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Spatial estimation of groundwater storage from a 2D specific yield in the crystalline aquifer of the Maheshwaram watershed

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Crystalline aquifers are present in most parts of southern India with limited resources of groundwater. The groundwater storage map in the Maheshwaram watershed has been estimated from the product of specific yield (Sy) and saturate aquifer thickness as a system being an unconfined weathered–fractured combined aquifer. Land-use data has been used for the estimation of groundwater abstraction at a spatial scale. Storage and scarcity mapping demonstrate that the watershed is clearly vulnerable to drought in some areas because of significant pumping. Therefore, the result shows that on average, the availability of groundwater storage corresponds to 1.5 yr of the present groundwater abstraction rate with successive low monsoons (i.e., insignificant recharge). Additionally, 13% of the area shows no storage at present, 28% of the area has less than 1 yr, 40% area has less than 2 yr and 12% area has less than 3% of storage. Very few cells can sustain for more than 3 yr. Additionally, the Sy of the aquifer ranges from 0.2% to 5% with a mean value of 1.8%. A geo-statistical technique has been applied for the estimation of Sy at unknown cells where either the cell was dry or no pumping occurred. This estimated two-dimensional Sy value can also be used in classical groundwater numerical modelling for a better understanding of groundwater resource management.

Keywords. Groundwater storage; crystalline aquifer; Maheshwaram watershed.

1. Introduction

Crystalline rock aquifers are complex systems with strong heterogeneity which render the problem of regionalising aquifer properties more complex. Degrees of fracturing and the interconnection within the fractures induce the high variation of aquifer properties at all scales (Paillet 1998; Le Borgne *et al.* 2004, 2006; Maréchal *et al.* 2004; Dewandel *et al.* 2011). Because of this, several researchers choose to produce classified transmissivity maps or potential aquifer zone maps instead of mapping aquifer properties (Krásný 1993, 2000; Darko and Krásný 2007; Dhakate *et al.* 2008; Madrucci *et al.* 2008). Recent studies show that significant improvements have occurred for the hydro-geological characterisation of hard-rock aquifers (Chilton and Foster 1995; Taylor and Howard 2000; Lachassagne *et al.* 2001; Maréchal *et al.* 2004; Wyns *et al.* 2004; Dewandel *et al.* 2006, 2012; Ayraud *et al.* 2008) and demonstrate that when hard rock is exposed by deep weathering processes at the regional level, the geometry and hydrodynamic properties of such aquifers are closely related to the weathering grade of the parent rock (Taylor and Howard 2000; Dewandel *et al.* 2006, 2012). In granitic rock, a typical weathering profile comprises two main nearly stratiform layers sub-parallel to the palaeo-surface at the time of the weathering process (Chilton and Foster 1995; Wyns *et al.* 1999, 2004; Krànsý and Sharp 2007; Maréchal *et al.* 2007; Reddy *et al.* 2009; Dewandel *et al.* 2011 and others). It can be considered as a two-layer aquifer system. In this case, the aquifer is constituted of two main sub-parallel hydrogeological layers, namely, saprolite (clayey–sandy material) and fractured (dense horizontal fissuring in the first few metres and decreases with depth) layers. It can be considered as a multi-layered aquifer system without any intervening aquiclude.

About 27 million hectares of agricultural land represented by India is irrigated by either groundwater or surface water. With the beginning of the Green revolution, the number of borewells shot up from 1 million in 1960 to more than 19 million in 2000 (Shah 2007). Therefore, groundwater resources have been under stress permanently, especially in crystalline rock aquifers and semi-arid areas. Thus, regionalisation of aquifer properties especially in crystalline rock will provide a better understanding of groundwater resource availability in the watershed. Presently, in most of the cases, numerical modelling in hard rock areas is a little bit biased because of the lack of regionalised data in this type of aquifers. The adopted simple methodology for the regionalisation of specific yield (Sy) or hydraulic conductivity can be an effective step in removing this kind of biases in the numerical models of the study area. In the Maheshwaram watershed, several studies have been performed by the researchers to estimate the aquifer properties but all measurements were at the point (borewell) scale. Dewandel *et al.* (2012) estimated the hydraulic conductivity and Sy at a spatial scale using the water table fluctuation (WTF) method with an upscaling of parameters. Groundwater availability in terms of storage and scarcity mapping at the cell scale has not been discussed.

