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Appraisal of natural groundwater reserve using entropy-based model at the proximity of Deccan Trap Basalt and Gondwana Sandstone in a part of Central India

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Abstract

Natural groundwater reserve is an essential key parameter in the budgeting of water resources and its management because rainfall is the primary source of groundwater reserve. Thus, this article deals with estimating natural groundwater recharge with the help of an entropy-based model adopted at the proximity of Deccan Trap Basalt and Gondwana Sandstone in a part of Central India. About 43 observation wells located (area: ~360 km^2) in shallow aquifer revealing basaltic and sandstone formations under unconfined conditions showing spatial variability in natural recharge were considered. Transinformation, $T(R,WT)$ among the rainfall (R) and groundwater table (WT) as well as marginal entropy, $H(R)$, of the rainfall, was calculated at these wells and was used for assessing natural groundwater reserve. Results show that the estimated natural recharge varies from 6.72 to 32.80%, with an average of 22.89% of the SW monsoon period. The estimated groundwater recharge is having a good correlation among both the groundwater potential zones and recharge potential zones, which are obtained by applying the RS and GIS, and water level fluctuation with concerning rainfall, with the coefficients of r:0.88 and r:0.88, respectively. It has been found that groundwater reserves vary from 62.08 to 98.04 MCM, with an average of 76.22 MCM in the rainy season for the period of 2012–2019. The minimum reserve (~62.08 MCM) is estimated in the year 2014, whereas the maximum (~98.04 MCM) in the year 2013 during the monsoon periods. The estimated groundwater reserve could be utilized for the sustainable management of groundwater resources.

Keywords Shallow aquifer · Rainfall · Entropy-based model · Natural groundwater reserve · Deccan Trap Basalt and Gondwana Sandstone · Central India

Introduction

Groundwater resources demand to increase in different sectors like agriculture, drinking water supply, industrial growth development, and other domestic purposes (Das 2020). Irregular groundwater resources management can prompt various issues such as high pumping rate, decline of the well yields, changes in seasonal rainfall patterns, and reduction of natural groundwater reserve rate, especially in semiarid

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regions (Sukhija et al. 1996). The Annual Replenishable Ground Water Resources in India is 433 billion cubic meter (BCM), and the precipitation is the main drive for the natural groundwater reserve. About 253 BCM, out of 433 BCM, is contributed by the seasonal rainfall recharge (CGWB 2015). But the total water requirement of the country as of 2025 is assessed as 982.81 BCM, while 1082 BCM of water resources is the ultimate utilizable, including groundwater resources of 391 BCM (Das 2020). Sustainability of groundwater management in semiarid areas, mostly in hard rock terrains, the different, general recharge estimation problems, includes remarkably variability of groundwater recharge both space and time depending upon the climatic factors, land use and land cover changes, and type of soil cover condition (De Vries and Simmers 2002). It is essential to evaluate the natural water reserve for the development of long-term management of groundwater resources. Mostly, the recharge, which is a downward flow toward the

groundwater table, is categorized into the localized recharge and direct and indirect recharges (Chung et al. 2016).

Primarily, the natural groundwater reserve can be assessed utilizing both direct and indirect methods (Zimmermann et al. 1967; Scanlon et al. 2006; Mondal et al. 2012; Chung et al. 2016). However, the tracer technique is one of the direct methods of assessing natural groundwater reserve, mainly works in the principle of the piston-flow model (Zimmermann et al. 1967; Munnich 1968), and is being utilized in many parts of the world (Gupta and Sharma 1984; Athavale et al. 1992; Rangarajan and Athavale 2000; Chand et al. 2005; Rangarajan et al. 2009). Stable isotopes are also found useful for evaluating recharge (Sukhija et al. 2006), as physical-based methods (i.e., remote sensing (RS) and geographical information system (GIS) techniques) (Chowdary et al. 2009; Salem et al. 2019; Ajay Kumar et al. 2020; Mukherjee and Singh 2020) and GIS-based WetSpass model (Meresa and Taye 2019). The base-flow separation method (Risser et al. 2009), water table fluctuation method (Healy and Cook 2002; Moon et al. 2004; Crosbie et al. 2005), and water budget method (Maréchal et al. 2006) can also be utilized for evaluating natural groundwater reserve. Furthermore, hydrogeophysical method (Maliva et al. 2009) and numerical simulation (Yidana et al. 2013) have taken important roles in arid and semiarid regions for estimating recharge at artificial recharge sites. Nonetheless, a significant number of the techniques can be troublesome and tedious and can give unpredictable reserve estimates when there is inadequate scale data.

In this context, there is another branch of science in entropy theory, which is being more popular and also applied for estimating hydrogeological parameters. This theory, first established by Shannon (1948), is a potential tool. Many researchers have been used in different fields such as financial time series analysis (Ponta and Carbone 2018), economic (Zhou et al. 2010), excavating industry (Siradeghyan et al. 2008), biological studies (Rojdestvenski and Cottam 2000), and ecosystem (Zhang et al. 2006). Many investigators have also applied the concept of entropy in the field of hydrology and water resources for landscape characterization (Johnson et al. 2001), estimation of different parameters streamflow forecasting (Singh and Cui 2015), rainfall network (Chen et al. 2008), spatiotemporal variability of precipitation (Guntu et al. 2020), groundwater monitoring network (Mondal and Singh 2012), assessment of groundwater quality (Amiri et al. 2014), and hydrogeological pollution risk (Mondal et al. 2018). This entropy-based approach has firstly been explored to estimating the natural groundwater recharge and also tested in the Kodaganar river basin, Southern India (Mondal and Singh 2010). It has been found that this entropy-based model is a quick and straightforward technique for estimating groundwater recharge. Further, this concept has been adopted in a granitic area, where the estimation of natural groundwater recharge has been compared with the groundwater recharge potential zones (Mondal et al. 2012). Therefore, this technique has been adopted in a juxtaposition of Deccan Trap Basalt (DTB) and Gondwana Sandstone (SST) in a part of Chandrabhaga watershed, Nagpur, Central India. The main objectives of this work are (i) evaluating natural groundwater recharge and its input to groundwater system using the entropy-based model and (ii) establishment relationships with the groundwater potential zones and groundwater recharge potential zones, which are the base maps of the study area.

The area

The study area (an area of ~360 km^2) is located at the longitudes: 78°42′ E to 78°59′ E and the latitudes: 21°10′ N to 21°19′ N in a portion of the Chandrabhaga watershed in the conjunction of DTB and SST formations of Central India (Fig. 1). Topography varied from 300 to 530 m, above mean sea level (m, amsl). Geologically, the area underlies by the DTB formation (area: ~313 km^2) and the SST formation (area: ~47 km^2) (Mehta 1989; Varade et al. 2017). Chandrabhaga (an ephemeral river) along with the main sub-streams of the Mortham and Saptadhara rivers flows in between Sillori and Wadhona villages from west to east and joins ultimately the Kolar river, which is located to the eastern part of the watershed (CGWB 2015). Agricultural activity, especially orange cultivation, is prominent, followed by pulses, sugarcane, and cotton, which are irrigated crops.

