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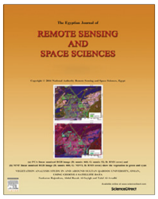

Research Paper

Hydrogeological delineation of groundwater vulnerability to droughts in semi-arid areas of western Ahmednagar district

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ABSTRACT

Groundwater, a renewable and finite natural resource, is a vital source of sustenance for humans and different ecosystems in the semi-arid regions. Rapid population growth in the last three decades has caused a rise in water demand which has inadvertently posed a stress on its availability. Occurrence of groundwater in the Deccan Volcanic Province is governed by the subsurface hydrogeological heterogeneity of basaltic lava flows and by the presence of geological structures like dykes, sills and fractures that influence spatial & vertical groundwater flow. The main objective of this paper is to map and assess areas that are naturally most susceptible to groundwater scarcity and at risk of depletion due to over extraction. The current study involves a field hydrogeological mapping that was integrated with remote sensing and GIS to delineate areas. This technique was based on using different thematic layers *viz.* lithology, slope, land-use and land cover, lineament, drainage, soil type, depth to groundwater and annual rainfall. Additionally, pumping tests were carried out to classify the study area into different hydrogeological typologies to help delineate communities that are most vulnerable to subsurface heterogeneity. This paper attempts to underline the groundwater scarcity zones based on different influencing thematic layers and provide a robust methodology to prioritize areas vulnerable to groundwater unavailability, by categorizing the study area into different vulnerable class types – extreme, high, moderate and low.

1. Introduction

Groundwater is a vital resource for communities and ecosystems in the semi-arid agro-climatic zone of Sangamner and Akole blocks of Ahmednagar district, Maharashtra, India. In the past few decades, groundwater withdrawal for public supplies, agriculture, industry and other uses has increased by a manifold. Agriculture intensification has resulted in expansion of groundwater irrigated area in India (Shah, 2008). Tian et al. (2014) studied large scale land transformations in India for the period of 130 years ranging from 1880–2010. The study indicated a dramatic shift in cropping patterns from rain-fed cereal crops to more water intensive cash crops; a significant loss of forest cover and an increase in cropland. These changes further pressurized the groundwater resources. Therefore its over-exploitation or indiscriminate extraction tends to deplete the shallow and deep aquifer water table. In mountainous areas, it also causes a reduction in the flow of springs (Thomas, 2011; Buono et al., 2015); a subsequent reduction in the base flows of streams and availability of water in open wells and lakes. Successive droughts and excessive extraction have induced a stress on the current aquifer regimes, which threatens the flow of many springs that emerge from this region (refer Fig. 1).

In the Deccan Trap Province, the occurrence of groundwater in basalts depends on differing hydrological properties of the rock types (compact, vesicular, amygdaloidal, inter-basaltic clay), degree of weathering and their intrinsic jointing patterns and fractures (Kulkarni et al., 2000). Rainfall plays a significant role regarding how water is distributed and is available for recharge in these regions. The underlying geology and deficiency in rains has seriously crippled the agrarian livelihood and could threaten the future of farmers who are dependent on irrigated agriculture (Shah, 2009; Udmale et al., 2014). Rampant well drilling due to groundwater unavailability for irrigation has pushed many of the farmers into a spiraling debt and ultimately to a suicide (Taylor, 2013). Knowledge of subsurface hydrogeology, hence, plays a vital role in regulation of drilling boreholes and aiding the communities to manage the underlying aquifers.

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Figure 1. Many remote communities are dependent on natural springs for drinking purposes, which ooze out through the basalt flow contacts (sheet pahoehoe flow units). (Location: *Kandobachiwadi, Pimpaldhari*).

The expanse of hard basaltic rocky terrain, also known as the Deccan Volcanic Province (DVP) or Deccan Traps, covers an area of more than 500,000 km^2 in the western central region of the country and exceeds more than1.5×10^6 km^2 of total flow, which makes it one of the largest, among other known continental flood basalt provinces namely Siberian and Paraná-Etendeka traps. The lava pile in DVP is thicker towards the Western Ghats and wanes down gradually towards the east. *Sangamner* and *Akole* region of Ahmednagar district, situated towards the western region, are underlined by massive lava pile consisting of flow units of varied thickness and belong to different flow types (Bondre et al., 2000, 2004). The flows are composed of compound pahoehoe (Duraiswami et al., 2001; Bondre et al., 2004), slabby pahoehoe (Duraiswami et al., 2003), rubbly pahoehoe (Duraiswami et al., 2008) and aa' types (Brown et al., 2011). The flow units are a result of volcanic eruptions which erupted through a series of long fissures that occurred approximately 65 million years ago (Chenet et al., 2007). The massiveness of these units presents itself as an impervious stratum which provides very little possibility for water to be recharged. Access to groundwater in such units is dependent on the availability of inherent structures like cooling joints, fractures and presence of intrusive features like dykes and sills. The region is cluttered with dyke swarms and fracture lineaments (Bondre et al., 2006) that are potential groundwater reservoirs (Duraiswami, 2005; Mège and Rango, 2010) and act as conduits for groundwater flow (Lie and Gudmundsson, 2002; Larsen and Gudmundsson, 2010) in the hard rock terrain (Deolankar et al., 1980; Peshwa et al., 1987; Babiker and Gudmundsson, 2004).

The failure of boreholes in the hard rock areas in Deccan Traps is a common phenomenon and has been happening more frequently than before. This can be attributed to over exploitation and incorrect site selection. Groundwater mainly exists in shallow weathered rock, vesicular and amygdaloidal rock, fractures and joints (refer to Fig. 2) (Kale and Kulkarni, 1993; Kulkarni et al., 2000). Locating groundwater productive zones and predicting the subsurface flow processes needs rigorous scientific survey. Recurring crop failures, due to insufficient rainfall and depleting groundwater in shallow aquifers, has resulted in a growing need for tapping deeper aquifers.

For spatial mapping of groundwater zones different methods like the overlay and index methods, process-based methods consisting of mathematical modelling and empirically based statistical methods (Eslamian, 2014) are available, but the overlay and index method was found to be suitable to delineate areas that are generally vulnerable to groundwater unavailability. Many studies based on integration of thematic layers have been geared towards identification of groundwater potential zones (Murthy, 2000; Dar et al., 2011; Magesh et al., 2012; Nag and Ray, 2014; Ibrahim-Bathis and Ahmed, 2016.) and recharge zones (Shaban et al., 2006; Duraiswami et al., 2009), however efforts to identify and delineate areas that face groundwater unavailability needs to be ascertained in order to increase knowledge at the village level. The multi influencing factor technique takes into consideration different thematic layers and its independent influences on each other. Hence this method is quite novel in spatial mapping of the vulnerable zones.

In lieu of vagaries of climate, this study aids in delineating vulnerable areas based on different influencing factors, which are at a serious risk from rainfall limitations and drought like conditions. It will also enable in strengthening the communities for sustainable management of their resources. Additionally it will aid in better formulation of adaptation strategies that requires to be adopted, given the current scenario of successive climatic drought conditions prevalent in this region.

2. Study area

The present study conducted in the year 2015–2016, comprised of seventeen villages from Sangamner and Akole block of Ahmednagar district as shown in Fig. 3 (*Jawalebaleshwar, Warudi Pathar, Gunjalwadi, Karjule Pathar, Mahalwadi, Sawargoan Ghule, Sarole Pathar, Dolasane, Malegoan Pathar, Khandgedara, Kuthe Khurd (kh), Kothe Budruk (Bk), Borban, Pemrewadi, Wankute, Bhojdari and Pimpaldhari*). These villages fall in the semi-arid region, with a mean annual precipitation being around 450 mm, and with a minimum and maximum average daily temperature of 12 °C and 42 °C respectively.

2.1. Geomorphology of the area

The study area depicts alluvial plains, undulating lands with mesas and buttes to dissected hills with escarpments and narrow valleys. The highest elevation in this area accounts to 1163 m

