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Original Research Article

Impacts of domestic and agricultural rainwater harvesting systems on watershed hydrology: A case study in the Albemarle-Pamlico river basins (USA)

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ABSTRACT

Rainwater harvesting (RWH) is increasingly relevant in the context of growing population and its demands on water quantity. Here, we present a method to better understand the hydrologic impacts of urban domestic and agricultural rainwater harvesting and apply the approach to three diverse watersheds within the Albemarle-Pamlico river basins in the southeastern USA. We summarize the design strategy of RWH and use of the Soil and Water Assessment Tool (SWAT) model to simulate baseline and RWH scenarios for urban and agricultural land uses. A high adoption rate (75–100%) of RWH throughout the watersheds reduced the downstream average monthly water yield up to 16%. A lower adoption rate (25%) reduced water yield approximately 6% for the Back Creek watershed (NC). We also present a ten-year average monthly low flow-based rainwater-harvest yield index (rainwater-harvest/water yield) as a RWH metric when comparing downstream impact on flows. The current study is intended to inform water resource sustainability and management decisions at the watershed scale.

1. Introduction

A rising world population, along with rapid urbanization and land development, exacerbate the global challenge of providing sufficient quantities of clean water. Watershed management activities are often unsustainable relative to water withdrawals, resulting in decreased downstream flows, especially in drought periods. For example, water rights disputes in the states of Florida, Georgia, and Alabama on Lake Sidney Lanier reservoir in the Apalachicola-Chattahoochee-Flint (ACF) River Basin may be partly attributed to growing water withdrawal due to population increase in north Georgia, USA, especially Atlanta (Lund, 2011). Lake Lanier is one of the lakes constructed and operated by the U.S. Army Corps of Engineers for flood protection, power production, water supply, navigation, and recreation (USACE, 2013). It is important to connect water resource management to the ecosystem services, allowing for more holistic decision-making. Ecosystem services are the benefits humans receive from the watershed, such as water supply, agricultural production, and recreation (MEA, 2005).

Traditionally, off-line and on-line impoundments and groundwater sources have been used to meet domestic water (potable and non-potable) and non-domestic water (agricultural irrigation, industrial processing such as power plant cooling, and hydro-power, for example) demands. Irrigational water use (that is, applied to farms, pastures, horticulture, orchards, etc.) in the U.S. was 31% of total water withdrawal (i.e., 485 Mm^3/day (128,000 Mgal/day) in 2005 (Kenny et al., 2009). Yet, irrigation needs may vary with year type (wet versus dry) as water withdrawals do.

An off-line impoundment is built on land to intercept water from runoff, groundwater, or land drainage, while an

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on-line reservoir is built on natural flows such as estuaries, wetlands, and rivers (SEPA, 2012). On-line impoundments may cause negative consequences such as degraded water quality, increased invasive species (Johnson et al., 2008), and contaminated sediments downstream (Winger and Lasier, 2004) which impact watershed ecosystem services. Similarly, excessive groundwater exploitation may cause seawater intrusion, reduction in surface water levels (e.g., reduced stream flows and reservoir levels), vegetation elimination (plants that rely on groundwater), and land subsidence (Zektser et al., 2005). Rainwater harvesting (RWH) has emerged as a strategy for meeting resource needs. Significant work highlighting the importance of RWH on water supplies has been done in the past (e.g., Helmreich and Horn, 2009; UKEA, 2008; Ward et al., 2010; Jones and Hunt, 2010); however, studies on the impact of RWH on watershed hydrology are few.

1.1. Rainwater harvesting: current understanding and research gap

Rainwater harvesting is a technique to capture rainwater for future use. The major techniques include in situ, on-site water storage (e.g., micro-catchment); external, distant collection and transportation (e.g., macro-catchment); and domestic (rooftop collection) (Ghimire et al., 2012; Helmreich and Horn, 2009). Micro-catchment harvesting is collection of water in the rootzone of an infiltration basin (e.g., a row of crops) within a small flow distance (<100 m) of a contributing catchment area (Boers and Ben-Asher, 1982). Macro-catchment harvesting is collection of rainwater from a remote catchment area that is then stored in a reservoir via channels and dams (Boers and Ben-Asher, 1982).

