatic regions of the continental U.S. to provide the broadest applicability of the results to local governments in the U.S. More details of the models and tools, data and precipitation patterns, and methods used in the analysis follow.

FIGURE 1. Locations of 23 Cities and Seven Regions Used in the Study.

Water-Balance Analysis to Determine Water Supply Benefits of Rainwater Harvesting

A computer tool was created for this study to analyze the water balance of an RWH system for inflow, ouflow, and overflow from a cistern, to determine water supply benefits evaluated through the term, water-saving efficiency (E_T) of RWH implemented for a residential parcel (Jensen, 2008). The tool accepts daily precipitation and water demand time series as primary inputs. Additional inputs are the size of the rooftop, the size of the total area excluding the rooftop, runoff coefficients for the rooftop and total area excluding the rooftop, and a range of rainwater cistern sizes for the analysis. The tool uses a water balance based on runoff input and water demand output. The change in water storage in the rainwater cistern is computed at the daily time step using:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \mathrm{I} - \mathrm{O}, \tag{1}$$

where $\boldsymbol{S}$ is the volume contained in storage, $\boldsymbol{I}$ the inflow rate to storage, and $\boldsymbol{O}$ the outflow rate from storage. The output of the analysis includes daily and annual summaries of:

- total site and rooftop runoff volume;
- runoff volume captured in barrel/cistern;
- volume of indoor, outdoor, and total water demand;
- volume of indoor, outdoor, and total water supplied by RWH.

Also, the tool computes a set of RWH system performance metrics including:

- percent total site and rooftop water yield captured;
- percent indoor, outdoor, and total water-saving efficiency for RWH.

The percent total site and rooftop water yield captured are calculated as the runoff volume captured by the cistern divided by the total site runoff or rooftop runoff volume, respectively. The water-saving efficiency E_T is computed using

$$E_T = \frac{\sum_t^T Y_t}{\sum_t^T D_t} \times 100 \tag{2}$$

where E_T is rainwater supplied $\boldsymbol{Y_t}$ divided by the water demand $\boldsymbol{D_t}$ for time steps $\boldsymbol{t}$, for different scenarios for long-term time period $\boldsymbol{T}$ (Fewkes, 1999b; Palla *et al.*, 2012).

The tool was tested by comparing long-term results against manual calculations completed by a spreadsheet. The spreadsheet analysis was performed using similar assumptions and equations. The objective of the testing was to compare the results using two different programs to debug the tool. The comparison indicated the calculations had negligible differences ±3%.

The key assumption for a rainwater cistern water-balance analysis is the order of operations of the water-balance calculation. The daily mass balance must assume to either let the cistern overflow given a runoff input prior to applying the day's water demand (yield after spill [YAS]) or to hold the captured runoff in a virtual storage and remove the water demand for the given day (yield before spill [YBS]) (Fewkes and Butler, 2000). The impact of this assumption was tested. It would cause approximately ±25% change for the smallest cistern sizes, with minimal difference for larger cisterns, <5%. For this study, the runoff was held in virtual storage until the water demand was removed, any excess water was directed to overflow (YBS). The assumption was followed because on average the bulk of water demand will be in the first half of the day with the morning peak indoor usage and the morning landscape irrigation peak.

Modeling of Stormwater Management Benefits of Rainwater Harvesting

To quantify the stormwater management benefits of RWH in the seven regions, SWMM was used to conduct the analysis. A 100-parcel, 11-hectare residential neighborhood in Salt Lake City, Utah, served as the case-study drainage catchment for this study (Figure 2). The performance of RWH for the case-study neighborhood was determined for the seven regions of the study by driving SWMM using the hourly rainfall record for a selected city in each region: Salt Lake City (region MW), Phoenix, Arizona (region SW), Savannah (region SE), Philadelphia, Pennsylvania (region EC), Milwaukee, Wisconsin (region MidW), Sacramento, California (region WC), and Portland (region PNW). The average lot size was 837 m^2 (9,000 ft^2), with lot sizes ranging from 697 m^2 (7,500 ft^2) to 1,587 m^2 (17,078 ft^2). All of the homes were single story residential buildings ranging in size

FIGURE 2. SWMM Model of Salt Lake City Neighborhood Enclosed by Black Line.

from 111m^2 (1,190 ft^2) to 424 m^2 (4,564 ft^2), with an average size of 169 m^2 (1,818 ft^2). The majority of lots had only one building on them; seven of the lots had other buildings on site. The building and lot size of the 100 lots were similar to one another, with only a few being larger attributing to the wide range of sizes.

Each residential parcel was modeled as four separate units by SWMM with two discrete subcatchments representing the rooftop, one representing other impervious surfaces and one representing other pervious areas (Figure 3). This configuration was chosen to provide a subcatchment area that could be directly connected to a storage unit representing the RWH storage. The amount of rooftop area to connect to RWH was subject to several factors. For this study, we assumed 50% of the rooftop drained to the RWH and the other half of the rooftop was connected to a pervious area. The third subcatchment included in the model represented the other building's rooftop area not connected to the RWH, which included garages, sheds, and so on. The fourth subcatchment for each parcel was the area that was not rooftop; this would include landscape area, hardscapes, and so on. The amount of hardscape (impervious area) in the fourth subcatchment of each parcel was 7.5% of the parcel (based on information contained in Mayer *et al.*, 1999). A summary of the assumptions for the SWMM parameters is summarized in Table 2. A sensitivity analysis was performed on the following assumptions: land surface slope, roof slope, Manning's n, and subcatchment width. A change in these parameters of ±50% resulted in a negligible change in the results of ±0.3%.