Geology and hydrogeology

Basically, the study area is underlain in the Deccan Trap Basaltic (DTB) formations of upper Cretaceous to Eocene age. A small portion (~47 km^2) in the N-E part is covered with the Gondwana formations of Permian age (Fig. 1) and also in the southern part with a patch. These formations comprise mainly shales and sandstones associated with the Gondwana super-group of Barakara and Kamthi stages. Sometimes, the Deccan flood basaltic flows are characterized by the weathered, compact massive, and vesicular structures overlying the Gondwana formations (CGWB 2015; Varade et al. 2017). Groundwater occurs in the water table condition in the uncovered lava flows, whereas the semi-confined to confined conditions are found in the deeper flows. In each lava flow, groundwater occurs in the interconnected pore

Fig. 1 Location of the study area showing the monitoring wells along with geology and drainage pattern in a part of Chandrabhaga watershed, Central India
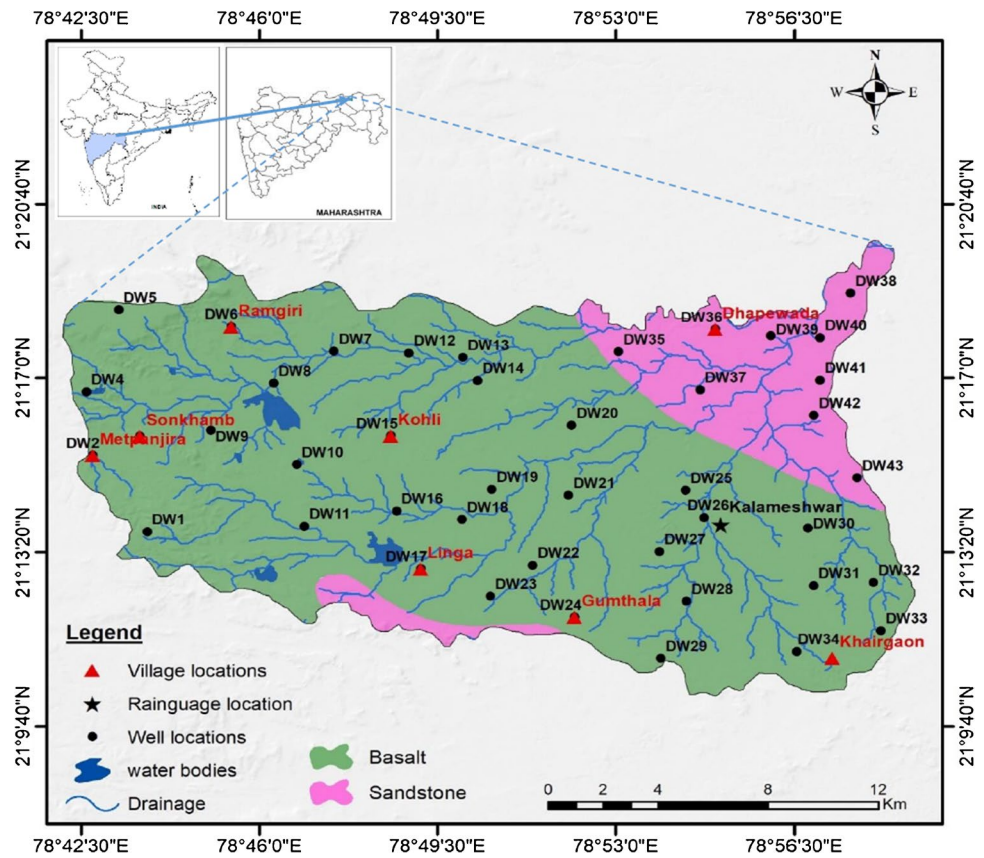
spaces of the vesicular basalts, joints, and fractures of massive basalts. Nonetheless, secondary porosity developed due to the weathering, fracturing, and jointing has substantially enhanced the volume of aquifer storativity. In the weathered basalts, the storage capacity depends upon the grain size and its shape in the regolith and also the degrees of cementation. The occurrence of shale with a sufficient thickness and another impervious unit above and beneath the sandstone also produces the confining condition in sandstone.

Materials and methods

Entropy-based model

Depth to the groundwater table (*WT*) fluctuates due to the natural groundwater recharge. The source of this recharge depends mainly upon the rainfall (*R*). But both are random variables, and for these random variables, the marginal entropies ($H(R)$ and $H(WT)$) are measured with the help of probability distribution and also characterized as the potential information of these variables (Mondal et al. 2012). Then the joint entropy denoted by $H(R,WT)$ is estimated as the total information having in both the *WT* and *R* measurements. Then the transinformation denoted by $T(R,WT)$ is calculated as the reduction

in the original uncertainty of the measurement of *WT* due to the knowledge gained in the measurement of rainfall (*R*). It will be provided us the measure of uncertainty that can be diminished in one of the variables when the other variable is known. Thus, the discrete forms of these entropies could be expressed as (Singh 1998)

$$H(R) = -\sum_{i=1}^{n} p(R_i) \ln p(R_i) \tag{1}$$

$$H(WT) = -\sum_{j=1}^{m} p(WT_j) \ln p(WT_j) \tag{2}$$

$$H(R, WT) = -\sum_{i=1}^{n} \sum_{j=1}^{m} p(R_i, WT_j) \ln p(R_i, WT_j) \tag{3}$$

$$T(R, WT) = H(R) + H(WT) - H(R, WT) \tag{4}$$

where *R* and *WT* are the discrete variables of rainfall and depth to water level. $R_i, i = 1, 2, …, n$, and $WT_j, j = 1, 2, …, m$, are defined in the same probability space. $p(R_i)$ and/or $p(WT_j)$ are the probabilities of *R* and *WT* occurrences; and $p(R_i, WT_j)$ are the joint probability of R_i and WT_j.
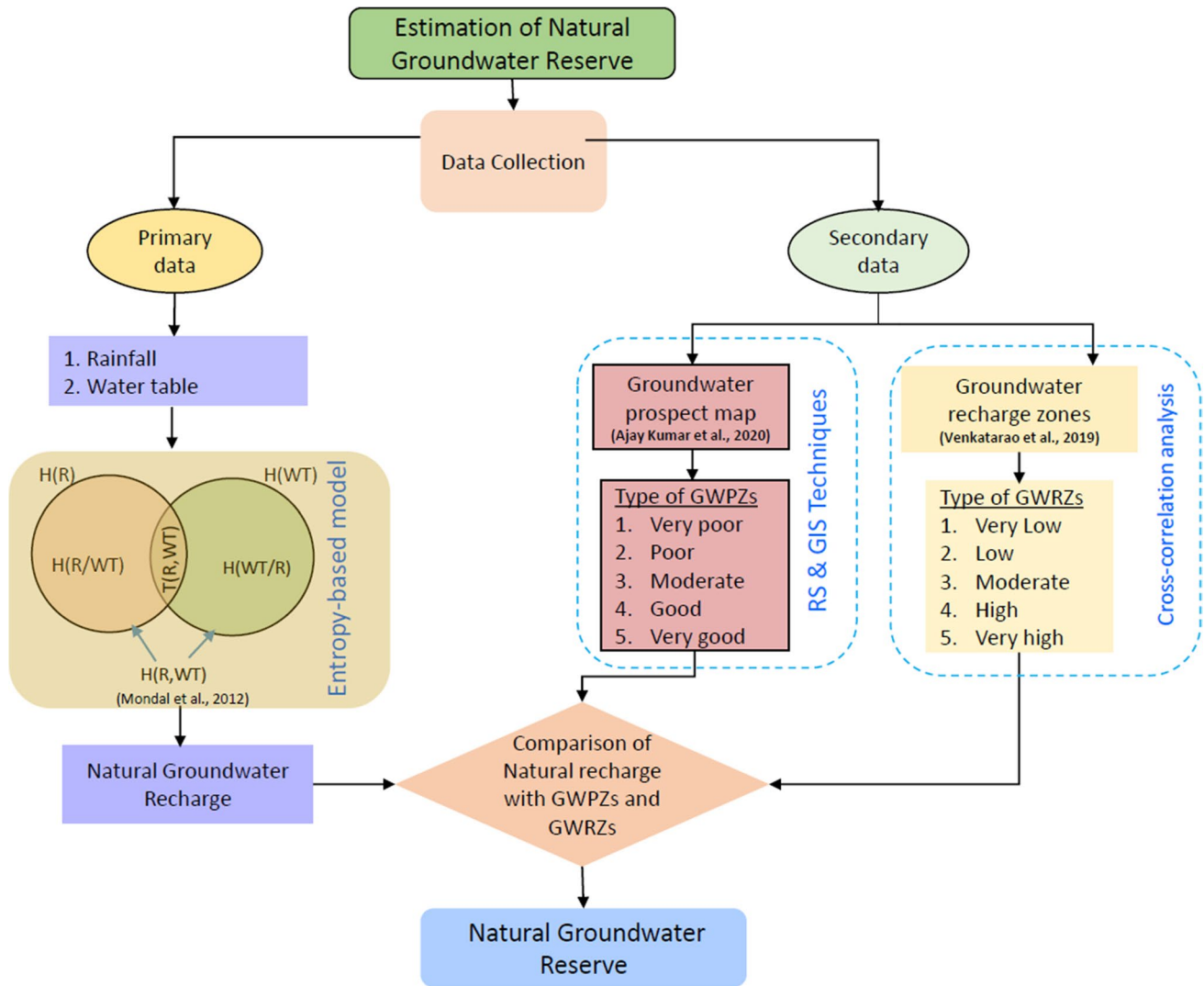
Fig. 2 Flowchart for estimating groundwater reserve at the proximity of Deccan Trap Basalt (DTB) and Gondwana Sandstone (SST) in Central India