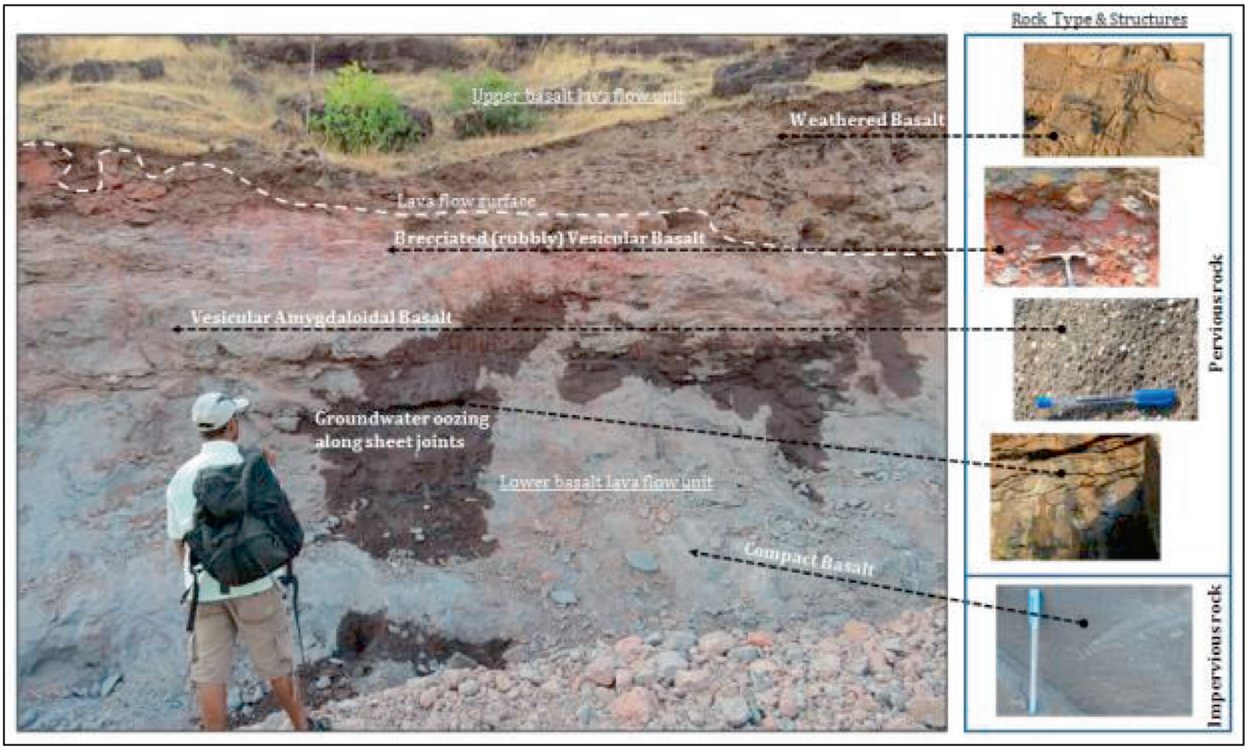

Figure 2. General anatomy of a basalt flow (rubbly pahoehoe flow) and typical groundwater occurrence in the Deccan traps.

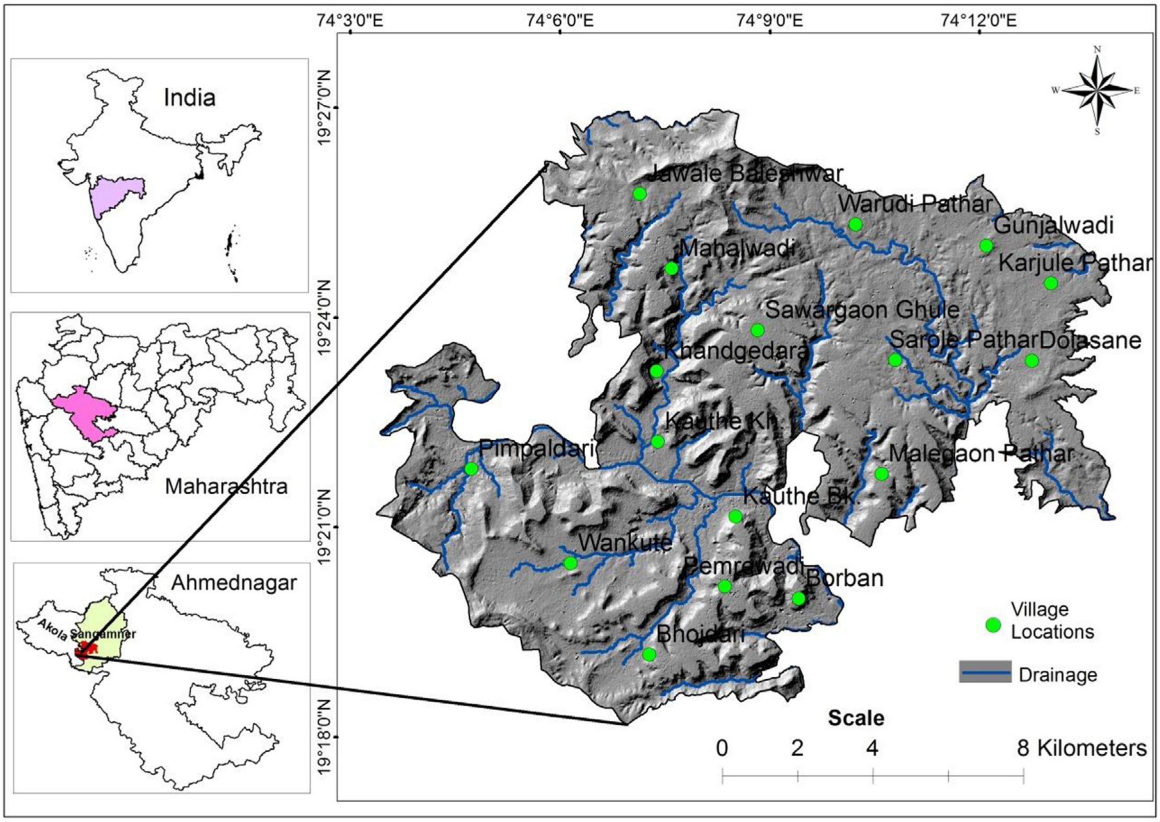

Figure 3. Location map of the study area – cluster of 17 villages with prominent drainage.

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above mean sea level (AMSL) to the north at *Jawalebaleshwar*, while the lowest elevation accounts to 620 m AMSL in the plains close to *Ghargoan*, towards east of study area.

The Mula River dissects the study area into northern and southern plateau regions, and is a sub-basin of Mula-Pravara tributary of the Godavari river basin. The study area consists of moderate to dense network of dendritic drainage pattern and portrays a slight structural control over the alignment of drainage channels because of the lineaments criss-crossing the area.

2.2. Geological and hydrogeological conditions

The study area consists of basalt flows that are nearly flat-lying (the sequence has a regional southerly dip of 0.5–1° and primarily belong to the Thakurvadi Formation of the Kalsubai Subgroup (Khadri et al., 1988; Bondre et al., 2006). Extensive colluvio-alluvial deposits of the late quaternary Pravara Formation (Bondre et al., 2000) overlie the basalts along the Pravara River and its tributaries. Patches of these sediments are also found along the Mula River (Refer Fig. 4). The basaltic flows belong to a varied range of flow types, compound pahoehoe, sheet pahoehoe, rubbly pahoehoe and aa' flow types (Refer Fig. 5a & b) (Bondre et al., 2004; Brown et al., 2011) and range in thickness from few tens of meters to over 50 m. They are made up of individual flow lobes ranging in thickness from a few cm to 20 m (Bondre et al., 2000, 2006).

In the Deccan Traps, the spatial and temporal distribution of compound pahoehoe and simple flows, differences in their internal structures with respect to brecciation, vesiculation, jointing patterns (colonnade, entablature & platy), and presence of intrusive features like dykes and sills (Refer Fig. 5c–h) have created diversity in the hydrogeological properties of these aquifers. This diversity is present within similar agro climatic zones. The inherent differences in the lava morphology, their geometry and the superimposing fabric of post volcanic tectonics are important, locally, in contributing to the anisotropic nature of the aquifer (Duraiswami et al., 2012). Owing to this anisotropic nature of the aquifers, multiple field traverses were undertaken to understand different hydrogeological scenarios existing in the area, which highlight the heterogeneity. Since the scope of the paper was to delineate areas at risk of groundwater unavailability, a general aquifer typology has been inferred, based on the geological (flow morphology) and hydrogeological investigations, namely – soft rock (alluvium), hard rock (basalt) and lineaments (dykes and fractures).

In most of the wells situated in the study area, groundwater was available until early months of summer. Many hamlets situated at higher elevations faced acute water scarcity during summers. Recoverable groundwater was restricted to two permeable zones of the flow i.e. the weathered upper portion to the vesicular crust and/or to the upper sheet joints and jointed core. Hydraulic conductivity between these zones and the shallow top-soil/alluvial aquifer determine the water bearing potentiality of the aquifer. The alternating geometry/disposition of flows results in a predominant horizontal permeability over vertical permeability (Duraiswami et al., 2012). Overall, the geological and hydrogeological conditions are not conducive for groundwater development that inadvertently hampers the overall groundwater availability. There has been push by the government of Maharashtra to provide farm ponds to each farmer owing to farmer suicides and agrarian crisis (GoM, 2016). Analysis of farm ponds and its impacts on the decline of groundwater is beyond the scope of this paper and needs further research. But during field studies, it was observed that these structures are lined with plastics and are used for surface storage of groundwater for irrigating annual crops. The authors believe that these structures are misplaced in context to semi-arid regions, where rainfall is scarce. Increase in the number of

