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Research paper

Effect of water storage structures on groundwater recharge in India

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ABSTRACT

Soil and water conservation works were taken up in Bajni watershed in Bundelkhand region of India. Two water storage structures, *viz. Dharam talaiya* and percolation pond were monitored daily for six years to assess their effect on groundwater recharge. Forty observation wells, well distributed around the two water harvesting structures were monitored fortnightly for the below-groundwater levels. Water from fifteen wells were sampled before and after monsoon for analysis of chemical properties. Results were used to develop chemical fingerprints of the groundwater quality. Potential recharge characteristics of the water harvesting structures were computed using the storage volume fluctuation technique. Perusal of data reveals that water table declined by a minimum of 3–4 m during six years, due to droughts (2004-07) and excessive withdrawal of groundwater for drinking and irrigation. The amount of rainfall required to trigger 1 mm recharge was determined as 90.2 and 260.2 mm in *Dharam talaiya* and the percolation pond, respectively. The data revealed the recharge efficacy and design efficiency of both storage structures. While *Dharam talaiya* has a better recharge efficacy, the percolation pond was better designed. The groundwater of the region belongs to the class: Ca-HCO_3 – shallow fresh water during pre-monsoon and to the mixed category of Ca-Na-HCO_3 during post monsoon as indicated by factor analysis, and Piper tri-linear and Gibb's plots. All wells seem to belong to same aquifer as corroborated from chemical fingerprinting, however the transmissivity is low. Groundwater is suitable for irrigation as residual sodium carbonate is within the threshold limits. Further, there is an improvement in groundwater quality, more so during high rainfall due to recharge, which confirms the connectivity of the aquifer.

1. Introduction

India is the largest groundwater user in the world, consuming about 230 cubic kilometers per year through an estimated 30 million groundwater withdrawal structures, *viz.* wells, tube wells and bore wells (Aeschbach-Hertig and Gleeson, 2012; CGWB, 2014; Kulkarni et al., 2015). Groundwater has been the mainstay for meeting the domestic needs of nearly 85 per cent of rural (World Bank, 2010) and 48 per cent of urban (Centre for Science and Environment, 2012) population in India. It is the single largest source of irrigation accounting for about 63.5% of the 64.6 million ha of irrigated land in the country (GoI, 2015). In arid and semi-arid areas, the dependency on groundwater for water supply is between 60% and 100% (Hetzel et al., 2008). Increased dependence on groundwater for irrigation has led to widespread over-abstraction of groundwater resources making it unsustainable. An assessment of 5842 administrative units (Blocks/ Talukas/ Mandals/ Districts) by the Central Ground Water Board revealed that around 14%, 3% and 9% of the units are overexploited, critical and semi-critical, respectively (CGWB, 2014). Overuse of groundwater is associated with significant risks of depletion and contamination of groundwater resources, resulting in the long-term irreversible degradation of water-bearing potential. Nearly 60% of various Indian districts have already shown evidence of either groundwater depletion or contamination or a combination of both (Kulkarni et al., 2015).

A study on changes in groundwater stock between 1980 and 2010 in India revealed a decline in groundwater levels 8–16 m below ground level (mbgl) in northwestern India and from 1 to 8 mbgl in the rest of the country (Sekhri, 2012). This accelerated depletion of groundwater resources is bound to adversely affect the livelihoods of the rural poor, particularly that of the small-scale farmers who rely on groundwater for irrigating crops. This calls for judicious and efficient groundwater

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management systems and policies in the country (Reddy, 2005; Fishman et al., 2015; Zaveri et al., 2016).

Quantification of groundwater recharge is a pre-requisite for efficient groundwater resource management. It is particularly important in the regions with large demands for groundwater, where it is the key to economic development. Aquifer recharge can be evaluated by a wide range of chemical, experimental and numerical methods. Choice of different methods has been reviewed by Scanlon et al. (2002). Grismer et al. (2000) focused on field methods for the evaluation of aquifer recharge in arid and semi-arid regions. Recharge estimations have been made by multiplying the magnitude of water-level fluctuations in wells, to the specific yield of the aquifer model (Avery et al., 1999; Ketchum et al., 2000).

Rainfall is the principal source for replenishment of moisture in the soil-water system and groundwater recharge. Empirical relationships have been derived for computation of natural recharge to groundwater from rainfall. Analysis of water table fluctuations (WTF) is a useful tool for determining the magnitude of both short- and long-term changes in groundwater recharge and has been widely applied under varying climatic conditions (Healy and Cook, 2002; Sharda et al., 2006). The Groundwater Estimation Committee (India) constituted in 1982 to improve the existing methodologies has also recommended this method for groundwater recharge estimation. Considering the hydrological cycle, fluctuations in the storage volume of a reservoir can be captured to assess the amount of recharge occurring in the region (Sharda et al., 2006). Such fluctuations are regional and site-specific, depending upon the climatic and geo-morphological set up. Various attempts are being made to augment groundwater replenishment through soil and water conservation prorgammes including water harvesting. However, there is lack of data to quantify groundwater recharge due to interventions, which hinders the planning and upscaling of recharge measures. This study quantifies the recharge effected by two water storage structures, and develops rainfall-recharge functions in a semi-arid watershed in the Bundelkhand region of Central India through the daily measurement of storage volume fluctuations. Attempt has also been made to understand the characteristic of aquifer though chemical fingerprinting of groundwater quality.