The marginal entropy, H(R) is described as the potential information of the rainfall measurement (Fig. 2), then the ratio of T(R,WT) and H(R) is simply estimated the natural groundwater reserve due to the rainfall. The percentage of rainfall, $R_e(\%)$, contributing to the natural groundwater reserve had been estimated with the help of the following equation (Mondal et al. 2012):

$$R_e(\%) = \frac{T(R, WT)}{H(R)} \times 100 \qquad (5)$$

The 2^k rule

The 2^k rule is the most common statistical rule in deciding the number of classes required in characterizing data sets

(Abdi 2007). This rule just estimates the number of classes k in given N data points by understanding the condition of $2^k \geq N$. The estimated natural groundwater recharge was changed by the changing number of classes and the class intervals at the time of computing recharge percentages using this approach. This rule was applied in the recharge estimation to reducing the error of recharge percentage at the well areas in the study area.

Collection of hydrogeological data

Primary data

Measurement of groundwater level was carried out monthly at 43 observation wells during October 2011–November 2014, and in the same period, monthly

rainfall data were also gathered at the rain gauge station of Kalameshwar (source: IMD). The transformation values, $T(R,WT)$, for the rainfall and WTs along with the marginal entropy, $H(WT)$, of the groundwater level at these wells had been calculated. Then the percentage of rainfall as a natural recharge had been estimated with the help of Eq. (5).

Secondary data

In addition, the base maps such as the groundwater prospect map (Ajay Kumar et al. 2020) and recharge potential zones map (Venkatarao et al. 2019) were gathered to compare the estimation recharge values at each well site. The groundwater prospect map of the study area had been categorized as five groundwater potential zones namely

very good, good, moderate, poor, and very poor, whereas the recharge potential map had also been categorized into five groundwater recharge potential zones such as very low, low, moderate, high, and very high (Venkatarao et al. 2019). Both these maps were utilized to compare the estimated groundwater reserve. A flowchart for the estimation of groundwater reserve is shown in Fig. 2.

Results and discussion

Climate and precipitation

The study area is characterized by a warm summer season and frequent dryness throughout the year, except in the south-west monsoon (in June to September). The

Fig. 3 Showing **a** mean annual precipitation (in mm) and **b** mean monthly precipitation during the year 2011–2019 at Kalameshwar town, Nagpur City, Maharashtra (source: IMD)
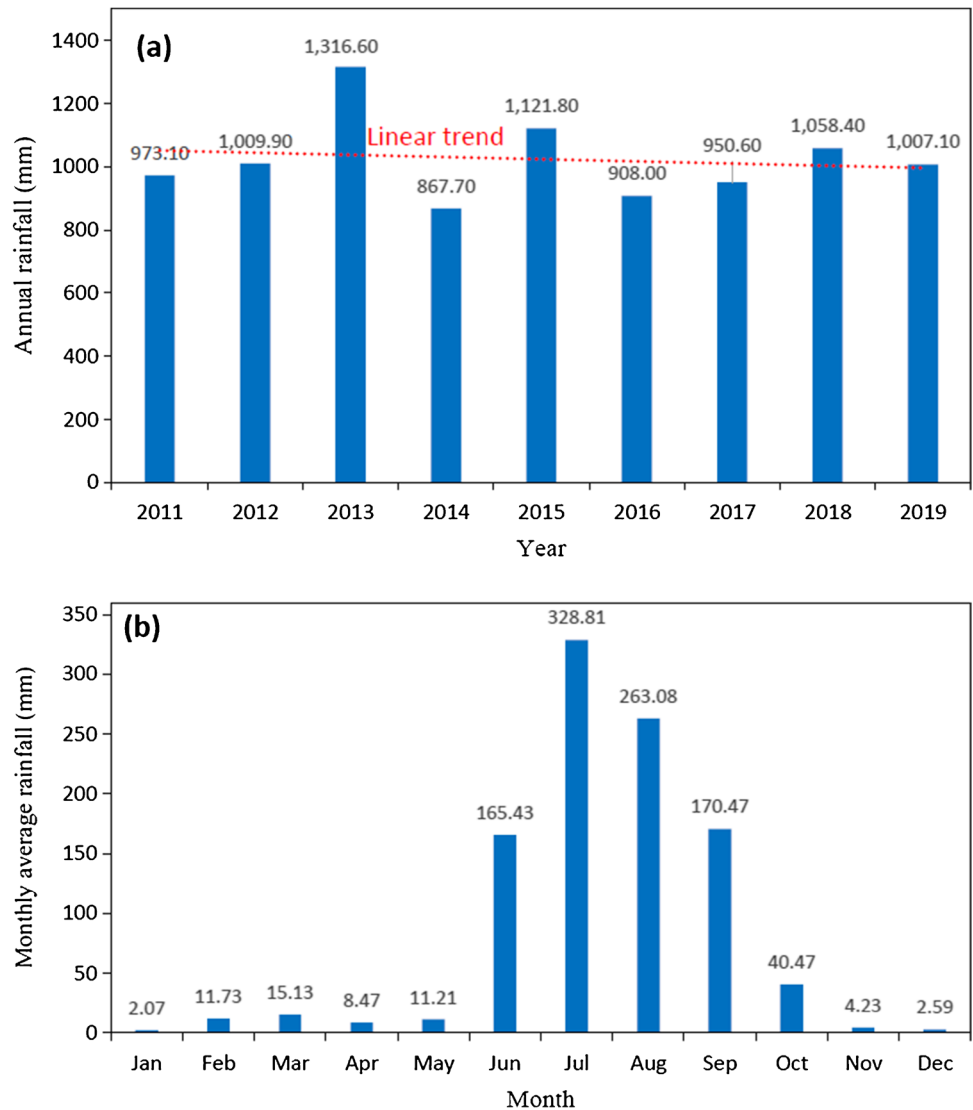
lowest temperature was recorded ~ 19.3 °C, and the highest temperature was ~ 36.3 °C. But the south-west monsoon was observed in June and ends in September and was more dominant (CGWB 2015). Monthly rainfall data was gathered for the period of 2011–2019 from a rain gauge station located at Kalameshwar town (situated at the N-W part of Nagpur City, Maharashtra). The analysis of rainfall data had indicated that the annual rainfall ranged from 867.7 to 1316.6 mm in the period of 2011–2019 (Fig. 3a) and the mean monthly precipitation is as shown in Fig. 3b. The seasonal wise rainfall contributes in various periods such as 1.75% of the annual rainfall precipitated in the months of January and February (winter season), 3.48% in pre-monsoon (March–May), 90.59% in the south-west rainy season (June–September), and 4.17% (October–December) in the post-monsoon (Fig. 3b). It had been observed that the seasonal rainfall was an average of 927.79 mm, which leads to contributing to the groundwater recharge due to the seasonal rainfall (Rangrajan and Athavale 2000; Mondal et al. 2012).