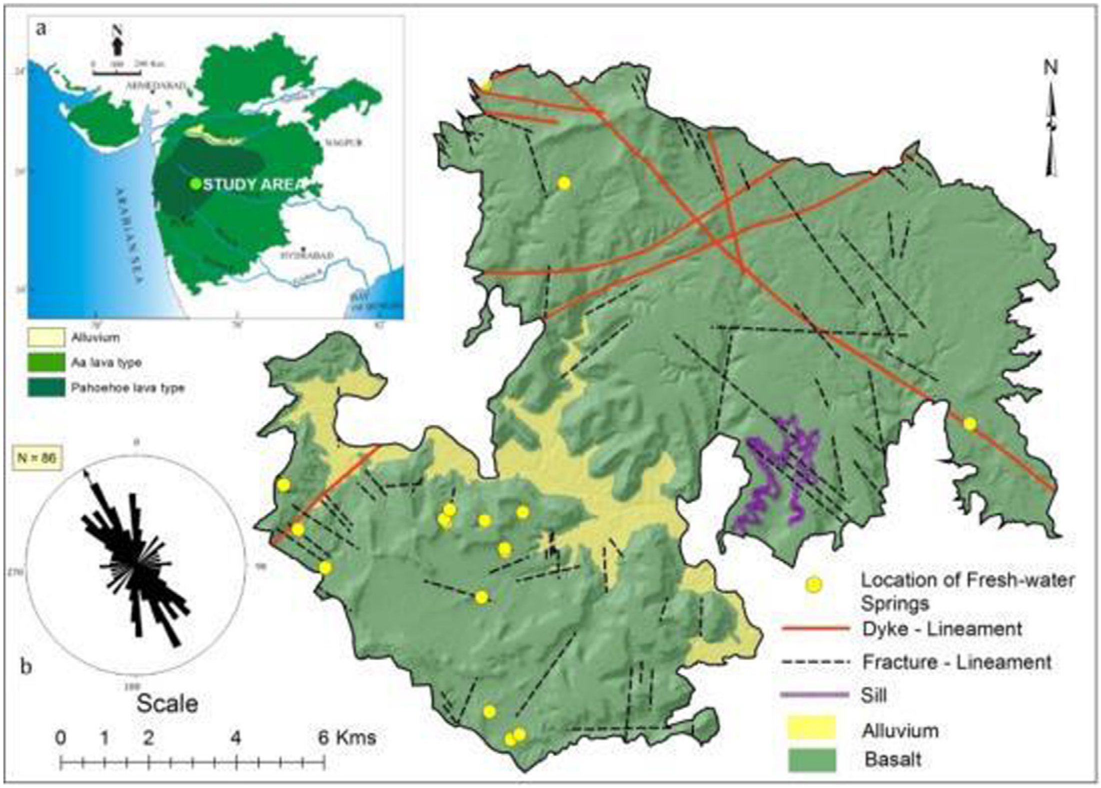

Figure 4. Hydrogeological map of the study area based on field transect surveys. Inset map: (a) Extent of the Deccan Volcanic Province and types of lava flows (adopted from Deshmukh and Sehgal (1988)) (b) Rossette Diagram of the lineament trend (n – 86) from the study area.

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a. Precursor Pahoehoe lava flow lobe seen in lower flow units at *Malegoan Pathar*. The lobe outline depicted in hashed line shows a red glassy rind.

b. Aa' flows showing jointed core and flow bottom breccia observed along the road between *Wankute* and *Bhojdari*

c. ~14 m thick vertical dyke cutting across the landscape at *Jawalebaleshwar*

Figure 5. Field photographs of different geological features from the study area villages.

farm ponds construction in the plateau region can have adverse impacts on groundwater available in the aquifers. The structures are supposed to be unlined and used for recharge. Under the government scheme; there has been a total of 349 farm pond constructed in the study villages. The recommended size being 10 m × 10 m × 3 m, but sizes greater than the recommended sizes were observed. This has allowed exposing of the finite groundwater resource to evaporation. This has serious repercussions on the availability of groundwater to other low income groups, putting people at high risk to future groundwater availability. Owing to low transmissivity and storativity of the aquifer, the communities are placed at a risk of resource unavailability over a long run.

Based on field observation studies and analysis of maps, three distinct aquifer typologies were identified namely – lineament zone, basalt zone and alluvium zone. In alluvial aquifer, the storativity of the aquifer is high and therefore the wells yield sufficient quantity of water throughout the year compared to basaltic aquifers. The groundwater generally flows from the plateau areas to the valley alluvial aquifer region. The storativity and transmissivity values range from low to moderate in fractured and jointed rocks. Wells located along the lineament zones tend to be more productive, owing to the openings that are available in the form of joints and fractures that allow groundwater to move easily. Springs that occur as natural flow of groundwater to the surface, feature along lineaments and along flow contacts. They are a vital source of drinking water for tribal communities.

Based on satellite imagery analysis and field survey, a network of lineaments in the cluster villages has been revealed. Majority of the lineaments trend in the NW – SE direction, but other minor lineaments also trending in N–S direction also feature in the study area. The lineaments in the area were composed of two types – fracture and dyke lineaments; only dyke lineaments were observed to having a curvilinear disposition. Analysis of fracture was carried out using Stereonet software (Allmendinger et al., 2011; Cardozo

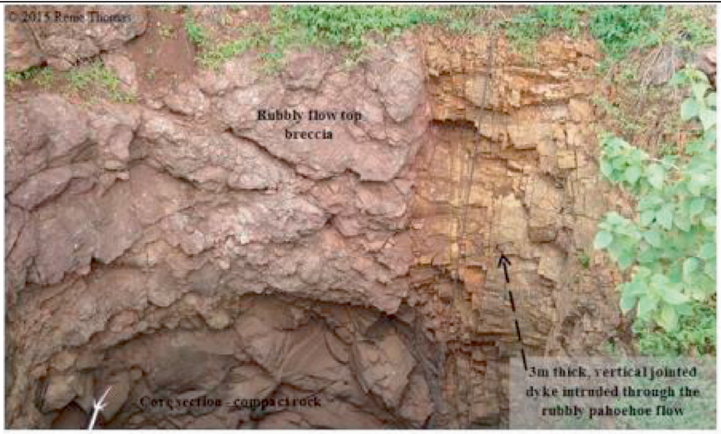
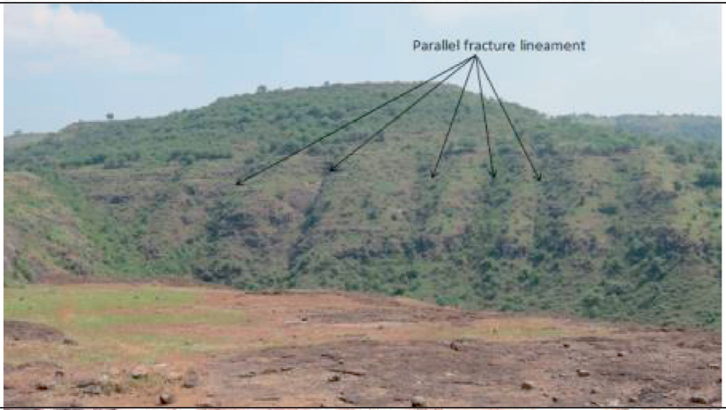
	d. Dug well exposing vertical dyke cutting through rubbly pahoehoe flow unit at *Sawargoan Ghule*
	e. Parallel fracture zones cutting across the Deccan lava pile exposed in *Jawalebaleshwar*
	f. Fracture lineament cutting through a dug well in *Pimpaldhari*

Fig. 5 (*continued*)

and Allmendinger, 2013). The fractures are usually related to shears and the dykes appeared to occupy dilatory tensional fractures (Deshmukh and Sehgal, 1988). Dykes occur as near vertical intrusions forming linear ridges of moderate relief and extend for tens of kilometers beyond the study area. They also show distinct vegetation growth along the ridges, which was used as one of the tool in spatial identification before embarking on ground verification of these features that indicate presence of shallow groundwater.

In *Malegoan Pathar*, sill intrusion was seen to be emplaced concordantly in a rubbly pahoehoe flow unit (Refer Fig. 5g & h), wherein the sill top margin was distinctly observed between a maximum elevation of 820–800 m and the bottom margin at a minimum elevation of 787–772 m. Its thickness approximates to about 30 m and shows a highly fractured rock and with a contorted joint pattern. Sill intrusion happens to be a common occurrence in the Deccan Traps (Duraiswami and Shaikh, 2013), and its presence in *Sangamner* tends to shed more light on the emplacement mechanism of the lava flows, the interconnected nature of unidentified nestled sill complex below and dyke intrusion in the region. The sill, that encircles the watershed boundary of *Malegaon*, was seen as a highly fractured and contorted one (slight folding observed within the sill segment) and happens to be hydrogeologically important, for its ability to soak in the recharge from precipitation. Documentation of dyke geochemistry (Bondre et al., 2006) and Aa' flow morphology (Brown et al., 2011) has been extensively carried out in the *Sangamner* region. The dykes are important hydrogeologically as they act as linear groundwater aquifers due to their close joint geometry (Duraiswami, 2005) and were seen crisscrossing villages in the north and in the south-west of the Mula River.

g. Highly fractured and thick (~30 m) sill emplaced in a rubbly flow unit seen on a winding road in *Malegoan pathar*

h. Highly fractured and contorted sill segment seen in *Malegoan Pathar*

Fig. 5 (*continued*)

Table 1
Dyke trend and their thicknesses as measured from the study area.

Dyke	Curvilinear – linear trend	Thickness (in m)
Pimpaldhari dyke	39°–41°–47°–50°–65°–38°	~7.0 to 7.5
Mahalwadi dyke	100°–90°–76°–62°–59°	~1.5 to 3.5
Jawalebaleshwar dyke 1	67°	~14.0
Jawalebaleshwar dyke 2	100°	~1.5 to 2.5
Jawalebaleshwar dyke 3	100°	~2.0 to 3.0
Warudi Pathar – Sawargaon Ghule	167°	~3.0 to 3.5
Dolasane – Sawargaon Ghule – Sarole Pathar dyke	302°–314°	~3.0 to 4.0

The dykes showed a curvilinear pattern; their general trends with their thickness are outlined in Table 1.

