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Assessing climate change impacts on the reliability of rainwater harvesting systems

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ABSTRACT

Rainwater harvesting (RWH) systems recycle runoff, increasing the sustainability of water supplies; they may also reduce runoff discharges, and thus help meet water quality objectives. RWH systems receive runoff and thus will likely be impacted by changes in rainfall induced by climate change (CC). In this paper, we assess CC impacts on RWH with respect to the reliability of water supply, defined as the proportion of demands that are met; and the reliability of runoff capture, defined as the amount stored and reused, but not spilled. Hypothetical RWH systems with varying storage, rooftop catchments, irrigated areas, and indoor water demand for 17 locations across the U.S. were simulated for historical (1971–1998) and future (2041–2068) periods using downscaled climate model data assuming future medium-high greenhouse gas emissions. The largest change in runoff capture reliability would occur in Chicago (−12.4%) and Los Angeles (+12.3%), respectively. The largest change in water supply reliability would occur in Miami (+22%) and Los Angeles (−17.9%), respectively. The effectiveness of RWH systems for runoff capture is likely to be reduced in the eastern, northwestern, and southeastern U.S. Conversely, for most locations in the western, southern, and central U.S., RWH systems are expected to become less effective for water supply purposes. The additional storage needed to compensate for these reductions in water supply and/or runoff capture benefits was estimated. The results of this study can be used to design more resilient RWH systems with respect to CC, and thus maximize the dual objectives of RWH.

1. Introduction

The impacts of CO_2 and other greenhouse gas (GHG) production and their effects on the magnitude and variability of the world's climate are well established. GHG emissions increase longwave radiation, resulting in an expected mean surface temperature increase between 1.1–6.4 °C. by 2100 (IPCC, 2014). Historical evaluations of the U.S. climate (1950–2009) indicates that significant temperature increases for nearly all U.S. cities are likely, and extreme precipitation increases may occur in one third of them due to CC (Mishra and Lettenmaier (2011). Various regional assessments of CC are available, e.g., the Northeast (Hayhoe et al., 2008), the Central U.S. (Hayhoe et al., 2010), and the mid-Atlantic (Najjar et al., 2010). The uncertainty introduced by CC undermines stationarity, the fundamental principle upon which most place-based hydrologic assessments are conducted for infrastructure design (Milly et al., 2008). Milly et al. (2008) and Yang (2010) suggest that, while there are many downsides to the demise of stationarity, perhaps the only upside may be the opportunity to improve the resiliency of urban infrastructure.

Virtually all infrastructure, because it is downgradient and must accommodate runoff impacted by CC, is potentially at risk (Ahmadisharaf and Kalyanapu, 2015; Berggren et al., 2012; Mishra and Lettenmaier, 2011; Nilsen et al., 2011; Rosenberg et al., 2010). Increases in rainfall magnitude and intensity for anticipated CC are likely to cause infrastructure failures (Asadabadi and Miller-Hooks, 2017a,b; Semadeni-Davies et al., 2008; Zahmatkesh et al., 2014). Increased flooding of urban areas may result from CC and its impact on urban infrastructure, which will require significant financial resources to address (Giuffria et al., 2017; Wright et al., 2012). Urban development increases imperviousness, resulting in large increases in the rate and volume of runoff, thus increasing the washoff of pollutants from the land into surface waters, resulting in streambank and stream channel erosion and degrading aquatic habitats. Urban development and CC are expected to work in tandem, increasing runoff, degrading streams, and increasing pollutant transport (Alamdari et al., 2017; Alberti et al., 2007; Hatt et al., 2004; Lee et al., 2013; Nelson and Booth, 2002;

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Nomenclature

BMP	Best Management Practices
CC	Climate Change
CMIP5	Coupled Model Intercomparison Project Phase 5
CSO	Combined Sewer Overflow
GCM	Global Climate Models
GHG	Greenhouse Gas
NARCCAP	North American Regional CC Assessment Program
RAP	Rainwater Accumulation Potential
RASP	Rainwater Analysis and Simulation Program
RCM	Regional Climate Models
RWH	Rainwater Harvesting
SARET	Storage and Reliability Estimation Tool
SCMs	Stormwater Control Measures
SWMM	Stormwater Management Model

Symbols

λ_{WS}	Water Supply Reliability
λ_{RC}	Runoff Capture Reliability
TankV	Tank Storage Volume
RoofA	Roof Area
IrArea	Irrigated Area
Pop	Indoor Demand

Schueler et al., 2009; Scully, 2010). There are ways to mitigate the impacts from urban development, and potentially CC, using stormwater control measures (SCMs), also known as best management practices (BMPs). Currently, SCM design focuses upon runoff capture and treatment, some are now able to mitigate CC impacts (Gill et al., 2007; Pyke et al., 2011).

