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Projected groundwater balance as a state indicator for addressing sustainability and management challenges of overexploited crystalline aquifers

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SUMMARY

In India, particularly in semi-arid regions, groundwater levels are declining at alarming rates due to overexploitation and the sustainable exploitation of groundwater resources is in deep crisis. There is little or no information on groundwater sustainability indicators, which can signal towards the challenges in water management. In this study we downscaled an entire watershed into three zones based on the different hydrodynamic behaviour recorded at the borewell scale. A process-based simple, multi-parameter linear auto-regressive model was developed to predict groundwater levels, which uses recharge, groundwater withdrawal and irrigation return flow as input variables. A comprehensive and predictive long-term groundwater balance is used as a state indicator to evaluate the sustainability and management challenges in the watershed. Two groundwater withdrawal scenarios were designed to assess the impact of groundwater withdrawal on the groundwater balance. We found that geological heterogeneities play a crucial role in controlling groundwater fluctuations. The storage change in two different groundwater withdrawal scenarios shows gradually declining groundwater storage in both scenarios. A long-term assessment of the groundwater balance helps to analyse the state of the groundwater system and to locate priority zones for watershed interventions.

1. Introduction

Exploitation of groundwater resources during the past fifty years has greatly contributed to the economic development of the world (Shah et al., 2007) but this development has also increased pressures on the water resources. India is now facing serious challenges due to the green revolution, global climate change, environmental and human influences, which have exacerbated the pressure and compromised the sustainability of its water resources. The negative impact of these pressures coupled with government subsidies of power tariffs and easier access to drilling technologies can be clearly observed in the continuously declining water-levels (Hong et al., 2003; Zu et al., 2003; Wang et al., 2007; Jago-on et al., 2009). In India, groundwater accounts for more than 45% of farmland irrigation (27 million ha) as compared to surface water irrigation (21 million ha) (Kumar et al., 2005. Over the last decade, large parts of India, particularly Andhra Pradesh, Karnataka, Maharashtra, Madhya Pradesh, Rajasthan and Gujarat, have suffered from drought and severe drops in groundwater levels, often by as much as 1–2 m/year (Singh and Singh, 2002; Negrel et al., 2011; Rodell et al., 2009). Unmanaged and intensive use of groundwater, particularly in hard-rock regions of semi-arid southern India has also led to a groundwater-quality deterioration (Perrin et al., 2011) and overexploitation of the resources (Maréchal et al., 2006a; Dewandel et al., 2007).

Water management in India is still in its initial stages. Monitoring of spatial and temporal information on groundwater storage is inadequate, which hinders the development of effective water-management plans (Shah et al., 2000). The planning of precise water-management and storage schemes is further complicated by strong population growth, rapid urbanisation and climate change, the unpredictable frequency and intensity of rainfall and undocumented groundwater withdrawal (Kumar et al., 2011a,

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2013). To ensure groundwater sustainability and cope with the growing pressure on water resources, several water policies have been drafted by the Government of India. The first one was adopted in 1987, revised in 2002 and updated in 2012. These policies advocate the establishment of data banks to exchange information, regulate groundwater exploitation, provide guidelines for water allocation priorities in various sectors (e.g., domestic, industrial, agricultural, hydropower), water pricing, setting-up of regulatory authorities, protecting groundwater quality and management of floods and droughts. The role of such policies remains limited to guidelines only as there is no regulatory body to enforce these measures.

In such cases, groundwater sustainability indicators can prove useful for protecting and managing the groundwater resources. Sustainability indicators include many indicators like pressure and state indicators. The pressure indicator shows the pressure on water resources exerted by human activities, e.g., groundwater withdrawal and over-exploitation. The state indicator, like the groundwater balance, shows the response and the state of the groundwater system induced by the exerted pressure. Sustainability indicators of groundwater management provide summary information concerning the present state and trends in groundwater systems and ultimately help in resource planning and policy (Vrba et al., 2006). The ability of the indicators to highlight trends makes it simpler to quantify, analyse and communicate otherwise complex information (Warhurst, 2002; Singh et al., 2009). The groundwater sustainability indicators are important because they describe the state of development, the stress and other aspects related to the conditions of aquifers and they are used by many scientists, groundwater management committees and national water policy-makers (Vrba et al., 2006; Mukherji and Shah, 2005; GEC, 1997; GOI, 2012). Despite the fact that groundwater sustainability indicators are valuable tools for groundwater management, there has so far been little scientific work on these indicators in India.

