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Reservoir volume optimization and performance evaluation of rooftop catchment systems in arid regions: A case study of Birjand, Iran

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Abstract

This study evaluated the performance of rooftop catchment systems in securing non-potable water supply in Birjand, located in an arid area in southeastern Iran. The rooftop catchment systems at seven study sites of different residential buildings were simulated for dry, normal, and wet water years, using 31-year rainfall records. The trial and error approach and mass diagram method were employed to optimize the volume of reservoirs in five different operation scenarios. Results showed that, during the dry water year from 2000 to 2001, for reservoirs with volumes of 200−20000 L, the proportion of days that could be secured for non-portable water supply was on average computed to be 16.4%−32.6% across all study sites. During the normal water year from 2009 to 2010 and the wet water year from 1995 to 1996, for reservoirs with volumes of 200−20000 L, the proportions were 20.8%−69.6% and 26.8%−80.3%, respectively. Therefore, a rooftop catchment system showed a high potential to meet a significant portion of non-potable water demand in the Birjand climatic region. Reservoir volume optimization using the mass diagram method produced results consistent with those obtained with the trial and error approach, except at sites #1, #2, and #5. At these sites, the trial and error approach performed better than the mass diagram method due to relatively high water consumption. It is concluded that the rooftop catchment system is applicable under the same climatic conditions as the study area, and it can be used as a drought mitigation strategy as well.

Keywords: Mass diagram analysis; Non-potable water demand; Reservoir volume optimization; Rooftop catchment; Rainwater harvesting

1. Introduction

Water scarcity affects many places around the globe. About 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, and 500 million people are approaching this situation. Another 1.6 billion people or almost one-quarter of the world's population face economic water shortage, without sufficient infrastructure to take water from rivers and aquifers (Watkins et al., 2006). Urban development not only increases the frequency and magnitude of the peak flow but also reduces the base flow. Therefore, water management in urban areas should seek to prevent negative hydrological changes (Price, 2014). Rainwater catchment systems are one of the management and operational methods of water harvesting that can affect the production of runoff and effectively improve the efficiency of rainwater use in different land uses (Oweis, 2001; Jacob, 2007; Sturm et al., 2009). Rainwater catchment systems are known as compatible systems in terms of water supply in arid and semi-arid areas and loss prevention in humid regions (Vohland and Boubacar, 2009; Tubeileh et al., 2009). Rainwater harvesting in upstream areas reduces further pollution and the cost of treatment (Teemusk and Mander, 2007). Rainwater harvesting for supplemental irrigation in dry seasons has been successfully used in many arid and semi-arid regions (Richardson et al., 2004; Qiang et al., 2006; Short and Lantzke, 2006; Arya and Yadav, 2006). The possibility of developing the use of rainwater harvesting systems in cities with water scarcity was investigated by Zhang et al. (2010). In another study by Villarreal and Dixon (2005), rainwater collection systems for

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storing water in Dansen, Sweden were analyzed. They created a computational model to determine the potential quantification of rainwater supply based on analysis of the optimal volume of a reservoir. Abu-Zreig et al. (2013) evaluated the potential of rainwater harvesting from rooftops in Jordan. In their study, it was estimated that about 14.7 million m^3 of rainwater could be extracted from rooftops, which would increase the water budget of the whole country by 6%. Abdulla and Al-Shareef (2009) and Assayed et al. (2013) described the role of rooftop catchment systems in saving water in a large part of Jordan, as well. The effectiveness of the system for securing water in arid areas with low rainfall and irregular distribution of precipitation was also clarified by Yuan et al. (2003). The application efficiency of a rooftop catchment system in desert areas of Palestine with an average rainfall of 90 mm was confirmed by Tabatabai Yazdi et al. (2006). The use of rooftop catchment systems was also recommended for securing an emergency water supply in dry regions of Australia (Stanton, 2005).

