Integrated multi-criteria analysis for groundwater potential mapping in Precambrian hard rock terranes (North Gujarat), India

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Abstract

In north Gujarat, local communities depend on Precambrian basement aquifers for their primary source of water supply. Increasing demand for potable water puts stress to explore groundwater from less reliable sources of basement rocks. The objective is to map groundwater potential zone (GWPZ) in water-scarce Precambrian terranes using integrated multi-criteria analysis (AHP and Geospatial techniques). Various important thematic has been prepared and the output of the GWPZ map was grouped into six different categories. The results show that very-high and high groundwater potentials extend over an area of 4.29% and 12.86% respectively of the total area. The Kappa index method was used for validation and its result showed an effective and reliable result between collected water level data with calculated GWPZ. It shows 83.3% accuracy for very-high, 85.7% accuracy for high, and 90.1% accuracy for moderate GWPZ. The synthesis of the work can be applied anywhere having similar setups for groundwater prospect and management.

Keywords: Groundwater; Analytical hierarchy process; GIS; Electrical resistivity tomography (ERT); Ambaji basin; Precambrian terrane

1 Introduction

Groundwater is considered being one of the most precious and limited resources stored in the subsurface and its utility to human, aquatic, and terrestrial ecosystems are great extent (Freeze and Cherry 1979, Fitts 2002). The occurrence and distribution of groundwater resources mostly rely on several factors such as lithology, geomorphic features, drainage networks, geologic structures (i.e. lineaments/joints/faults), and slope (Greenbaum 1992, Teeuw 1995, Gyeltshen *et al.* 2019). In the last few decades, water demand has been increased significantly, especially in arid and semi-arid regions of the world. The ever increasing water demand has imposed huge pressure on limited freshwater resources. In developing countries like India, groundwater is considered as a significant source for domestic, agriculture, and industrial uses (Mohanty *et al.* 2008). Further, the groundwater resources are depleting day by day due to an increase in population, industrialization, and overexploitation of aquifer systems which are not restored sufficiently (Rodell *et al.* 2009). In India, about three-fourth of the households do not have a right to access to get potable water for their needs (NITI AAYOG Report 2017-18, Govt. of India). The total annual groundwater recharge has been estimated as 432 Billion Cubic Metre (BCM) and the annual extractable groundwater resource is 393 BCM. Further, the total annual extractable groundwater resource is 249 BCM (as of March 2017) (CGWB 2019). The freshwater situation in India will become challenge and alarming by 2025 if proper measures are not taken (World Bank Report 2006). This poses the need for a better understanding and mapping of the available freshwater resources of the country.

In recent years, the northwestern Indian states mainly, Gujarat, Rajasthan, Haryana, and Punjab are heavily stressed with water resources due to less rainfall, high evapotranspiration rates, and overexploitation of the aquifer systems. The overexploitation of aquifers leads to depletion in the groundwater level (Rodell *et al.* 2009), water exhaustion, deterioration of water quality issues, etc. (World Bank 2011, Souissi *et al.* 2017). Most of the northwestern Indian states heavily depend on groundwater resources than surface water resources for their domestic and agricultural needs. Due to the huge groundwater-dependent population, variations in climatic condition and indiscriminate land-use changes with urbanization are among many factors for water scarcity in both qualitatively and quantitatively. The traditional methods used for identifying groundwater potential zones and mapping are, hydrogeological surveys, geophysical surveys, logging, and outcrop mapping, etc. which are generally expensive and time-consuming (Sander *et al.* 1996, Sturchio *et al.* 2004, Israil *et al.* 2006, Jha *et al.* 2010, Singh *et al.* 2013). On the other hand, remote sensing (RS) and geographic information system (GIS) technology provide a unique platform that can be used for the evaluation of natural resources due to their ability and efficiency in developing spatio-temporal information and complex spatial data analysis of a large area within a short period (Tweed *et al.* 2007, Souissi *et al.* 2018, Wieland and Pittore 2017).

