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Hydrological impacts of rainwater harvesting (RWH) in a case study catchment: The Arvari River, Rajasthan, India Part 2. Catchment-scale impacts

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ABSTRACT

A key question in relation to rainwater harvesting (RWH) is whether the technique increases the sustainability of irrigated agriculture. A conceptual water balance model, based on field data from the Arvari River catchment, was developed to study and understand catchment-scale trade-offs of rainwater harvesting (RWH). The model incorporates an effective representation of RWH function and impact, and works on a daily time step. Catchment spatial variability is captured through sub-basins. Within each sub-basin hydrological response units (HRUs) describe the different land use/soil combinations associated with the case study catchment, including irrigated agriculture. Sustainability indices, based on irrigated agriculture water demand, were used to compare conceptual management scenarios. The results show that as RWH area increases, it reaches a limiting capacity from where additional RWH structures do not increase the benefit to groundwater stores, but reduces stream flow. If the irrigation area is increased at the optimal level of RWH, where the sustainability indices were greatest, the resilience of the system actually decreased. Nevertheless RWH in a system increased the overall sustainability of the water resource for irrigated agriculture, compared to a system without RWH. Also RWH provided a slight buffer in the groundwater store when drought occurred. The conceptual analysis highlights the important link between irrigation area and RWH area, and the impact of RWH on the catchment water balance.

1. Introduction

Rainwater harvesting (RWH) is a small-scale catchment development tool with a long tradition in many countries, including India (Agarwal and Narain, 1997). In many parts of India RWH captures and stores the intensive monsoonal runoff to recharge groundwater. Where RWH is present, it increases the capacity of small-holder farmers to irrigate with groundwater, so there is a greater need to understand how this catchment development tool impacts larger scale catchment water balances. The resulting shifts in the water balance could impact the resilience of agricultural livelihoods, which means communities could be more vulnerable to shocks such as drought (Mudrakartha, 2007). An individual RWH structure may not have a large effect on stream flow or aquifer storage, but the cumulative effect of many RWH structures within a large catchment would be more significant. For example the construction of farm dams in some catchments of the Murray Darling Basin in Australia caused statistically significant reductions in the quantity of potential stream flow response (Schreider et al., 2002).

Extensive detailed field studies could provide some answers, but local-scale measurement of recharge is difficult as most field methods are expensive, time consuming, or do not deliver the desired accuracy (Healy and Cook, 2002). In addition high temporal and spatial variability of rainfall, soil and aquifer hydraulic properties means that long time series of data are needed (Silberstein, 2006). However, data is very limited in semi-arid/arid regions where populations are sparse and economic resources are limited (particularly in developing countries) (Sen, 2008). Given the general lack of hydrological field data in semi-arid catchments, a model is a useful and inexpensive way of extrapolating limited field data and investigating management scenarios in a larger scale catchment. Simulation modelling of catchment hydrology might offer a way of assessing the impact of RWH at a larger catchment scale, but model input and accuracy will determine the usefulness of the final results (Silberstein, 2006). Specifically, this study uses a conceptual model to better understand the processes and dynamics of RWH to guide further detailed investigations.

The semi-arid areas where RWH is found means that the large data requirements of existing models, for example the Soil Water Assessment Tool (SWAT) (Arnold and Fohrer, 2005), cannot be met. A key limitation is the lack of stream flow gauging data, which means calibration and validation of a hydrological model

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is almost impossible. Predictions in semi-arid areas are also difficult because climatic conditions tend to be temporally and spatially variable (Wheater and Al-Weshah, 2002). Additionally, the surface water–groundwater interactions, which are necessary to represent RWH hydrological processes, do not exist in many models. For example the Tool for Estimating Dam Impact (TEDI) model, used to estimate small farm dam impacts in Australia, has no groundwater component.

The aim of this paper is to describe the development and application of a conceptual model to study trade-offs related to RWH impacts in a catchment from a sustainability perspective. The model will be a generalised conceptual system based on the field scale impacts of RWH in the semi-arid Arvari River catchment, described in the companion paper (Glendenning and Vervoort, 2010). The model is applied to study the sustainability of irrigated agriculture with and without RWH in a typical catchment.

1.1. Water resources sustainability indices

Due to collection and storage of runoff, RWH may change the catchment water balance, but also may increase the sustainability of irrigated agriculture as a result of more reliable groundwater stores. To quantify that impact, sustainability indices are a useful way to measure changes in a water resource system. Quantification of the sustainability of water resource systems can be achieved by using measures of reliability, resilience and vulnerability. The indices are based on whether a specified demand threshold is met by a defined water resource system (Ajami et al., 2008; Hashimoto et al., 1982; Loucks, 1997; McMahon et al., 2006; Zongxue et al., 1998).