The dykes and sill showed a distinct cooling joint pattern, and were observed to be highly fractured that are naturally resistant to weathering. Due to their distinct fractured rocks, they act as conduits for groundwater movement and flow. Most of the wells situated along these features showed a distinct groundwater hydrology when compared to the host basaltic lava flow sequence.

3. Methodology

The approach adopted for the present study area has been presented in the form of a flowchart (Fig. 6).

It was used to create indices based upon the aggregation, or overlay, of many variables or factors collected based on field surveys and integration of remote sensed data sets that were deemed important in delineation of vulnerable zones. The formulation of the base map was based on Survey of India map (Toposheet No. 47 I/3), LANDSAT 8 and ASTER GDEM (30 m resolution) that was further pan sharpened to 15 m using band 8. As the study area falls under the Deccan Volcanic Province, consisting of hard basaltic rock type with varying aquifer properties influencing groundwater availability, field transect surveys were carried out to map the local subsurface heterogeneity in the rocks and to delineate the geological structures – lineaments in the area that are potential aquifers for groundwater storage. A total of 101 dug wells were monitored for the groundwater level during the pre-monsoon season and has been interpolated using inverse distance weighted method. Aquifer Performance Test (APT) was carried out to calculate storativity and transmissivity values for selected wells in different representative typologies. This was carried out using Theis (1935) and Cooper and Jacob (1946) methods, for unconfined & confined aquifers. The pumping test was scheduled to be in sync with irrigation timings of the farmers in order to prevent any wastage of water.

Eight influencing factors were considered to delineate groundwater vulnerable zones, *viz.* lithology, slope, land-use, lineament, drainage, soil, depth to groundwater and rainfall. These factors influence each other, hence, are interdependent. Their interrelationship is shown in Fig. 10. Based on the field inputs and different thematic layers generated using RS studies, each of these factors were allocated a fixed score and weight as shown in Table 2; that was computed using multi influencing factor (MIF) technique (adopted from Magesh et al., 2012). The effect of each major and minor factor was assigned a weightage of 1.0 and 0.5 respectively (Fig. 7). The cumulative weightage of both major and minor effects were considered for calculating the relative rates (Table 2). This rate was further used to calculate the score of each influencing factor. The proposed score for each influencing factor was calculated by using the formula:

$$\left[A + B/\sum(A + B)\right] \times 100$$

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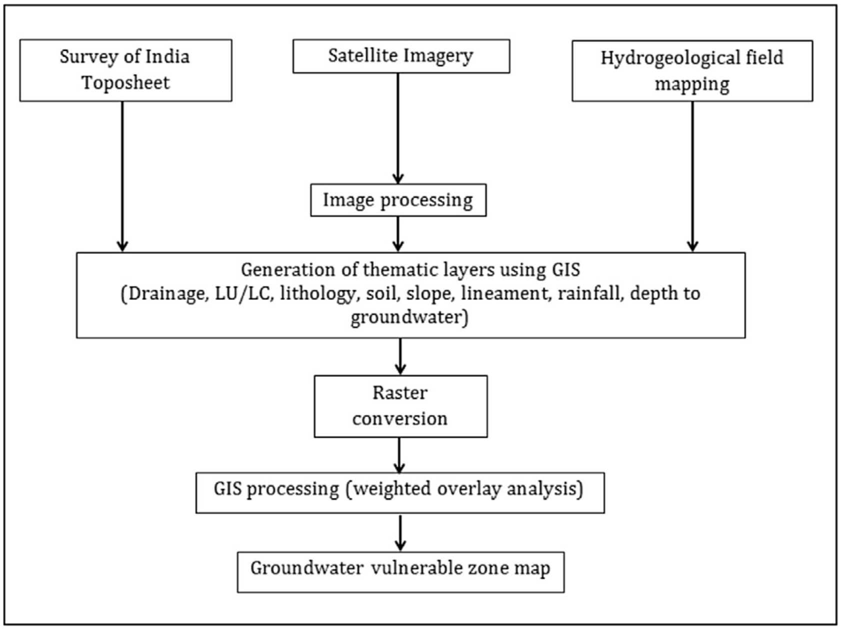

Figure 6. Flowchart for delineating the groundwater vulnerable zone.

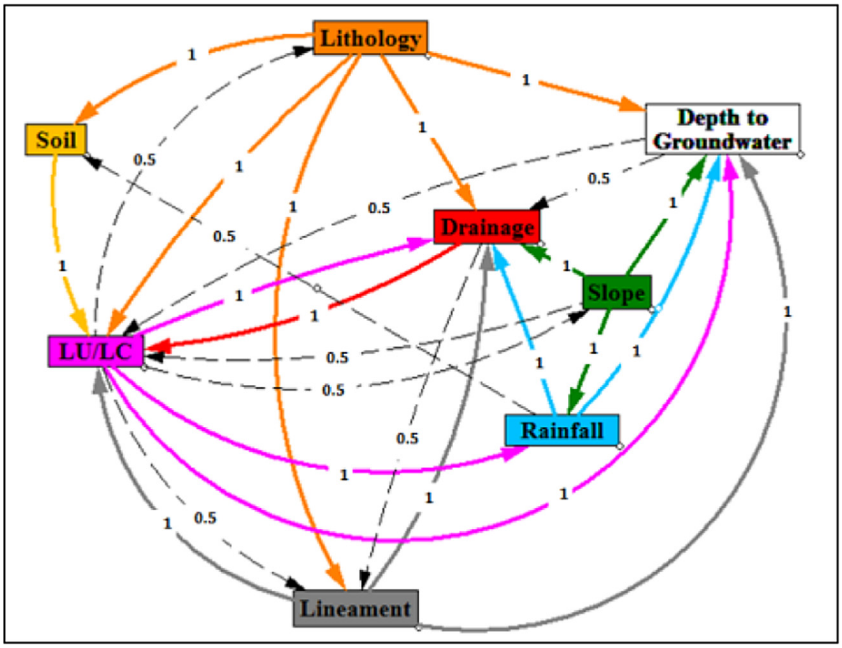

Figure 7. Multi influencing factors and their interrelationship used for delineation of groundwater vulnerable zone.

where,

A is major interrelationship between two factors, and

B is minor interrelationship between two factors.

Each relationship was weighted according to its strength. The representative weight of a factor of the vulnerable zone accounts to be the sum of all weights arising from each factor. A factor with a higher weight value shows a larger impact and a factor with a lower weight value shows a smaller impact on groundwater vulnerable zones. Integration of these factors with their potential weights was computed using weighted overlay analysis in ArcGIS.

Each weighted thematic layer was statistically computed to identify the groundwater vulnerable zones. The groundwater vulnerable zones, thus obtained were divided into four categories, *viz*., extreme, high, moderate and low vulnerable zones. The results depicted the groundwater scarcity zones based on different influencing thematic layers of the study area.

The concerned score for each influencing factor was divided equally and assigned to each of the reclassified factor (Table 3). The domains controlling the groundwater flow and availability in the hard rock terrain has been identified from various literatures dealing with the groundwater zonation. The domain linkages were ascertained with expert knowledge and based on collected data from the field studies. The corresponding weights have been identified from the major and minor effects of the domains.

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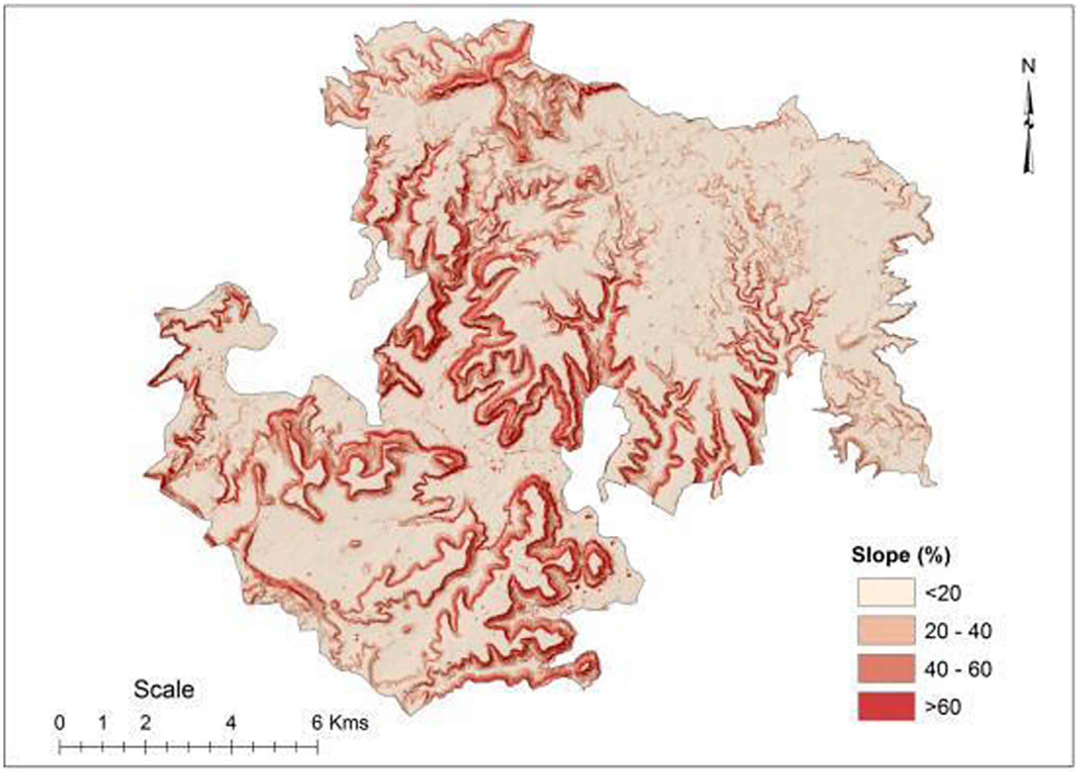

Figure 8. Slope map of the study area.