In the recent past, several researchers have used different bivariate and multivariate statistical methods (Table 1) with different accuracy to delineate groundwater potential zones (GWPZ) and mapping viz. probabilistic frequency ratio model (Manap *et al.* 2014, Naghibi and Pourghasemi 2015, Moghaddam *et al.* 2015), weight-of-evidence model (Corsini *et al.* 2009, Ozdemir 2011a, Tahmassebipoor *et al.* 2016), fuzzy-gamma (Antonakos *et al.* 2014), multi-criteria decision-making analysis (Kumar *et al.* 2014, Machiwal and Singh 2015, Rahmati *et al.* 2015, Singh *et al.* 2018, Al-Ruzouq *et al.* 2019, Arulbalaji *et al.* 2019, Sandoval and Tiburan 2019), Shannon's entropy (Naghibi *et al.* 2015), artificial neural network studies (Banerjee *et al.* 2009, Lee *et al.* 2012), random forest machine learning techniques (Naghibi and Pourghasemi 2015, Naghibi *et al.* 2016, Rahmati *et al.* 2016), and logistic regression methods (Ozdemir 2011a and 2011b, Park *et al.* 2017, Chen *et al.* 2018). Of the various methods, RS and GIS act as a powerful, cost-effective, and rapid in generating results (Oh *et al.* 2011) compared to the traditional approaches of hydrogeological surveys and has a great significance in groundwater exploration in water-scarce Precambrian hard rock terranes (Jha *et al.* 2010). Several studies have already been done using RS and GIS techniques for delineation and mapping GWPZ in different parts of the world (Saraf and Choudhury 1998, Solomon and Quiel 2006, Madrucci *et al.* 2008, Pradhan 2009, Yeh *et al.* 2009, Dar *et al.* 2010, Gupta *et al.* 2010, Mukherjee and Singh 2020, Fildes *et al.* 2020, Lentswe and Molwalefhe 2020).

In this study, we integrated the analytical hierarchy process (AHP) and geographic information system (GIS) techniques to properly assess and map groundwater potential zones. In 1980, Thomas Saaty first introduced the AHP method that has a huge advantage in groundwater related studies as it reduces the complex results to a sequence of pair-wise assessments and then generates the results (Saaty 1980). Moreover, the AHP tool is a suitable technique for computing the consistency of the results, thus it reduces the bias in the decision-making process. The multi-criteria analysis (i.e. AHP and GIS) can also apply different environmental management purposes, etc. Further, the integration of geospatial analysis for the preparation of different influencing thematic layers, such as geology, lineament, lineament density, hydrogeomorphology, drainage, drainage density, slope, land use land cover, etc. along with suitable weightage assignment using AHP technique facilitates in demarcating groundwater bearing zones and recharge zones. For example, Mukherjee and Singh (2020) successfully identified GWPZ in drought-prone semi-arid regions of East India using AHP and GIS analysis. Kumar and Krishna (2016) evaluated GWPZ in the coal mining area of Ramgarh and parts of Hazaribagh district, Jharkhand, India. Adiat et al. (2012) used the AHP for groundwater potential mapping in Kedah Peninsula, Malaysia and the result stated that the AHP requires pairwise comparison and expert knowledge to assign weightages to different thematic layers. Also, the AHP technique successfully applied for mapping groundwater recharge zones in different parts of the world (Chenini *et al.* 2010, Chowdhury *et al.* 2010, Rahimi *et al.* 2014, Agarwal and Garg 2016, Lentswe and Molwalefhe 2020).