The present work provides information about spatial groundwater storage and scarcity maps in terms of groundwater availability which is the crucial parameter in making the right decision. Also, we have regenerated the spatial Sy map with recent data sets and validated our values with the earlier maps.

2. Study area

The Maheshwaram watershed (53 km^2) lies 40 km south of Hyderabad in Ranga Reddy district (figure 1). The area has a relatively flat topography with an elevation of 640–670 amsl (above mean sea level). The watershed is influenced by the south-west monsoon and the aridity index (0.42; Dewandel *et al.* 2010) classified into the semi-arid climate. June–October is represented by the monsoon season (*Kharif*) and the non-monsoon season (*Rabi*) is from November–May. Average annual precipitation is about 700 mm and more than 90% precipitation occurred during the monsoon period. The area is mainly inhabited by the rural population.

The geology of the area represents mainly Archaean biotite granite and it is intruded by small bodies of leucocratic granites locally. The granitic terrain of the area is affected by a deep weathering (*in-situ*) process (Dewandel *et al.* 2006, 2012). Figure 2 shows the vertical profile of the weathering layer. A variation of the saprolite layer and the total aquifer ranges from 0 to 20 and 10 to 50 m, respectively (Dewandel *et al.* 2006, 2012).

3. Spatial discretisation

Sy value at the watershed scale was estimated by earlier researchers (Maréchal *et al.* 2006; Dewandel *et al.* 2010) and they arrived at a global value of 1.4 ± 0.3%. At the watershed scale, horizontal inflow ($q_{\rm in}$) and outflow ($q_{\rm out}$) are very low (less than 1 mm/yr) and thus their net balance can be neglected ($q_{\rm in} - q_{\rm out} \sim 0$), but the net balance of inflow and outflow in small cell size affected by pumping is not negligible because the radius of influence of the pumping in the cell will be definitely larger than the size of the cell (Dewandel *et al.* 2012). Dewandel *et al.* (2012) computed the Sy value with the percentage of the affected cell by pumping at eight different cell sizes varying from 50 m × 50 m to 1040 m × 1040 m in this watershed. They observed that the Sy values are high and unrealistic at small cell sizes because of non-negligible $q_{\rm in} - q_{\rm out}$, but it rapidly decreases with increasing cell size. At a cell size more than 600 m × 600 m, Sy values are more realistic than values estimated at the watershed scale by earlier researchers (Maréchal *et al.* 2006; Dewandel *et al.* 2010), because abstraction wells are predominant in the area and group of wells create a large