Rainwater harvesting may reduce stormwater runoff and prevent watershed pollution, which facilitates water conservation and energy savings (USEPA, 2012). It may also augment water supply systems, especially during extreme drought events as well as during high demand from rising population (GADCA, 2009). For purposes of the current study, we define RWH as a technique of capturing rainwater for (i) domestic non-potable household use (toilet flushing, clothes washing, etc.) and (ii) agricultural irrigation (crop, pasture and hay watering, etc.).

RWH is gaining global momentum. Countries in North America, Europe, and Australia have utilized it primarily for non-potable uses; countries in Asia and South Africa employ it for potable uses (Ghimire et al., 2012; Welderufael et al., 2011). Research agencies and institutes have studied RWH system design (e.g., UKEA, 2008; Ward et al., 2010); evaluation (e.g., Kahinda et al., 2009); agricultural irrigation guidelines (UNFAO, 1986); and policies (USEPA, 2012). In 2007, the U.S. Environmental Protection Agency (EPA) and four national groups presented guidelines to promote green infrastructure as a wet weather management strategy (USEPA, 2008, 2012). Others highlighted the life-cycle assessment of RWH (Ghimire et al., 2012; Roebuck and Ashley, 2007) and the impact of land use on watershed hydrology and erosion (Quilbe et al., 2007; Fohrer et al., 2001). Recently, Glendenning et al. (2012) presented the impact of RWH on groundwater recharge in India which pointed out a research gap related to hydrologic impacts.

Despite so much interest, the impact of RWH on watershed-scale hydrology still is not well-understood (Welderufael et al., 2011; Kahinda et al., 2009). A few hydrologic impact studies conducted in Africa primarily focused on in-field agricultural RWH (Welderufael et al., 2011; Mutiga et al., 2011; Ouessar et al., 2009; Kahinda et al., 2009; Ngigi, 2003). Welderufael et al. (2011) studied hydrologic impact of in-field RWH for crop production in a watershed in South Africa and reported that it reduced direct flow (surface flow plus lateral flow) by 38% and contributed to 105% higher base flow, compared to conventional farming methods. Mutiga et al. (2011) studied the effect of land-use changes on Kenyan watershed hydrology and reported decreased baseflow from overgrazing and deforestation for agriculture with no significant downstream impact; this directly contradicts Welderufael et al. (2011). Complexity of the watershed and connection of physical processes within the watershed (e.g., agricultural or other land-use development activities) also make hydrologic forecasting difficult (Quilbe et al., 2007).

Along with sustainable management of water resources, we are particularly interested in ecological impacts such as downstream water availability, including minimum flow for aquatic habitat and other designated requirements (i.e., aquatic life use). Issues such as downstream impacts on water quality, ecological compatibility of RWH, sediment transport, crop yield, and groundwater recharge exist; however, they are beyond the scope of our study. Because RWH has the potential to meet growing water demands, it is important to evaluate its impact on watershed hydrology. To our knowledge, no other study has incorporated both domestic and agricultural RWH to assess a U.S.-based watershed.

1.2. Objectives and scope

The main objective of this study is to understand the hydrologic impact of domestic and agricultural RWH on three watersheds within the Albemarle-Pamlico (A-P) river basins located in the states of Virginia (VA) and North Carolina (NC), USA. Specific objectives are to apply the Soil and Water Assessment Tool (SWAT) model for four scenarios: baseline (No-RWH), urban domestic RWH (DRWH), agricultural RWH (ARWH), and DRWH-plus-ARWH; and assess impacts of the scenarios on downstream flows in three watersheds within the Albemarle-Pamlico river basins. We use the terms "river basins" to refer to the Albemarle-Pamlico river basins, "watershed" to refer to the three selected watersheds (Back Creek, Sycamore, and Green Mills) within the river basins, and "sub-watershed" to refer to the seven subdivisions within each watershed.

2. Methods and tools

The methods are:

Step 1: Selection of watersheds
Step 2: Design of DRWH and ARWH systems