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Estimation of specific yield using water table fluctuations and cropped area in a hardrock aquifer system of Rajasthan, India

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ABSTRACT

Assessment of specific yields is important for effective groundwater management in semi-arid hardrock aquifers, especially in India with its unsustainable groundwater usage rates. The Dharta watershed in the Udaipur district of Rajasthan is one such hardrock area in India where the groundwater extraction rate is a concern. In this study, we use groundwater balance analysis to estimate the specific yield (S_y) based on crop irrigation water use and changes in water table depths, during the irrigation season, to develop an understanding of the volume of groundwater recharge from pre and post monsoon water table depths and an understanding of the spatial and temporal changes in estimates of specific yield in the study area. The analysis used here estimates values at village scale (average area 3.65 km^2) and is a technique compatible with the farmers monitoring of groundwater levels to facilitate local cooperative groundwater management. Five villages in the Dharta watershed in Rajasthan were selected and 50 wells per village were monitored for water table depth, at weekly intervals, over a two-year period. This resulted in a total of 250 wells in the study area and the monitoring was carried out by local farmer volunteers − called *Bhujal Jankaars* (BJs), a Hindi word meaning 'groundwater informed.' Crop area coverage (with a total of 40 crops) was examined for two years in the study area. Estimates of S_y in the five villages were between 1.4 and 8%, resulting in values comparable with previous studies. The watershed area-weighted average S_y was 3.8%. The method used in this study enabled estimates of recharge without needing a calibrated groundwater model in an area with sparse information on aquifer hydraulic characteristics and unreliable digital elevation maps.

1. Introduction

Groundwater has become a critical natural resource with great economic value in both urban and rural areas (Burness and Brill, 2001; Qureshi et al., 2010; Groenfeldt, 2013). Groundwater has been recognised as the major source of irrigation water in India, particularly in states with inadequate supplies from surface water sources and limited rainfall (Maheshwari et al., 2014; Varua et al., 2016). This is further complicated by the fact that monsoonal rainfall in India has become more erratic with frequent floods and drought as well as a shift of the monsoon peak rainfall, probably due to the effect of climate change (Howe et al., 2014). The erratic nature of rainfall is more evident nowadays, and for this reason, farmers are more dependent on groundwater to avoid crop failure during the Kharif season and successfully grow crops during the Rabi season (Chinnasamy, 2016; Chinnasamy et al., 2017).

India is the world's largest groundwater user with a usage of 230 km^3 per year (CGWB, 2013; Hoekstra, 2013). Globally, India has 39 million ha of agricultural land under groundwater irrigation, followed by China and the USA with 19 and 17 million ha, respectively (World Bank, 2010; Siebert et al., 2010). India's groundwater use has increased dramatically over the last 40 years, due to easy availability and affordability of diesel and electric pumps to farmers. With such an increase in the ease of accessing groundwater, post monsoon crops (Rabi crop) in many regions in India are solely irrigated using groundwater, which has resulted in increasing crop yield. Undoubtedly, groundwater irrigation in India has enhanced farmer livelihood over the past few decades, resulting in substantial socio-economic benefits (Chinnasamy

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and Agoramoorthy, 2015; Agoramoorthy et al., 2016) but it has also led to complex groundwater sustainability and management challenges (Burke and Moench, 2000; Chinnasamy and Agoramoorthy, 2016). Groundwater use by industries and a growing urban population in recent years has further increased stress on groundwater resources and the continual lowering of groundwater levels (Chinnasamy et al., 2013; Chinnasamy et al., 2015a).

Without any regulation on groundwater pumping, the aforementioned socio-economic growth and agricultural growth also meant that annual groundwater use began to exceed the annual natural rainfall recharge (Shah, 2008; Chinnasamy and Agoramoorthy, 2015). Consequently, over the past decade, many dug wells and surface water stores are now dry and have been abandoned. The groundwater levels surrounding these areas have also declined deeply due to the limited recharge from surface water. As a result, farmers with limited shallow groundwater resources have started drilling tube wells to access water from deeper aquifers (Shah, 2010; Shah et al., 2003; Chinnasamy and Agoramoorthy, 2016). This extensive, unregulated and unsustainable use of groundwater resources by Indian agricultural, domestic and industrial users has created a set of complex management problems and sustainability concerns. Thus there is a need for efficient groundwater management, especially in the semi-arid regions of India where groundwater recharge is low and pumping is high (Chinnasamy et al., 2015a; Chinnasamy et al., 2015b; Chinnasamy and Agoramoorthy, 2015).