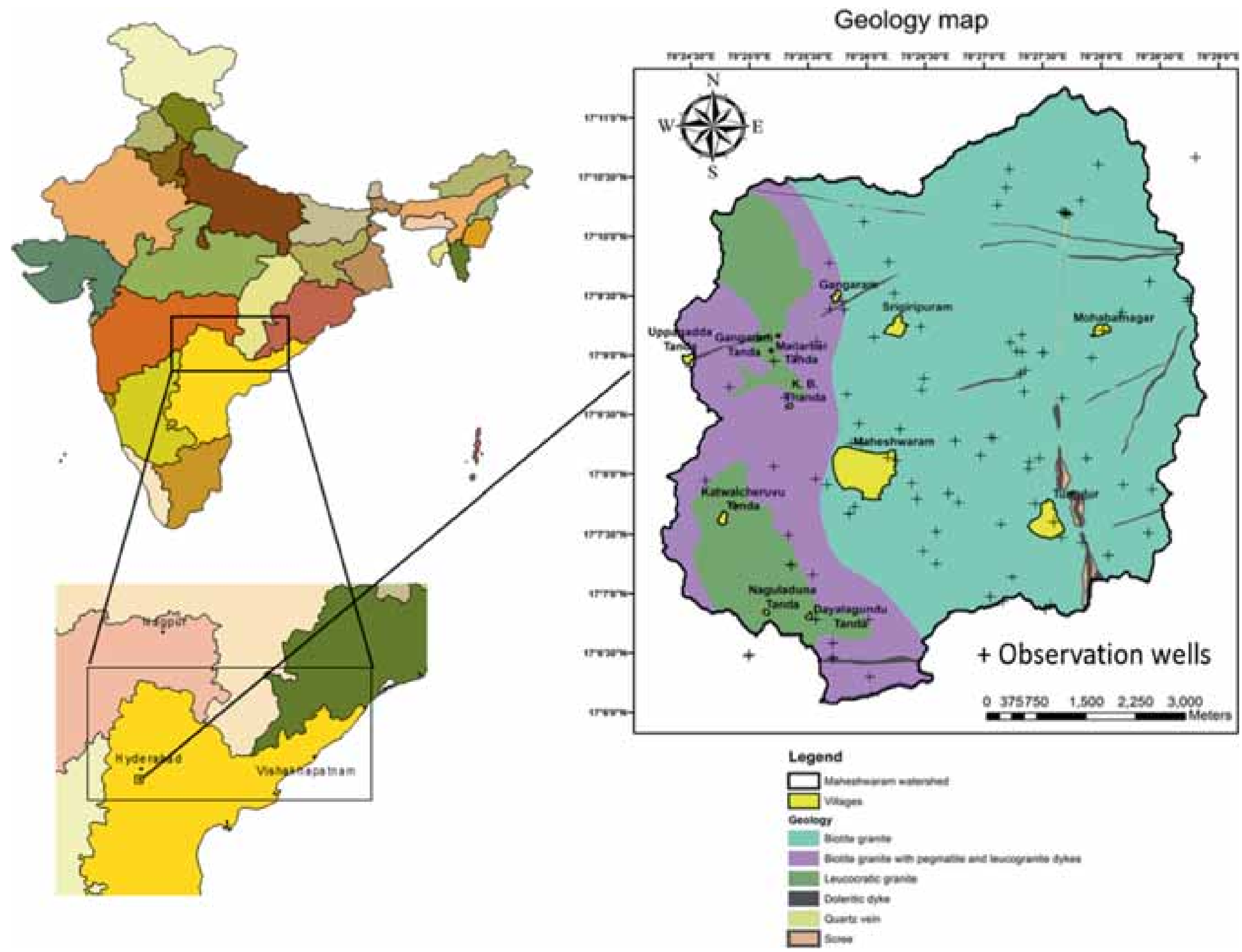

Figure 1. Location and geological map of the Maheshwaram watershed.

depression of water level that influences all the area. Large cells were consequently important to include such well groups. As a result, a value is reached when almost all the cells of the area are influenced by pumping (>80%). Therefore, all the computations have been carried at a cell size of 685 m × 685 m where net $q_{\mathrm{in}} - q_{\mathrm{out}}$ can be negligible and this allows a good spatial discretisation of the area (113 cells).

4. Methods

For Sys, the WTF method and groundwater budget equation were combined (equation 1) and applied in the rabi (dry) season where natural recharge is absent (Dewandel *et al.* 2012). The change in groundwater storage of an unconfined aquifer in the absence of recharge was calculated as (Schicht and Walton 1961; Maréchal *et al.* 2006; Zaidi *et al.* 2007)

$$\Delta S = \mathrm{Sy} \times \Delta h = E + Q - \mathrm{IRF} + q_{\mathrm{out}} - q_{\mathrm{in}} + q_{\mathrm{bf}}, \quad (1)$$

where ΔS represents the change in groundwater storage, Sy is the specific yield, Δh is the WTF, E is the evaporation from the water table, Q is the groundwater abstraction by pumping, IRF is the return flow by irrigation, q_{in} and q_{out} are groundwater horizontal flows in the aquifer system and q_{bf} is the groundwater discharge into the stream. All units of the components of equation (1) are in millimetres except Sy.

The water table in the watershed is relatively deep. There is no perennial river in the watershed; thus the base flow is nil (Dewandel *et al.* 2010). Grid size selection was based on the studies carried

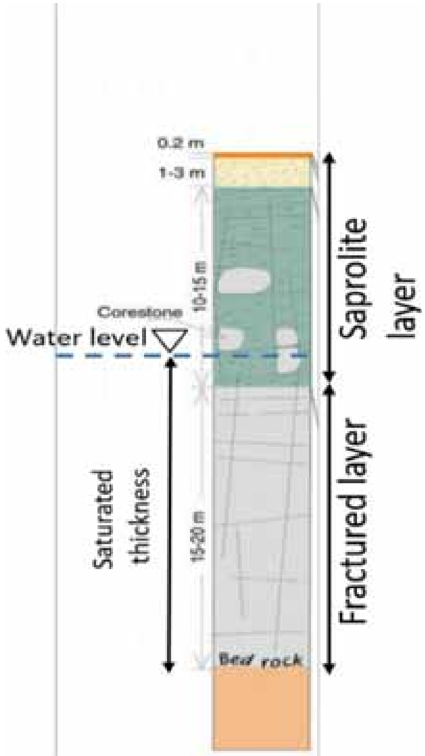

Figure 2. Weathering profile of the Maheshwaram watershed.

