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Comparison of surface and groundwater balance approaches in the evaluation of managed aquifer recharge structures: Case of a percolation tank in a crystalline aquifer in India

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SUMMARY

To face the problem of groundwater depletion, the Indian Government relies on large projects of Managed Aquifer Recharge (MAR). Numerous recharge structures such as percolation tanks exist but the impact of these structures on groundwater resources remains poorly understood. Although the evaporation/infiltration ratio of percolation tanks was determined in several studies in semi-arid contexts using surface water balance methods, few studies evaluated the impact on the aquifer recharge. However, knowledge on recharge dynamics over time and space is essential for (1) the quantitative evaluation of stored water volumes, (2) the identification of beneficiaries (farmers) and (3) the estimation of percolation tanks recharge zone to the extent that is required to define proper management regulations at basin scale. These three points are of prime importance in the case of semi-arid regions where a limited number of rain events determine the water stored over the entire year. Assessment of the stored groundwater is even more difficult in crystalline aquifers due to the heterogeneous structure of flow paths.

To date no methodological guidelines exist for local assessment of percolation tanks in crystalline aquifers. In this paper, we develop a method for calculating a local groundwater budget and we compare it with a computed surface balance. The method is applied to a case study in semi-arid crystalline context. From the groundwater balance we draw conclusions on (1) the limited amount of stored water in the aquifer, (2) the delayed recharge of the aquifer highlighting temporary storage/slow groundwater movement in the unsaturated zone and (3) the limited number of beneficiaries in years of medium monsoon rainfall.

These results complement the understanding of the hydrodynamic functioning of percolation tanks, and their impact on the local groundwater balance.

1. Introduction

With the development of irrigation since the green revolution in the 1970s, India became the country with the highest annual groundwater abstraction. It is estimated that, at the country scale, 85% of rural domestic water and 50% of irrigation water comes from groundwater exploitation via 26–28 million abstraction structures (Mukherji and Shah, 2005). This extensive use of groundwater has led to the overexploitation of numerous aquifers. The groundwater survey performed by the Central Ground Water Board (CGWB) at the national scale shows that more than 15% of the assessed units suffer from over-exploitation defined as annual groundwater extraction exceeding the net annual groundwater availability with significant decline in long term ground water level (CGWB, 2009). Moreover, the water demand in India is expected to increase by 15% between 2010 and 2015 (Kumar et al., 2005).

To buffer temporal rainfall variability related to the monsoon regime and meet the water demand (compensate/limit over exploitation), India largely relies on managed aquifer recharge structures (MARs) and rainwater harvesting. Sakthivadivel (2007)

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estimates the number of MAR structures to be 0.5 million of which 0.25 million are located above crystalline aquifers. Since 1992 the Indian Government has promoted MAR through various "Master plans for artificial recharge", drawing renewed interest in such rainwater harvesting structures. The most recent plan (CGWB, 2013) recommends building 11 million artificial recharge and water harvesting structures at the national level. It is estimated that about 36 km^3 of water (1% of the rainfall) could be stored annually (CGWB, 2007). The Andhra Pradesh Government has set an objective to increase, aquifer recharge from 9% of the total rainfall under natural conditions to 15% under managed conditions by 2020 (Government of Andhra Pradesh, 2002).

Despite the common view and some studies supporting the belief that MAR is a possible solution to the actual water scarcity problems, various authors such as Dillon et al. (2009), Kumar et al. (2006), Oblinger et al. (2010) point to the lack of available data for an accurate assessment and the scarce evidence of a positive impact of such recharge structures at local scale. A modeling approach at small watershed scale showed that percolation tanks can on average contribute to significant local aquifer recharge (up to 33% of total recharge), although this managed recharge is highly variable spatially (Perrin et al., 2012). Some authors (Calder et al., 2008; Glendenning et al., 2012; Sakthivadivel, 2007) point out a possible negative impact due to downstream effects of upstream harvesting and recharge. This thought is shared by other authors who assessed large watershed programs focusing on both hydrological and socio-economic aspects (Batchelor et al., 2003; Bouma et al., 2011; Kerr et al., 2002; Kumar et al., 2008). They argue that the limited or negative impact is the result of improper management of the projects due to a lack of knowledge of the impact of the recharge structures at both local and watershed scale. In addition, the existence of these recharge structures may tend to increase local water abstraction due to a larger local water availability created by new water distribution (Adhikari et al., 2013; Batchelor et al., 2003; Machiwal et al., 2004).