Shallow groundwater level

Monthly depth to the groundwater levels was collected from October 2011 to November 2014 measured at 43 monitoring wells (depth: 6.37–21.30 m, bgl), which had been uniformly spread in the entire study area (Fig. 1). The measurements of groundwater levels were mainly observed of the unconfined aquifer with the depth range of 2.40 to 13.30 m below ground level (m, bgl) (Table 1). In the DTB, the depth to groundwater level varied from 2.40 to 13.30 m, bgl, with a mean value of 6.07 m, bgl. But in the SST, the water table varied from 4.81 to 13.20 m, bgl, with a mean value of 8.27 m, bgl. The water level fluctuation also varied from 0.01 to 6.97 m, with a mean of 1.71 m during the monsoon period in the year 2014. It indicates that the water level in both formations was raised due to the rainfall where the response was comparatively more in the SST than that in the DTB areas. When water level hydrographs with rainfall data had been plotted, there was an approximately 1-month time lag in the response of water table to rainfall events (Venkatarao et al. 2019). Monthly variations of water levels and corresponding rainfall of well hydrographs at well DW38 (in SST) and DW20 (in DTB) are as shown in Fig. 4.

Entropy measure

To calculate information measures for the precipitation (R) and depth to water table (WT), the joint probability is essential, and this can be estimated using a contingency table (Mondal et al. 2012). An illustration of a 2-D contingency table has been made and also presented in Table 2. To construct this table, rainfall (R) data had been composed of u categories (class intervals), whereas the depth to water table (WT) data was assumed to the v categories (class intervals). Then, the joint frequency of (R,WT) categories by (i, j) is denoted by f_{ij}, $i = 1, 2,...,$ u, and $j = 1, 2,..., v$, where "i" is considered the column and "j" considered the row. Subsequently, the marginal frequencies were symbolized by fi. and fj. for the column and row of the random variables, respectively.

In Deccan trap basaltic areas, groundwater occurs in shallow weathered and fractured zones. The rise of groundwater levels was an immediate result of precipitation, especially in the rainy season, when groundwater extraction was minimum. The rise in the water table depends upon the typical feature of the unsaturated zone, which is site specific (Mondal and Singh 2004). Hence, for a specific area, there existed a certain relationship of the water level fluctuation corresponding to the precipitation. In the entropy prospective related to the two random variables having an individual information, some information was being transmitted from the precipitation to the groundwater. This transmission is defined as transinformation, $T(R,WT)$, and could be offered as proportional to groundwater reserve (Mondal et al. 2012). This idea was adopted to quantifying the groundwater recharge or identifying favorable recharge sites with the help of the base maps such as groundwater potential and groundwater recharge zones of the study area.

The 2^k rule

The change of estimated recharge values at a specific observation well to the number of classes had been plotted (Abdi 2007). It had been observed that the natural recharge at each well was computed for five distinctive class intervals with the number of classes of 4, 5, 6, 7, and 8, respectively. It had been observed that the minimum and precise values were for the number of classes was 6. A typical example from both the geological settings such as DTB and SST formations is shown in Fig. 5. The total number of events, N, was 38, and then the value of k was higher than or equivalent to 6. Therefore, using the k value of 6, the natural recharge values at each well were estimated in the study area.

Estimation of natural recharge

The entropy theory was adopted to estimate natural groundwater recharge. For this, the marginal and joint probabilities were calculated separately using a 2-D

Table 1 Details of monitoring wells along with the geology, groundwater potential zones (GWPz), and recharge zones (GWRz) at the proximity of Deccan Trap Basalt and Gondwana Sandstone in Central India

Well Id	Village (s)	Longitude (in degree)	Latitude (in degree)	Geology	GWPz	GWRz	Elevation (m, amsl)	MP (m)	Dia.(m)	Well depth (m, bgl)	Pre-monsoon WL (m, May 2014)	Post-monsoon WL (m, Nov. 2014)	Water level fluctuation (m, bgl)
DW1	Vasboli	78.730	21.229	Deccan Traps	VP	L	483.10	0.80	3.00	13.55	4.23	3.53	0.70
DW2	Metpanjira	78.712	21.256	Deccan Traps	VP	VL	426.16	0.38	4.15	12.17	8.39	6.82	1.57
DW3	Sonkhamb	78.728	21.263	Deccan Traps	VP	L	403.08	0.30	4.30	11.80	7.50	4.60	2.90
DW4	Lakholi	78.710	21.278	Deccan Traps	VP	VL	433.00	0.50	3.50	8.80	5.37	2.49	2.88
DW5	Malegaon	78.721	21.307	Deccan Traps	VP	VL	517.11	0.40	3.00	7.35	6.89	6.30	0.59
DW6	Ramgiri	78.758	21.301	Deccan Traps	VP	L	422.16	0.50	5.05	8.85	4.70	3.10	1.60
DW7	Khairul	78.791	21.293	Deccan Traps	P	M	363.81	0.65	1.10	6.75	4.82	3.75	1.07
DW8	Pardi	78.771	21.281	Deccan Traps	P	L	374.99	0.23	1.17	8.12	5.12	4.17	0.95
DW9	Chargaon	78.751	21.265	Deccan Traps	P	L	396.10	0.40	3.60	10.50	7.65	5.50	2.15
DW10	Dorli	78.779	21.253	Deccan Traps	P	M	382.12	0.60	3.60	12.70	6.97	5.30	1.67
DW11	Raulgaon	78.781	21.231	Deccan Traps	VP	VL	396.11	0.60	3.60	9.25	3.80	3.70	0.10
DW12	Susundri	78.816	21.292	Deccan Traps	G	VH	352.70	0.60	1.99	8.50	8.22	6.32	1.90
DW13	Sawangi	78.833	21.290	Deccan Traps	VP	VL	344.00	0.70	0.55	7.30	5.10	4.90	0.20
DW14	Wathoda	78.838	21.282	Deccan Traps	VG	VH	348.11	0.95	1.35	10.40	5.51	4.45	1.06
DW15	Kohali	78.810	21.263	Deccan Traps	M	L	301.00	0.45	2.80	11.25	7.37	5.05	2.32
DW16	Pohi	78.812	21.237	Deccan Traps	G	H	366.11	0.75	3.05	7.25	6.59	5.85	0.74
DW17	Linga	78.820	21.216	Deccan Traps	P	M	304.11	0.60	4.60	7.80	3.70	3.40	0.30
DW18	Sonegaon	78.833	21.234	Deccan Traps	M	M	356.80	0.00	6.40	8.30	4.16	2.60	1.56
DW19	Khapri	78.843	21.244	Deccan Traps	VG	VH	364.11	0.60	1.75	12.30	11.03	4.06	6.97
DW20	Ubali	78.869	21.267	Deccan Traps	VG	VH	338.10	0.50	1.60	14.00	11.15	9.00	2.15
DW21	Ghogali	78.868	21.242	Deccan Traps	P	M	338.00	0.75	2.95	12.15	8.25	7.88	0.37
DW22	Upparwahi	78.856	21.217	Deccan Traps	P	L	356.27	0.55	3.00	8.55	5.20	4.75	0.45
DW23	Nimboli	78.842	21.207	Deccan Traps	VP	VL	358.70	0.50	2.90	6.37	3.80	2.40	1.40
DW24	Gumthala	78.870	21.199	Deccan Traps	M	M	359.70	0.65	1.60	11.60	6.35	5.85	0.50
DW25	Brahmani	78.906	21.244	Deccan Traps	G	H	322.00	0.52	3.15	15.85	6.85	4.25	2.60
DW26	Kalmeshwar	78.913	21.234	Deccan Traps	M	L	329.11	0.50	2.50	10.35	10.10	7.23	2.87
DW27	Sawangi	78.898	21.222	Deccan Traps	M	VL	344.11	0.00	2.75	18.00	13.30	12.20	1.10
DW28	Waroda	78.907	21.205	Deccan Traps	VP	VL	326.00	0.80	1.93	10.72	6.77	6.50	0.27
DW29	Ketapur	78.898	21.185	Deccan Traps	VG	VH	358.60	0.50	4.00	10.10	5.70	4.23	1.47
DW30	Kalmeshwar	78.946	21.231	Deccan Traps	M	VL	327.00	0.50	2.90	13.55	5.90	4.32	1.58
DW31	Dahegaon	78.948	21.210	Deccan Traps	M	H	338.11	0.65	3.70	8.55	7.24	5.23	2.01
DW32	Ashti	78.968	21.211	Deccan Traps	P	H	328.11	0.35	2.70	13.25	7.65	7.05	0.60
DW33	Chicholi	78.970	21.194	Deccan Traps	G	H	348.71	0.45	3.15	12.25	6.85	5.40	1.45
DW34	Sahuli	78.942	21.187	Deccan Traps	M	L	351.29	0.80	3.00	12.20	10.15	7.90	2.25
DW35	Wadhone Buzurg	78.884	21.292	Gondwana	VP	VL	333.00	0.40	1.50	16.25	12.40	10.05	2.35

