Journal of Hydrology 550 (2017) 42–53

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Seeking urbanization security and sustainability: Multi-objective optimization of rainwater harvesting systems in China

Yi Li [a,*], Quanliang Ye [a], An Liu [b], Fangang Meng [c], Wenlong Zhang [a], Wei Xiong [a], Peifang Wang [a], Chao Wang [a]

[a] Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, College of Environment, Hohai University, Nanjing 210098, PR China
[b] College of Chemistry and Environmental Engineering, Shenzhen University, Shenzhen 518060, PR China
[c] SYSU-HKUST Research Center for Innovative Environmental Technology (SHRCIET), School of Environmental Science and Engineering, Sun Yat-sen University, Guangzhou 510275, PR China

ARTICLE INFO

Article history:
Received 17 January 2017
Received in revised form 16 April 2017
Accepted 18 April 2017
Available online 23 April 2017
This manuscript was handled by G. Syme, Editor-in-Chief

Keywords:
Rainwater harvesting
Multi-objective optimization
Stormwater runoff control
Water logging
Water scarcity

ABSTRACT

Urban rainwater management need to achieve an optimal compromise among water resource augmentation, water loggings alleviation, economic investment and pollutants reduction. Rainwater harvesting (RWH) systems, such as green rooftops, porous pavements, and green lands, have been successfully implemented as viable approaches to alleviate water-logging disasters and water scarcity problems caused by rapid urbanization. However, there is limited guidance to determine the construction areas of RWH systems, especially for stormwater runoff control due to increasing extreme precipitation. This study firstly developed a multi-objective model to optimize the construction areas of green rooftops, porous pavements and green lands, considering the trade-offs among 24 h-interval RWH volume, stormwater runoff volume control ratio (R), economic cost, and rainfall runoff pollutant reduction. Pareto fronts of RWH system areas for 31 provinces of China were obtained through nondominated sorting genetic algorithm. On the national level, the control strategies for the construction rate (the ratio between the area of single RWH system and the total areas of RWH systems) of green rooftops (η_{GR}), porous pavements (η_{PP}) and green lands (η_{GL}) were 12%, 26% and 62%, and the corresponding RWH volume and total suspended solids reduction was 14.84 billion m^3 and 228.19 kilotons, respectively. Optimal η_{GR}, η_{PP} and η_{GL} in different regions varied from 1 to 33%, 6 to 54%, and 30 to 89%, respectively. Particularly, green lands were the most important RWH system in 25 provinces with η_{GL} more than 50%, η_{GR} mainly less than 15%, and η_{PP} mainly between 10 and 30%. Results also indicated whether considering the objective *MaxR* made a non-significant difference for RWH system areas whereas exerted a great influence on the result of stormwater runoff control. Maximum daily rainfall under control increased, exceeding 200% after the construction of the optimal RWH system compared with that before construction. Optimal RWH system areas presented a general picture for urban development policy makers in China.

1. Introduction

Rapid urbanization has caused environmental problems by negatively affecting the hydrological cycles of urban water systems, which would exacerbate in the future (Roesner and Bledsoe, 2001; Cadavid et al., 2013). Roads and buildings reduced pervious surface area, which limited natural water infiltration and increased rainfall runoff during rainstorm events. Excess rainwater deteriorated the quality and changed the flow patterns of the runoff leading to severe non-point source pollutions and effects on the ecosystem health of receiving water bodies (Damodaram et al., 2013; Moglia et al., 2016a; Montaseri et al., 2015). On the other hand, urbanization concentrated the population and other social resources in urban areas. This transformation led to an increasing demand of fresh water, and thus exacerbated the scarcity of water resources (Ghimire et al., 2014; Thomas et al., 2014). In this situation, rainwater has grown in popularity as an accessible water supply source (Li et al., 2000). Small on-site rainwater harvesting (RWH) technologies, such as green rooftops, porous pavements, and bioretention or green lands, have been successfully implemented as viable approaches to harvest rainwater in most regions (Melville-Shreeve et al., 2016; Moglia et al., 2016b; Palla et al., 2011; Walsh et al., 2012). Moreover, RWH systems were intended