A limited but growing number of studies on percolation tanks exist (e.g., Gale et al., 2006; Massuel et al., 2014; Mehta and Jain, 1997; Perrin et al., 2009). However, the efficiency of these structures is a matter of debate. For instance CGWB (2011) recorded efficiencies, defined as the ratio of storage/infiltration, of up to 98% while most other authors estimated their efficiency around 60% (Mehta and Jain, 1997: 57%; Perrin et al., 2009: 56%; Singh et al., 2004: 63%). These surface water balances estimate water infiltration to be equal to aquifer recharge. Effective recharge to the aquifer can be over-estimated, as processes in the unsaturated zone where groundwater flow might be delayed, stored or subsequently extracted by evapotranspiration are not considered (de Vries and Simmers, 2002). To date, few studies on percolation tanks have tried to address actual recharge amounts to the aquifer while taking into account groundwater level evolution (De Silva and Rushton, 2007; Gore et al., 1998; Hassan and Bhutta, 1996; Massuel et al., 2014; Oblinger et al., 2010; Sharda et al., 2006).

The quantitative evaluation of recharge is a fundamental necessity especially in crystalline aquifers. First, knowledge of the local impact of recharge structures is prerequisite to enhancing the accuracy of larger studies (e.g., Agarwal et al., 2013) which are commonly used for planning. Second, flow heterogeneity may affect the equity between farmers for resource accessibility. In semi-arid regions, surface water balances are commonly used, although quality data are often less common and less representative than in temperate regions (de Vries and Simmers, 2002; Hrachowitz et al., 2011; Scanlon et al., 2006). Uncertainties in the estimation of recharge, one of the main components of the water balance, can hamper an accurate estimation of the water budget at basin scale. Accurate recharge estimation requires proper measurements and sensitivity analysis. Beyond improving the actual groundwater recharge estimates, combining results from surface water and groundwater budgets also allows consolidating the results. As highlighted by several authors (e.g. De Silva and Rushton, 2007; Hrachowitz et al., 2011), combining various complementary approaches is the easiest way to improve understanding of hydrological system functioning in semi-arid environments suffering from data scarcity.

In this study we develop a methodological framework to assess MAR impact on ground water applicable to small recharge structures (typically percolation tanks) where the surface reservoir is underlain by an unsaturated zone. The method is based on two independently-computed water balances: a groundwater balance and a surface water balance using the same rainfall inputs.

On the one hand, surface water balance is appropriate to estimate the potential recharge. On the other hand, a groundwater balance estimate the actual recharge and a better understanding of the recharge processes since it consider flow below the root zone but also the processes occurring within the unsaturated zone. The confidence interval of the different water budgets was addressed by running various sensitivity tests. Although the parameters are difficult to assess directly, once averaged spatially, the method may be integrative enough to reduce the impact of artifacts related to local geological, soil and meteorological heterogeneities. In addition, the comparison of surface water balance and ground water balance with soil water balance as input highlights the role of the unsaturated zone on groundwater flow and storage which remain an important knowledge gap (Scanlon et al., 1997).

The objectives of the developed methodology are (1) to assess the potential recharge from the tank, (2) to estimate its physical extension and impact scale, (3) to identify the beneficiaries and quantify volume received from the structure, and (4) to estimate the impact of storage in the unsaturated zone.

This analysis was performed over a typical case of percolation tank, representative of the semi-arid crystalline context of southern India: the Tumulur percolation tank located in Maheshwaram watershed (Telangana).

2. Material and methods

Two independent approaches to assess the tank impact are used: a Surface Water Balance (SWB) and a Groundwater Balance (GWB) including a soil water balance as input. SWB is used to evaluate the infiltrated volume from the tank to subsurface (V_{swb}) and GWB to evaluate the recharge volume issued from the tank (V_{gwb}) reaching the aquifer.

2.1. Surface water balance (SWB)

The SWB approach quantifies the change of infiltrated volume from the tank to the aquifer on daily basis (ΔV_{swb}, [$L^3\,T^{-1}$]) from the change of volume of the water stored in the tank at the surface ΔV [$L^3\,T^{-1}$] which can be calculated using the following water balance:

$$\Delta V = A_{Tank} \cdot P + R \cdot a - A_{Tank} \cdot E - A_{Tank} \cdot q_{swb} - U \quad (1)$$

where the infiltration from the tank is defined as:

$$\Delta V_{swb} = A_{Tank} \cdot q_{swb} \quad (2)$$

with A_{Tank} the tank flooded area that changes with time [L^2] and q_{swb} the infiltration rate [$L\,T^{-1}$], P is the precipitations [$L\,T^{-1}$], R the runoff [$L\,T^{-1}$], a the "effective" drainage area of runoff [L^2], E the evaporation [$L\,T^{-1}$], and U the uptake by direct irrigation or livestock consumption [$L^3\,T^{-1}$]. These elements are presented for two water level conditions (Fig. 1). Runoff R [$L\,T^{-1}$] is estimated using