out by Dewandel *et al.* (2012), more than 600 m cell size is the threshold size where net $q_{in} - q_{out}$ can be neglected; $|q_{in} - q_{out}| << \text{(Q-IRF)}$. Evaporation from the water table is also a small component of the total budget because of deep water level (typically less than 1 mm/yr; Dewandel *et al.* 2012) and it can also be neglected. A hydrological year (June 13–May 14) has been divided into monsoon (Kharif; June 2013–October 2013) and non-monsoon (rabi; November 13–May 14) seasons for this particular study.

Thus, equation (1) can be rewritten for the rabi (dry) season for this particular watershed:

$$\text{Sy} = (\text{IRF}_{\text{dry}} - Q_{\text{dry}})/\Delta h_{\text{dry}}. \quad (2)$$

However, this method could only be used to estimate the Sy values where the water table fluctuates, and not for the entire aquifer (Dewandel *et al.* 2012). The geostatistical method (kriging) has been applied to estimate the Sy values where there were no data. Groundwater abstraction and water level measurement were also required at the same spatial scale (Dewandel *et al.* 2017).

Finally, Sy values were arranged to produce an Sy map at the watershed scale. The aggregated map of Sy was used for the estimation of the groundwater storage map (Dewandel *et al.* 2017):

$$\text{Storage} = \text{Sy} \times \text{saturated thickness of aquifer}. \quad (3)$$

5. Field data

5.1 *Groundwater and irrigation*

In the present study, land-use and remote sensing techniques have been used for the estimation of groundwater pumping ($Q = \text{Pg}_\text{i} \times A \times t$), where Q is the total groundwater abstraction, Pg_i is the daily input of water for individual crops in m, A is the occupied area by crops and t the number of days of watering in season. Land-use maps of the rabi season of November 2013–May 2014 have been divided into 685 m × 685 m cells and the individual crop areas from the grids have been extracted. The average paddy irrigated area is around 3.7% followed by vegetable 0.8%, orchards 2.5% and the remaining area is occupied by built-up lands, barren rocky and forest area. Details of crop cultivation and irrigation, as well as watering techniques, were collected from farmers to obtain the data on crop calendar and stages. Daily input water of particular crop value has been taken from Dewandel *et al.* (2008). The mean daily water input for rice during the dry season is 15 mm, whereas during the wet season, it is only 10 mm, and the remaining comes from the rain. For vegetables and orchards, the numbers are 7 and 4.9 mm, respectively, independent of the season. The combination of land-use, daily water input for each crop and the number of days for the cultivation of each crop allows the computing of the seasonal groundwater abstraction in the watershed at a spatial scale. Crops are also irrigated during monsoon with groundwater, but at a lower rate (1.5 times lesser; Dewandel *et al.* 2010). Groundwater also contributes to domestic use, the amount of which is based on census data (Indian census 2011; 65,125 inhabitants) and daily groundwater consumption per person (25 l/day). The groundwater abstraction rate in the watershed ranges from 0 (no pumping) to 318 mm for the November 2013–May 2014 season (Mean 115 mm; figure 3).

The water-level map was drawn based on the groundwater-level measurement from 85 bore wells (figure 3). Water-level measurements of two seasons (post-monsoon; November 2013 and pre-monsoon; May 2014) were obtained to know the WTF in the dry season. The average water level