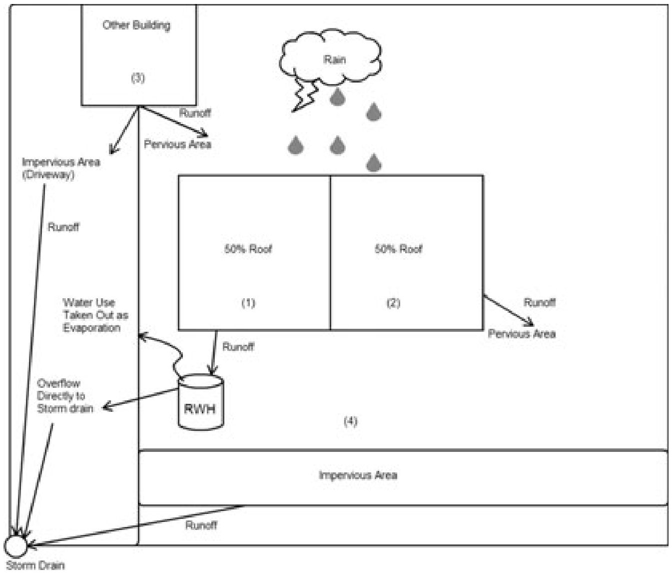

FIGURE 3. Illustration of Conceptual SWMM Subcatchments for Residential Parcel in Salt Lake City Neighborhood.

The RWH cistern was represented as a storage unit in SWMM. The LID controls option available in SWMM (Rossman, 2010) was not used for this study because the representation of the water demand patterns was desired. An overflow weir was set at the maximum depth of the cistern and overflow was directed to a downstream element as demonstrated in Figure 3. The water demand patterns were created for a household of four people, described later in this article. The water use patterns were input at an hourly increment for total nonpotable total, and outdoor water demand, described later. Stormwater runoff from part of the rooftop was directed into the cistern. The overflow from the cistern and runoff generated from the other pervious and impervious areas of the parcel subcatchments were directed to a junction representing the inlet to the storm drainage system. Storm drain conduits collected all the stormwater runoff from each parcel and directed it to a single outfall from the neighborhood that served as the analysis point for the study.

The SWMM model was tested by comparing results against a simplified stormwater analysis using the RWH tool described previously. As the residential neighborhood chosen had similar building and lot sizes, the analysis tool was executed for three different lot and rooftop areas for comparison with SWMM. The stormwater capture results were multiplied by the number of parcels that corresponded to the three different lot and rooftop areas to equal the neighborhood scale results. This analysis was performed for a 190-l (50-gal) cistern, which would contain the largest difference, due to different time steps, hourly for SWMM and daily for the RWH tool. The difference between these two methods was 0 to 4.5%, which is reasonable based on the time steps used and the difference in assumptions.

Data Collection

The water supply benefits and stormwater management benefits were estimated using precipitation records and water demand patterns for the 23 cities included in the study. Daily and hourly precipitation records were downloaded from the National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov). Within each city a rain gauge location was arbitrarily selected, usually the airport gauge. The daily rainfall records were checked against the following criteria and, in some cases, modified to ensure acceptability for the study:

- At least 50 years of record.
- If a month was missing 10 days or more of data, the month was replaced with the average month for that city.

TABLE 2. Estimation of SWMM Parameters.

Parameter	Estimation Approach
	The directly connected impervious area (DCIA) parameters are summarized below
	Land Use Type — Percent Impervious
Percent imperviousness	Rooftop — 100 Total area — 9 Other buildings — 100
Land surface slope	Average slope of 0.5% estimated using 4-ft elevation contours acquired from Utah ArcGIS website
Roof slope	Slope of 50%
Manning's *n*	Land surface roughness was assumed to be 0.1 for pervious area and 0.01 for impervious area
Subcatchment width	One half the smallest width of the subcatchment, measured in GIS

TABLE 3. Precipitation Characteristics for Cities and Regions.

Region	City	Annual Avg. Depth (mm)	Event (mm) Avg. Depth	Event (mm) 90% Depth
Mountain West	Salt Lake City	389	6.8	15.2
	Denver	367	7.4	17.3
Southwest	Albuquerque	221	5.9	13.2
	Phoenix	185	8.5	19.1
	Las Vegas	105	7.0	16.5
Southeast	Atlanta	1,230	15.4	38.1
	Miami	1,503	14.6	34.9
	Savannah	1,232	15.3	35.6
	Tampa	1,157	15.1	35.6
	Memphis	1,292	17.0	40.6
East Coast	Baltimore	1,046	13.9	32.0
	Norfolk	1,126	14.4	33.0
	Richmond	1,100	14.1	33.0
	Boston	1,091	13.6	33.0
	Philadelphia	1,040	13.6	31.8
	Providence	1,147	14.5	35.6
Midwest	Milwaukee	812	10.4	25.4
	Columbus	969	10.6	22.9
West Coast	Los Angeles	310	14.0	33.0
	Sacramento	426	12.0	26.7
	San Diego	247	9.7	22.9
Pacific Northwest	Seattle	939	9.6	20.3
	Portland	931	9.3	20.6

- If more than three months or 90 days were missing from a year the year was replaced with an average year.

An assessment of these criteria indicated that the record modifications implemented did not appreciably change monthly or annual totals, but did provide a more reasonable record to perform the study. The average length of the precipitation records is 60 years, with 95% of the data records complete for both daily and hourly precipitation.