* Corresponding author.
E-mail address: envly@hhu.edu.cn (Y. Li).

http://dx.doi.org/10.1016/j.jhydrol.2017.04.042
0022-1694/

to preserve and reinstate the pre-developed condition of urban lands. For this purpose, a number of approaches integrated RWH existed in developed and developing countries, such as Water Sensitive Urban Design (WSUD) in Australia (Coombes et al., 1999; Coutts et al., 2012); Best Management Practices (BMPs) and Low Impact Development (LID) in USA (Bhaskar et al., 2016; DER, 1999); the Building Research Establishment Environmental Assessment Method (BREEAM) and Sustainable Urban Drainage Systems (SuDS) in the UK (Andoh and Iwugo, 2004; BREEAM, 2011); the Sponge City Construction and Development in China (China Housing and Urban-Rural Development, 2014).

RWH optimization techniques and evaluation models have been used extensively to design and optimize RWH systems. Silva et al. (2015) evaluated the technical feasibility and economic viability of domestic RWH systems in Porto and Almada, Portugal. Liang et al. (2011) analyzed the economic and financial performance of RWH systems in rural areas of Beijing using cost benefit analysis. Chen and Adams (2007) developed an urban stormwater quality model to evaluate rainwater pollutant buildup and washoff processes. On the other hand, stormwater runoff control has been a new challenge for urban rainwater management. Significant reduction of municipal peak flow may be provided by implementing RWH systems in urban areas (Jensen et al., 2010). Zhang et al. (2012) calculated the potential of collectable rainwater and the possibility of runoff volume reduction. Liu et al. (2015a) used a process-based stormwater runoff model to evaluate the runoff reduction effectiveness under various setting sizes of green infrastructure in Beijing, China. Sample and Liu (2014) used a rainwater simulation model to evaluate decentralized RWH systems in terms of water supply and runoff capture reliability across a wide range of land uses and locations in Virginia, USA.

Most of the previous studies either showed the contribution of RWH in water resource supplementation or in stormwater runoff control through some particular criterions (such as storage size, water saving efficiency, economic analysis and environmental impacts) of interest. In spite of the achievements listed above, there were only a few studies integrating the two ultimate rainwater management components (i.e. RWH for water supplement and stormwater runoff control). Did it mean that rainwater harvesting objectives of water supplement and stormwater runoff control conflicted? To answer this question, many management efforts were requested throughout a watershed. However, there was no single RWH system that could be effective for the objectives in all regions (Lee et al., 2012). The characteristics of rainfall, economic development level, and pollution situations varied among different regions. The major problem was to select the best combination of RWH systems among different options available that obtained a practical, efficient, and sustainable strategy for the regions of different objectives, such as water resource augmenting, stormwater runoff control, economic feasibility and pollutants reduction. Thus, modeling methods and tools, like multi-objective optimization model, were needed to support the selection and assessment of feasible RWH systems, which could determine the construction area of RWH systems that achieved urbanization security and sustainability.

Multi-objective optimization model has been widely applied in solving water resource problems (Alzraiee et al., 2013; Arad et al., 2013; Reddy and Kumar, 2007; Vasan and Raju, 2006). Non-dominated Sorting Genetic Algorithm II (NSGA II) is one of the most efficient, multi-objective, evolutionary algorithms using the elitist approach (Deb et al., 2002) and has gained popularity in finding the near optimal solutions for optimization problems (A. Vasan and Simonovic, 2010). Van Meter et al. (2014) recommended a holistic watershed-scale approach that accounts for trade-offs among water availability and socioeconomic wellbeing to explore the social, economic, and environmental dimensions of agricultural