2. Materials and methods

2.1. Study area

Bundelkhand region of Central India, with an area of 7.04 M ha comprises of 13 districts of the states of Madhya Pradesh and Uttar Pradesh. It is well regarded for natural resource management, various developmental activities and socio-economic upliftment. Groundwater resources have been developed to the extent of 43–50% across different districts of the region, and the depth to groundwater in the districts vary from 5 to 20 m below ground level (CGWB, 2012). Any programme to augment groundwater recharge in the region is thwarted by the occurrence of frequent droughts and by the fact that annual evapotranspiration rates exceed precipitation by at least 150%.

Watersheds are the ideal functional units for effectively quantifying the inflow and outflow components of the water balance model. A watershed named Bajni (5.32 km^2 area, 78°27' E, 25°43' N, 260 m above mean sea level, land slope: 1–15%), situated in Datia district of Madhya Pradesh part of Bundelkhand region in Central India was selected for this study (Fig. 1). The watershed typifies the semi-arid set up of Bundelkhand physiography, with extreme summers and winters, undulating topography, existence of rock outcrops at the surface and poor vegetation cover. The annual rainfall in the region is 820 mm with a high coefficient of variation (28%). Nearly 90% of the total precipitation occurs between mid-June and mid-September. High intensity rainfall cause runoff and soil loss. The distribution of rainfall is erratic and even the wet months of July and August may experience long dry spells. Solar radiation is intense and annual evapotranspiration is as high as 1400–1700 mm, which is almost double the annual rainfall. The period from April to June is very hot with the maximum temperature rising to 46–47 °C, whereas in winters, minimum temperature drops to 1–2 °C.

The watershed has about 24% of the area under agriculture, 31% listed as scrub forest with poor vegetation cover, and the remaining area as cultivable and community wastelands. While the *kharif* (July to September) crops are predominantly rainfed, farmers mostly cultivate irrigated (bore wells) wheat and chickpea during the winter (*rabi*) season. About 57 per cent of the agricultural land is irrigated. The soils of the watershed are generally coarse textured with sand content varying from 52% to 79%, infiltration rate ranging from 1.0 to 4.2 cm h^{-1}, and bulk density, from 1.4 to 1.6 Mg m^{-3}. The pH values of soils are near the neutral range, whereas the soil organic carbon and nitrogen content are low throughout the watershed. In general, the watershed presents an undulating landscape, with slope varying from 1 to 15 per cent. The watershed is part of the Bundelkhand massif, occupied by outcrops of gneissic rocks known as Bundelkhand gneiss complex, and regarded as one of the oldest rock types in India. The formation is mostly dominated by Palaeo-Proterozoic granitoids known as Bundelkhand granitoids, traversed by gigantic quartz reefs forming the hill ranges. Sandstone and slates are also believed to co-exist.

Two water harvesting structures, *viz.* a community pond known as *Dharam talaiya*, constructed by the villagers, and the percolation pond, constructed by Indian Institute of Soil and Water Conservation (ICAR), Research Centre, Datia, were selected for full-scale hydrological monitoring. *Dharam talaiya* is spread over 11000 m^2 area. The planar area of upper level of water at full storage is 9900 m^2, and the maximum depth of storage is 4.5 m. The total water storage capacity of this structure is 14000 m^3. The percolation pond is spread over 10000 m^2, and the maximum depth of the storage facility is 3 m. The percolation pond has a total storage capacity of 11500 m^3. The characteristics of both water harvesting structures and average soil property of top 30 cm of soil are presented in Table 1.

Both the structures were provided with vertical measuring scales for recording fluctuations in water depth on a daily basis. Daily observations were recorded from 2003–04 to 2008-09. Forty observation wells, that were well distributed around recharge structures were selected for monitoring the depth to groundwater table fortnightly.

2.2. Estimation of recharge functions

The meteorological parameters, *viz.* rainfall and evaporation were recorded on a daily basis from the observatory located near the recharge structures. These parameters, along with the water level, area and volume fluctuations in the water harvesting structures were tabulated for calculations of rainfall-recharge functions.

The potential recharge was calculated using simple storage balance equation by relating the important components of hydrologic cycle (Fig. 2). The general storage balance equations can be expressed as (Sharda et al., 2006):

$$\text{Rainfall } (P) - \text{Infiltration } (I_f) - \text{Evapotranspiration } (ET) = \text{Runoff } (RO)\ldots \tag{1}$$

Here runoff (RO) is input to the structures. The RO is subjected to storage, evaporation, recharge and out flow.

$$\text{Runoff } (RO) = A_s^{\cdot}\,\Delta h + \text{Evaporation } (EV) + \text{Recharge } (R_{ep}) + \text{Outflow } (O_f)\ldots \tag{2}$$

where A_s is the average planar area (m^2) of submergence = $A_{s,t} + A_{s,t-1} + \surd\ A_{s,t}.\ A_{s,t-1}/3$, Δh is the change in depth (m) in water level in the structure $=(h_t - h_{t-1})$, h_t is the absolute depth of water impounding (m) on tth day, and h_{t-1} is the absolute depth of water impounding (m) on (t−1)th day.

Potential recharge during the non-event (or no-rainfall and no