An analysis of the precipitation records indicated that the patterns varied across regions. Figure 4 shows the seasonal precipitation pattern for one city selected from each of the seven regions. The annual precipitation, and each storm precipitation depth, was similar for the cities in a given region (Table 3), but was found to vary significantly across regions (Figure 4). An analysis of the hourly precipitation for each of the 23 cities was performed to determine the average annual precipitation, and average and 90% storm event depths. A frequency analysis was performed to determine the average and 90% storm event depths. The 90% storm event depth represents the storm at which 90% of the storm event depths are smaller than this storm. Each precipitation event was characterized by a depth >1.27 mm (0.05 in) and dry interval between each event of 6 h. The results of this analysis are shown in Table 3. The Southeast, East Coast, and Midwest have higher annual precipitation with numerous storms distributed fairly evenly through the year, whereas the Southwest and Mountain West have lower annual precipitation amounts with long dry periods. Both the West Coast and the Pacific Northwest have a wet winter, whereas the summer season is drier. The 90% storm event depth in the East Coast is significantly higher than depths in regions such as the Southwest and the Mountain West. The annual average depth ranges from a low of 102 mm (4 in) in the Southwest to a high of 1,499 mm (59 in) in the Southeast. Each region has similar annual and event precipitation characteristics among cities, with difference shown between the cities selected to represent the regions (Table 3).

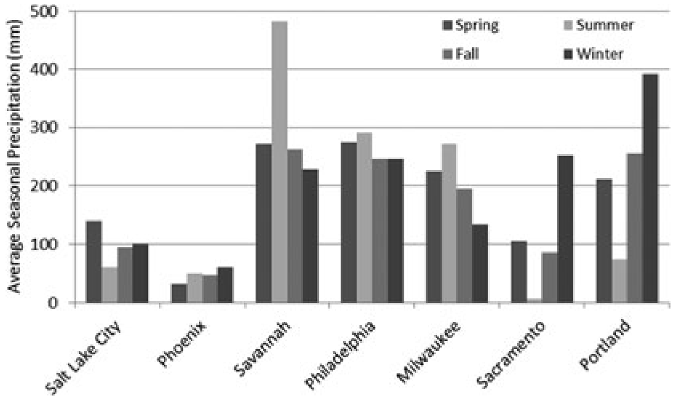

FIGURE 4. Precipitation Patterns in Each Region. Seasons: Spring (March-May), Summer (June-Aug), Fall (Sept-Nov), Winter (Dec-Feb). Regions: Salt Lake City (MW), Phoenix (SW), Savannah (SE), Philadelphia (EC), Milwaukee (MidW), Sacramento (WC), Portland (PNW).

Residential water demand patterns were created using a combination of available data and reasonable assumptions. The first step in their creation involved defining a standard residential parcel to be used in the analysis of each city. A residential parcel size of 762 m^2 (8,200 ft^2) was selected and compared with aerial images for Salt Lake City and Philadelphia. The rooftop plan area for the parcel was selected to be 186 m^2 (2,000 ft^2), which was found to be a reasonable value by checking against aerial images for Salt Lake City and Philadelphia. An additional validation of the selected parcel and rooftop plan area was achieved by reviewing statistics in the American Housing Survey for the median lot size, square footage of unit, and number of stories of unit, for several of the cities used in the study (U.S. Department of Housing and Urban Development and U.S. Census Bureau, 1998-2007).

The second step was to determine the number of residents in a dwelling. For the water supply benefit analysis, it was assumed that each dwelling had three residents, whereas in stormwater management benefit analysis four residents per dwelling were assumed due to larger dwelling and parcel sizes. These assumptions are slightly higher than the range of median residents per dwelling of 2.07 to 2.99 for the cities in the study (U.S. Census Bureau, 2006-2008). The median indoor water demand for each city was then determined, estimated, and assigned based on indoor water use values contained in Table 4. The indoor water demand included all typical indoor water usage such as from dishwashers, toilets, sinks, and showers. The indoor water use was based on information found for each city, or region when possible, from studies conducted by the cities, states, or other organizations such as the American Water Works Association (AWWA). For cities where no reasonable water use information was identified, the water use was estimated to be the average of all the indoor water use found for this study.

The outdoor water demand pattern was defined for this study based on a fixed irrigation schedule and application rate. The duration of irrigation over a growing season was specified for each city based on

TABLE 4. Information Used to Create Water Demand Patterns for Each City.

Region	City	Indoor Water Use (Lpcd)	Irrigation Period	Max Irrigation Days Per Week and Corresponding Month/s	
Mountain West	Salt Lake City	254[5]	March-October[4]	4	July-August
	Denver	246[5]	April 16th-October 15th[1]	3	June-August
Southwest	Albuquerque	257[5]	March-November[2]	3	June-August
	Phoenix	253[5]	March-November[1]	4	May-June
	Las Vegas	261[5]	Year round[1]	4	May-August
Southeast	Atlanta	322[6]	Year round[1]	3	August-September
	Miami	246[7]	Year round[3]	1	January-December
	Savannah	265[7]	Year round[3]	1	January-December
	Tampa	223[5]	Year round[1]	1	January-December
	Memphis	246[8]	February-November[4]	2	June-August
East Coast	Baltimore	246[8]	May-October[3]	1	May-October
	Norfolk	204[7]	April-October[3]	1	April-October
	Richmond	204[7]	April-October[3]	1	April-October
	Boston	225[6]	May-September[4]	1	May-September
	Philadelphia	246[8]	May-October[4]	1	May-October
	Providence	246[8]	May-October[4]	1	May-October
Midwest	Milwaukee	246[8]	May-October[3]	2	July-August
	Columbus	246[8]	May-October[2]	2	June-August
West Coast	Los Angeles	246[8]	Year round[1]	2	April-October
	Sacramento	246[8]	Year round[1]	3	June-Sept
	San Diego	205[5]	Year round[1]	3	June-August
Pacific Northwest	Portland	204[6]	April-October[2]	3	July
	Seattle	204[5]	April-September[3]	2	July-August

