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Assessing efficiency and economic viability of rainwater harvesting systems for meeting non-potable water demands in four climatic zones of China

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ABSTRACT

Rainwater harvesting is now increasingly used to manage urban flood and alleviate water scarcity crisis. In this study, a computational tool based on water balance equation is developed to assess stormwater capture and water saving efficiency and economic viability of rainwater harvesting systems (RHS) in eight cities across four climatic zones of China. It requires daily rainfall, contributing area, runoff losses, first flush volume, storage capacity, daily water demand and economic parameters as inputs. Three non-potable water demand scenarios (i.e., toilet flushing, lawn irrigation, and combination of them) are considered. The water demand for lawn irrigation is estimated using the Cropwat 8.0 and Climwat 2.0. Results indicate that higher water saving efficiency and water supply time reliability can be achieved for RHS with larger storage capacities, for lower water demand scenarios and located in more humid regions, while higher stormwater capture efficiency is associated with larger storage capacity, higher water demand scenarios and less rainfall. For instance, a 40 m^3 RHS in Shanghai (humid climate) for lawn irrigation can capture 17% of stormwater, while its water saving efficiency and time reliability can reach 96% and 98%, respectively. The water saving efficiency and time reliability of a 20 m^3 RHS in Xining (semi-arid climate) for toilet flushing are 19% and 16%, respectively, but it can capture 63% of stormwater. With the current values of economic parameters, economic viability of RHS can be achieved in humid and semi-humid regions for reasonably designed RHS; however, it is not financially viable to install RHS in arid regions as the benefit-cost ratio is much smaller than 1.0.

1. Introduction

Urbanization is a worldwide process with well-known adverse hydrologic and environmental effects such as increasing flooding damage and decreasing water quality (Loganathan and Delleur, 1984; Zhang and Guo, 2013a). Along with urbanization, population in many cities of the world are quickly increasing and water supply systems in these cities are consequently under stress (Zhang et al., 2012). Moreover, uncertainties associated with climate change will intensify the pressure of future water supply and stormwater management systems in most urban areas (Hanson and Palmer, 2014). Rainwater harvesting systems (RHS) are operated to collect and store rainwater from contributing areas (e.g., building roofs and parking lots) during rainfall events, and store it in cisterns for use on dry days between rainfall events (Guo and Baetz, 2007; Khastagir and Jayasuriya, 2010). As RHS can alleviate urban water supply pressure and reinforce urban stormwater management system at the same time, it has been more and more widely used in many nations (Rahman et al., 2010; Mehrabadi et al., 2013; Jones and Hunt, 2010; Kim and Yoo, 2009; Ghisi, 2010; Vialle et al., 2015).

Harvested rainwater can be used to substitute tap water for potable (e.g., drinking and cooking) or non-potable (e.g., flushing toilets, washing clothes and irrigating lawns) purposes (USEPA, 2004) depending on its quality. As a result, rainwater harvesting can reduce urban water supply stress (Appan, 2000; Handia et al., 2003). Rainwater is usually one of the cleanest available water sources and rainwater harvesting is one of the best methods available for establishing sustainable water cycles in urban developments (Zhang and Hu, 2014). A study of RHS in 195 cities of Southeastern Brazil indicated that the tap water saving potential of RHS ranges from 12% to 79% (Ghisi et al., 2007). Zhang and Hu (2014) reported that 9.8×10^6 m^3 rainwater can be harvested in one year from an industrial park (about 8 km^2) located in a humid climatic zone of China. In several cities (dry climatic zone) of Saudi Arabia, the amounts of rainwater that can be harvested were estimated to be larger than 7.5 m^3/100 m^2 per year (Guizani, 2016). Karim et al. (2015) revealed that about 250 kL to 550 kL of rainwater can be harvested per year under catchment sizes varying from 140 m^2 to 200 m^2 in Dhaka, Bangladesh.