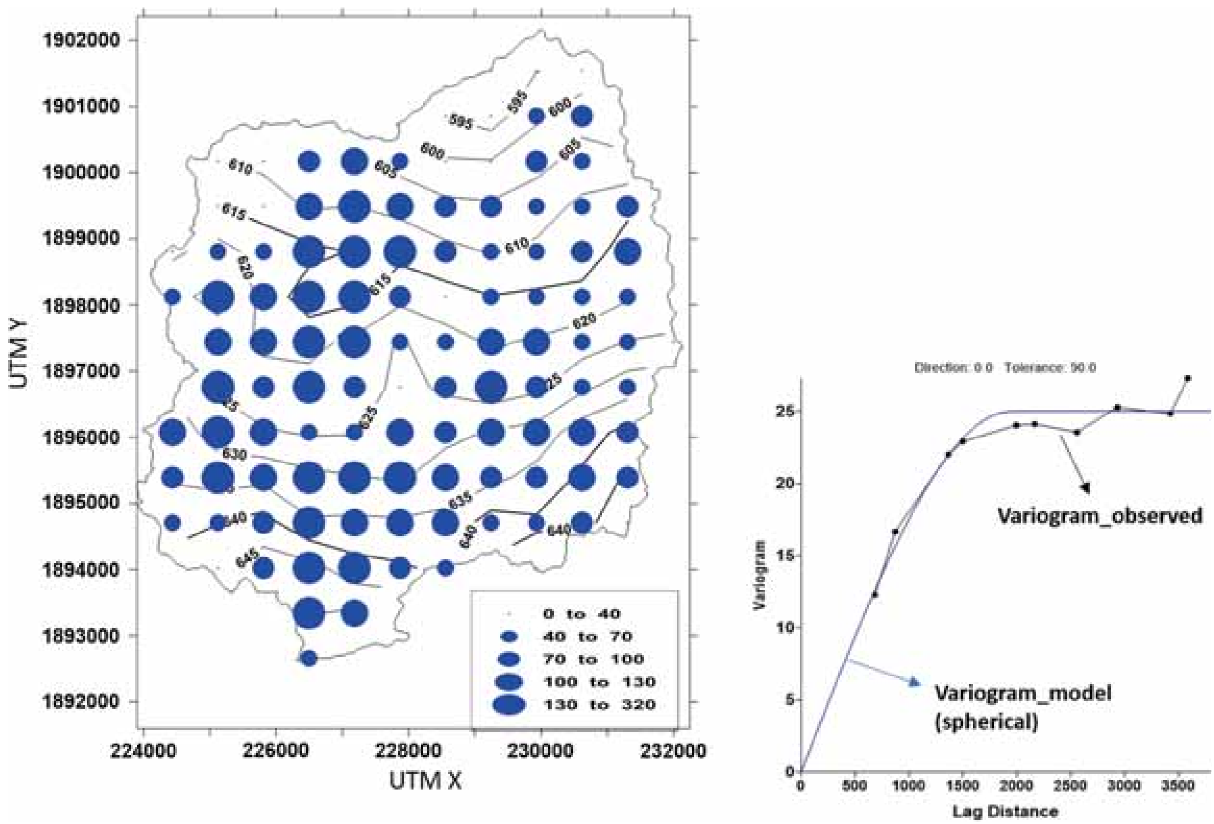

Figure 3. Groundwater level elevation map (masl: metre above sea level) with groundwater abstraction (in mm) at a spatial scale. The variogram (x-axis is showing lag distance in metres and y-axis is variance in metre^2) was used for water-level estimation (model: spherical, range: 130 m and sill: 25 m^2).

Table 1. *Irrigation return flow coefficient (from Maréchal et al. 2006; Dewandel et al. 2008).*

	Rabi	Kharif
Use	Return flow coefficient	Return flow coefficient
Rice	0.48	0.51
Vegetables	0.24	0.26
Fruits	0	0
Domestic	0.2	0.2

Note. Rabi: dry season; Kharif: rainy season.

fluctuation is around 4.1 m in this watershed and mainly lies within the fractured layer.

5.2 *Irrigation return flow (IRF)*

IRF was estimated based on the coefficient values of each crop type (IRF= Cf $\times$ Q; where Cf is the return flow coefficient). Table 1 presents the documented return flow coefficient for this particular watershed (Maréchal *et al.* 2006; Dewandel *et al.* 2008). Each coefficient value was applied to the corresponding groundwater use for the particular season, which allows estimated net groundwater abstraction in each cell. No IRF was computed for orchards because of the drip irrigation method.

6. Results

6.1 *Specific yield*

Net groundwater abstraction (Q-IRF) and WTF (Δh) spatial distribution were estimated for the rabi season (November 2013–May 2014). Figure 4 presents the (Q-IRF) and (Δh) map at 685 m $\times$ 685 m scale for the rabi (dry) season. The WTF (Δh) map is based on 85 observation wells and the standard kriging technique. Mean Δh is 4.1 m at the watershed scale and ranges from 0 to 14 m at the cell scale. Mean Q-IRF is 75 mm at the watershed scale for November 2013–May 2014.

