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Harvesting rooftop runoff to flush toilets: Drawing conclusions from four major U.S. cities

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A B S T R A C T

As it provides the simultaneous benefits of reducing the demand for potable water and the generation of water runoff, rainwater harvesting (RWH) has received increasing attention from urban water managers in the past decades. This study employs a mass balance based method to estimate RWH performance for four large metropolitan areas of the United States, namely New York City, Philadelphia, Chicago, and Seattle. Geospatial analysis is used in concert with climatic records to characterize the cityscape and climatic patterns of each city and evaluate the RWH systems performance both in terms of potable water savings and roof runoff reductions. The analysis indicates that typical urban rainwater harvesting setups, consisting of a 100 m^2 roof connected to a 5 m^3 storage volume, would be able to reduce potable water demand by over 65% in all cities while contextually reduce roof runoff generation by over 75%. Small differences in performance are observed among cities due to differences in precipitation patterns, typical roof area, and population density. Furthermore, an evaluation of the total water savings and runoff reduction for the application of RWH practices at maximum build out for all four study cities is provided, and the sensitivity of our estimates of performance to precipitation patterns and to the systems' operating algorithm is also analyzed and discussed.

1. Introduction

Water resource management has always constituted a paramount factor in the planning, development and sustainability of large urban areas. The sustainment of urban activities is dependent on the presence of reliable supplies of water, as well as on cost-effective strategies for treating discharges of stormwater, blackwater, and greywater generated within the urban landscape and infrastructure matrix. Sustainable urban development requires high performance infrastructure systems, designed to address multiple sets of urban constraints simultaneously.

In this context, rainwater harvesting (RWH) is ever more considered among the most effective urban water management strategies (Daigger, 2009; Basinger et al., 2010; Morales-Pinzón et al., 2012; Rygaard et al., 2011). Originating in ancient times (Boers and Asher, 1982; Phoca and Valavanis, 1999; Lee et al., 2000; Bergamini, 1991; Radhakrishna, 2003; Abdulla and Al-Shareef, 2009; Gianighian, 1996), RWH is part of a broad range of sustainable urban strategies currently known as green infrastructure (GI), low impact development (LID), or sustainable urban drainage systems (SUDS). Provided their broad application, such practices would contribute to mitigate of the negative impacts of metropolitan development on water resources (Elliott and Trowsdale, 2007), with benefit that can ultimately extend to greater energy efficiency and lower greenhouse emissions (Devkota et al., 2013). The benefits of RWH systems are dual. On one hand, the harvested water can be used to supplant potable water for non-potable uses, thus reducing the overall pressure on the existing water supply. On the other hand, RWH contributes to the reduction of the rate and quantity of runoff generated in the subcatchments from which these supplies are harvested (Elliott and Trowsdale, 2007; Palla et al., 2011), mitigating the overall stormwater load on the urban hydraulic network, both above and below the ground.

Assessing the performance of RWH has been the focus of several studies (Abdulla and Al-Shareef, 2009; Basinger et al., 2010; Burns et al., 2015; Campisano and Modica, 2015; Campisano et al., 2013a, 2013b; Coombes et al., 1999; Devkota et al., 2013; Ghisi, 2006; Hermann and Schmida, 1999; Morales-Pinzón et al., 2012; Okoye et al., 2015; Peterson, 2016; Petrucci et al., 2012; Rygaard et al., 2011; Silva et al., 2015; Zhang et al., 2009). Hanson et al. (2009) developed a regression to estimate optimal storages at desired levels of reliability across the whole US. Campisano et al. (2013a,

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2013b) discussed the impact of climatic factors on the performance and the optimal design of RWH systems. Ghisi et al. (2007, 2009) focused on RWH residential water savings and water savings for auto vehicles washing in Brazil and estimated them being in the range 12–79% and 9.2–57.2% respectively. A study done in Sydney, Newcastle and Wollongong assessed the performance of RWH systems in multi-unit buildings and showed that the use of large tanks helps maximizing water savings in those three cities (Eroksuz and Rahman, 2010). Basinger et al. (2010) introduces the Storage and Reliability Estimation Tool (SARET) and uses it to quantify the time-based reliability with which rooftop RWH practices can satisfy non-potable water uses in NYC. Rostad and Montalto (2012), uses SARET to estimate potential water savings from RWH for toilet flushing.

In this paper, the authors use a direct application of the water balance to provide a thorough assessment of the performance of RWH for residential toilet flushing, which is the largest domestic use of water and accounts for about one third of indoor residential usage in the United States and the UK (Mayer et al., 1999; Fewkes, 1999). Recognizing how sensitive the performance of RWH system can be to climatic patterns and cityscapes (Campisano et al., 2013a, 2013b; Ghisi et al., 2009, 2007; Hanson et al., 2009; Imteaz et al., 2012; Palla et al., 2011, 2012), our assessment looks at four large US cities, namely Philadelphia, New York, Chicago and Seattle. The authors carry out a detailed geospatial analysis to characterize the number of individuals living in each building and available rooftop area for rainfall harvesting, that is, the two primary factors driving, respectively, water demand for toilet flushing (WDTF) and water supply. The authors then test the performance of the RWH systems, both in terms of potable water savings and in terms of roof runoff reductions under a set of different WDTF scenarios and storage volume setups and, crucially, evaluate the impact of the simulation algorithm on the estimation of the systems' performance.