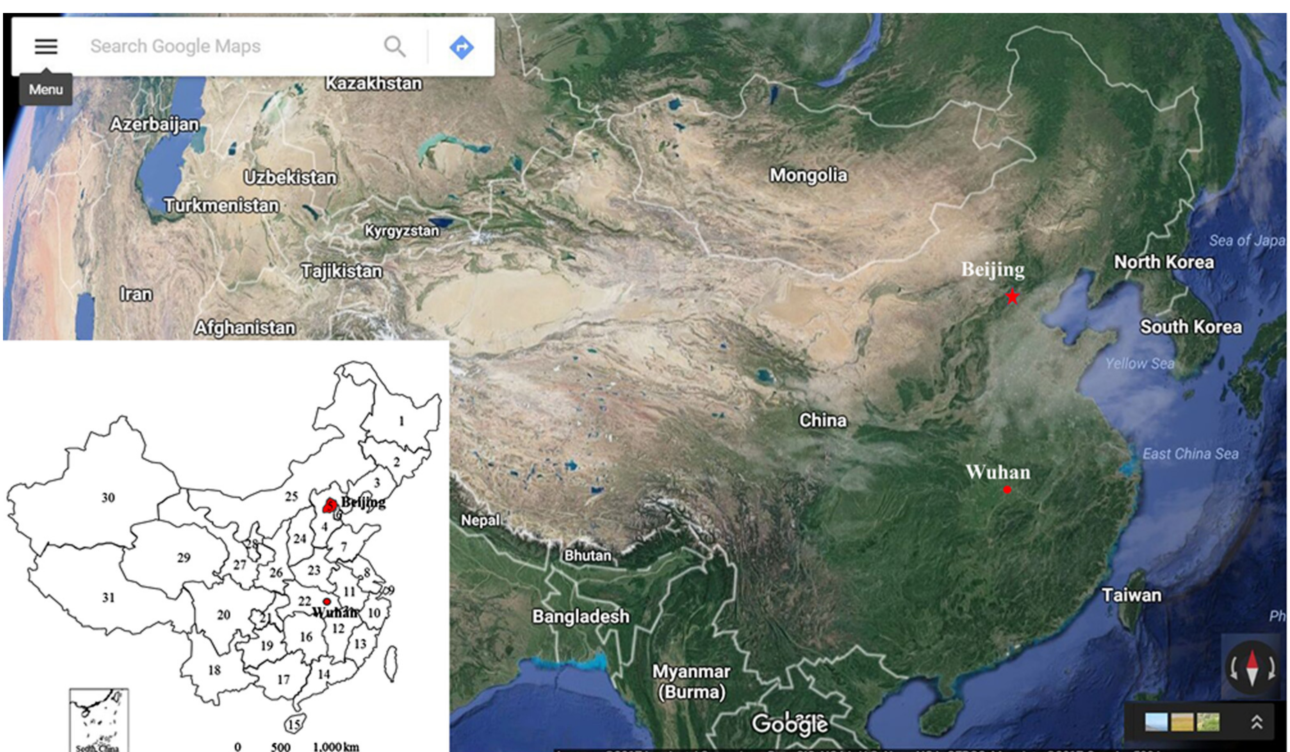

Fig. 1. The study areas and the geographic location of Beijing city and Wuhan city. 1: Heilongjiang, 2: Jilin, 3: Liaoning, 4: Hebei, 5: Beijing, 6: Tianjin, 7: Shandong, 8: Jiangsu, 9: Shanghai, 10: Zhejiang, 11: Anhui, 12: Jiangxi, 13: Fujian, 14: Guangdong, 15: Hainan, 16: Hunan, 17: Guangxi, 18: Yunnan, 19: Guizhou, 20: Sichuan, 21: Chongqing, 22: Hubei, 23: Henan, 24: Shanxi, 25: Inner Mongolia, 26: Shaanxi, 27: Gansu, 28: Ningxia, 29: Qinghai, 30: Xinjiang, 31: Tibet.