Table 1 (continued)

Well Id	Village (s)	Longitude (in degree)	Latitude (in degree)	Geology	GWPz	GWRz	Elevation (m, amsl)	MP (m)	Dia.(m)	Well depth (m, bgl)	Pre-monsoon WL (m, May 2014)	Post-monsoon WL (m, Nov. 2014)	Water level fluctuation (m, bgl)
DW36	Dhapewada	78.916	21.300	Gondwana	G	VH	328.11	0.80	3.00	14.25	10.55	8.23	2.32
DW37	Warode	78.911	21.279	Gondwana	G	H	322.17	0.75	4.40	21.30	8.05	4.81	3.24
DW38	Silori	78.960	21.313	Gondwana	M	H	302.91	0.52	2.65	10.53	8.38	7.28	1.10
DW39	Badangi	78.934	21.298	Gondwana	P	L	310.43	0.50	2.35	11.85	9.80	7.25	2.55
DW40	Borgaon	78.950	21.297	Gondwana	G	H	305.71	0.75	3.00	9.95	7.51	5.85	1.66
DW41	Tondakharil	78.950	21.282	Gondwana	VG	VH	319.00	0.50	0.20	19.10	13.20	10.00	3.20
DW42	Gowari	78.948	21.270	Gondwana	M	H	318.12	0.45	3.00	8.55	7.35	5.36	1.99
DW43	Pardi	78.962	21.248	Gondwana	G	VH	321.70	0.90	2.60	10.20	7.82	4.90	2.92

DW dug well, *MP* measuring point, *Dia* diameter of the well, *GWPz* groundwater potential zones, *GWRz* groundwater recharge zones, *VP* very poor, *P* poor, *M* moderate, *G* good, *VG* very good, *VL* very low, *L* low, *H* high, and *VH* very high

contingency chart for the water level as well as SW monsoon rainfall data at the proximity of DTB and SST formations in the Chandrabhaga watershed. In total, 38 and 12 events were separately utilized to the construct contingency tables of the monthly and SW monsoon data. A representation of a 2-D probability distribution at the well of DW18 (at village: Sonegaon) is presented in Table 3. The ranges of 0–80, 80–160, 160–240, 240–320, 320–400, and 400–480 mm for the rainfall data were considered to comprise 6 class intervals, while the water level as the ranges of 0–3, 3–6, 6–9, 9–12, 12–15, and 15–18 m, bgl, respectively. However, the joint frequency (i, j) was assumed as "i" for the rainfall and "j" for the depth to water table. Then, f_i and f_j were considered for the marginal frequencies of these two variables, respectively. The calculated marginal entropies of rainfall and water table, joint entropy, and transinformation were obtained as 1.496, 1.509, 2.772, and 0.233 bits, respectively (Table 3). Then the rate of natural recharge due to the rainfall was calculated with the help of Eq. (5) as 15.59% in the area of well DW18. In the same time, the natural groundwater recharge was estimated at all the well sites and also tabulated in Table 4 for both monthly and SW monsoon rainfall data. In the monthly data, the estimated transinformations were ranged from 0.019 to 0.469 bits, with a mean value of 0.295 bits, whereas it was ranged from 0.147 to 0.718 bits, with a mean value of 0.501 bits for the monsoon data. It indicates that the information gained in between rainfall and groundwater level was more dominant in the SW monsoon period compared to that in the monthly rainfall of the year. The average information gained was ~ 0.471 bits at the DTB and ~ 0.617 bits at the SST during the monsoon period. The estimated recharge was varied from 1.27 to 31.35%, with an average of 19.74% during the entire period (Table 4). In the SW monsoon, it was ranged from 6.72 to 32.80%, with a mean of 22.89% of the monsoon rainfall. But it was more as an average of 28.18% of the rainfall in the SST compared to the DTB of about 21.49% during the monsoon rainfall.

Relationship with the GWPz and GWRz

Cross plots of the estimated natural groundwater recharge with groundwater potential zone (GWPz) and groundwater recharge zones (GWRz) (Venkatarao et al. 2019; Ajay Kumar et al. 2020) had been separately made. The positive correlation in between the groundwater potential index (GWPI) and the percentage of natural groundwater recharge in the monsoon period was obtained with the value of $r = 0.88$ overall the study area, as shown in Fig. 6a. However, a significant positive correlation was noticed between GWPI against the percentage of
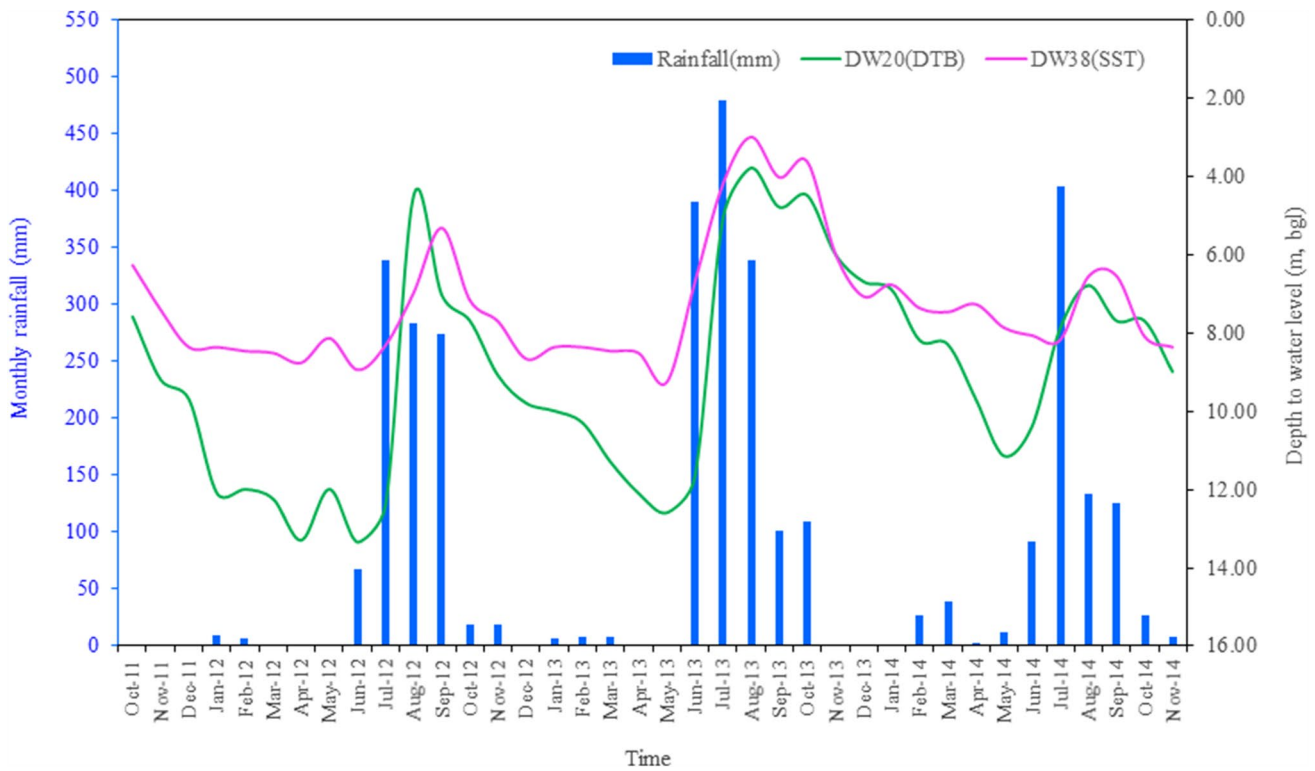
Fig. 4 Selective well hydrographs corresponding to the rainfall at well DW20 (in DTB) and DW38 (in SST) in the study area

