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A water harvesting model for optimizing rainwater harvesting in the wadi Oum Zessar watershed, Tunisia

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ABSTRACT

Rainwater harvesting (RWH) techniques have been adapted in arid and semi-arid regions to minimise the risk from droughts. The demand for water has increased but water resources have become scarcer, so the assessment and modelling of surface water related to RWH in catchments has become a necessity. An understanding of the hydrological processes at the sub-catchment level is generally lacking, and little attention has been given to the assessment of RWH after implementation. The objective of this study was to develop a simple but generally applicable water-harvesting model and test it at sub-catchment level to evaluate and optimize the performance of RWH under different design and management scenarios. The model was applied to rainfall data for 1980–2004 in 25 sub-catchments of the watershed of Wadi Oum Zessar (south-eastern Tunisia). The performance and analysis of RWH in three types of years (dry, normal, and wet) are presented and discussed. This study emphasises the advantages of simulating long-term water balances at the sub-catchment level for improving our understanding of hydrological processes in the RWH system and provides several solutions for optimizing RWH performance in various scenarios. Changing the spillway heights together with the flow directions had a significant impact on the performance of RWH by making 92% of all sub-catchments supply sufficient water for crop requirements, compared to 44% of the sub-catchments in case of no changes.

1. Introduction

The pressure on water resources is increasing due to climate change and growing demands for water for agricultural and urban development. Aridity and climatic uncertainty are the major challenges faced by farmers in arid and semi-arid regions. These regions have low average annual rainfalls and a highly variable temporal and spatial rainfall distribution. Inhabitants of dry areas have constructed and developed several techniques of rainwater harvesting (RWH) for increasing the availability of water for crop and cattle production.

RWH is a method for inducing, collecting, storing, and conserving local surface runoff for agriculture in arid and semi-arid regions (Gupta et al., 1997). Understanding the performance of RWH, the water yield of a catchment, and the flood flows for planning the structures for harvesting rainwater are amongst the most important objectives of hydrological engineers. RWH structures are designed to catch as much of the expected runoff as possible in a specific recurrence interval while satisfying the water requirements of crops/trees (Adham et al., 2016). RWH must balance water requirements and storage capacity (structure design). Understanding the relationship between rainfall and runoff in catchments is thus necessary. Studying the water balance can provide insights into the hydrological behaviour of catchments and RWH structures and can help to identify the dominant hydrological processes (Uhlenbrook et al., 2008). The water-balance equation presents the values of inflow, outflow, and the change in water storage for an area or water body (Tadesse et al., 2010). Thornthwaite (1948) published the first monthly water balance, and the method has since been adapted, modified, and used in numerous studies (e.g. Gabos and Gasparri 1983; Xu and Vandewiele 1992; Arnell, 1992). Durbude and Venkatesh (2004) applied the Thornthwaite and Mather (TM) models with remote sensing and a Geographic

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Information System (GIS) to identify potential zones of runoff and suitable sites for RWH in Africa, such as contours, farm ponds, gully plugs, and percolation tanks. Jasrotia et al. (2009) applied the TM models with remote sensing and a GIS to understand the water balance of RWH structures in the Devak-Rui watershed in India.

Budyko (1974) developed an empirical relationship between the ratio of mean annual evaporation, rainfall and dryness index of the catchment to analyse the catchment water balance (Gebrekristos, 2015). Budyko's framework has been widely applied in the catchments around the world (Donohue et al., 2006; Gebrekristos, 2015; Potter and Zhang, 2009; Yang et al., 2009). Yang et al. (2007) analysed the spatiotemporal variability of annual evaporation and runoff for 108 catchments in China and explored both regional and inter-annual variability in annual water balance. Tekleab et al. (2011) applied water balance to analyse twenty catchments in the Upper Blue Nile using top-down modelling based on Budyko's hypotheses for temporal and spatial scales.

Rainfall is the most important term in the water balance equation, so the interpretation of past records of rainfall and hydrological events in terms of future probabilities of occurrence is one of the challenges for engineers designers and hydrologists. Analysis of maximum rainfall over a catchment area at different frequencies or return periods is a basic tool for safe and economic planning, management of water resources applications and designing of hydraulic structures (Bhakar et al., 2008; Chow et al., 1988; Durbude, 2008). Probability and frequency analysis of rainfall data can be applied to obtain predicted amounts of precipitation for various probabilities (Bhakar et al., 2008). Similar analysis techniques can be applied to predict maximum daily rainfall of future events from the available data (Kumar and Kumar, 1989). Frequency analysis of rainfall is a tool for solving various water management problems (Kumar et al., 2007). Therefore, the probability and frequency of the occurrence of future events of rainfall can be used to minimise flood risks and periods of drought, and for planning and designing of water resources related to engineering such as small dams, reservoirs, culverts, drainage works, and rainwater harvesting structures (Dabral et al., 2009).

