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Managed aquifer recharge in South India: What to expect from small percolation tanks in hard rock?

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SUMMARY

Many states in India are currently facing general overuse of their groundwater resources mainly due to growing demand for irrigated agriculture. Groundwater levels are declining despite water harvesting measures to enhance aquifer recharge which are supported on a massive scale by watershed development programmes. New programmes are being implemented to improve artificial percolation (i.e., managed aquifer recharge, MAR) although the impact of former measures on aquifer recharge has not yet been assessed. It is therefore crucial to increase our understanding of MAR to successfully overcome the threat of groundwater scarcity in the near future.

This paper scrutinizes the ability of a typical percolation tank to recharge the aquifer using a comprehensive approach combining water accounting, geochemistry and hydrodynamic modelling. Over 2 years of observation, the percolation efficiency (percolated fraction of stored water) of the tank ranged from 57% to 63%, the rest being evaporated. Modelling showed that the percolated water was mostly (80%) pumped straight back by the neighbouring boreholes, limiting the area of MAR influence but increasing percolation efficiency.

1. Introduction

Since independence in 1947, India has continued to expand its irrigation systems and to convert land from rain-fed to irrigated agriculture to improve food security and support economic growth. This policy has helped the country generate valuable returns but in the meantime, the remarkable development of irrigation (e.g. from 12 Mha in 1970–71 to 33 Mha in 1998–99) and water use seriously threatens the sustainability of the water resource even though water is not in short supply yet (e.g. Batchelor et al., 2003; Shah, 2012).

In Andhra Pradesh, large quantities of groundwater are available at low cost (through subsidised electricity) and the supply is individually controlled by farmers, a situation which encourages them to increasingly rely on groundwater. Originally used as an alternative supply to scarce surface water, groundwater has become by far the main water resource for irrigation, even in surface irrigation schemes (Shah et al., 2012). Groundwater supported a substantial change in cropping patterns in the region by increasing dry season paddy and sugarcane at the expense of traditional low water demanding crops such as pulses and sorghum (Van Steenbergen, 2006). A direct consequence of the overexploitation of the shallow crystalline aquifer systems is the long term drop of groundwater levels (Massuel et al., 2007, 2013) which now threatens farmers' livelihoods (Reddy, 2005). Hard-rock and semi-arid regions are particularly sensitive to overexploitation, because storage is limited by the aquifer geometry and properties, and recharge is highly variable (Maréchal et al., 2006; Dewandel et al., 2006; Perrin et al., 2012).

Since the 1990s, water harvesting has been promoted and funded on a massive scale through different large-scale programmes by the Ministry of rural development like MGNREGA (employment programme) or integrated watershed development programmes, and through non-government watershed development programmes. The stated objectives were to conserve and protect drinking water supplies, increase or stabilise agricultural production, reduce erosion to conserve the soil, and enhance aquifer recharge to sustain groundwater levels. Thousands of small reservoirs (tanks) were rehabilitated or built, reproducing the ancestral agrarian system of surface water harvesting at a large

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scale (Gunnell and Krishnamurthy, 2003; Gunnell et al., 2007), but in this case, to enhance percolation and recharge. Typically, intermittent streams are dammed by crescent-shaped earth weirs in a cascade down the axes of shallow inland valleys. The smallest tanks (<40 ha of surface irrigation capacity) were converted into percolation tanks to recharge groundwater (managed aquifer recharge, MAR).

In 1993–94, the 2nd Minor Irrigation Census (Government of India – Ministry of water resources, 1995) totaled 79,953 percolation tanks in Andhra Pradesh, 37% of which were not in use for irrigation. The Ministry of water resources launched a reparation, renovation and restoration programme for 23 000 water bodies (Government of India – Ministry of water resources, 2009). The State's objective was to increase aquifer recharge from 9% of total rainfall under natural conditions to 15% by the year 2020 (Government of Andhra Pradesh, 2003). The most recent master plan of the Indian government (Central Ground Water Board, 2013) recommended the building of 11 million artificial recharge structures at the national level, including 3838 percolation tanks in Andhra Pradesh.

Meanwhile, in 2004, the Water Land and Trees Act for aquifer conservation was enforced, requiring registration of existing wells, licensing of drilling rig operators, and a permit for any newly constructed borehole.