Table 2 Two-dimensional contingency chart (frequency) (Mondal et al. 2012)

WT (j)	R (i)					Total
	1	2	3	……	u	
1	f_{11}	f_{12}	f_{13}	……	f_{1u}	f_1
2	f_{21}	f_{22}	f_{23}	……	f_{2u}	f_2
3	f_{31}	f_{32}	f_{33}	……	f_{3u}	f_3
			……			
			……			
			……			
v	f_{v1}	f_{v2}	f_{v3}	……	f_{vu}	f_v
Total	$f_{.1}$	$f_{.2}$	$f_{.3}$	……	$f_{.u}$	f_x or f_y

monsoon groundwater recharge at the DTB and SST areas with the correlation coefficient (r) values of $r = 0.88$ and 0.87 as shown in Fig. 6b, c.

We had also plotted the cross-correlation coefficients obtained with the fluctuation of the water table corresponding to the rainfall on the x-axis (Venkatarao et al. 2019) against the percentage of natural groundwater recharge in the monsoon period on the y-axis. A good linear relationship with the coefficient of $r = 0.88$ had been observed, as shown in Fig. 6d. However, the positive linear relationship between the cross-correlation coefficients compared to the percentage of monsoon groundwater recharge in both the DTB and SST with the correlation coefficients of 0.86, and 0.87, respectively, is obtained and is shown in Fig. 6e, f. It indicates that the estimated natural groundwater recharge was a good agreement with the demarketed groundwater potential and recharge potential zones at the proximity of DTB and SST in Central India.

Fig. 5 Estimate natural ground-water recharge (%) with respect to the variable class intervals
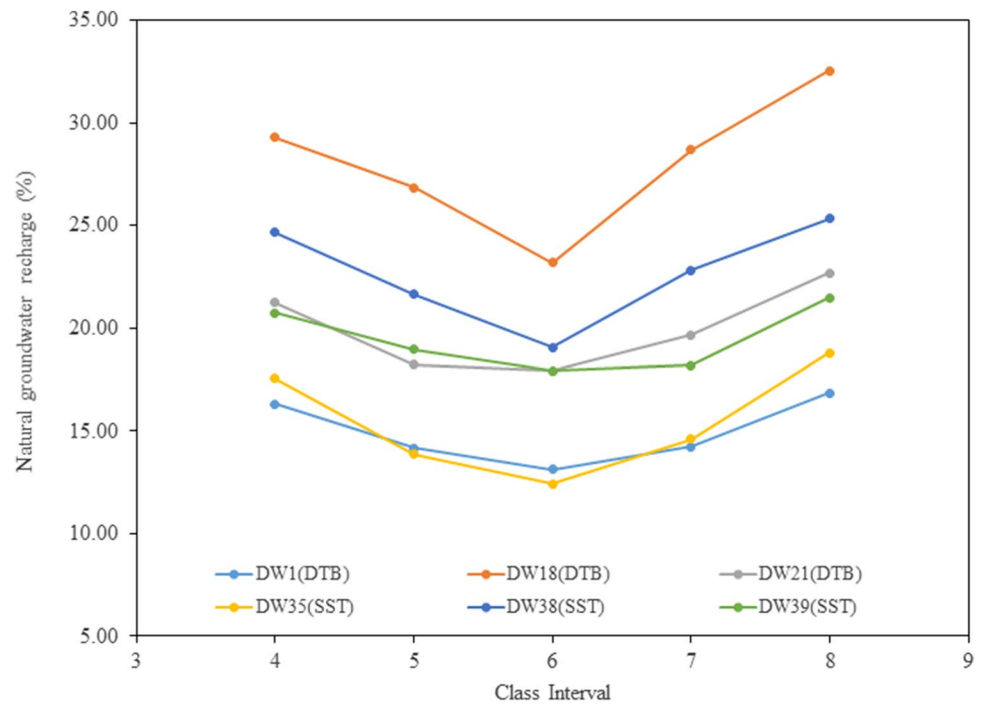
Natural groundwater reserve

The natural groundwater reserve was calculated using an entropy-based model at the proximity of DTB and SST in Central India, and it ranged from 62.08 to 98.04 MCM/monsoon rainfall, with an average of 76.22 MCM for the period of 2012–2019 (Fig. 7), which is almost the equivalent value reported by CGWB in the year 2008 (CGWB 2015). The minimum reserve of 62.08 MCM was estimated in the year 2014 and the maximum of 98.04 MCM in the year 2013. It had also found that an average groundwater reserve is more in Gondwana Sandstone with an average of 93.82 MCM than that in the Deccan Trap Basalt area with an average of 71.56 MCM in the Chandrabhaga river basin, Nagpur, Central India.

The spatial distribution of natural groundwater reserve for the monsoon period of 2019 had been made available and is also shown in Fig. 8. It had been observed that the natural groundwater reserve varied spatially depending upon the influence factors such as geological, geomorphology, soil, lineaments, and drain pattern of the study area. Its magnitude had nicely collaborated with the groundwater recharge potential zone of the study area (Venkatarao et al. 2019).

Conclusions

Natural groundwater reserve using an entropy-based model has been estimated at the proximity of Deccan Trap Basalt and Gondwana Sandstone formations in Central India. The study reveals that the estimated natural recharge ranged from 1.27 to 31.35% of rainfall, with an average of 19.74% annually. In the SW monsoon, it varies from 6.72 to 32.80%, with an average of 22.89%. The percentage of natural groundwater recharge has positive correlations with the groundwater potential zone ($r = 0.88$) as well as groundwater recharge zones ($r = 0.88$) achieved using the RS and GIS techniques and the correlation coefficients among the depth to water level and rainfall, respectively. The calculated natural groundwater reserve varies from 62.08 to 98.04 MCM, with an average of 76.22 MCM during the monsoon period. The reserve is nicely manifested with the recharge prospect zones of the study area, which will help to develop groundwater management practices such as the construction of artificial recharge structures.