[1] Restricted by city.
[2] Recommended by city.
[3] Based on regional recommendations.
[4] Assumed.
[5] Based on studies.
[6] City or utilities estimates.
[7] Based on regional estimates.
[8] Average of known indoor use for this study.

landscape irrigation guidance provided by the city or a nearby city. The irrigated landscape area was determined by subtracting the assumed rooftop area and additional impervious hardscape of 7.5% of the area (Mayer *et al.*, 1999) from the overall parcel area. Thirteen millimeters (0.5 in) of water was set as the application rate for all locations (Utah Botanical Center, 2011). The irrigation volume for a day was the application rate multiplied by the landscape area. Table 4 summarizes the characteristics and assumptions of the outdoor water demand patterns. Salt Lake City was assumed to have a maximum irrigation of four times a week for July and August; this means that four times a week the irrigation volume was applied to the landscape area. The irrigation times for the rest of the season, March-October, ranged from one to three. Figure 5 summarizes the total water demand including indoor and outdoor water demand for the spring, summer, fall, and winter. The water use patterns vary for the cities selected to represent the different regions mainly due to the outdoor water use. Regions such as the Mountain West and Southwest receive less precipitation especially during the summer, and require higher irrigation rates to compensate for this.

Analysis Scenarios

The analysis of water supply benefits for RWH implemented at a residential parcel was determined for a range of cistern sizes from 190 l (50 gal) to 15,142 l (4,000 gal), by 190-l (50-gal) increments. The 190-l (50-gal) rain barrel represents the smallest cistern commercially available. These rain barrels can range in size from 150 to 230 l (40-60 gal), with a maximum difference between results of 10% for the modified indoor, the smallest water demand, but with a 30% difference between a rain barrel and a 380-l (100-gal) cistern. The 15,142-l (4,000-gal) cistern captures between 90 and 100% of the rooftop water yield capture, and larger cisterns do not appreciably change the results.

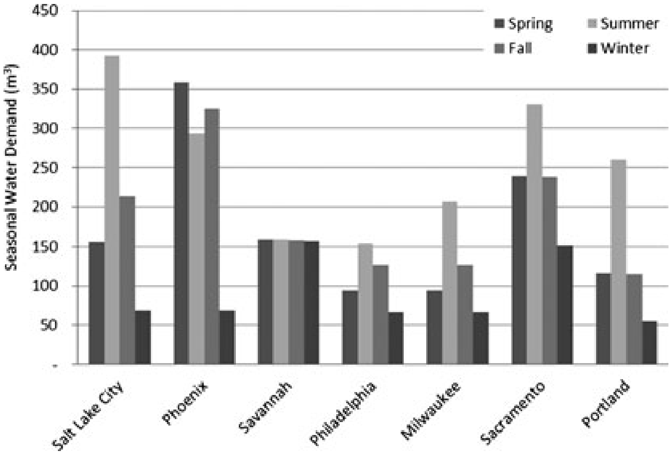

FIGURE 5. Water Demand Patterns in Seleted Cities (Regions) Salt Lake City (MW), Phoenix (SW), Savannah (SE), Philadelphia (EC), Milwaukee (MidW), Sacramento (WC), Portland (PNW).

The analysis was repeated for five water demand patterns: (1) outdoor only, (2) indoor only, (3) total (including indoor and outdoor), (4) modified indoor (nonpotable water use), and (5) modified total (nonpotable water use and outdoor). Although, captured rainwater is rarely used for drinking in residential areas in U.S. cities, if at all, the total scenario was included in this analysis to represent an extreme of water use. The modified (nonpotable) indoor water use pattern represents a more realistic scenario with 27% of the indoor water use designated as nonpotable use, including only toilet usage (Mayer *et al.*, 1999). Although there are other possible uses for rainwater in the home, toilet usage would need the lowest treatment. Modified total water demand pattern includes nonpotable and outdoor water use. Outdoor water demand patterns include an irrigation schedule as summarized in Table 4, and during times of no irrigation, no water is removed from the cistern. Another stormwater management-focused scenario would be to simply release the captured rainwater after a set delay time. Given the high water usage in the U.S., the total water demand scenario represents this scenario. The computations were performed at a daily time step for 57-60 years of precipitation record, depending on the city.

The stormwater management benefits analysis was executed over a period of at least 50 years, corresponding to the duration of the long-term hourly rainfall records used in the study. SWMM was executed without rainwater cisterns and then with them for the 100 households in the neighborhood to create two simulations for comparison. The analysis was performed for a single rain barrel (190 l [50 gal]), two rain barrels (380 l [100 gal]), and a 1,890-l (500-gal) cistern installed at every household. The single rain barrel (190 l [50 gal]) corresponded to the smallest cistern used in the water supply benefit analysis. The 380-l (100-gal) cistern represented two rain barrels, which would be simple to implement at a household scale. Larger cistern sizes were tested, but did not appreciably change the results from those found with the 1,890-l (500-gal) cistern for most of the cities and therefore are not included here. Above 1,890 l (500 gal), the cistern is capturing all rooftop runoff and is reaching the maximum capture for all regions. A 1,890-l (500-gal) cistern was chosen as the maximum size because one region reached the maximum capture, and all other regions were near to maximum capture and still showed differences between regions.