2. Estimation of aquifer properties

Effective groundwater management requires an estimation of annual recharge and groundwater volume that can be pumped from a given area. For this, we need reliable estimates of aquifer properties such as specific yield and other hydrogeological information (Freeze and Cherry, 1979). The estimate of groundwater volume that is available for pumping is important for commencing a meaningful dialogue with local villagers, managers in government agencies and policy makers. This helps in creating objectivity and a better understanding of the groundwater situation and options for future actions. Further, to estimate the sustainable groundwater yield, the first step in this process is to determine storage change using groundwater level data and specific yield of aquifer. These estimates can provide a scientific basis to explore alternative management scenarios and strategies with the farming community for improving their livelihood while sustaining the groundwater resource.

In most semi-arid regions in India, there is a scarcity of aquifer data, especially groundwater levels and aquifer hydro-geologic data (Chinnasamy et al., 2015a). Due to the property of hardrock aquifers, there is often a large spatial variation in aquifer hydraulic parameters. This is further complicated by the variation in aquifer material types and properties with depth from the land surface; particularly evident when there are significant changes in the water table during monsoon and pumping seasons. Therefore, the aquifer properties based on methods that are traditionally used in alluvial aquifers, e.g., pumping test method, may not provide representative values of the aquifer properties in hardrock areas (Machiwal and Jha, 2014). In particular, the estimation of specific yield has been difficult in hardrock aquifers, while detailed and sophisticated measurements of groundwater balance components in a developing country situation is often difficult and beyond the financial resources of most government agencies.

In the past, specific yield has been determined by a number of methods that include pumping tests, soil moisture measurements, geophysical methods, water balance methods and the water table fluctuation technique (GEC, 2009; Freeze and Cherry, 1979). In response to growing concerns pertaining to uncertainties in groundwater resource estimation, the Indian government established the Central Groundwater Board (CGWB) in 1970 (CGWB, 2004), under the Ministry of Agriculture, to quantify and regulate groundwater resources nationwide. On this note, the CGWB, in collaboration with the Groundwater Resource Estimation Committee (GEC), developed and validated scientific methods to monitor groundwater resources, and also included the state groundwater departments (GEC, 2009). Due to this collaboration, many scientific reports, at district and state levels have been published to date (e.g., CGWB, 2011). The CGWB and GEC recommend the use of the water balance method and water table fluctuation methods to estimate specific yield in India's hardrock regions, especially in shallow water tables and unconfined aquifers (GEC, 2009; NABARD, 2006; CGWB, 1997).

For estimating specific yield in hardrock areas, the methods based on groundwater level data tended to yield more reliable values (Machiwal and Jha, 2014). In general, the methodology for estimating specific yield needs to be robust and defensible and provide good estimates of groundwater balance components and insights into groundwater dynamics at the village level. Effective methods also need to account for considerable spatial variations in specific yield values, which are due to heterogeneity and anisotropy in aquifer properties that are characteristic of hardrock aquifers.

The main objective of this study is to estimate the specific yield based on crop irrigation water use and changes in the pre and post irrigation season water table depths. The other objective is to understand the spatial and temporal changes in specific yield in the study area. Unlike other studies in the past, the current study takes into account spatial and temporal variations by incorporating site-specific high frequency (weekly) water table depth information. One important outcome of the analysis is to develop a methodology for the estimation of specific yield based on data that can be easily collected by local farmers and government agencies.

Subsequently, the computed specific yield is considered with pre and post monsoon groundwater levels to give a simple and reliable method to indicate recharge to hard rock aquifers in the absence or scarcity of data on which other methods rely. Such a simplified method can aid land managers and farmers to estimate specific yields from their limited field data, and also aid in estimating total water storage for a given water level change, using the Water Table Fluctuation (WTF) method.

3. Study area

The study was conducted in the Dharta watershed of the Udaipur district, Rajasthan, India (Fig. 1). The watershed has a semi-arid climate, with an average annual rainfall of 600 mm, however almost 90% of this rainfall is concentrated during the monsoon months of June to October (CGWB, 2010). The dry months are from November to March. The farmers in the watershed grow cluster bean, groundnut, soya bean, maize, black gram, mung-bean, guar and vegetables as Kharif crops during the monsoon season. Wheat, gram, sorghum and mustard are the main Rabi crops grown during the winter season. Farmers with groundwater and surface water access (e.g. canal water) grow two crops a year, while a limited number of farmers with year round water grow some summer crops such as vegetables and fodder. Most farmers in the watershed are from mainstream groups.

Since agriculture is the dominant occupation in the watershed, there is a need to quantify water resources that can increase agricultural production and eventually improve livelihoods of farmers. In the watershed, the occurrence and distribution of rainfall is highly uneven in time and space. As a result, Kharif crops (which are monsoon dependent) often face either complete or partial crop failure because of below average rainfall, or absence of rainfall at critical stages of crop growth. During such instances, crop failure can be averted by using rainwater stored in ponds, check dams or groundwater. A number of in situ water conservation measures (e.g. farm ponds, percolation ponds and check dams) have been constructed in the watershed by the Integrated Watershed Management (IWM) and Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA) programs, funded by the