An understanding of the hydrological processes at the sub-catchment level is generally lacking in practice. Relatively, little attention has been paid to the evaluation of RWH systems after implementation. Few studies have investigated the effectiveness of catching and storing water and the utility of RWH within the existing land use and farm management. The objective of the study was to develop a simple but generally applicable water-harvesting model and apply it at sub-catchment level to evaluate and optimize the performance of RWH under different design and management scenarios. The target was to improve water availability for different RWH systems based on crop water requirements, the rainfall-runoff relationship, and the design of RWH structures.

2. Materials and method

2.1. Study area

A 50 ha catchment in an upstream area of the Wadi Oum Zessar watershed in south-eastern Tunisia was selected for the case study. The watershed has a surface area of 367 km^2, and the catchment consists of 25 sub-catchments (Fig. 1). The area has an arid Mediterranean climate, with an average annual rainfall of 150–230 mm, an average annual temperature of 19–22 °C, and an average annual potential evapotranspiration of 1450 mm (Adham et al., 2016; Ouessar, 2007).

Farmers in the study area have built two types of RWH structures for satisfying the water requirements for rainfed annual crops (cereals and legumes) and trees (mainly olive): jessour (in medium to high slopes areas) and tabias (in gently-sloping foothill areas). Each jessr (singular of jessour) or tabia consists of three parts: an impluvium or catchment area providing the runoff, a terrace or cultivated area where the runoff is collected and crops or trees are grown, and a dyke to catch the water and sediment. Each dyke has a spillway (*menfes* if the spillway is on one or both sides, and *masref* if the spillway is in the middle of the dyke) to regulate water flow between dykes (Fig. 2).

2.2. Data collection

Time-series of daily rainfall records for a period of 25 years (1980–2004) were collected from the Institute des Régions Arides (*IRA*) in Tunisia. They concern seven rain gauge stations:Ben Khedache, Toujan Edkhila, Allamat, Koutine, Sidi Makhlouf, Ksar Hallouf, and Ksar Jedid. Annual maximum daily rainfall was extracted from these data and using statistical techniques for data analysis. Other data were collected from field measurements in the watershed as explained in the next sections.

2.2.1. Catchment characteristics

Physical characteristics (e.g. catchment area, retention area, cropping area, and RWH structural dimensions) were measured for each sub-catchment. All areas, dimensions of the RWH structures, and heights of the existing dykes and spillways for each site were measured by measuring tape and the Global Positioning System (GPS). The total volume of water that could potentially be collected behind each dyke was calculated from these measurements.

To obtain soil textural data from the catchment, each sub-catchment was sampled in different sites (1–3 samples for each site, based on the size of sub-catchment) and depths up to 1.3 m. The samples were taken to the IRA laboratory and analysed. The slope of each sub-catchment was obtained from the DEM (30 m resolution) using ArcGIS 10.0.

A limitation of this study is that, just like in most arid and semi-arid regions, there are no measured runoff data available. Therefore we drew our conclusions about the model performance from field observations and interviews with farmers. Based on these sources, we noticed that some sub-catchments (e.g. 10 and 15) were abandoned and some trees were dead, while other sub-catchment's trees are growing well (e.g. 20 and 22). The main reasons for that are lack of water and unequal distribution of rainwater between these sites.

Field measurements and observation status of 25 sub-catchments are presented in Table 1. In this table a value of one (poor), two (medium) or three (well), was assigned to each sub-catchment, based upon field observations and farmers interviews. The function status represents the efficient work of each structure (collected and storage rainwater), production yield, trees growing and the relation between up and downstream. Whereas, maintenance is related to the structure such as restoring the spillway height after each storm, keeping the dam in shape and removing the obstacles that block the main waterway.

2.2.2. Measurements of infiltration rate

The infiltration rate was determined using a double-ring infiltrometer (Al-Qinna and Abu-Awwad, 1998). Based on previous field measurements conducted by Bosch et al. (2014) in the same region, we used infiltrometers of two sizes: small (18/30 cm inner-/outer-ring diameter) and large (32/51 cm). Generally, two measurements took place for each site to ensure reliable results. The small infiltrometers were used at least once in each sub-catchment, but the large infiltrometers were used in only 11 sub-catchments because the measurements required much more water. The infiltration rates were measured on the retention (terrace) basin in each sub-catchment. The rings were driven 5–10 cm into the ground carefully