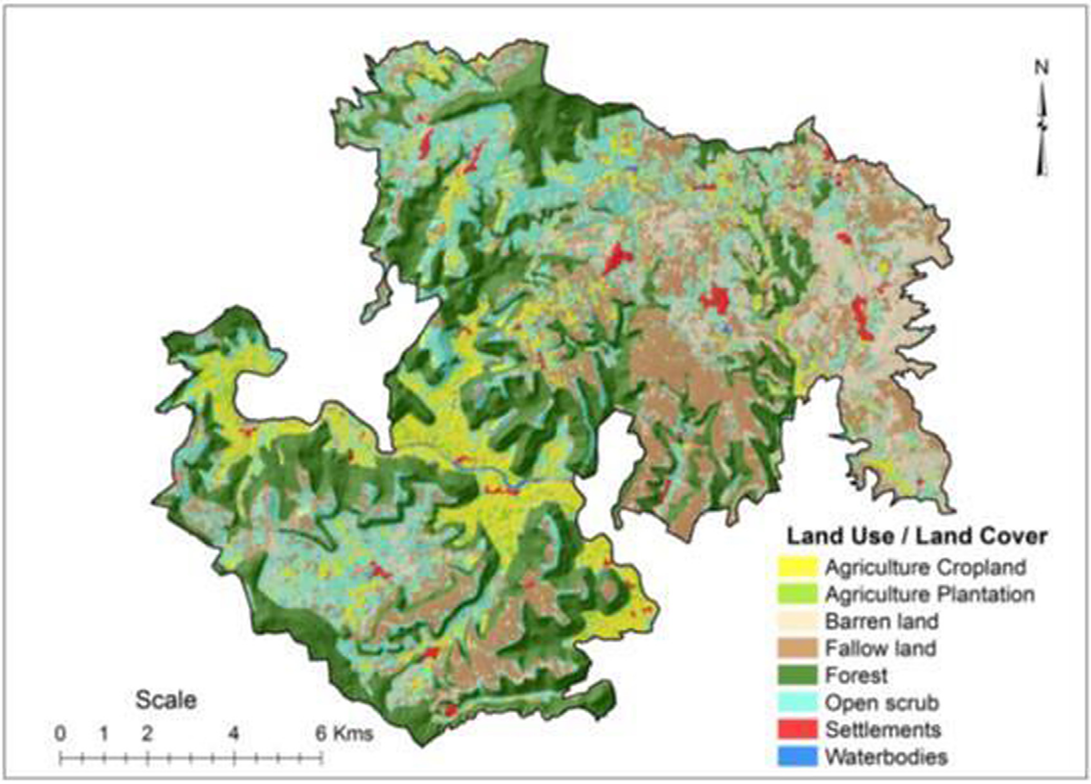

Figure 9. Land Use and Land Cover classification map of the study area.

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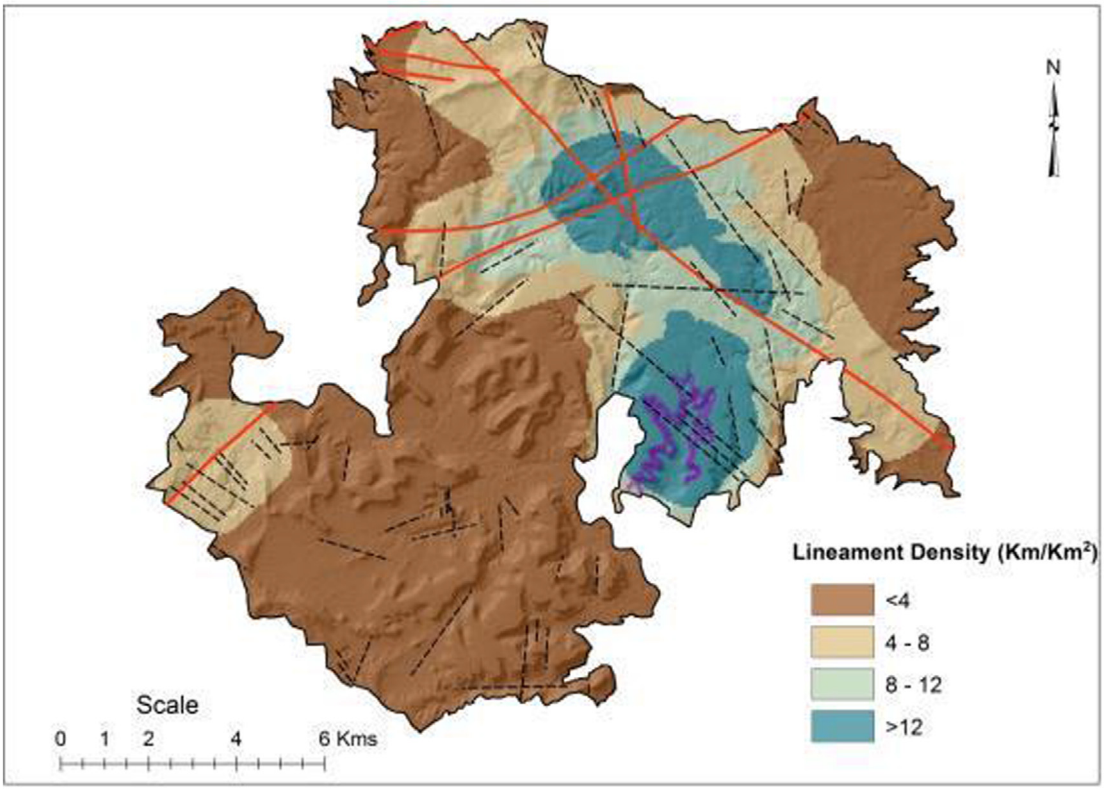

Figure 10. Lineament Density map of the study area.

Table 2
Effect of influencing factor, relative rates and score for each potential factor.

Factor	Major effect (A)	Minor effect (B)	Proposed relative rates (A + B)	Proposed score of each influencing factor
Lithology	1 + 1 + 1 + 1 + 1	0	5	22.72
Slope	1 + 1 + 1	0.5	3.5	15.91
LU/LC	1 + 1 + 1	0.5 + 0.5 + 0.5	4.5	20.45
Lineament density	1 + 1 + 1	0	3	13.63
Drainage density	1	0.5	1.5	6.82
Soil	1	0	1	4.55
Depth to groundwater	0	0.5 + 0.5	1	4.55
Rainfall	1 + 1	0.5	2.5	11.36
			$\sum 22$	99.99

4. Results

A major part of the study area falls under the hard basaltic typology which was further divided into sub-typologies based on the rock type, and alluvial cover was restricted to the valley region; their properties and integration of different thematic layers has helped in classifying them under different vulnerability risk as outlined in Table 4.

4.1. Lithology

In the study area, 94% of the area was found to be covered with Deccan basalts of Cretaceous age, 0.5% of lineament containing intruded dykes and fractures and the rest 5.5% of the area by the valley fill sediments and minor alluvium of recent quaternary age along the drainage courses (Fig. 4). The basaltic lava flow units consisted of vesicular, amygdaloidal and compact basalts and the thicknesses of the flow units also seemed to differ. The shallow weathered depth varied from place to place, which predominantly depended on the slope and degree of weathering. The sedimentary aquifers consist of alluvial with clay-lenses that forms unconfined to semi-confined conditions.

4.2. Slope

Slope is an important factor that influenced the groundwater availability. A higher degree of slope results in a higher run-off potential. The slope map was prepared using ASTER GDEM, wherein 65% of the area was <20% with low runoff, 19% of the area was between 20 and 40 with moderate runoff, 11% was 40–60 with high runoff and 5% of the area was >60% with very high runoff. (Refer Fig. 8).

4.3. Land-Use/Land cover

The major land-use and land cover type in the study area belonged to agricultural cropland and plantation, barren land,

Table 3
Vulnerability index weightage for different factors.