RESULTS

Water-Saving Efficiency

Tables 5 and 6 present an average of the results for each city in a region for the indoor and total water demand pattern and the nonpotable water demand pattern. In Table 5, the output for each region represents the cistern size necessary to capture 80% of the average annual rooftop water yield (i.e., runoff) and the corresponding water-saving efficiency for the indoor, total, and outdoor water demand patterns. The results indicate the wide variation in cistern size required to achieve 80% water yield capture. It is interesting to note the relatively small size cisterns recommended for the semiarid western U.S. cities. The corresponding water-saving efficiency is significant given the relatively small cistern sizes. The indoor water demand that can be provided by the target RWH (80% yield capture) ranges from 8 to 59%. Regions that have higher annual precipitation (see Table 3) require larger cisterns, but can provide significant water-saving efficiency. Regions with lower annual precipitation (Table 3) require smaller cisterns for the 80% yield capture, but provide significantly less water-saving efficiency potential.

Table 6 shows the water-saving efficiency when the simulation was executed for the modified (nonpotable) water demand pattern. The modified (nonpotable) water-saving efficiency increases for both indoor and total water use patterns across all regions. The modified indoor (nonpotable) water-saving efficiency increases from 30 to 40% for all regions except the Southwest and West Coast, which show an increase from 10 to 20%. For the East Coast, Southeast, and Midwest regions, modified indoor water-saving efficiency ranges from 92 to 98%. Water-saving efficiency benefits are better for higher precipitation regions. Tables 5 and 6 show the trend that regions with higher precipitation can save more indoor water, while requiring a larger cistern, whereas regions with lower precipitation can capture the 80% capture yield with a smaller cistern but are unable to supply a significant amount of water.

Tables 7 and 8 list the water-saving efficiency benefits associated with the installation of a single rain

TABLE 5. Water-Saving Efficiency by Region for 80% Rooftop Water Yield Capture for Simulations Executed with Indoor Only and Total Water Demand Scenario.

		E_T		
Region (cities)	**Cistern Size (l)**	**Total Scenario**	**Indoor Scenario**	**Outdoor Scenario**
Mountain West (Denver, Salt Lake City)	946	7	19	6
Southwest (Albuquerque, Phoenix, Las Vegas)	757	3	8	2
Southeast (Atlanta, Miami, Savannah, Tampa, Memphis)	5,678	28	56	40
East Coast (Baltimore, Norfolk, Richmond, Boston, Philadelphia, Providence)	4,732	37	57	39
Midwest (Milwaukee, Columbus)	2,650	25	44	24
West Coast (Los Angeles, Sacramento, San Diego)	3,028	5	16	6
Pacific North West (Portland, Seattle)	6,814	27	59	19

TABLE 6. Water-Saving Efficiency by Region for 80% Rooftop Water Yield Capture for Simulations Executed with the Modified (nonpotable) Water Demand Pattern.

		E_T	
Region (cities)	**Cistern Size (l)**	**Modified Indoor Scenario**	**Total Modified Scenario**
Mountain West (Denver, Salt Lake City)	946	47	8
Southwest (Albuquerque, Phoenix, Las Vegas)	757	19	3
Southeast (Atlanta, Miami, Savannah, Tampa)	5,678	95	36
East Coast (Baltimore, Norfolk, Richmond, Boston, Philadelphia, Providence)	4,732	98	44
Midwest (Milwaukee, Columbus)	2,650	92	30
West Coast (Los Angeles, Sacramento, San Diego)	3,028	39	6
Pacific North West (Portland, Seattle)	6,814	95	24

TABLE 7. Water-Saving Efficiency Benefits by Region Based on Installation of a Single Rain Barrel (190 l [50 gal]) for Simulations Executed with the Original Water Demand Pattern.

Region (cities)	Rooftop Water Yield Capture %	E_T Total Scenario	E_T Indoor Scenario	E_T Outdoor Scenario
Mountain West (Denver, Salt Lake City)	68	6	15	4
Southwest (Albuquerque, Phoenix, Las Vegas)	73	2	6	2
Southeast (Atlanta, Miami, Savannah, Tampa, Memphis)	41	14	25	10
East Coast (Baltimore, Norfolk, Richmond, Boston, Philadelphia, Providence)	39	17	26	10
Midwest (Milwaukee, Columbus)	50	15	25	9
West Coast (Los Angeles, Sacramento, San Diego)	51	3	9	2
Pacific Northwest (Portland, Seattle)	47	16	33	5

TABLE 8. Water-Saving Efficiency Benefits by Region Based on Installation of a Single Rain Barrel (190 l [50 gal]) for Simulations Executed with the Nonpotable Water Demand Pattern.

Region (cities)	Rooftop Water Yield Capture %	E_T Modified Indoor Scenario	E_T Total Modified Scenario
Mountain West (Denver, Salt Lake City)	68	29	6
Southwest (Albuquerque, Phoenix, Las Vegas)	73	13	2
Southeast (Atlanta, Miami, Savannah, Tampa, Memphis)	41	40	13
East Coast (Baltimore, Norfolk, Richmond, Boston, Philadelphia, Providence)	39	44	17
Midwest (Milwaukee, Columbus)	50	44	15
West Coast (Los Angeles, Sacramento, San Diego)	51	15	3
Pacific Northwest (Portland, Seattle)	47	51	12

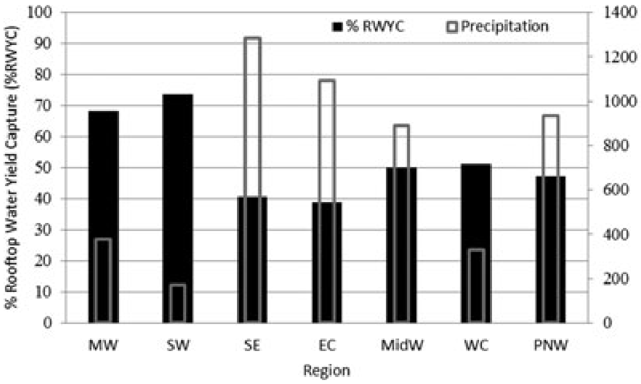

FIGURE 6. Relationship Between Regional Precipitation Amounts and Rooftop Water Yield Capture (% RWYC) for a Single 190-l (50 gal) Rain Barrel.

barrel at a residential parcel for the total water demand pattern and the nonpotable water demand pattern, respectively. Comparing the regions, the semiarid locations have very high water yield capture percentages (i.e., in cities of the Southwest, Mountain West, and West Coast regions, RWH could capture a large fraction of the runoff from the residential rooftop) compared with humid regions of the East Coast, Midwest, Southeast, and Pacific Northwest (Figure 7).