Equation (2) was used for the estimation of Sy. Figure 5 shows the estimated Sy at a 685 m $\times$ 685 m grid. The average value of Sy is 0.018 and ranges from 0.002 to 0.05 within the watershed. Variographic analysis was performed for the estimation of the unknown Sy values of the watershed using

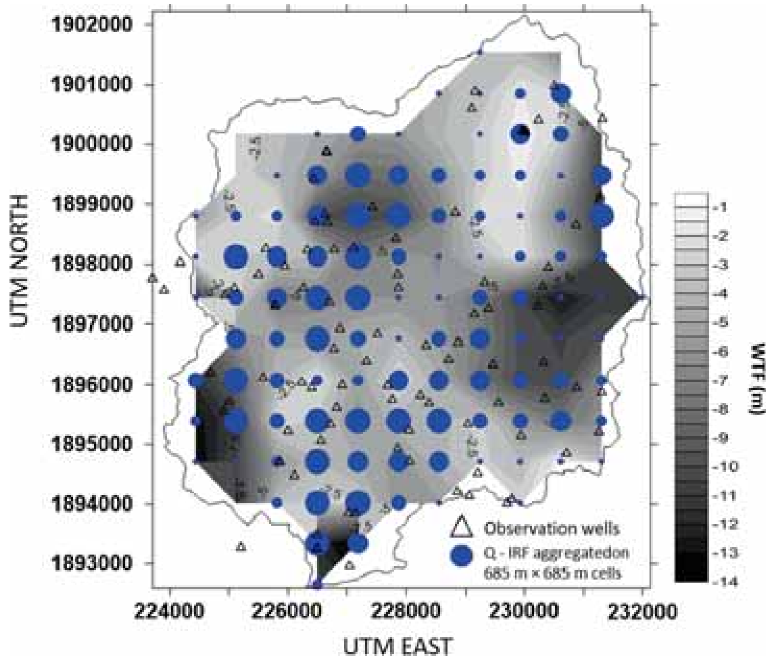

Figure 4. WTF map (85 observation wells). Aggregation of Q-IRF on the grid with 685 m × 685 m cells shown as dot-proportional (0.05 inch) values.

standard kriging. The variogram seems to show a strong spatial dependency of Sy due to low nugget effect.

This Sy values closely agrees with the result of earlier researchers at the watershed scale and the spatial scale (Sy; 0.014, Maréchal *et al.* 2006; Dewandel *et al.* 2010 and Sy; 0.008–0.03, Dewandel *et al.* 2012). The mean value of Sy was slightly higher than previous results because the average water level fluctuation during November 2013–May 2014 was close to saprolite thickness (Dewandel *et al.* 2010). Similarly, Sy values at the cell scale showed a different range because the WTF map of November 2013–May 2014 have different elevation in comparison with the WTF elevation map used by Dewandel *et al.* (2012). Dewandel *et al.* (2017) indicated that the vertical variation of Sy is related to the variation in the percentage of fissures with depth. However, the overall variation pattern agrees with the previous results.

6.2 *Groundwater storage and scarcity mapping*

The groundwater storage map (figure 6a) was estimated using equation (3) with combining spatial Sy map and saturated thickness of the aquifer. It provides the location of the potential aquifer zone.

To understand how an aquifer is exposed to drought, figure 6(b) shows water scarcity and vulnerability to overexploitation of the aquifer within the watershed which has been prepared by the ratio of groundwater storage over net annual groundwater abstraction (Q-IRF). Therefore, the result shows that on average, the availability of groundwater storage corresponds to 1.5 yr with the present groundwater abstraction rate and on the assumption of low monsoons in successive years (i.e., insignificant recharge from rainfall). Additionally, 13% area shows no storage presently, 28% of the area has less than 1 yr, 40% area has less than 2 yr and 12% area has less than 3% of storage. Very few cells can sustain more than 3 yr. This implies that the Maheshwaram watershed is clearly vulnerable to drought due to intensive groundwater abstraction. These maps of the watershed do not have a focus to forecasting groundwater sustainability in terms of the year but flashes the status of groundwater scarcity in the watershed.