Factors	Domain of effect	Weightage
Lithology	Basalt	23
	Alluvium	12
Slope	<20%	4
	20–40%	8
	40–60%	12
	>60%	16
LU/LC	Open scrub, barren land & fallow land	20
	Settlement	15
	Agriculture plantation & forest	10
	Crop land	5
Lineament density	<4 km/km^2	14
	4–8 km/km^2	11
	8–12 km/km^2	7
	>12 km/km^2	4
Drainage density	<4 km/km^2	7
	4–6 km/km^2	5
	6–8 km/km^2	4
	>8 km/km^2	2
Soil	Clay	5
	Sandy Clay Loam	3
	Sandy Loam	2
Depth to Groundwater	<2 m	1
	2–5 m	3
	5–10 m	4
	>10 m	5
Rainfall	<400 mm	11
	400–450 mm	8
	450–500 mm	6
	>500 mm	3

fallow land, forest, open scrub, settlements and waterbodies. These land-use classes were identified using LANDSAT 8 satellite data using supervised classification (Rawat and Kumar, 2015). The classes were sub-divided into four groups namely; (i) crop land, (ii) agriculture plantation & forest, (iii) open scrub, barren land & fallow land, and (iv) settlement. The above groups were further regrouped based on the decreasing severity to groundwater availability criteria. Of the total area – open scrub, barren land & fallow land form the major class covering an area of 54%, followed by agriculture plantation & forests covering 32% of the study area, and the remaining area of 13% and 1% by crop land and settlement respectively (Refer Fig. 9).

4.4. Lineament density

Lineaments were found to be linear or curvilinear geological structural features and represent zones of structural weak planes denoting fracturing and faulting. Two distinct lineament types were identified with the aid of LANDSAT 8 and, ASTER GDEM data sets (Abdullah et al., 2010; Assatse et al., 2016) that were used to delineate dyke and fracture lineaments. Field traverses were undertaken to cross-validate the linear features. Greater density of lineament usually denotes permeable zone as the rock type is highly fractured and jointed. The lineament density map of the study area as shown in Fig. 10, reveals a high lineament density in the north-east and central region of the study area with a value ranging from 4 to >12 km/km^2 (Refer Fig. 10).

4.5. Drainage density

Drainage map was created by using ASTER GDEM and Toposheet. The drainage pattern was predominantly dendritic with most of drainage lines aligned to the lineaments. These classes were assigned into four groups, based on closeness of spacing of stream channel. Drainage density is a measure of the total length of the stream segment of all orders per unit area, calculated using line density analysis tool in ArcGIS software. High drainage density (>8 km/km^2) was recorded in the north-eastern and central alluvial plains. The drainage density is an inverse function of permeability. The less permeable a rock means less the infiltration of rainfall, which conversely tends to be concentrated in surface runoff. Groundwater scarcity areas of <4 km/km^2 density covered almost 68% of the total area, making it impermeable for groundwater recharge. (Refer Fig. 11).

4.6. Soil

Soil is an important factor for delineating the groundwater vulnerable zones. The moderate to deep black cotton clayey soils is a product of weathering of compact basalt rocks. The analysis of the soil type (based on Maharashtra Soils Sheet 1, National Bureau of Soil Survey (NBSS) and Land Use Planning (LUP), with Scale of 1:50000, revealed that the study area was predominantly covered by clayey soil (in the hilly and plateau region) with sandy clay loam occupying the parts of the plateau slopes and sandy loam soil along in the flood plains (Refer Fig. 12).

4.7. Depth of groundwater

As shown in Fig. 13and 65% of the area comprised of groundwater, whose depth ranged between 5 and 10 m below ground level (bgl). The groundwater level map was generated based on the pre-monsoon dug well static water levels of 101 wells. The depth of groundwater was found to be greater than 10 m in the villages of *Pimpaldhar*i, *Wankute*, *Swargoan Ghule*, *Gunjalwadi* and *Sarole Pathar*, wherein excessive pumping has been resulting in severe water shortages with most of the wells running dry by the end of January month. Most of bore-wells have reached almost 152 m depth, hence taping deeper confined aquifers.

4.8. Rainfall

The annual rainfall acts as an important factor that influences groundwater available for recharge in the semi-arid region. The annual average rainfall in the study area was found to be around 450 mm. Based on the automatic weather stations installed by Watershed Organisation Trust (WOTR); the local isohyetal precipitation map was delineated for the study area (Refer Fig. 14). The annual precipitation was observed to decrease from west to east.

The different thematic layers of lithology, lineament density, drainage density, slope, soil, depth to groundwater, land-use/land cover and rainfall were prepared with the help of satellite imageries coupled with cross validation on the field. The various thematic layers were assigned an appropriate weightage through MIF technique and then integrated into the GIS environment in order to prepare the groundwater vulnerable zone map of the study area as shown in Fig. 15.

In the study area, the majority of villages fall under ‘high’ vulnerability category (refer Fig. 16). The villages Wankute, Dolasane, and Sawargaon Ghule showed high proportion of area under ‘extreme’ groundwater vulnerable status, while Jawale Baleshwar village showed larger area under ‘extreme’ category. The reason for extreme vulnerability in the same village is mainly attributed to percentage area under different influencing factors and presence of higher weightage domain effects provided under various factors. The differing domains effects occurring in the same village boundary add to the complexity of different vulnerabilities. Irrespective of the administrative boundaries, the spatial distribution of controlling domains of the groundwater plays a major role on classifying the different vulnerabilities.

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Table 4
Aquifer properties of various typologies vis-à-vis vulnerability class defined for the study area villages (S & T values ranges adopted from Duraiswami et al. (2012)$^{\#}$ and CGWB groundwater exploration data (Lamsoge et al., 2015)$^{\#1}$, * – indicate field pumping test carried out at select wells by the author of this paper).

Typologies		Dominant Aquifer type	Storativity	Transmissivity (m^2/day)	Vulnerability class	Study area villages
Basalts	Weathered	Compound lobate – sheet lobate aquifers	0.001–2.8$^{\#}$ 0.11*	6–534$^{\#}$ 47.43*	High	Borban Malegoan Pathar* Bhojdhari
	Vesicular	Compound lobate – sheet lobate aquifers	0.8–2.9$^{\#}$	80–503$^{\#}$	High	Borban Bhojdhari Malegoan Pathar, Jawalebaleshwar, Sawargoan Ghule, Pemrewadi, Pimpaldhari
	Fractured/jointed	Sill, dykes & (columnar & sheet) joints	0.6–2.9$^{\#}$ 0.13*	26–450$^{\#}$ 112.6*	Moderate	Malegoan Pathar, Pimpaldhari, Sawargoan Ghule*, Warudi Pathar, Dolasane, Jawalebaleshwar, Mahalwadi, Sarole Pathar, Kandegedhara, Wankute, Bhojdhari
	Compact	Simple confined aquifers	0.08–0.1$^{\#}$	6–15$^{\#}$	Extreme	Dolasane, Karjule Pathar, Gunjalwadi, Warudi Pathar, Sarole Pathar, Sawargoan Ghule, Jawalebaleshwar, Mahalwadi Malegoan Pathar, Wankute, Pimpaldhari, Bhojdhari, Borban, Pemrewadi, Kandegedhara
Alluvium		Unconfined to semi-confined with clay lenses	0.16–3.5$^{\#1}$ 0.27*	12.7–2314$^{\#1}$ 174.2*	Low	Kothe Budruk*, Kothe Khurd, Kandegedhara, Pimpaldhari, Borban

5. Discussion

The half decadal cycle of climatic drought (scarcity of surface water) followed by agricultural drought (crop failure, fodder scarcity) leading to hydrological drought (drying of wells, and scarcity of drinking water) is familiar in the Trappean province. Groundwater, therefore, becomes the sole source of water for domestic and irrigation purpose (Duraiswami et al., 2012). The general anatomy of cooling joints, flow contacts and fractured rocks, and the vertical and spatial extent of individual flow units form potential aquifers in otherwise hard impervious basaltic terrain. Changing rainfall regimes and falling groundwater tables have aggravated the issue of water scarcity, and hence, tend to be one of the key drivers for excessive drilling and over-extraction of the groundwater in the region.

Even though there are different vulnerable categories exist in a same village, the majority of the area falls under ‘high’ and ‘extreme’ vulnerable category. The ‘low’ vulnerable zones exist, where the alluvial landforms, higher order stream channel in the planes and presence of structural lineaments support groundwater flow and storage. The current trend of groundwater usage (addition of new wells tapping multiple aquifers and pumping out groundwater for storing in the farm ponds) in the study area can induce the change of the ‘low’ vulnerable zones into ‘high’ and ‘extreme’ categories in the coming years. This persistent pressure on the limited groundwater resources needs proper management and conservation measures to sustain the existing climate change scenario. A pragmatic definition of the relative vulnerable zones and their corresponding scenarios is given in Table 5.

6. Conclusion

As the groundwater potential is low and the current practice of excessive pumping, regular impounding of groundwater in the farm ponds, drilling of new deeper wells with limited rainfall further aggravates its availability for future use. If the current practices continue ‘business as usual’, the ‘high’ category groundwater vulnerable villages are at further risk of being transformed into ‘extreme’ category. Hence, the delineation of groundwater vulnerable zones in the sixteen villages from Sangamner and one from Akole block, Ahmednagar district in Maharashtra using hydrogeological mapping, remote sensing, GIS and MIF techniques was found to be very useful for identifying areas that has a high probability to face recurring hydrological droughts due to groundwater unavailability and prioritize adaptive strategies for effective management of common pool groundwater resources.