Rainwater harvesting (RWH) has been used for millennia to meet water supply needs and has recently been repurposed as an SCM for managing runoff as a water quality protection measure (Alam et al., 2012; Kahinda et al., 2010; Lassaux et al., 2007; Steffen et al., 2013; Tam et al., 2010). RWH systems store runoff from rooftops or other impervious areas for later use for outdoor irrigation or indoor nonpotable uses such as flushing toilets (Silva et al., 2015). A recent, comprehensive review of RWH is available in Campisano et al. (2017). By reusing stored rainfall instead of discharging it, RWH systems reduce runoff in addition to providing an alternative nonpotable water supply. Young et al. (2009) found that RWH systems could be designed to mimic the function of other SCMs such as sand filters, vegetated roofs, and porous pavement. In many older urban areas, drainage and sewage share a common conveyance, known as a combined sewer. Depending upon capacity, the combined sewer will overflow during moderate to heavy rainfall events, causing significant water quality degradation downstream (Even et al., 2007; Tavakol-Davani et al., 2016). Gold et al. (2010) found that RWH could reduce combined sewer overflows (CSOs) by reducing runoff and decreasing water withdrawals. Tavakol-Davani et al. (2015) found RWH was a cost effective strategy for CSO control.

A variety of models have been used to simulate RWH and thus potentially help in assessing its benefits. Basinger et al. (2010) developed the Storage and Reliability Estimation Tool (SARET) and used it to simulate RWH reliability and yield. The model was used to size RWH systems to supply flush low flow toilets within a Bronx, New York, U.S. Reductions in runoff volume and nonpotable water demand were predicted to be 28% and 53%, respectively. Ghisi (2010) developed a RWH model and applied it to three cities in Sao Paulo State, Brazil. The authors found that site-specific studies must be performed to consider local rainfall patterns, roof area, indoor and outdoor water demand to design a RWH system and quantify its benefits. Kim and Yoo (2009) assessed flood control and water supply with and without RWH using a hydrologic model, and found that, for a given urban area, if runoff from 10% of rooftops were diverted to RWH systems, floods would be reduced by 1%. Jensen et al. (2010) developed RWHTools, a daily mass balance model, and applied it to 20 cities in the U.S. to evaluate RWH with respect to the amount of runoff captured and water demand met. The authors found that these two objectives were complementary rather than competitive; however, for the same benefit that met both objectives, a significantly larger tank was often required for some locations and climates. Jones and Hunt (2010) evaluated several installed RWH systems within North Carolina, and found that they are often underutilized. The authors found that nonpotable uses such as toilet flushing may be essential to providing stormwater retention volume as this demand must be met irrespective of hydrologic conditions. Campisano and Modica (2012) determined the optimal size of domestic RWH tanks using the ratio of storage to rainfall multiplied by effective roof area. The authors found that this parameter, termed “storage fraction”, generalized rainfall patterns and RWH system performance. The performance of rainwater tanks in Melbourne, Australia was evaluated and optimized using a spreadsheet based daily water balance model by Imteaz et al. (2013), Imteaz et al. (2012). A dry year, an average year, and a wet year was selected. Results indicated that 100% water supply reliability was not achieved for small roof sizes (less than or equal to 100 m^2), even with tanks as large as 10 m^3. Karim et al. (2015) evaluated the reliability and feasibility of the RWH systems in Dhaka City, Bangladesh by employing a daily water balance model and three climate scenarios including wet, average, and dry. The authors found an insignificant increase in the reliability of the RWH system beyond the tank volume of 30 m^3 for three scenarios. Sample et al. (2012) developed the Rainwater Analysis and Simulation Program (RASP) and applied it to assess the dual benefits of water supply and runoff capture reliability of RWH implementation in Richmond, Virginia using tradeoff curves. A key finding of this study was that some input variables were interchangeable if reliability was held constant.

RWH was found to be an effective water supply adaptation strategy for mitigating CC effects, particularly in areas with high water demand (Aladenola and Adeboye, 2010; Boelee et al., 2013; Kahinda et al., 2010; Mukheibir, 2008; Pandey et al., 2003; Rozos et al., 2009). Youn et al. (2012) found that, due to CC, the effective storage capacity of RWH systems in Korea would likely be reduced. Similar results were found by Lash et al. (2014) for the U.K. who used a statistical analysis of projected rainfall for an assessment of CC. Lo and Koralegedara (2015) evaluated the effects of CC on urban RWH in Colombo City, Sri Lanka, and found that residential RWH systems would likely be more affected by CC than non-residential systems. Palla et al. (2012) assessed the performance of domestic RWH systems across Europe with respect to optimal design under CC. Results indicated that the duration of antecedent dry conditions was strongly correlated with RWH system behavior, while event rainfall depth, intensity and duration were weakly correlated. Haque et al. (2016) evaluated the impact of CC on the performance of a residential RWH using a daily water balance model at five locations in the Greater Sydney region, Australia. As a result of CC, precipitation is anticipated to be reduced, and duration between events increased. The authors found that, for a 3 kL tank, water savings would be reduced between 2–14%. Water supply reliability was found to be reduced between 3–16%, and the number of days the tank would be completely empty is projected to increase from 8% to 12%. CC impacts on RWH are likely to be greater in the dry season than wet. In contrast, Almazroui et al. (2017) found that in Wadi Al-Lith, Saudi Arabia, CC would likely result in increased precipitation and duration, increasing the feasibility of RWH. The effects of both CC and El Niño on rainfall patterns on the capacity of RWH in Jamaica were evaluated by Aladenola et al. (2016). Results indicated that the higher variability is