About 90% of the Indian Peninsula is covered with Precambrian hard rocks. In those terranes, delineation of GWPZ and mapping are relatively complicated task due to lack of reliable and existing data sets, and heterogeneity in lithology (Anbazhagan *et al.* 2011). By considering all these, here we studied a basin (i.e. Ambaji Basin) from a semi-arid region of Aravalli (North Gujarat), that lies in the NW part of the Indian Peninsula. The large percentage of area is mostly underlain by granitic rocks. The residents in these regions heavily dependent on groundwater resources and faces huge water scarcity throughout the year as there is no proper understanding of the aquifer systems. Despite being a highly water-scarce and overpopulated area, yet there is no such scientific communication has been made related to groundwater prospect zones, management, and developments in this region. So, the main aim of the study is to identify and demarcate groundwater bearing zones through integrated multi-criteria analysis using AHP and Geospatial techniques in water-scarce Precambrian hard rock terranes of the Ambaji basin (North Gujarat), India as an example for sustainable groundwater development and management.

2 Study area

2.1 Location

The study area (Ambaji basin) covers a part of Aravalli terrane and is situated in Amirgarh and Danta taluka of Banaskantha District (North Gujarat), India (Figure1). The area extends over an area of 450 km^2 approximately and lies between latitudes 24° 12ʹN to 24° 21ʹ N and longitudes 72º 31̍ E to72º 48’ E in the northwest part of Gujarat. The area covers a total of eighteen (18) major villages and divided into two talukas (Amirgarh taluka and Danta taluka) with a population density of ~42,000 based on 2011 Indian census data. The area falls under the Survey of India (SOI) toposheet no. 45D/11, 45D/12, and 45D/15 (1:50,000 scale). The area has experienced a diverse landscape and is characterized by structural hills, various piedmont zones with alluvium, alluvial plains, and residual hills. The elevation ranges from 215 to 809 m above MSL in the west- and east-part, respectively. The area belongs to semi-arid climatic regions where extreme heat in the summer months and dryness in winter, erratic, and scanty rainfalls with high evapotranspiration are the typical characteristic climatic features (Pradhan and Biswal 2018). The average annual rainfall is 771 mm (Figure 2) and mostly receives through the south-west monsoon season. The average temperature ranges from 35-42 ºC during the summer and 15-30 ºC during the winter season.

2.2 Geological and hydrogeological settings

The Ambaji basin lies in Precambrian terranes of Aravalli range of North Gujarat, India. The area consists of granulites (pelitic, calcareous, and mafic varieties) and granites belonging to Neoproterozoic- Cryogenian age. The rocks are deformed by multiple phases of folding, ductile shearing, and brittle faulting (Singh *et al.* 2010, Tiwari and Biswal 2020). Based on the geographical setting and the south-western monsoon, the study area experiences a heavy water scarcity during summer. In the summer months, the groundwater table lowers down to several meters, which affects directly the livelihood (Machiwal *et al.*2011). The major aquifer systems are fractured rock granitic aquifers. The main sources of drinking and irrigation use in this region were groundwater resources and less on surface water. In the recent past, surface water (Balaram River) was primarily used for domestic and irrigation use but in recent years the surface water (river) dried up due to less and erratic rainfalls. As the area falls under a semi-arid climatic region, the rivers namely Balaram River and Teliya Nadi flowing in the basin are ephemeral (Pradhan and Biswal 2018). The drainage network is mainly constituted by Banas River and the tributaries therein viz. Balaram River and Teliya Nadi. The aquifer systems are constituted of two hydrogeological units in this area. The first one is shallow unconfined or weathered aquifer units range a few meters. The second hydrogeological unit is the fractured bearing layer ranges from 15 m to 90 m (and above). The groundwater table (below ground level) ranges from 2.5 to 20.65 m (in pre-monsoon) and 0.65 to 17.85 m (in post-monsoon) and the regional flow direction of groundwater is from north-east to south-west (Pradhan *et al.* 2019 accepted).