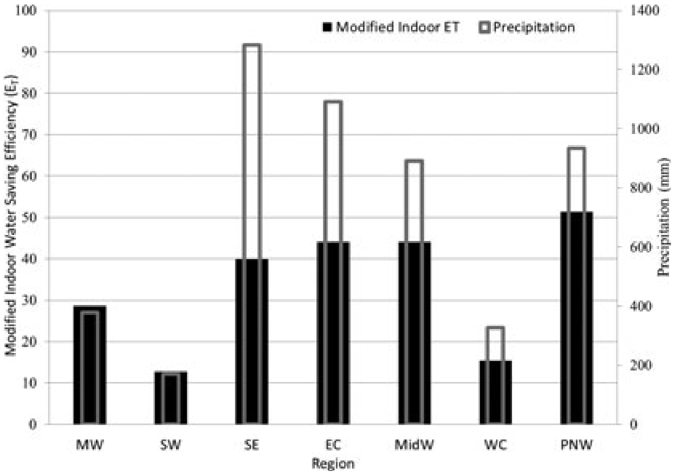

FIGURE 7. Relationship Between Modified Indoor Water-Saving Efficiency from RWH and Precipitation by Region for a Single 190-l (50 gal) Rain Barrel.

Figures 6 and 7 display the relationship between precipitation and performance of RWH, and the variation across regions. For a single 190-l (50-gal) rain barrel, regions with higher precipitation (>750 mm average annual) capture smaller percentages of the total rooftop runoff. The percent that can be saved from rainwater is higher in regions where the precipitation is greater. In regions such as the Mountain West and Southwest, the rooftop water yield capture ranges from 68 to 73%, with corresponding modified indoor water-saving efficiency of 29 and 13%. A large percentage of the precipitation is being captured from the regions with lower precipitation (Mountain West and Southwest), but even with this high capture there is limited water-saving efficiency.

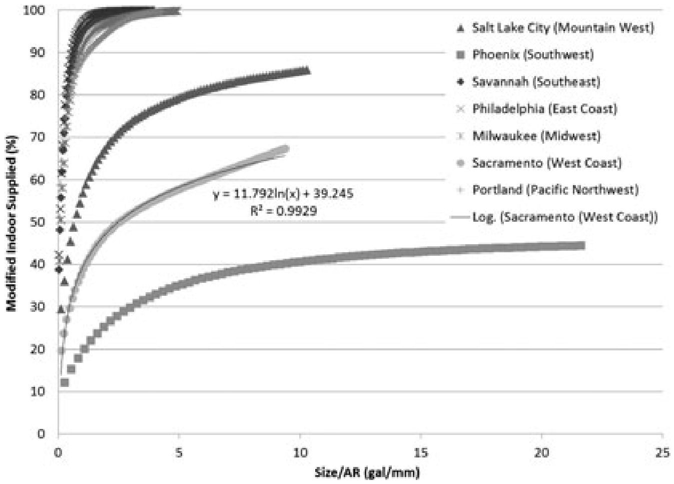

FIGURE 8. Relationship Between Modified Indoor Water-Saving Efficiency from RWH and Cistern Size and Annual Precipitation (AR) for a City in Each Region.

When precipitation is >762 mm (30 in) annually, nonpotable water-saving efficiency is >40% for parcels with a 190-l (50-gal) rain barrel. The rooftop water yield capture for these regions is from 40 to 50%, with a significant percentage of precipitation that can still be captured and supplied.

Figure 8 displays the relationship between cistern size and annual rainfall for modified indoor water-saving efficiency for a city representing each region. Regions with lower annual precipitation (Southwest, Mountain West, and West Coast) have lower percentages of modified indoor water-saving efficiency, whereas regions with higher annual precipitation (Southeast, East Coast, Midwest, and Pacific Northwest) have higher modified indoor water-saving efficiency percentages and are grouped together at the top of Figure 8. Table 9 lists the natural logarithm trend line fit for all cities and grouped by regions. Figure 8 shows a trend line for Sacramento, and visually displays the grouping of regions. Cities with lower annual precipitation have lower C values ranging from 10 to 60, whereas cities with higher annual precipitation have higher C values ranging from 85 to 93.

Stormwater Management Benefits

The stormwater management benefits of volume reduction by RWH implemented at a neighborhood

TABLE 9. Natural Logarithm Trend Line Equations Based on Water-Saving Efficiency for Modified Indoor Water Scenario and Cistern Size Divided by Annual Precipitation for Each City Grouped by Regions.

	y = Aln(x) + C	**Modified Indoor Water-Saving Efficiency (E_T)**		
Region	**City**	**A**	**C**	**R^2**
Mountain West	Salt Lake City	13.2	57.1	0.99
	Denver	13.2	52.6	1.00
Southwest	Albuquerque	7.9	30.7	0.98
	Phoenix	8.0	21.4	0.99
	Las Vegas	3.9	11.9	0.95
Southeast	Atlanta	13.5	89.3	0.92
	Miami	11.6	91.5	0.95
	Savannah	12.4	90.2	0.90
	Tampa	13.1	87.8	0.95
	Memphis	11.0	92.9	0.81
East Coast	Baltimore	11.0	90.7	0.82
	Norfolk	11.0	91.5	0.82
	Richmond	8.8	93.4	0.73
	Boston	8.6	93.5	0.73
	Philadelphia	10.4	91.2	0.81
	Providence	9.4	93.2	0.77
Midwest	Milwaukee	11.7	85.8	0.89
	Columbus	8.8	92.0	0.77
West Coast	Los Angeles	10.4	23.9	0.99
	Sacramento	11.8	39.2	0.99
	San Diego	10.9	26.1	0.99
Pacific Northwest	Portland	10.5	86.5	0.98
	Seattle	9.9	88.4	0.96

