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Land cover properties and rain water harvesting in urban environments

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ABSTRACT

Water harvesting is an ancient practice that has been used, mainly in dry environments, to increase efficiency of water collection and use by directing water from a large natural watershed or man-made collection surface into a small basin where the water can be stored in underground reservoirs or to be used directly for irrigation or domestic uses. In modern era water harvesting has been neglected, particularly at the developed countries, due to the technological achievements in the fields of water production and transport. Nevertheless, over recent years, water harvesting in modern-urban environments becomes a necessary practice. The urban regions are being paved and built, resulting in reduction of groundwater recharge area. Consequently, large amount of good quality water that rains over the cities is withdrawn from recharge as it is directed into the municipal drainage system. Moreover, in extreme rain events the drainage systems may be over-flooded which may lead to ecologic and economic hazards. This work reviews the history of rain water harvesting and discusses the impact of rain water harvesting in modern-urban environments on the hydrological system. Two types of rain water harvesting methods are being discussed and compared: storing of the harvested water in reservoirs and direct infiltration of the harvested water into the aquifer. Quantitative examples from Tel-Aviv, Israel are given and indicate that rain water harvesting may play an important role in the local and regional hydrological cycle and that direct infiltration of the harvested water into the aquifer is preferable for heavily populated cities.

1. Introduction

Rain Water Harvesting (RWH) is a common and old practice in which rain water is being collected and stored in order to be used for domestic and small scale agricultural uses. While RWH is being used in rural and urban places for centuries, in modern cities, its use is more limited. Nevertheless, over recent years there is a growing trend to use RWH in modern – urban environments as part of the solution to the growing challenges associated to the supply of good quality water to the world population which is being concentrated in cities (Buhaug & Urdal, 2013; Issar & Livshitz, 2013). Moreover, most urban environments have a deleterious impact on the hydrological cycle and a sustainable management of the urban hydrological system is needed (Buhaug & Urdal, 2013; Carmon, Shamir, & Meiron-Pistiner, 1997). Since urban development is not likely to be halted for water considerations, it is crucial to guide urban planners on how to manage urban development with minimal damage to groundwater resources (Carmon et al., 1997). In this paper RWH and its potential impact on the hydrological cycle is being discussed, based on a case study from Tel-Aviv, Israel.

1.1. Water stress in urban environments

At the modern era, humanity confronts a major challenge of water scarcity, mainly due to the rapidly growing world population and global climatic changes (Schewe et al., 2014). This is particularly true for urban environments which are among the most vulnerable systems as they bear great environmental pressures, associated with large ecological footprints, and are dependent to a great extent on water from distant sources, which is transported by means of large infrastructures. Approximately 53% of the world's population is concentrated in cities and more than 75% of the population in North America, Europe, and Oceania (Ghimire, Johnston, Ingwersen, & Hawkins, 2014; UN, 2015). Climate change together with the cities growing population, further increase the stress on water resources availability in urban areas (Ghimire et al., 2014).

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The major hydrological concerns in urban environments are the reduction of infiltration and groundwater recharge due to the existence of large impervious areas and changes in the pattern of surface runoff and river flow (Niemczynowicz, 1999). These changes impose high peak flows and large runoff volumes that increase the risk of flood events and accelerate the transport of pollutants and sediment from the urban areas. In order to cope with these challenges and for a sustainable urban future, there is a need to move towards the goal of efficient and appropriate water use and management, mainly in arid and semi-arid climates (Abdulla & Al-Shareef, 2009).

2. Rain water harvesting

Rain water harvesting, which is collection, storage, delivery and use of rain water for various purposes (Stec & Kordana, 2015), has great potential to be a sustainable way to cope with the hydrological challenges imposed by the urban environment (Abdulla & Al-Shareef, 2009; Angrill et al., 2012; Dillon, 2005; Makropoulos, Natsis, Liu, Mittas, & Butler, 2008; Marlow, Moglia, Cook, & Beale, 2013; Stec & Kordana, 2015; Sturm, Zimmermann, Schütz, Urban, & Hartung, 2009; Zhang, Gersberg, Wilhelm, & Voigt, 2009).