A rooftop catchment system can be divided into two main parts: (1) an insulation surface that collects rainwater and (2) cisterns for rainwater storage on rainy days. The excess rainwater can be stored for use in dry seasons. In each rooftop catchment system, the cost of a water storage tank is the highest, so the determination of the optimal volume of reservoir is vital for structural stability and maximum capture of rainfall at a minimum cost (Kahinda et al., 2007; Tam et al., 2010). The reservoir size depends on runoff production potential and the demand for rainwater (Ghisi et al., 2007). Su et al. (2009) established a relationship between the volume of a reservoir and water supply for residents of Taipei. Several other studies have been conducted on hydrological analysis of the performance of rooftop catchment systems for rainwater harvesting in residential areas. For instance, Jones and Hunt (2010) presented a computational model to evaluate the performance of rainwater harvesting from rooftops in the Southern United States. Rahman et al. (2010) showed that larger rooftops are more efficient in terms of water saving and financial benefits. Reservoir payback period analysis showed that the total cost of reservoir construction can be amortized in 15−21 years, depending on the reservoir size and weather conditions. Imteaz et al. (2011) conducted a study to design rainwater collection tanks in Melbourne, Australia and to develop a comprehensive model for their performance analysis. Palla et al. (2011) studied the optimal performance of a rainwater harvesting system. They proposed a suitable model for assessment of the impacts of inflow, outflow, and storage volume alterations on system performance. In a survey by Campisano and Modica (2012), the optimal size of a reservoir was estimated based on daily rainfall, recorded at rainfall stations near the study region. Hashim et al. (2013) proposed a new way of designing a reservoir that could be implemented on a large scale, reducing the pressure on water resources. Singh et al. (2013) explored a methodology based on one of the most popular and versatile hydrological models, the soil conservation service-curve number (SCS-CN) model, and its variants. Results showed that the model has an inherent ability to incorporate the major factors of runoff production in rooftop/urban areas, i.e., the surface characteristics, initial abstraction, and antecedent dry weather period (ADWP) of catchments. They concluded that the SCS-CN model would be a better tool for runoff quantification than other methods only using empirical runoff coefficients.

Birjand, in southeastern Iran, is currently experiencing water shortage problems due to extensive development, drought conditions, and unmanaged agricultural activities in surrounding basins, creating a need to find alternative and potential sources of potable and non-potable water. Rooftop catchment systems can be an efficient source of water, especially in arid and semi-arid areas. This study aimed at evaluating the performance of rooftop catchment systems in securing a non-potable water supply in Birjand. The optimal volume of reservoirs was investigated based on comparison of the results from the mass diagram method and trial and error approach.

2. Materials and methods

2.1. Study area

Birjand is the capital of Southern Khorasan Province, centered at a latitude of 32°52′N and a longitude of 59°12′E (Fig. 1), with an area of 42.7 km^2 and an elevation of 1491 m above sea level. The weather in the area is categorized as a desert climate based on Gossen's classification approach (Memarian et al., 2016), with the xerothermic index of 321, and it normally has cold winters and hot dry summers. The average annual precipitation is 159.7 mm, according to the daily rainfall data from 1970 to 2010, recorded at the Birjand Synoptic Station. According to the rainfall time series at the Birjand Synoptic Station, 87% of the annual precipitation occurs from November to March (Fig. 2).

2.2. Methodology

Hydrological simulation of rooftop catchment systems was conducted for seven residential buildings (Fig. 1) with different

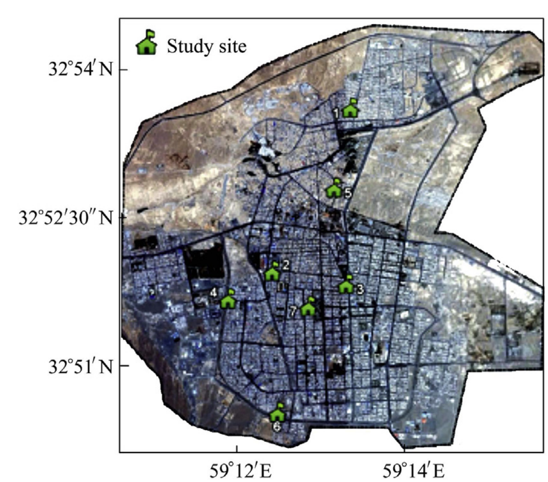

Fig. 1. Geographic locations of study sites.