Note: A and C are coefficients of the natural logarithm equation.

scale are presented in Figures 9-11, for the different regions considered in this study. A single 189-l (50-gal) rain barrel implemented at every house in the model neighborhood could reduce average annual stormwater volume up to 12% in Mountain West cities such as Salt Lake City, and as low as 4% in Savannah. Using less water consistently (as is the case for the nonpotable water demand pattern) leads to a reduction in stormwater management benefits. This is an important observation because it suggests the need to operate the RWH system differently if water supply or stormwater management is the overriding objective.

Overall, the larger the cistern, the higher the stormwater control potential. The same trend is present as in the water supply benefits that regions with higher precipitation tend to have lower stormwater control potential than semiarid regions. The highest stormwater control potential for this neighborhood is 17%. At 17% stormwater control, all of the rooftop runoff is captured by RWH, which only occurs for Salt Lake City by using a 1,890-l (500-gal) cistern with the total water use pattern. For a 1,890-l (500-gal) cistern, the stormwater control percentage is above 10% for all cities for total, and modified total water use patterns. The 1,890-l (500-gal) cistern is too large for most cities because it was shown to capture the majority of runoff from the rooftops.

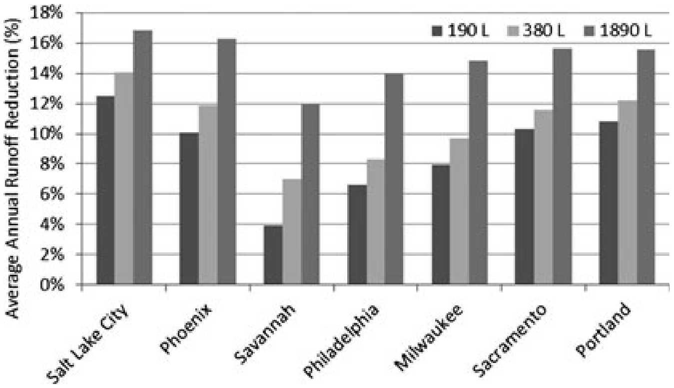

FIGURE 9. SWMM Neighborhood RWH Stormwater Control Results for Total Water Use Pattern for 190-l (50-gal), 380-l (100-gal), and 1,890-l (500-gal) Cisterns.

As the water use level (i.e. water demand) decreases so does the ability of RWH to act as a stormwater control measure. For outdoor usage, the stormwater control percentage dropped for all cities especially for the 190-l (50-gal) cistern. The stormwater control potential is low, ranging from 0 to 2% for cities that have higher precipitation (Savannah, Philadelphia, Milwaukee, and Portland).

Figure 12 illustrates the annual stormwater reduction for each of the seven cities for water uses (total, modified total, and outdoor) and for cistern sizes ranging from 190 to 1,890 l (50-500 gal) and the range of analysis allows for its creation. The annual stormwater reduction is the amount of stormwater that is used by RWH and does not enter the storm drains. The maximum annual stormwater reduction is 756,000 m^3 (2 million gal) for Savannah with total water demand. The annual stormwater reduction is approximately 6,000 m^3 (1.5 million gal) for a 1,890-l (500-gal) cistern. The annual stormwater reduction is significantly less for a 190-l (50-gal) cistern for the outdoor water demand pattern, resulting in an annual reduction of <1,000 m^3 (0.26 million gal).

Figure 12 shows the dependence of RWH effectiveness on precipitation pattern. Regions with lower precipitation (Salt Lake City, Phoenix, Sacramento) have lower annual stormwater reductions. The increasing cistern size and the different water use does not greatly increase the ability to reduce storm-

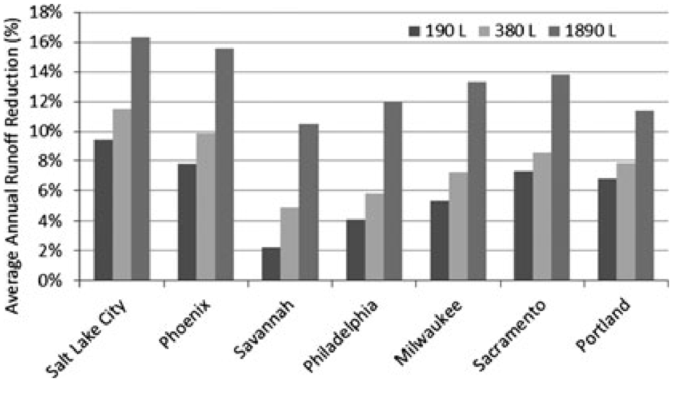

FIGURE 10. SWMM Neighborhood RWH Stormwater Control for Modified Total Water Use for 190-l (50-gal), 380-l (100-gal), and 1,890-l (500-gal) Cisterns.