2.1. Rain water harvesting in the past

RWH was used, historically, mainly in arid environments. Le Houérou and Lundholm (1976) estimated that 3–5% of the arid zones worldwide could be cultivated by proper use of RWH, which is in an equal footing with traditional irrigation techniques, at these regions, from rivers, springs or lakes (Bruins, Evenari, & Nessler, 1986). The most ancient archaeological evidences of primitive RWH systems are estimated to be 9000 years old and are found at the Middle East in the city of Beidha in Jordan (Bruins et al., 1986). Similar evidences were found in the Negev Desert – Israel, where today annual precipitation is in the order of 100 mm. The archaeological evidences from the Negev, dated to 2000 B.C., point on the existence of agriculture practices that required the use of flood water irrigation (Evenari, Aharoni, Shanan, & Tadmor, 1958) which is the most basic application of RWH (Abdelkhaleq & Ahmed, 2007; Abdulla & Al-Shareef, 2009; Bruins et al., 1986). In flood water irrigation, surface runoff, following rain events is being routed towards topographical depressions where it is being used for irrigation as presented in Fig. 1A (Young, Gowing, Wyseure, & Hatibu, 2002). In the Negev desert, full exploiting of surface runoff from small watersheds for water storage, which included complex channel systems to deliver rain and surface runoff water towards underground cisterns (Fig. 1B) is dating as far back as 850-600 B.C. (Evenari et al., 1958). Kedar (1967) and Evenari et al. (1982) estimated that during the Nabatean-Byzantine period (100–700 AD.) rainwater harvesting supported cultivation of 4000 [ha], out of an area of 200,000 [ha], at the Negev desert and wheat, barley, grapes, olives, dates and other crops were successfully grown (Bruins et al., 1986). In Yemen complex RWH systems dated back to 750 B.C. were found and some of them are still being used today (Brunner & Haefner, 1986). Other ancient RWH systems in various degrees of complexity were found in Egypt, Algeria, Tunisia, Sahel and West Africa, India, china, Turkmenistan region, North and South America and more (Bruins et al., 1986; Evenari et al., 1958). Nevertheless, even though RWH does not require high technological skills and as shown by Le Houérou and Lundholm (1976) its contribution for agriculture and domestic water use is significant, still – in many regions worldwide it has never been tried, both in the past and in modern days, apparently due to ignorance (Bruins et al., 1986).

2.2. Modern times rain water harvesting

In modern times RWH consists of rainwater collection from large surfaces, mainly rooftops (Liaw & Tsai, 2004), and storage of the water in under or above ground reservoirs (Fig. 1B). Based on water quality, which is mainly affected by the quality and state of the water collection surfaces and the delivery systems, the water can be used for drinking, domestic uses and irrigation (e.g., Abdulla & Al-Shareef, 2009; Jones & Hunt, 2010; Sturm et al., 2009; Zhang et al., 2009). RWH is a renewable source of clean water that is ideal for domestic and small scale agricultural uses and the greater attraction of a rainwater harvesting system is in its low cost, accessibility and simple maintenance at the household level (Abdulla & Al-Shareef, 2009). RWH can promote significant water saving in residences in different countries. For example: In Germany, Herrmann and Schmida (2000) showed that a potential saving of potable water in a house might vary from 30% to 60%, depending on the demand and size of the rainwater collection area. In Newcastle – Australia, Coombes, Argue, & Kuczera (2000) concluded that RWH would save 60% of potable water and in Brazil, Ghisi (2006), showed a potential water saving by using water harvesting in the range of 34% to 92%, with an average of 69%. Abdulla and Al-Shareef (2009) indicated on potential water saving of up to 20% of drinking water by applying RWH in urban environment in Jordan.

While traditional RWH systems consist of storing of the harvested rain water in storage containers at site and self-use of the water by the property owners, recently, few works have discussed the option of allowing the harvested rain water to recharge the local aquifers through infiltration wells, usually after overfilling the storages tanks (e.g., Dillon, 2005; Mun & Han, 2012). Stec and Kordana (2015) described state of the art RWH system at a four-story building with 24 apartments, where rain water is being collected from the rooftop and stored in storage tanks. The water is being used for various non-potable uses and any excess water which exceeds the storing capacity of the tanks is routed to infiltration wells located at the site. In additions, harvested water can be directly routed to gardens where they are being consumed by vegetation and infiltrate to groundwater (Gao et al., 2016).

Construction of infiltration wells for the harvested rain water has to account for the hydrological and climatological conditions at the site, as well as the surface area of the collection surface. For example, in Tel-Aviv, Israel, annual precipitation is in the order of 550 [mm] and extreme storm events that occur every few years may have high precipitation rates in the order of 100 [mm/day] (data from Israel meteorological service). Typical hydraulic conductivity of the vadose zone in the region is relatively low, in the order of 1–2 [m/day], which is an order of magnitude lower than hydraulic conductivity of the saturated aquifer underneath (Bear, Zhou, & Bensabat, 2001; Rimon, Dahan, Nativ, & Geyer, 2007). This disparity is due to the presence of a narrow loamy layer at the upper parts of the vadose zone (Rimon et al., 2007; Schwarz, Bear, & Dagan, 2015) and differences in wetness between the saturated and the unsaturated zones (Bear et al., 2001). For an estimated typical roof surface area of 250 [m^2] the volume of harvested water in a single extreme storm is in the order of 25 [m^3]. Consequently, in order to ensure efficient infiltration of harvested rain water into the aquifer with no over flood of the infiltration well system, it is required to construct the infiltration well sufficiently deep with a filter length long enough to enable sufficiently high water flow from the well into the ground, while considering the hydraulic properties of the medium at the specific site of infiltration. Hereon the discussion will focus on RWH systems that consist of infiltration of the harvested water to groundwater and it will be termed as “rain water harvesting and recharge system” (RWHR).