Such initiatives are crucial for groundwater resource sustainability, but the operational effectiveness of these programmes on groundwater recharge is still poorly understood. Published surveys on the subject are scarce and usually limited to water accounts and do not focus on hydrodynamic processes (e.g. Muralidharan et al., 1995; Selvarajan et al., 1995; Gore et al., 1998; Chary and Subbarao, 2003; Sudarshan, 2003; Machiwal et al., 2004; Sukhija et al., 2005; Sharda et al., 2006; Stiefel et al., 2009). However, various authors have pointed to the lack of knowledge and data for a proper evaluation of artificial recharge structures (e.g. Dillon et al., 2009; Glendenning et al., 2012) and existing evaluations of large programmes (e.g. Kerr et al., 2002) often tend to show limited local impact. Some authors even consider that such structures could increase over-exploitation (Batchelor et al., 2003; Adhikari et al., 2013), create river basin closure (Sakthivadivel, 2007; Calder et al., 2008; Glendenning et al., 2012) and have a negative impact on social equity (Bouma et al., 2011). At the same time, the impact on runoff of upstream water harvesting and consumption is likely to surpass the impact of climate variability (Bouwer et al., 2006).

In 2012, the Central Ground Water Board classified 25% of the administrative units of India as 'semi-critical to overexploited areas', compared to 28% in 2009. In this context, future MAR plans need to be put into practice in the most effective way and hence draw lessons from former plans. This is why the present paper focuses on a small percolation tank, one of the most widespread percolation structures for MAR in Andhra Pradesh. The objectives were to identify the hydrological processes involved in the control of the key components of the tank water budget and their effect on groundwater recharge. A detailed water budget was drawn up over the 2 years of observation and the assessment of the percolation efficiency (percolated fraction of stored water) was determined. A hydrodynamic conceptual model is proposed and the implications for MAR are discussed.

2. Study area

The study focuses on a typical percolation tank in Andhra Pradesh (in terms of size, shape, building materials), located near Sangapur village, in the Gajwel watershed (Fig. 1). The region is semi-arid, with a mean total annual rainfall of 780 mm, 86% of which falls during the monsoon period from June to October. The area is mostly flat with intermittent streams running through shallow valleys.

The geology is characterised by the predominance of orthogneiss granite (a.k.a. pink granite) and limited occurrence of leucocratic granite. A few dolerite dykes and pegmatite veins are also present. The granite is weathered and covered by a layer of saprolite from 10 to 15 m thick, except for some rare outcrops of bare granite. In most places, the saprolite is totally unsaturated and overlies a saturated fissured layer of 25–40 m thick.

The Gajwel watershed is in a rural area. Half of the area is cultivated including 20–25% irrigated crops (paddy dominated) exclusively supplied by groundwater. Consequently, the crystalline aquifer is extremely tapped with for instance, approximately 1200 irrigation boreholes in use in the basin (84 km^2). The remaining cultivated land is used for rainfed crops (mainly cotton and maize).

The selected percolation tank is located in red soils (alfisoils), in the upstream part of a drainage line. This was to avoid the interference of any upstream-tank overflow in the water balance. The chosen geometry is flat and smooth to enable accurate mapping of the storage capacity. The surface area at maximum reservoir capacity is 7 ha. A dolerite dyke parallel to the valley axis was evidenced by a geophysical survey (Perrin et al., 2011) along with dolerite outcrops at the southern edge of the tank (Fig. 1).

As a result of semi-arid conditions and landscape modifications by human activities, the tank can be fed by two sub-catchments, depending on storm intensity. The usual catchment is 50 ha and covered by forest and natural shrub (Fig. 1). According to Perrin et al. (2010), at the early stage of the wet season, around 40 mm of total rainfall is used for soil moisture replenishment before any significant runoff appears. Then, during rainfall events of more than 30 mm, an additional catchment area of 40 ha in the South also feeds the reservoir and forms a 90-ha watershed with the reservoir as only outlet. The South catchment is covered by shrub but also by cultivated and bare rocky areas (Fig. 1).

3. Methodology

3.1. Data

The monitoring equipment and data collection are described in detail in Perrin et al. (2008) and Massuel et al. (2008b). Fig. 1 shows the location of the monitoring equipment. In short, over the period 2007–2009, pressure loggers recorded the water level in the tank as well as in surrounding boreholes every 15 min. The wet surface outline was delineated using GPS at several drying stages to obtain precise elevation contour lines. The topography of the tank bottom was then inferred and the relationships between water level, volume and surface were established. An automatic tipping bucket rain gauge and a Class A evaporation pan monitored precipitation and evaporation. Lithology was inferred from three boreholes drilled for the purpose of the study within 80 m of the tank. Water samples from the tank were taken fortnightly for stable isotope, chloride and electrical conductivity (EC) measurements. EC was also measured fortnightly in boreholes. The daily pumping duration in the surrounding boreholes in use was determined using temperature loggers according to the procedure recommended in Massuel et al. (2008a). The discharge of the boreholes in use was gauged every fortnight to estimate the pumped groundwater volumes.

3.2. Tank water balance formulation

To assess the recharge from other similar percolation tanks, various water balance based methods have been used so far at different time scales, with environmental tracers (e.g. Sukhija et al.,