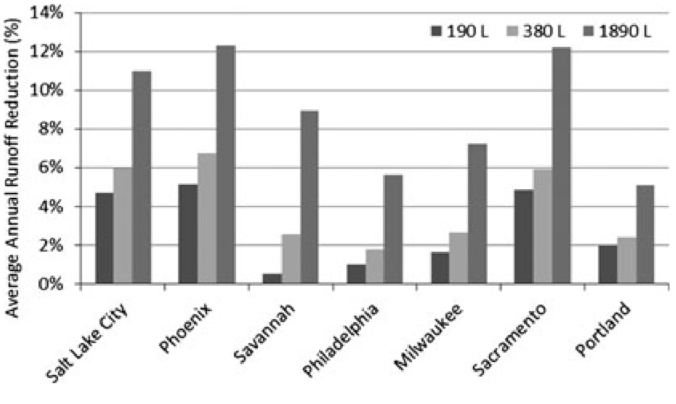

FIGURE 11. SWMM Neighborhood RWH Stormwater Control for Outdoor Water Use for 190-l (50-gal), 380-l (100-gal), and 1,890-l (500-gal) Cisterns.

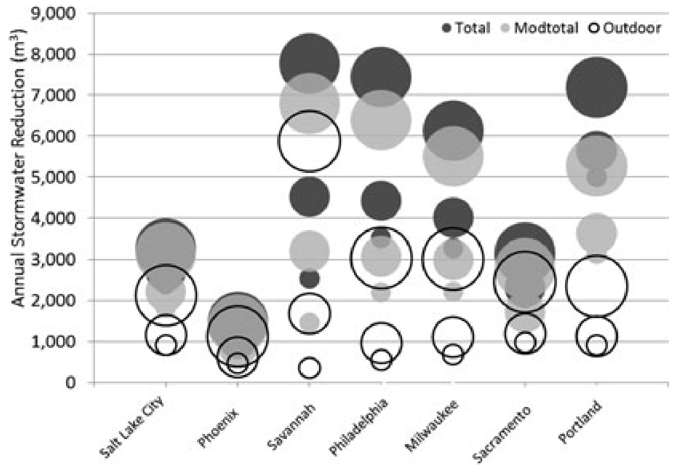

FIGURE 12. Annual Average Stormwater Reduction for Each of the Regional Cities for a 190 l (50 gal) (small circle), 380 (100 gal) (middle size circle), and 1,890 l (500 gal) (large size circle) Cistern for Total (dark gray), Modified Total (light gray), and Outdoor (open) Water Use Patterns.

water runoff in these regions. For Phoenix, the range in annual stormwater reduction is approximately 1,000 m^3 (0.3 million gal) for all of the different simulations, whereas in other cities the range is about 7,000 m^3 (1.8 million gal). The difference in ranges may be dependent on the frequency and size of the storms. On the other hand, regions with higher precipitation have a wider distribution of stormwater reduction values for different water use and cistern sizes. Larger cisterns are needed for higher stormwater reduction for regions with higher precipitation.

CONCLUSION

This article presented a study of the potential water supply and stormwater management benefits of RWH in 23 cities in seven regions in the U.S. Water-saving efficiency benefits were determined using a water-balance approach applied at a daily time step for a range of rainwater cistern sizes. The analysis was conducted for a standard residential parcel size and rooftop size using daily precipitation records and a daily water demand pattern developed for each city. Stormwater management benefits were quantified using USEPA SWMM to simulate the performance of an 11-hectare, 100-parcel residential neighborhood for precipitation patterns representing the seven regions.

The results suggest high potential for RWH to provide supplemental water supply and stormwater benefits. Water-saving efficiency benefits for regions with precipitation above 762 mm (30 in) were over 90% for modified (nonpotable) indoor water use, such as the Southeast, East Coast, Midwest, and Pacific Northwest. For regions with less precipitation, the potential water-saving efficiency ranged from 20 to 50% for 80% rooftop water yield. RWH has the potential to provide supplementary water with a higher potential in regions with average annual precipitation over 762 mm (30 in). The ability of RWH to supply water is dependent on several factors including cistern size, water use pattern, and precipitation. The cistern size required to capture 80% or more of the average annual runoff from the residential rooftop ranged in size from 757 to 6,814 l (190 to 1,800 gal). Of interest was the potential for high rooftop yield capture from RWH in the semiarid cities, while accomplishing lower water-saving efficiency benefits in these regions. In addition, more than 17 of the 23 cities could have >25% of the stormwater runoff from the residential parcel controlled by simply installing a 190-l (50-gal) rain barrel.

Other studies have shown that increasing water use for rainwater increases the rooftop yield capture because consistent, but low water usage does not drain large cisterns (DeBusk *et al.*, 2010; Jones and Hunt, 2010; Mun and Han, 2012). The total water demand scenario results in higher rooftop yield capture for all regions due to this reason. Jones and Hunt (2010) showed similar results for the Southeast for a 5,300-l cistern installed for the purpose of supplementing toilet usage. This cistern supplemented all of the toilet water needs, and this article estimates a water-saving efficiency above 90% for the modified indoor water usage will be supplied by a 5,000- to 6,000-l cistern for the East Coast and Southeast.

There is modest potential for stormwater management when RWH is implemented for every household in a neighborhood. Overall, the model neighborhood can reduce up to 12% of the total stormwater runoff by installing a single 190-l (50-gal) rain barrel at every home in Salt Lake City. Stormwater control in the seven different regions ranged from 17 to 1% depending on the water use pattern and the climate of the region. The regions with the higher stormwater management potential are the semiarid regions with <762 mm (30 in) of annual precipitation (Mountain West, West Coast, and Southwest). These are the same regions with the lowest water-saving efficiency. In conclusion, RWH has the potential for water supply benefits and stormwater management. The potential is dependent on several factors including precipitation, cistern size, and water usage pattern. Regions with higher precipitation have a higher water-saving efficiency, with a lower stormwater management potential. Semiarid regions have modest stormwater management potential at the neighborhood scale.

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