While some of the specific techniques and algorithms used in this study have been adopted in similar analyses, our study contributes a thorough analysis of the RWH systems for four major US cities, exploring the role of climatology and cityscape within the context of water savings and runoff reduction. Specifically, the overarching objectives of this study are: (1) assessing the reliability of RWH systems in meeting WDTF in all study cities; (2) estimating the potential reductions in roof runoff that RWH systems can generate; (3) studying the individual roles that precipitation patterns, roof sizes, population density and operating rules play on the performance of RWH systems; (4) providing a quantitative assessment of the water savings and rooftop runoff reductions that cities would have if all residential buildings were equipped with storage tanks for rainfall harvesting.

The modeling framework, data sources and simulation procedure adopted in this study are described in detail in the next section. Analysis of the performance of the RWH systems and their sensitivity to both exogenous (e.g. precipitation patterns, roof sizes, population density, etc.) and endogenous (e.g. modeling algorithms) factors, are discussed for individual cities as well as across cities; recommendations are provided both at the building and at the urban scale.

2. Materials and methods

2.1. Datasets

A detailed geographic information system (GIS) database was developed for each of the four cities in order to estimate roof areas and residential WDTF. Planimetrics (outlines of buildings and other surfaces), zoning boundaries, tax parcels, and census tract outlines were retrieved from a variety of sources (Rostad and Montalto, 2012). Chicago zoning boundaries were obtained via a Freedom of Information Act request, while the rest of the relevant information for Philadelphia and Chicago was publically available online. Seattle and New York City datasets were retrieved from the cities' GIS departments for a nominal fee. Finally, population information for all four cities in year 2000 was obtained from the online data portal of the U.S. Census Bureau (Rostad and Montalto, 2012).

Only roofs located in residential or mixed residential districts were considered in the study. In an attempt to further restrict the analysis to primary residences, a minimum threshold for roof surface was set in order to disregard secondary non-residential structures, such as cabins or storage units (Rostad and Montalto, 2012). Distributions of roof surfaces for the four study cities are shown in Table 1. Estimates of per capita roof area were obtained as the ratio between the total roof surface present in a given census tract and the population of the census tract, while the ratio between the roof area of a given building and the per capita roof area was used to calculate the number of residents in the building (see Table 2).

Historical precipitation records were obtained for each city from the National Climatic Data Center (NCDC) stations, as summarized in Table 3. With 1105 mm/year, New York City is the wettest among the study cities (1105 mm/year). Philadelphia, Seattle and Chicago follow, with 1055 mm/year, 940 mm/year and 885 mm/year, respectively (Fig. 1). No obvious seasonal patterns are present in New York City or Philadelphia, as the average monthly precipitation of both cities is bounded roughly between 50 mm and 100 mm. Seasonality is, however, noticeable in Chicago and Seattle with rainy seasons occurring, respectively, in the summer and in the winter months. All study cities are characterized by a humid climate, according to the Köppen–Geiger classification (Kottek et al., 2006; Peel et al., 2007), with New York and Philadelphia both falling within the Cfa category ("Temperate, humid, hot summer"), Seattle falling within the Cfb category ("Temperate, humid, warm summer") and Chicago within the Dfa category ("Snow, humid, hot summer"), as reported in Table 3.

2.2. Water balance of RWH systems

To estimate RWH system reliability and runoff reduction, water balances were performed at for each city using the 25-year historical precipitation records. A daily time step, appropriate as far as water savings estimations are concerned (Campisano and Modica, 2015), was chosen for all simulations. The system reliability was estimated by dividing the number of days where the WDTF was entirely met by the total number of days. This time-based reliability metric is more conservative than volumetric reliability, that is, the ratio between volumetric yield from the tank and WDTF, as the latter takes into account also the time steps where the WDTF is only partially met (Palla et al., 2011). The systems were modeled starting with an empty tank. Volume of tank overflow, yield from the tank, and water stored in the tank at the end of each time step were calculated using the following equations:

$$Y_i = \min(S_{i-1} + R_c \cdot A \cdot P_i - O_i, D_i) \quad (1)$$

$$S_i = \min(S_{i-1} + R_c \cdot A \cdot P_i - Y_i, S_{\max} - Y_i) \quad (2)$$

$$O_i = \max(S_{i-1} + R_c \cdot A \cdot P_i - S_{\max}, 0) \quad (3)$$

where the subscript i indicates the given time step (day) of simulation, Y is the yield from the tank, S is the volume of water in storage at end of time step, O is the overflow from the tank, A is the catchment area, P is the precipitation, D is the WDTF, $S_{\max}$ is the tank volume and R_c is the runoff coefficient.

The system was simulated using a set of combinations of roof areas, WDTF and storage tank volumes for each building. The roof areas for each building ranged from 5 to 305 m^2, in increments of