3 Data and Methodology

3.1 Data used and preparation of different thematic layers

For the present work, geospatial methods were used for mapping GWPZ in Precambrian terranes of the Amabji basin (Aravalli terrane) using factor analysis of 10 groundwater influencing layers. To prepare the GWPZ map, different thematic layers viz. geology, lineament density, lineament proximity, LULC, hydrogeomorphology, slope, drainage density, drainage proximity, groundwater level, and groundwater quality (total dissolved solids)were generated from remote sensing image, existing Geological map (Geological Survey of India, 1: 50,000 scale), SOI toposheet, and through field data. For the lithological study, the GSI geological map was used to identify different geological units followed by ground truth verifications. The pre-processing analysis of remotely sensed data of the Ambaji basin was performed using ERDAS Imagine 2011. ArcGIS 10.1 software package was used for preparing thematic layers (Table 2). The hydrogeomorphology and land use land cover features were demarcated from Resource Sat2 LISS IV (acquired from NRSC, ISRO) image through visual interpretations. The Shuttle Radar Topography Mission (SRTM) (30m resolution) data was employed for the demarcation of the basin boundary. The detailed methodology used in this study was presented in a flowchart (Figure 3). The SOI toposheets

(45D/11, 45D/12, and 45D/15) were used for the extraction of drainage layers. All the input data sets were georeferenced with a WGS1984 coordinate system. Further, the geospatial results were validated with groundwater level (depth to the water table), well yield data, and subsurface resistivity data. A sum of fifty-eight groundwater level (dug well/bore well) data were collected during 2016-18 through fieldwork and from existing data sets obtained from Central Groundwater Board, Ahmedabad. The data were then used through an Inverse Distance Weighted (IDW) interpolation tool in ArcGIS 10.1 for making the spatial distribution of the groundwater level. A total of 9 well yield data has been collected through fieldwork and from CGWB and GWRDC, Ahmedabad. For subsurface resistivity study, a total of seven (07) electrical resistivity tomography (ERT) traverses were conducted using IRIS SYSCAL Pro 48 multi-electrode channel (France) resistivity system in December 2017 and 2018. A combined inversion Wenner-Schlumberger (WS) configuration has been used with an electrode spacing of 5.0 m in this survey. The total spreading length for each profile was 235.0 m. The obtained WS datasets were processed through a RES2DINV inversion software package to determine the distribution of true resistivity from apparent resistivity values (Griffiths and Baeker 1993). Further, to compare with field data, the obtained WS data sets were inverted using multiple iterations to derive a model distribution that produces a section with a root mean square (RMS) less than or equal to 5% (Acworth 2001, Pradhan *et al.* 2019 accepted).

3.2 Analytical hierarchy process (AHP) technique

The AHP method is a semi-quantitative and multi-criteria analysis method established by Thomas Saaty in 1980 for analyzing the complicated problems. This enables the user to arrive at a scale of choices drawn from multiple alternatives (Yalcin *et al.* 2011). In recent years, AHP method gained wide applicability in site selection, landslide susceptibility analysis, groundwater potential zone mapping, regional planning, etc. (Ayalew *et al.* 2005, Yalcin *et al.* 2011, Pourghasemi *et al.* 2012, Althuwaynee *et al.* 2014, 2016, Mumtaz *et al.* 2019). Based on Saaty's scale of preference, the AHP method was implemented to estimate weight factors and the rankings of the class in every groundwater influencing parameter over the pair-wise comparison matrix (Saaty 1980). The AHP technique helps to integrate all thematic layers and for this study, sums of ten thematic layers were used. The selected thematic layers are expected to be the controlling parameters for groundwater occurrence and movement in this area. The associations of these selected influencing parameters weighted based on their interrelationships and the experts' opinion. An influencing parameter with a high weightage demonstrates high influence whereas a parameter with a low weightage demonstrates low influence on groundwater prospects (Arulbalaji *et al.* 2019). The weightage of each influencing parameter was assigned based on Saaty's scale (Table 3) which varies from 1 (equal importance) to 9 (extremely high importance). In this study, the weightage assignments given based on the existing literature knowledge and field experience. Further, based on the Saaty's classification, different weightages were assigned to different layers based on their significance and water-bearing capacity. Saaty (1980) stated that the scale will be between 1 to 9 in the pair-wise comparison matrix if the influencing factors on the vertical axis have a higher degree of preference with reference to the horizontal axis (Balamurugan *et al.* 2017). On the other hand, the scale will be reciprocals (1/2 to 1/9), if the influencing factors in the horizontal axis of the matrix have higher degrees of preference with reference to the vertical axis (Table 4). For this work, the scale preference has been used based on objective and subjective methods. Further, the input values are given based on influencing factors for groundwater potentials as well as subjective knowledge (Balamurugan *et al.* 2017). Saaty (1980) formulated the effect of subjectivity through the consistency index (CI) using Eq. (1), and the consistency ratio (CR) using by Eq. (2)

