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Review

Balancing watershed and local scale impacts of rain water harvesting in India—A review

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ABSTRACT

Agricultural production in India has become increasingly reliant on groundwater and this has resulted in depletion of groundwater resources. Rainwater harvesting (RWH) for groundwater recharge is seen as one of the solutions to solve the groundwater problem. This is reflected in an increase in watershed development programs, in which RWH is an important structural component. Understanding the net effect of these development programs is crucial to ensure that net effect on groundwater is positive both locally and within a watershed. Hence, this review focuses on the hydrological impacts of RWH for recharge at the local (individual structure) and watershed scale in rural areas. Surprisingly little field evidence of the stated positive impacts at the local scale is available, and there are several potential negative impacts at the watershed scale. The watershed scale is underrepresented in the field studies and is mainly approached through modelling. Modelling is seen as a possible tool to extend limited field data and scenario studies can be used to examine potential impacts. However, many past modelling studies examining RWH have either had limited focus or have been based on insufficient data. Development of new modelling tools is needed in combination with increased field data collection. Increased use of remote sensing and advanced statistical techniques are suggested as possible new opportunities. In addition, some evaluation criteria are proposed to assess the local and watershed scale hydrological, and other, impacts of RWH as part of watershed development.

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1. Introduction

In India, groundwater accounts for more than 45% of the total irrigation supply (Kumar et al., 2005), and for about 9% of India's Gross Domestic Product (GDP) (Mudrakartha, 2007). This has not always been the case; over the last 50 years India has seen a huge boom in the use of groundwater, resulting in an exponential increase in the number of tube wells to an estimated total of 19 million in 2000 (Shah et al., 2003). As a result agricultural livelihoods of small-holder farmers in India have improved dramatically because groundwater requires little transport, can be accessed relatively easily and cheaply, is produced where it is needed and provides a relatively reliable source of water (Dhawan, 1995). However, it has also contributed to serious groundwater depletion, with the water table declining at the rate of 1–2 m/year in many parts of India (Rodell et al., 2009; Singh and Singh, 2002).

The main replenishment of groundwater is through recharge from rainfall, covering both diffuse sources (as leakage below the root zone of vegetation) and focussed sources (through transmission losses from rivers and from lakes and ponds) (de Vries and Simmers, 2002; Lange, 2005; Shentsis et al., 1999). Recharge can be highly variable and total volumes are difficult to predict (Bouwer, 2002). In India, this is exacerbated by the fact that rainfall patterns are monsoonal with approximately 75–90% of rainfall concentrated in the summer months, June to September (Mooley and Parthasarathy, 1984).

As a result of this rainfall pattern, India has a long history of rainwater harvesting (RWH) (Sakthivadivel, 2007; Shah, 2001). In many rural areas of India, a specific purpose of RWH is to catch and store monsoonal runoff, which then percolates to groundwater tables (Keller et al., 2000). Given the current threat of groundwater depletion and the potential of increasing recharge, the implementation and planning of RWH continues to grow in India (Agarwal and Narain, 1997; Shah et al., 2009). However, the economical value and long term sustainability of structures in terms of maintenance has been questioned (Bouma et al., 2007, 2011; Raju et al., 2009).

In practice, the impact of RWH on the hydrological balance of a watershed is that water is stored and delayed with a transfer of surface runoff into groundwater, evaporation and transpiration. This can also be understood as the transfer of 'blue' water (rivers and aquifers) to 'green' water (soil water and plant water use). As more water is 'captured' through irrigated land use, blue water is converted into green water (Falkenmark, 2003). The potential increase in available groundwater may encourage increased groundwater abstraction for crop irrigation or other uses resulting in socio-economic impacts, while the impact on the water balance may be zero or negative. Hence, in general, RWH will change the water balance within a watershed. From a watershed perspective, this means it is important to quantify the hydrological impact of RWH structures and the related downstream trade-offs for a given level of watershed development. To achieve this, the changes in the spatial and temporal distribution of water and the changes in the volume of blue and green water would need to be quantified.

Such quantification can be complex, because the local hydrological impact of RWH will depend on factors such as geological and geomorphological settings, RWH local watershed size, design of the structures and the nature of the underlying groundwater system (Mishra et al., 2010). As a result, some quantitative studies on RWH have focussed on identifying optimal sites for RWH in order to plan watershed development programs (De Winnaar et al., 2007; Jasrotia et al., 2009; Kahinda et al., 2008; Mbilinyi et al., 2007, 2005). Overall, this research is fairly applied and mostly based on remotely sensed data. More importantly, for the overall watershed scale, many other factors need to be considered, beyond the questions of where to install RWH and how many structures can be built in a single watershed. For example, this might need to include the spatial distribution of RWH structures relative to the spatial variability of rainfall, in combination with the distribution and management of groundwater demand. Finally an assessment of the overall groundwater sustainability would be needed.

Definitions for groundwater sustainability are argued in many papers (Kalf and Woolley, 2005; Loucks, 2000; Sophocleous, 2000), and it is often defined as safe yield, or the maintenance of a long-term balance between the annual groundwater withdrawal relative to the recharge (Sanford, 2002; Sophocleous, 1997). More recently, several authors have argued that this is too simplistic (Alley and Leake, 2004; Sophocleous, 1997, 2000) as it does not take into account capture, which is the reduction in groundwater discharge or increase in recharge (Kalf and Woolley, 2005; Maddock and Vionnet, 1998). Hence, understanding the impacts of demand and supply-side groundwater management, including extraction for irrigation and recharge from RWH, are important to understand and enhance groundwater sustainability.

It has been suggested that despite the widespread use of RWH techniques for groundwater recharge in India, there is limited research examining the combined local and watershed scale hydrological impacts of RWH, and this limits socio-economical analysis beyond the traditional cost–benefit analysis at the local scale (Machiwal et al., 2004; Srivastava et al., 2009). For example, Bouma et al. (2011) used annual totals for hydrological variables in their economic analysis of the watershed scale effect of rain water harvesting, which ignores dynamic seasonal effects. Also, there is a need to consider meso-catchment scale impacts of RWH, particularly in rainfed agriculture, where RWH plays an integral role (Rockström et al., 2010). In addition, we could not find any comprehensive review of RWH with particular focus on groundwater augmentation in rural India.

This review therefore examines the existing literature on RWH hydrological impacts on groundwater systems and watershed scale water balances to understand the knowledge gaps. These knowledge gaps are important to identify because the goal of RWH is to have long-term positive impacts on people's livelihoods, which needs to be achieved without major environmental impacts. This review will specifically focus on RWH for groundwater recharge in rural areas, which is where most of the watershed development in India takes place. The paper first reviews the groundwater problem in India and the definitions of RWH. It subsequently reviews local scale methods and studies that measure the hydrological impacts of RWH before evaluating how this affects the overall watershed scale. Finally, this review further aims to develop a set of evaluation criteria to assess the hydrological and other impacts of RWH at the local and watershed scales. This can assist with the planning of watershed development of RWH structures and the development of policy to guide further investment in RWH vis à vis groundwater sustainability in India.

2. Background

2.1. Groundwater use and problems in India

Eighty percent of global groundwater use occurs in Bangladesh, China, India, Iran, Pakistan and the US (Shah et al., 2007), with India being the largest groundwater irrigator in the world (Shah et al., 2006). Groundwater development has been extremely important for rural poverty alleviation. In India and China combined, 1–1.2 billion poor small-holder farmers are supported by groundwater (Shah et al., 2007). This is because groundwater irrigation tends to be less biased against the poor compared with large scale surface water irrigation projects (Deb Roy and Shah, 2002). Groundwater is