In lieu of declining precipitation rates, identifying villages that are at serious risk of groundwater unavailability can provide useful guide to assist government and village bodies in making effective policy changes related to the land use planning and management

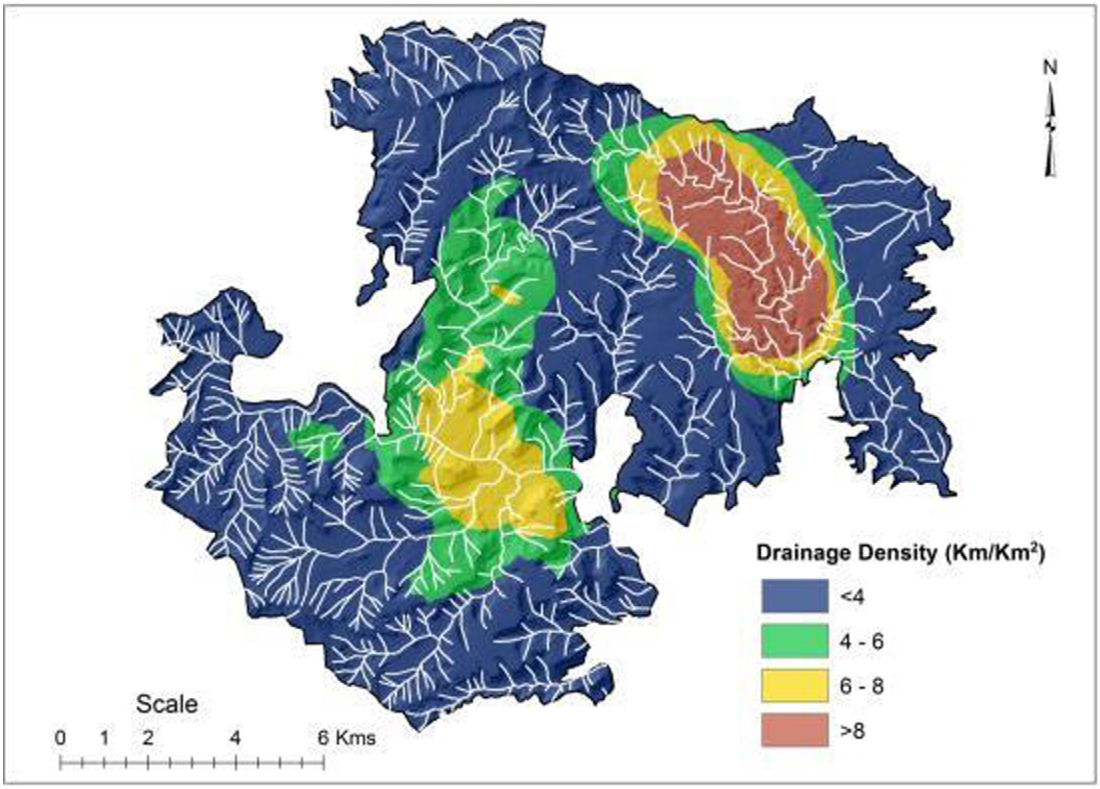

Figure 11. Drainage density map of the study area.

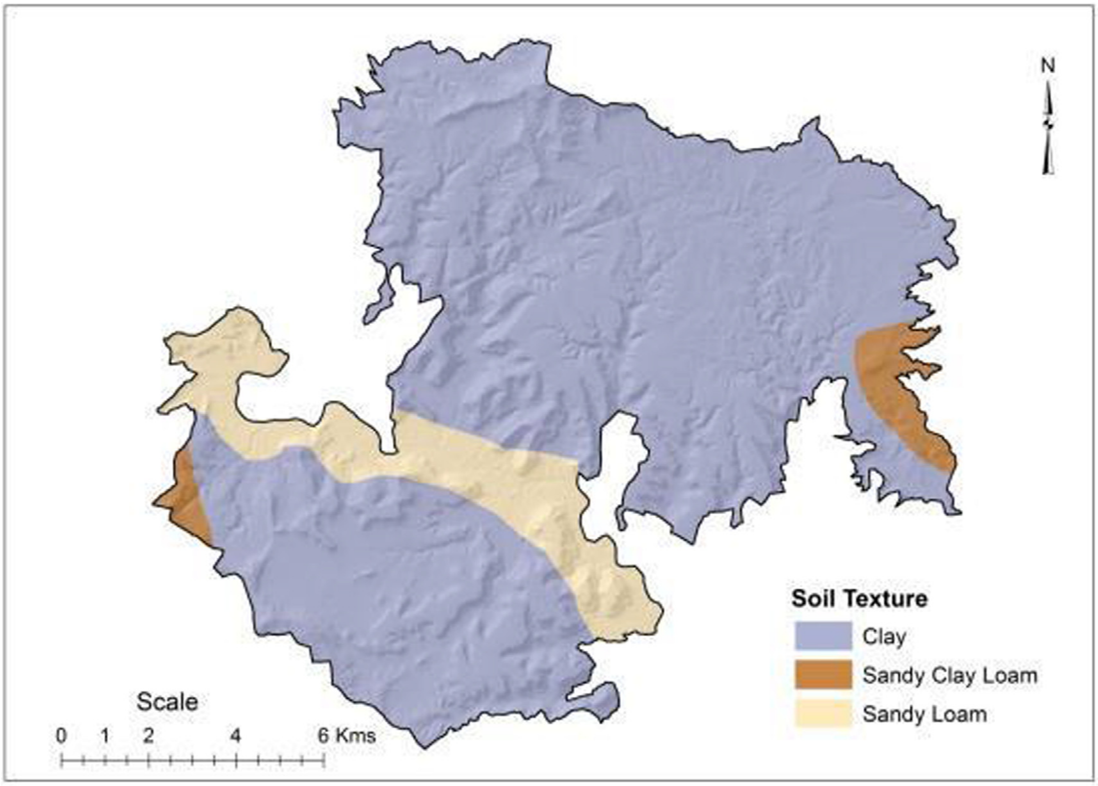

Figure 12. Soil map of the study area (adopted and modified from Maharashtra Soils Sheet 1, National Bureau of Soil Survey (NBSS) and Land Use Planning (LUP).

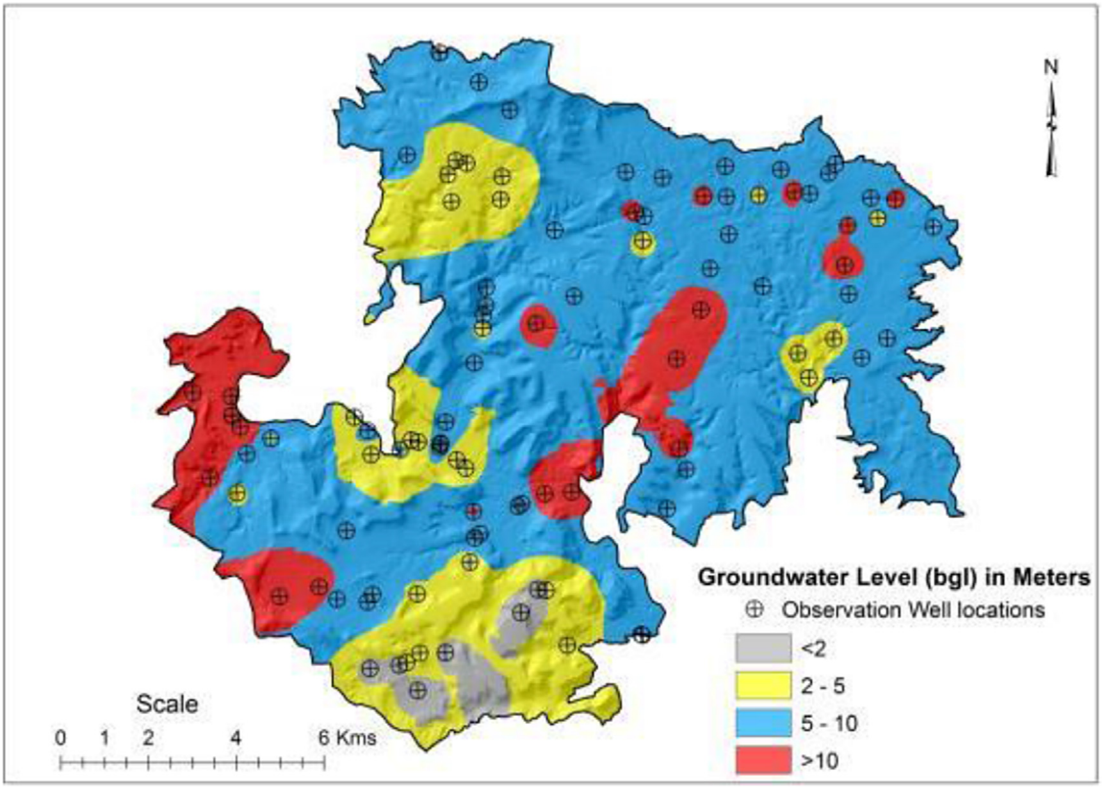

Figure 13. Pre-monsoon depth of groundwater level map in the study area.