$$\mathrm{CI} = \frac{(\lambda_{\max}-1)}{(n-1)} \text{ ---------------------- } (1)$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \text{ -------------------------------- } (2)$$

where "λ_{max}" denotes the Principal Eigen value and "n" is the number of the causative factors used in the pairwise comparison matrix.

Further, CR can be formulated by taking a ratio of CI/RI, where RI is the random index based on the number of random samples (Saaty 1980) (Table 4). In the pair-wise comparison matrix, if CR > 0.1, it means there is an existence of inconsistency and requires further modification in the scale preference (Saaty 1980). To prepare a GWPZ map of the Ambaji basin (North Gujarat), all ten thematic layers were incorporated with all the scores acquired by multiplying the weight of factor with a rating of the class using Eq. (3)

$$\mathrm{GWPZ} = \sum_{j=1}^{n} (\mathrm{Wj} \times \mathrm{wij}) \text{ ------------------------- } (3)$$

where, GWPZ is the groundwater potential zone, "Wj" represents the weight value of causative factor "j", "wij" denotes the weight value of class "i" in causative factor "j", and "n" is the number of causative factors. The final GWPZ map was then classified into six categories i.e. very-high, high, moderate, moderately-low, low, and very low.

3.3 Delineation of groundwater potential zone (GWPZ) using AHP technique

For this study, the GWPZ signifies groundwater in quantifiable form, i.e. high groundwater potential index (GWPI) signifies the higher groundwater potentiality and lower GWPI signifies the lower groundwater potentiality. The GWPI prepared through the incorporation of all thematic layers in the raster calculator tool in Arc GIS 10.1 software package by using Eq. (4).

$$\mathrm{GWPI_{AHP}} = \sum(\mathrm{GE_{AHP}} + \mathrm{HG_{AHP}} + \mathrm{LULC_{AHP}} + \mathrm{LD_{AHP}} + \mathrm{DD_{AHP}} + \mathrm{WL_{AHP}} + \mathrm{LP_{AHP}} + \mathrm{DP_{AHP}} + \mathrm{SL_{AHP}} + \mathrm{GWQ_{AHP}}) \text{ ---------------------- } (4)$$

Where $\mathrm{GWPI_{AHP}}$ =Groundwater Potential Index. $_{\mathrm{AHP}}$ – Analytical Hierarchy Process, $\mathrm{GE_{AHP}}$ - geology, $\mathrm{HG_{AHP}}$ - hydrogeomorphology, $\mathrm{LULC_{AHP}}$ - land use and land cover, $\mathrm{LD_{AHP}}$ - lineament density, $\mathrm{DD_{AHP}}$ - drainage density, $\mathrm{WL_{AHP}}$ - water level, $\mathrm{LP_{AHP}}$ - lineament proximity, DP_{AHP} - drainage proximity, SL_{AHP} - slope, GWQ_{AHP}- groundwater quality (total dissolved solids)