Table 3 Absolute frequency 2-D contingency chart for the depth to groundwater table (*WT*, m, bgl) and rainfall (*R*, in mm) at well DW18 at the DTB formation, Central India

WT(j)/DWL(m)		R (i)/Rainfall (mm)						Total	Pj	ln Pj	Pj ln Pj
		i=1	i=2	i=3	i=4	i=5	i=6				
		0–80	80–160	160–240	240–320	320–400	400–480				
j=1	0–3	9	4		2	1	2	18	0.474	−1.078	−0.511
j=2	3–6	11	0	0	0	1	0	12	0.316	−1.663	−0.525
j=3	6–9	6	1			1		8	0.211	−2.248	−0.473
j=4	9–12	0	0	0		0	0	0	0.000	0.000	0.000
j=5	12–15	0	0	0		0	0	0	0.000	0.000	0.000
j=6	15–18	0	0	0		0	0	0	0.000	0.000	0.000
	Total	26	5	0	2	3	2	38			
	Pi	0.684	0.132	0.000	0.053	0.079	0.053				
	Log Pi	−0.547	−2.926	0.000	−4.248	−3.663	−4.248				
	Pi*Log Pi	−0.375	−0.385	0.000	−0.224	−0.289	−0.224				
Pi,j		0.237	0.105	0.000	0.053	0.026	0.053				
		0.289	0.000	0.000	0.000	0.026	0.000				
		0.158	0.026	0.000	0.000	0.026	0.000				
		0.000	0.000	0.000	0.000	0.000	0.000				
		0.000	0.000	0.000	0.000	0.000	0.000				
		0.000	0.000	0.000	0.000	0.000	0.000				
Pi,j ln Pi,j		−0.492	−0.342	0.000	−0.224	−0.138	−0.224				
		−0.518	0.000	0.000	0.000	−0.138	0.000				
		−0.420	−0.138	0.000	0.000	0.000	0.000				
		0.000	0.000	0.000	0.000	0.000	0.000				
		0.000	0.000	0.000	0.000	0.000	0.000				
		0.000	0.000	0.000	0.000	0.000	0.000				

$H(WT)$ = 1.509 bits calculated from Eq. (2)

H(R) = 1.496 bits calculated from Eq. (1)

H(R, WT) = 2.772 bits calculated from Eq. (3)

T(R, WT) = 0.233 bits calculated from Eq. (4)

Re(%) = 15.59 calculated from Eq. (5)

Table 4 Showing the calculated natural recharge due to the rainfall using entropy-based model for (a) monthly and (b) monsoon data nearby dug well areas

| Well Ids	(a)For monthly data					(b)For monsoon season data				
	$H(x)$	$H(y)$	$H(x, y)$	$T(x, y)$	Natural recharge (%)	$H(x)$	$H(y)$	$H(x, y)$	$T(x, y)$	Natural recharge (%)
DW1	1.496	1.136	2.436	0.196	13.10	2.189	0.811	2.622	0.378	17.27
DW2	1.496	1.236	2.523	0.209	13.97	2.189	0.925	2.756	0.358	16.35
DW3	1.496	1.833	3.067	0.262	17.51	2.189	1.055	2.855	0.389	17.77
DW4	1.496	1.566	2.910	0.152	10.16	2.189	1.325	3.252	0.262	11.97
DW5	1.496	1.553	2.856	0.193	12.90	2.189	0.982	2.855	0.316	14.44
DW6	1.496	1.190	2.445	0.241	16.11	2.189	0.811	2.626	0.374	17.09
DW7	1.496	1.518	2.746	0.268	17.91	2.189	0.98	2.752	0.417	19.05
DW8	1.496	1.219	2.434	0.281	18.78	2.189	1.125	2.889	0.425	19.42
DW9	1.496	1.069	2.280	0.285	19.05	2.189	1.041	2.789	0.441	20.15
DW10	1.496	2.076	3.278	0.294	19.65	2.189	1.041	2.689	0.541	24.71
DW11	1.496	1.544	2.866	0.174	11.63	2.189	0.811	2.689	0.311	14.21
DW12	1.496	1.693	2.776	0.413	27.61	2.189	1.189	2.759	0.619	28.28
DW13	1.496	0.398	1.762	0.132	8.82	2.189	0.795	2.522	0.462	21.11
DW14	1.496	1.029	2.056	0.469	31.35	2.189	1.551	3.022	0.718	32.80
DW15	1.496	1.079	2.280	0.295	19.72	2.189	1.551	3.288	0.452	20.65
DW16	1.496	1.022	2.132	0.386	25.80	2.189	1.325	2.918	0.596	27.23
DW17	1.496	0.995	2.085	0.406	17.78	2.189	1.483	3.252	0.42	19.19
DW18	1.496	1.509	2.772	0.233	15.59	2.189	1.115	2.789	0.515	23.53
DW19	1.496	1.851	2.942	0.405	27.07	2.189	1.288	2.818	0.659	30.11
DW20	1.496	1.913	2.993	0.416	27.81	2.189	1.918	3.418	0.689	31.48
DW21	1.496	1.209	2.437	0.268	17.91	2.189	1.325	3.022	0.492	22.48
DW22	1.496	0.591	1.889	0.198	13.24	2.189	1.089	2.896	0.382	17.45
DW23	1.496	0.949	2.426	0.019	1.27	2.189	0.98	3.022	0.147	6.72
DW24	1.496	1.069	2.278	0.287	19.18	2.189	1.685	3.418	0.456	20.83
DW25	1.496	1.038	2.173	0.361	24.13	2.189	1.041	2.689	0.541	24.71
DW26	1.496	2.046	3.245	0.297	19.85	2.189	1.18	2.892	0.477	21.79
DW27	1.496	1.013	2.238	0.271	18.08	2.189	1.186	2.922	0.453	20.69
DW28	1.496	0.949	2.249	0.196	13.10	2.189	0.98	2.855	0.314	14.34
DW29	1.496	1.058	2.099	0.455	30.41	2.189	1.28	2.752	0.717	32.75
DW30	1.496	2.044	3.255	0.285	19.05	2.189	1.158	2.892	0.455	20.79
DW31	1.496	1.557	2.823	0.230	18.23	2.189	1.252	2.918	0.523	23.89
DW32	1.496	1.771	2.962	0.305	20.39	2.189	1.784	3.418	0.555	25.35
DW33	1.496	1.648	2.738	0.406	27.14	2.189	1.384	2.918	0.655	29.92
DW34	1.496	1.669	2.867	0.298	19.92	2.189	1.384	3.085	0.488	22.29
DW35	1.496	1.325	2.635	0.186	12.43	2.189	1.189	2.918	0.46	21.01
DW36	1.496	1.705	2.786	0.415	27.74	2.189	1.384	2.918	0.655	29.92
DW37	1.496	1.705	2.786	0.415	27.74	2.189	1.324	2.918	0.595	27.18
DW38	1.496	1.069	2.280	0.285	19.05	2.189	1.298	2.952	0.535	24.44
DW39	1.496	1.518	2.746	0.268	17.91	2.189	1.281	2.855	0.615	28.10
DW40	1.496	2.278	3.368	0.406	27.14	2.189	1.041	2.585	0.645	29.47
DW41	1.496	1.883	3.067	0.312	29.21	2.189	1.265	2.755	0.699	31.93
DW42	1.496	1.021	2.122	0.395	26.40	2.189	1.325	2.855	0.659	30.11
DW43	1.496	1.959	3.049	0.406	27.14	2.189	1.418	2.918	0.689	31.48
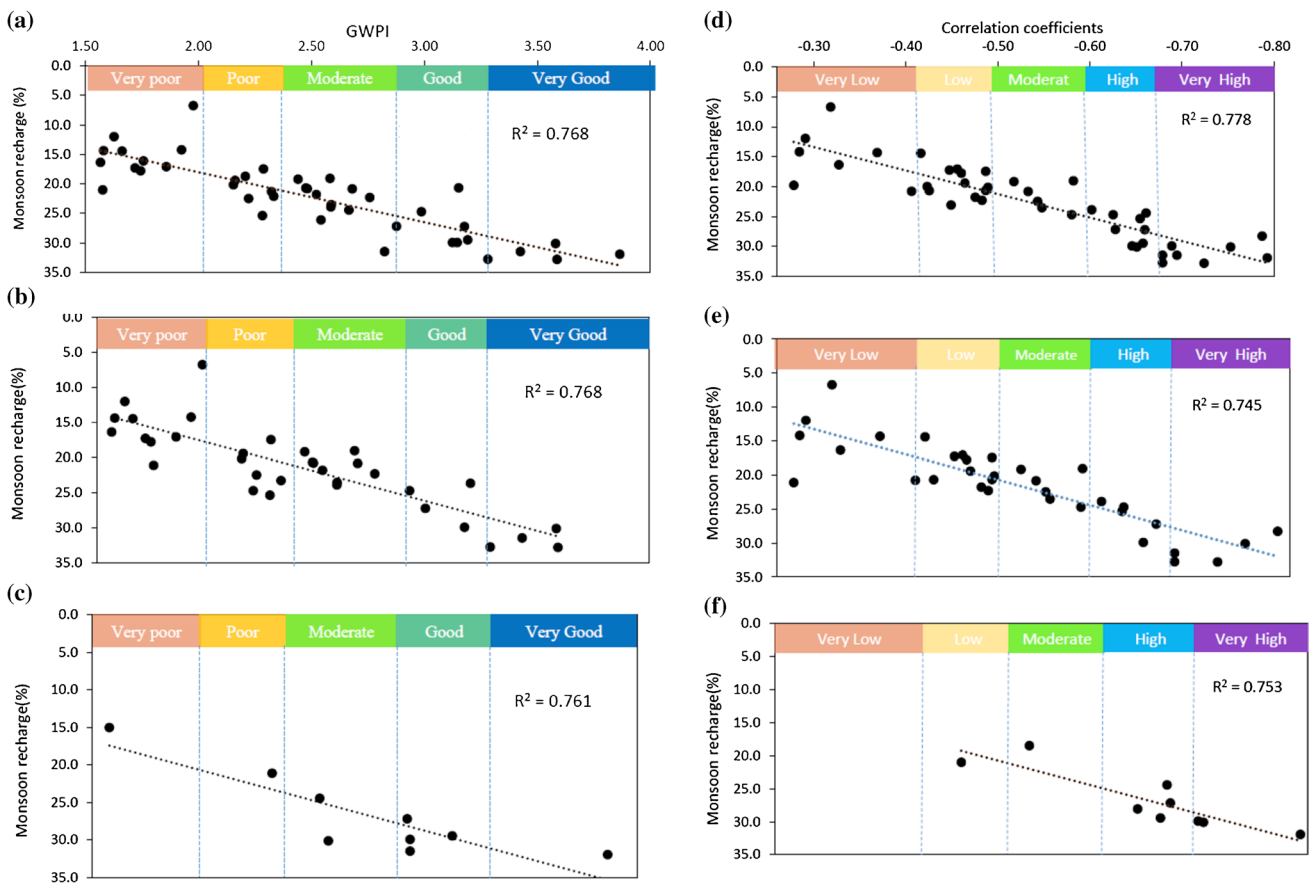
Fig. 6 Cross plots of the natural monsoon recharge with the groundwater potential zones for the **a** entire, **b** DTB, and **c** SST areas; and with the groundwater recharge zones for the **d** entire, **e** DTB, and **f** SST areas