In this study, pressure and state indicators are used to reveal the groundwater sustainability challenges. The study was carried out in crystalline rocks in a semi-arid region where groundwater is overexploited and the management is challenging because of the climate and the nature of the aquifer. The watershed is downscaled into three zones based on their different hydrodynamic behaviours. The influence of the pressure indicator (groundwater withdrawal and over-exploitation) on the sustainability of each zone is discussed. The estimated and projected groundwater balances are used in different groundwater withdrawal scenarios to indicate and visualize the state of the aquifer and delineate priority zones for watershed interventions.

2. Geological setting and hydrogeology of the watershed

The Maheshwaram watershed (53 km^2) (Fig. 1) in Andhra Pradesh, India, is a crystalline formation composed mainly of pink and grey, medium-to-course-grained, Archean granites of the Hyderabad group. The leucocratic granite also occupies the south-west and southern parts of the watershed and is generally fine-grained and fairly resistant to weathering. The crystalline rocks are intruded by quartz veins and dolerite dykes, with variable degrees of weathering. The profile consists of a thin layer of red soil (10–40 cm), a 1–3 m-thick layer of sandy regolith, locally capped by a lateritic crust (<50 cm in thickness), followed by a 10–15 m-thick layer of laminated saprolite. The saprolite layer has a horizontally laminated structure, with sub-horizontal and sub-vertical fissures partially filled by clay minerals. The saprolite layer is followed by fissured unweathered granite, which occupies the next 15–20 m, followed by an unfractured granite (bedrock). The unweathered bedrock is permeable only where tectonic fractures are present (GSI, 2002; Dewandel et al., 2006). The average depth of weathered rock is 11 m and that of fractured rock is 22 m. Fractures form the major structural features of the study area and are classified as mineralized fractures, fractures traversed by dykes and fractures represented by joints. The dolerite dykes are well exposed in the northern and western parts of the watershed. The quartz veins running in a north–south direction are highly fractured and form a very prominent linear feature of the watershed. The general groundwater flow is in the SW–NE direction and follows the general topography.

The laminated saprolite and fissured layers act as a two-tier aquifer system. The saprolite layer has a high storage capacity but poor transmissivity while the fissured layer is poorly capacitive, but highly transmissive (Maréchal et al., 2003). In the 1970s, before borewell irrigation started, the water table was shallow and lying in the saprolite under semi-confined conditions. The watershed now is highly overexploited (over 700 barrels) with a water table as deep as 15–25 m below ground level (bgl), disconnected from the surface water. The saprolite is completely dry and groundwater is found mostly in the fractured zone in unconfined conditions (Maréchal et al., 2004, 2006b; Zaidi et al., 2007a; Ahmed et al., 2010). The mean annual precipitation is 750 mm and the potential evapotranspiration is 1800 mm. Rainfall occurs in the monsoon season (June–October). The streams are mostly of the first and second order, non-perennial, and run only during the monsoon period. The area has a relatively flat topography with elevations between 590–670 m amsl (meters above mean sea level). Landuse of the area is dominated by paddy which consumes the major part of the irrigation water. Other crops include vegetables (tomatoes, chilies, peas, cabbage, maize, cotton, flowers, etc.). A substantial area is covered by forests and scrubland. The watershed is also covered by built-up land including human settlements, poultry farms, an industrial enclave, brick kilns, etc. (Khan et al., 2011).

3. Materials and methods

3.1. Piezometric network and monitoring

As this study concerns observed and projected groundwater balance for a period of twenty years (2001–2021), both measured and predicted water-level data were used. There exist over 900 wells (Fig. 2) in the Maheshwaram watershed of which 150–200 are abandoned. These wells act as potential piezometers ideal for monitoring seasonal water-level variations. A piezometric network of 25 borewells (Fig. 2) named IFPs specially drilled for monitoring was selected from an earlier study in the watershed. The selected borewells are negligibly (10–20 centimeters) influenced by the pumping in the nearby wells (Zaidi et al., 2007a). Automatic Water-Level Recorders (AWLR) were fitted in ten observation wells. Monthly manual measurements of the water-level were also made in the 25 borewells continuously over a period of 6 years (2001–2006). This network was further reduced due to technical constraints and monitoring was carried out in only five borewells for (2008–2011).

3.2. Zonation of the watershed and selection of representative wells

Crystalline aquifers are subjected to a number of structural discontinuities in the form of intrusions. The present study area contains all possible intrusives, i.e., dolerite dykes, a quartz reef and pegmatite veins. Most of the pegmatite veins are present in the form of sills and do not affect the groundwater movement. However, dolerite dykes are very important and play a major role. They are conductive down to a certain, but unknown, depth, due to