7. Discussion

We present the spatial Sy (figure 5) and groundwater storage map (figure 6a) for a better understanding of groundwater resource management. The spatial variation of Sy suggests a slightly higher value of Sy in the western part as compared to the eastern part of the watershed. A similar variation was also observed by Dewandel *et al.* (2012). The Sy value does not show any clear

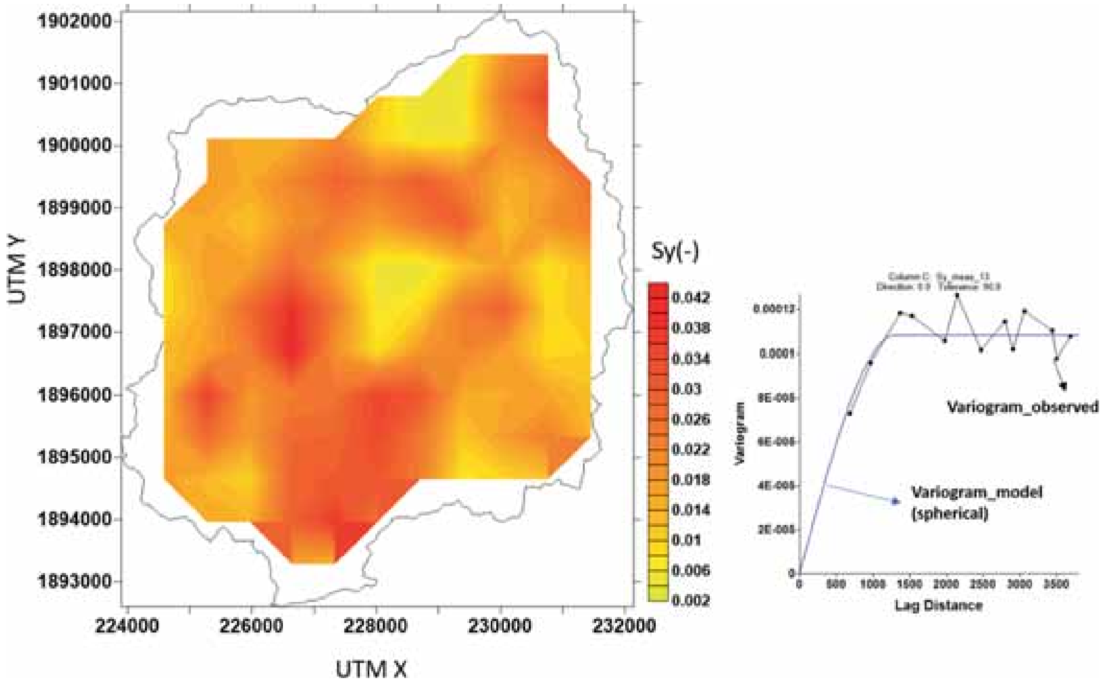

Figure 5. Spatial Sy map at 685 m × 685 m cell scale. The variogram (x-axis is showing lag distance and y-axis is variance) was used for Sy data interpolation (model: spherical; length: 1050 m, sill: 0.00011).