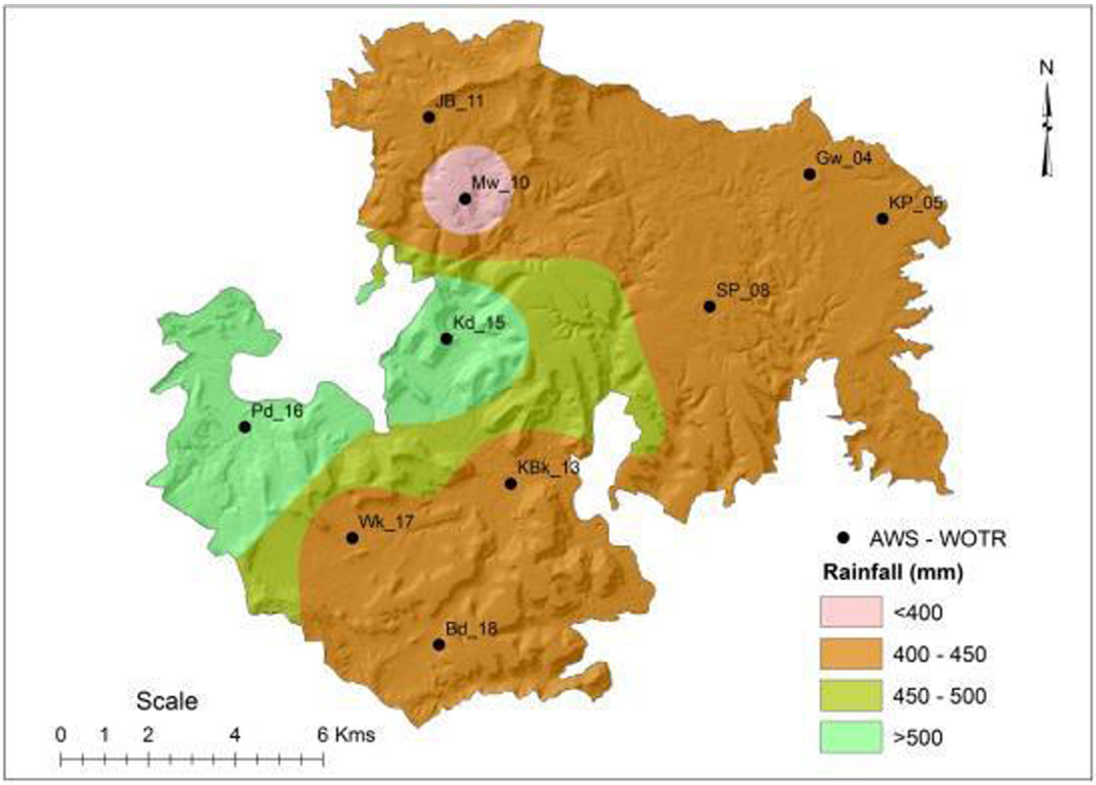

Figure 14. Rainfall distribution map in the study area based on Automatic Weather Stations installed by WOTR, Pune.

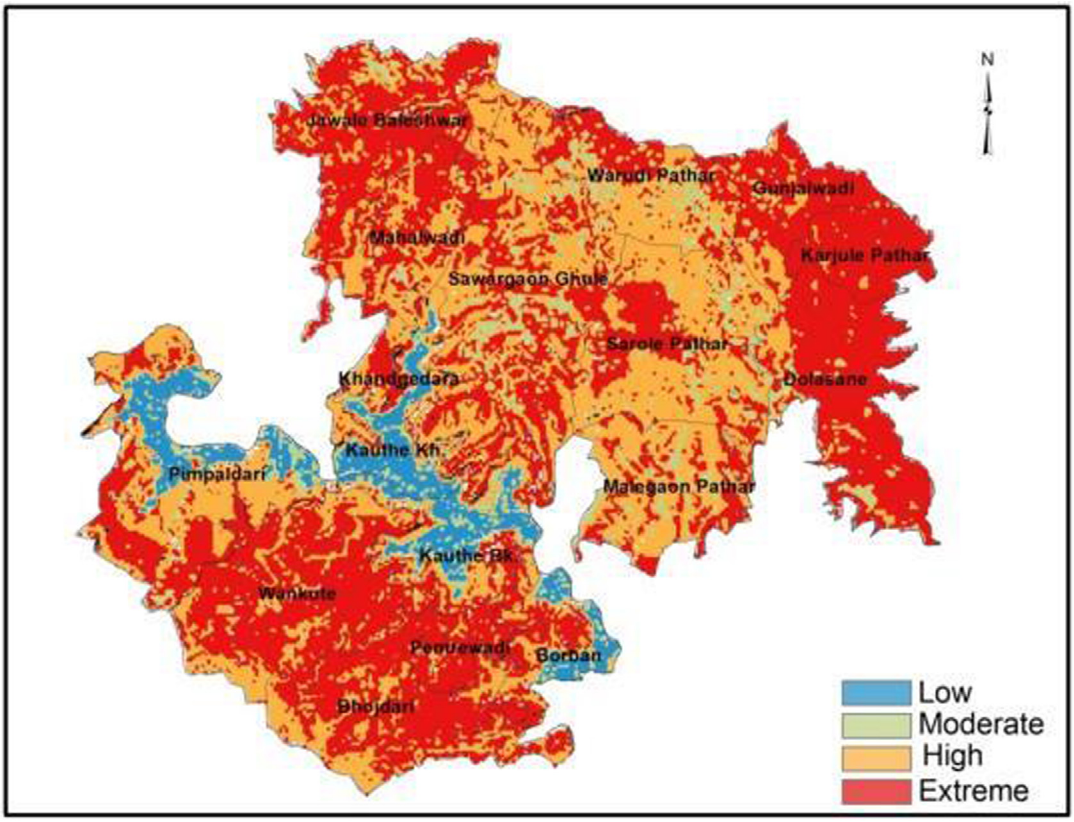

Figure 15. Groundwater vulnerable zone of the study area.

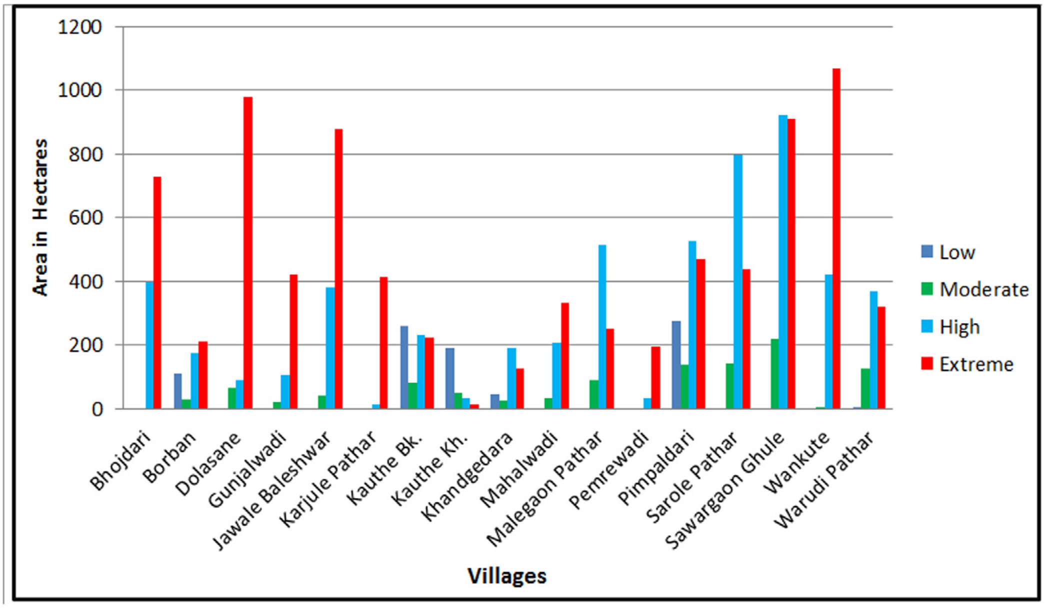

Figure 16. Area of vulnerable zones in different villages.

of common pool aquifers; thereby enabling a quick and effective decision-making for sustainable water resources management. For effective climate smart interventions in the form of watershed treatments and groundwater management at a local scale, the results of the present study can serve as guidelines for prioritizing mitigation strategies in the face of reduced precipitation in the region, thus ensuring sustainable groundwater utilization and its timely management. This method can be widely applied to other drought prone areas, provided that it is backed with field data. It also highlights one of the key knowledge gaps of identifying groundwater vulnerable areas that exist at the community level, additionally attempting to foreground the necessity for effective adaptation in the face of variability in rainfall and groundwater recharge, in the semi-arid regions of Ahmednagar.

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Table 5
A pragmatic definition of the relative classes of groundwater vulnerability at any given location based on integration of different thematic layers.

Vulnerability class	Corresponding scenarios
Extreme	Vulnerable to extreme water shortages. Owing to depletion of unconfined aquifers, water being tapped from deeper confining aquifers. Serious risk of multiple confined aquifers is being depleted due to – reduced rainfall, presence of massive basaltic units limiting groundwater recharge and availability, significant land use/land cover changes and excessive pumping of wells for irrigation
High	Risk to water shortages is high that further depends on the land use, limited groundwater storage in shallow unconfined aquifers, excessive pumping of wells and a gradual shift to groundwater exploration of deeper confined aquifers and being deprived from any other sources of surface water
Moderate	Presence of dykes, fractures, weathered rocks and drainage lines that provide moderate water; however is limited to presence of fracture connectivity and frequency of groundwater pumping from such lineament zones
Low	Presence of thick alluvial aquifers that have higher capacity to store and transmit groundwater. Groundwater and surface water availability is almost year round; however is dependent on annual replenishment of aquifers from rainfall

Conflict of interest

There is no conflict of interest.

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