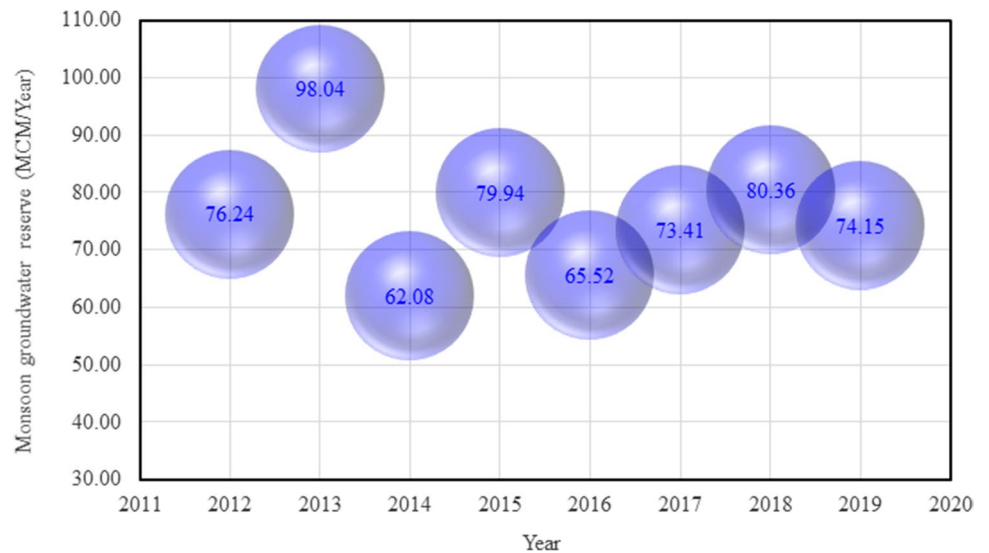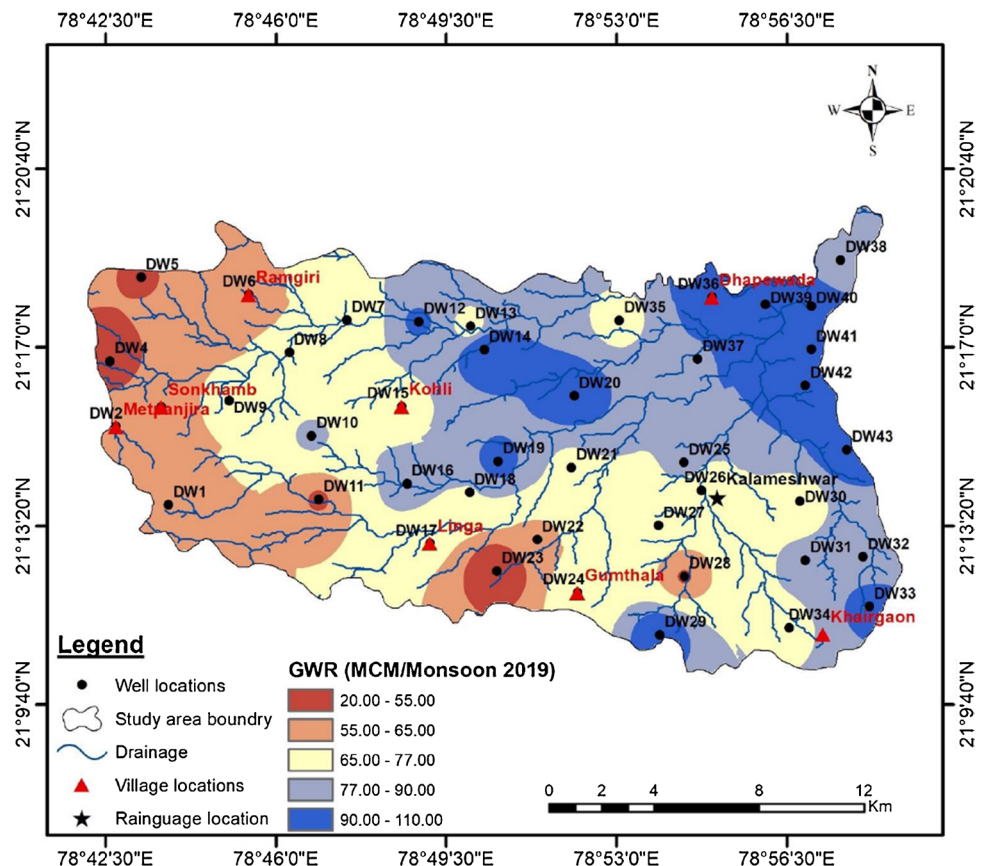**Fig. 7** Natural groundwater reserve in a part of Chandrabhaga watershed, Central India, in the period of 2012–2019

Fig. 8 Spatial distribution of natural groundwater reserve at the proximity of Deccan Trap Basalt and Gondwana Sandstone in Central India during the monsoon season

Declarations

Conflict of interest The authors declare that they have no competing interests.

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