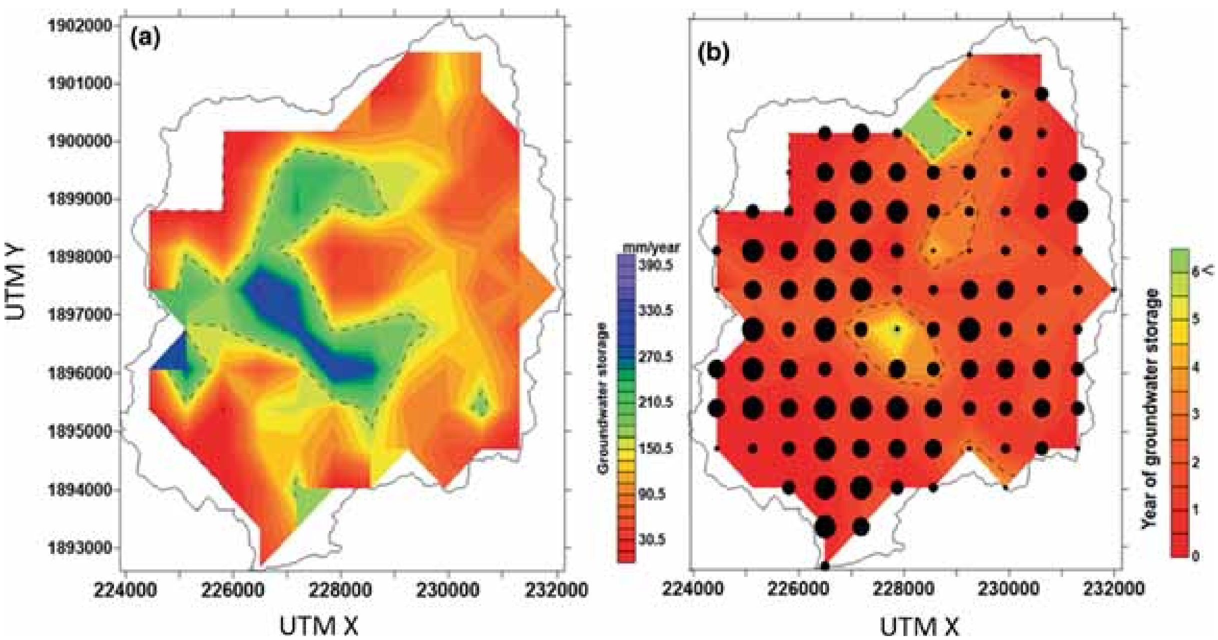

Figure 6. (**a**) Groundwater storage map at a spatial scale and (**b**) groundwater scarcity map over net pumping of the aquifer (cell size 685 m × 685 m).

relation with geology (figure 1) of the area, but Dewandel *et al.* (2012) observed that the low permeable zone of the watershed more or less coincides with the low Sy zone and vice versa. At the watershed scale, the spatial variability of Sy suggests that within the same weathering profile, a degree of weathering or density of fracture may notably vary from place to place. A similar observation was identified by Dewandel *et al.* (2017) in the different granitic terrain of India.

The groundwater storage and scarcity map (figure 6a and b) suggest that the groundwater-resource management measures are needed to limit the negative climatic impact on the farming economy. This could be done through maximising surface-water usage (direct use from tanks and favouring the cultivation of rain-fed crops; Perrin *et al.* 2012), through preserving and managing the artificial recharge structures (i.e., tanks; Boisson *et al.* 2014), and through the preservation of groundwater reserves to be used as a supplementary resource in dry years. This would, however, require strict demand-management measures (less pumping during dry years) and community-based water resource management.

The variation of groundwater pumping could be refined by using an almost real-time estimation of the irrigated areas. A method as described by Ferrant *et al.* (2017), for instance, could be used for monitoring the high short-term variability of irrigated areas as a proxy for estimating groundwater extraction.

8. Conclusions

A simple WTF method and groundwater budget equation with upscaling and regionalising of aquifer parameters, Sy values in two dimensions provide significant results in spite of the large variability and complexity in crystalline rock aquifers. This method is purely adapted in fractured aquifers, where hydro-dynamic aquifer parameters are not generally available on adequate location from the hydraulic test. This method required a good data set of water-level variation in the absence of recharge that is comparatively simpler and achievable with the use of automatic water level recorders (AWLR). We estimated the Sy values in the dry seasons because of the absence of recharge (>90% rainfall in the monsoon period). The Sy estimation at cell scale ranges from 0.2% to 5% (1.8% on average). The result closely matches with those of earlier studies in the area. In spite of the close match of the Sy range with that of Dewandel *et al.* (2012) values, a slightly different value was observed because of the corresponding elevation difference which suggests that the three-dimensional Sy model may be developed for the more accurate groundwater resource estimation (Dewandel *et al.* 2017; Mizan *et al.* 2019). This method provides the spatial distribution of Sy that can be used in groundwater modelling and for the testing of climate change impact (Ferrant *et al.* 2014; Dewandel *et al.* 2017).

The produced storage map is very useful for improving groundwater management policies because water demand in agricultural and industrial development has been increasing day by day, which leads to the overexploitation of numerous aquifers (e.g., Rodell *et al.* 2009; Tiwari *et al.* 2009). Water scarcity or drought map is of interest in the identification of the more exposed area to groundwater scarcity. Results from the maps have shown that two or three consecutive low monsoons may lead to drought in most of the area of the watershed. These maps also provide scientific basis to policymakers to enhance the capability of farmers to adapt their cropping pattern according to the natural resource availability.

These maps cannot predict the sustainability of groundwater in terms of the year without knowing the recharge pattern at the watershed scale. Thus, further research will be on the estimation of spatial recharge map at the watershed scale and its relation with rainfall, land use and soil pattern within the watershed. Based on this, long-term sustainable plans can be drawn for irrigation and domestic use.

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