RHS can be viewed as miniature multipurpose stormwater

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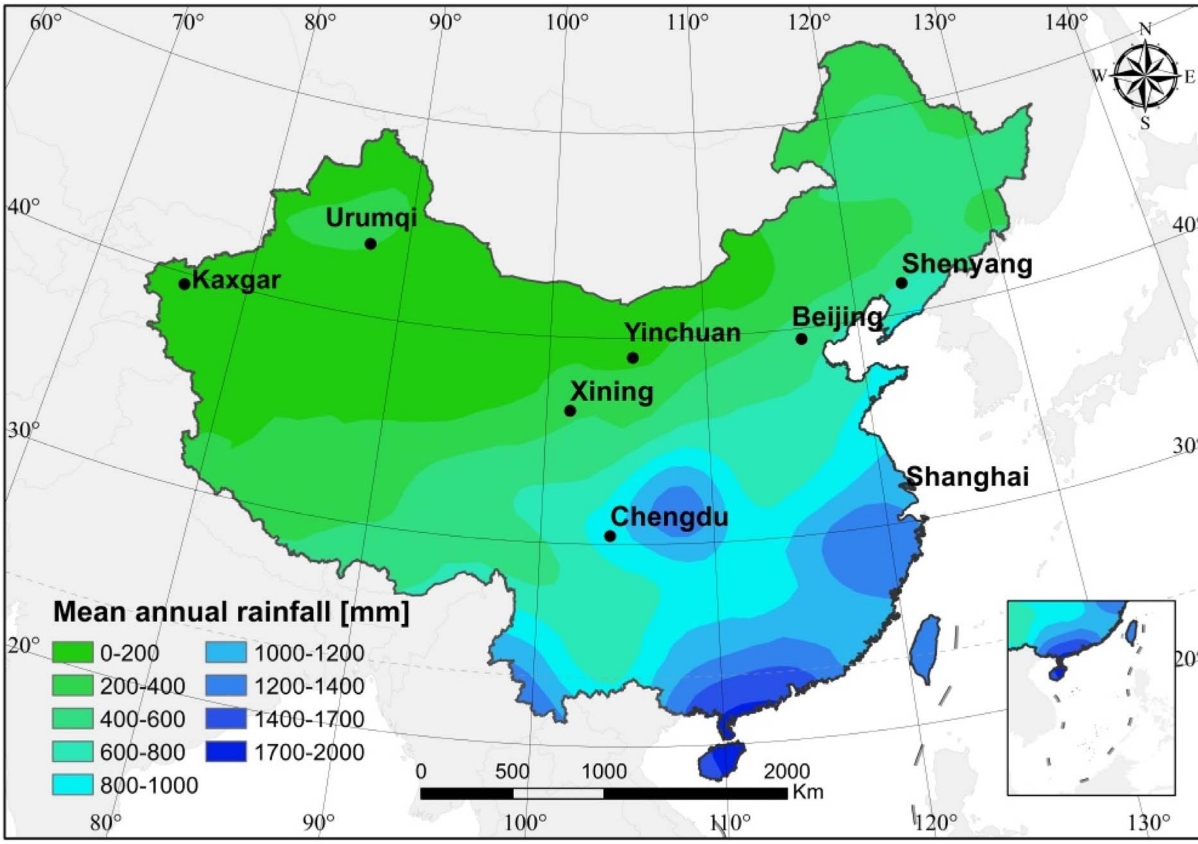

Fig. 1. Spatial distribution of mean annual rainfall and locations of the eight cities.

management facilities (Kim et al., 2015). The implementation of RHS diverts surface runoff away from stormwater collection systems and reduces the volume of runoff that needs to be managed during rainfall events (Guo and Baetz, 2007; Rostad et al., 2016). Steffen (2013) evaluated stormwater management performance of RHS located in 23 cities within 4 different climatic regions in the USA and found that higher stormwater capture efficiency could be achieved in semi-arid regions than in humid regions. As reported by Litofsky and Jennings (2014), the stormwater capture efficiency of rain barrel-urban garden systems for 70 selected locations across the USA over 2000–2009 time period ranged from 3.0% to 44.5%. Based on EPA SWMM simulations, Palla et al. (2017) reported that the average discharge peak and volume reduction rates of implementing domestic RHS in a residential urban block located in Genoa (Italy) were 33% and 26%, respectively (with maximum values of 65% for peak and 51% for volume).

Implementation of RHS can also bring considerable economic and environmental benefits. Tam et al. (2010) evaluated the cost effectiveness of RHS in 7 cities of Australia and indicated that RHS are economically feasible in Gold Coast, Brisbane, and Sydney due to more rainfall and higher reliability. Zuo et al. (2010) developed an economic evaluation system to assess 267 RHS in Beijing and concluded that 66.7% of the systems could produce significant economic benefits. A financial comparison between using rainwater and using groundwater for agricultural irrigation in the rural areas of Beijing showed that using rainwater was economically feasible and had positive effects for society (Liang and Dijk, 2011). In Saudi Arabia, a study showed that harvested rainwater is cheaper than desalinated water produced from renewable energy-driven desalination plants but that is not the case for fossil fuel-powered desalination (Guizani, 2016).

Even the scale of most RHS are small, sizing of rainwater storage units for them should be rigorously treated as a hydrologic engineering design similar to other stormwater management facilities (Guo and Baetz, 2007). Various approaches can be used in RHS size design and optimization, such as the design storm approach (Vaes and Berlamont, 2001), continuous simulations (Jenkins, 2007; Kim and Yoo, 2009; Campisano and Modica, 2012), the analytical probabilistic approach (Guo and Baetz, 2007), linear programming approach (Okoye et al., 2015), the nonlinear metaheuristic algorithm (Sample and Liu, 2014), and the dimensionless methodology (Campisano and Modica, 2012). Among these approaches, long-term continuous simulations based on water balance theory are most frequently applied to assess the stormwater management performance and economic benefit of RHS (Hajani and Rahman, 2014; Silva et al., 2015) and to optimize their storage unit size (Imteaz et al., 2011a; Hashim et al., 2013).

China has been facing increasingly serious urban water scarcity crisis as the result of rapid industrialization and urbanization as well as extremely high density of population (Zuo et al., 2010). The application of RHS as multipurpose facilities has been widely promoted by the central and many local governments in China (Chen, 2013). Despite beneficial uses of RHS have been demonstrated by numerous researchers (Zuo et al., 2010; Liang and Dijk, 2011; Zhang and Hu, 2014) and many incentive programs (Li, 2009) have been provided by governments, there is still a reluctance in general communities to adopt them on a wider scale. This reluctance can be mainly attributed to lake of information about the environmental effectiveness and economic benefit of using RHS and easy-to-use tools to determine the size of them.

The novelty of this study is the development of an easy-to-use computational tool which can be used in stormwater capture and water saving efficiency and economic viability assessment of RHS. Taking daily rainfall data, contributing roof area, rainfall loss factors, design storage capacity, and daily rainwater usage rate into consideration, a daily water balance model is developed and used to assess the stormwater management and water saving efficiency of RHS. Comparing the present value of benefits to the present value of costs of RHS, a benefit-cost ratio is defined and calculated to evaluate their economic viability.