Hashimoto et al. (1982) describe three criteria for evaluating the performance of water resource systems:

1. Reliability (*RE*) is the frequency or probability that a system is in a satisfactory state (Fowler et al., 2003):

$$RE = prob[X_t \in S] \quad \text{where } RE = \sum_{t=1}^{T} Z_t \tag{1}$$

X_t is the output state or status of the system at time t, Z_t is a binary measure where X_t is either an element of S values (output or performance of the water resource system in a satisfactory state) or F values (output or performance of the water resource system in a failure state). The *RE* index ranges from 0 to 1, where 1 reflects 100% reliability.

2. Resiliency (*RS*) is the probability that when a system is in a failure state, the next time step is a satisfactory state (Ajami et al., 2008; Fowler et al., 2003):

$$RS = prob\{X_{t+1} \in F\} \quad \text{where } RS = \sum_{t=1}^{T} \frac{W_t}{T - \sum_{t=1}^{T} Z_t} \tag{2}$$

$W_t = 1$ if X_t is element of F and then X_{t+1} is an element of S otherwise $W_t = 0$. The resilience index ranges from 0 to 1, where 1 is a system with 100% resilience.

3. Vulnerability (*V*) is the maximum of the sum of the difference between the threshold (criteria *C*) and the actual level (X_t) for any failure periods (J_i) (Ajami et al., 2008; Fowler et al., 2003).

$$V = \max\left\{\sum t \in Ji\, C - X_t, \quad i = 1, \ldots, N\right\} \tag{3}$$

It thus reflects the severity of the failure. The vulnerability index can have a wide range depending on the difference between X_t and C, but higher values indicate higher vulnerability, lower values represent a less vulnerable system.

In order to quantify these indices, the operational status of the water resource system needs to be described as either satisfactory (S) or unsatisfactory (F), using defined thresholds. The thresholds for the calculation of the sustainability indices in this study relate to water demand for irrigated agriculture. There is sufficient evidence to show that there is a direct link between irrigation and poverty alleviation. Groundwater development increases irrigation area, which leads to agricultural growth (Mukherji and Shah, 2005) and is seen as a more effective way to target poverty than surface water, due to its reliability and spatial availability (Wegerich, 2006). Additionally, as RWH increases groundwater recharge, where RWH is introduced, irrigated agriculture increases (Srivastava et al., 2008). Consequently, the sustainability indices provide a useful method to compare differences in catchment water balances, specifically the groundwater resource, under different land use scenarios, including the area of RWH.

2. Study area description

The catchment chosen to base the modelling work is the semi-arid ephemeral Arvari River (476 km^2), located in the eastern part of the Indian state of Rajasthan. Since 1985, over 366 rainwater harvesting structures have been built throughout the catchment by the community and a local non-government organisation (NGO), Tarun Bharat Sangh. The different RWH structure types include:

- *ANICUT*: small concrete dam or weir that dams the main reach of the river.
- *BANDH*: small concrete dam that dams the tributary to the main river reach.
- *JOHAD*: small earthen crescent moon shaped dam found at the foothills of small hilly catchments.
- *TALAB*: village ponds for bathing and livestock drinking, similar to *Johads*.

Data is sparse; the catchment is ungauged with no climate station, and existing information on aquifer properties, geology and soils is at a very large scale, which does not capture the spatial and temporal variability at finer scales within the catchment. Eighty percent of the rain falls during the south-west monsoon (June-September). The closest rainfall station to the Arvari River catchment is in Thanagazi (15 km to the North of the catchment), which has an average yearly rainfall of 705.8 mm and 8 rainfall days greater than 35 mm with an average of 31 rainy days a year (1901–2002). There is limited small-scale information about geological and soil characteristics in this catchment, though field soil samples revealed land use reflects soil type. Field-scale impact studies of RWH were carried out in 2007–2008 with estimates of RWH recharge and rainfall characteristics (Glendenning and Vervoort, 2010).

3. Methods

3.1. The model

An existing highly parameterised model would not have been suitable to model the hydrological processes in the Arvari River catchment because of the large gaps of knowledge and data, including lack of data on aquifer properties and basic hydrological data, including long term weather observations in the catchment and a gauging station on the river. In contrast, simpler existing models do not incorporate the hydrological processes related to RWH. As a result a conceptual water balance model was purpose built to capture the relevant hydrological processes in the catchment that are influenced by RWH. This includes surface water–groundwater interactions and recharge volumes from RWH.