4 Results

4.1 Thematic layers for groundwater potential zone mapping

4.1.1 Geology

The role of geological features considered as one of the most important factors for a hydrogeological investigation study. The main attention is to be made on lithological units, which control the storage, flow, and chemistry of the groundwater system. The different litho-units demarcated based on the fieldwork, visual interpretations of the satellite image, and existing geological map. Geologically, the study area comes under the Meso-proterozoic age of South Delhi terrane (1100-900 Ma) of Aravalli mobile belt (Singh *et al.* 2010). The rocks found in this terrane were mainly of pelitic-, calcareous- and basic granulites, where three phases of granite intruded namely G1 (gneissic), G2 (medium to coarse-grained) and G3 (fine-grained) (Pradhan and Biswal 2018). Unconsolidated sediments and fractured hard rocks are more suitable for groundwater occurrence and movement than a massive metamorphic or igneous rock. Secondary porosity (faults, fractures, and shear zones) and weathered zones only allow groundwater flow and occurrence in hard rock terrane (Singhal and Gupta 2010). From a geological point of view, the granites (G2, G3, and G1), alluvial/sand, and recent sediments were the major aquifers in this area (Figure 4a). The G1, G2, and G3 granites named after their geologic age. Further, G2 and G3 granites are coarse to fine-grained and highly fractured, whereas G1 granite is gneissic in nature (Pradhan and Biswal 2018). The thickness of weathered zones varies from 5-20 m. The fractures encountered at a depth of 5-150 m in hard rocks. A proper weightage assignment has been given to the hydrogeologically important rock types. Based on the rock types, a high weightage is assigned to G2 granite and alluvial/sand, moderate to moderately-low weightage for G3 granite and recent sediments, and low to very-low weightage assigned for G1 granite, basic granulite, and calc-granulites (Table 6).

4.1.2 Hydrogeomorphology

The geomorphological setting of an area may affect groundwater potentials to a great extent as it reflects various landforms and topography of an area that has a direct impact on the distribution of groundwater. The identification of geomorphic features is essential for tracing potential groundwater bearing zones. The slope, relief, thickness of soils/weathered zones, type of weathering, and different landforms are the result of long-term denudation of fluvial processes. The hydrogeomorphological features of the present study area mapped by using Resource Sat2 LISS IV Satellite image. The different erosional and depositional hydrogeomorphic units viz. structural hills, residual hills, denudational hills, buried pediments, deep buried pediments, shallow pediments, and valley fills are mapped (Figure 4b). The highland part mainly consists of hilly terranes with a highly undulating surface, whereas the lowland areas are of less and gently undulating surfaces. The main hydrogeomorphic units in the Ambaji basin are structural hills (44.51%), buried pediments moderate (18.90%), denudational hills (14.42%), deep buried pediments (14.24%), valley fills (4.28%), river (0.74%) and shallow buried pediments (0.52%) (Table 6). Further, the upper catchment of the basin is mainly comprised of structural hills, while the lower catchment is covered with alluvial/sandy zones.

4.1.3 Land-use and land-cover (LULC)

The LULC of a particular area plays an important role in recharge-discharge, infiltration, and runoff, which are mainly controlled by the nature of surface material. The LULC is one of the key parameters in hydrogeological studies because it provides valuable information about the degree of groundwater requirements and utilization (Gupta and Srivastava 2010). Todd and Mays (2005) studied dense vegetation in a land-use map as an excellent indicator of a suitable site for groundwater exploration. The LULC of the study basin was categorized into six different classes viz. agricultural land, fallow land, mixed forest, open forest, river, and scrub forest through visual interpretation of Resource sat2 LISS IV satellite data (Figure 4c). The map was reclassified by assigning different scores for various LULC classes. The scrub forest (64.98%), agricultural land (14.68%), and fallow lands (7.85%) were the major LULC type in the study area. Further, the high score assigned to the river and agricultural lands while for scrub forest and open forest lower score was given due to poor permeability. The various LULC types and their spatial distributions were given in Figure 3c. The different scores assigned to various classes are summarized in Table 6. The hilly terranes and agricultural land are predominantly found throughout the study area. The accuracy was further calculated using the Kappa index method (Balamurugan *et al.* 2017).

4.1.4 Lineament density and lineament proximity

Lineaments are the linear surface features or expression of faults, shear zones, or geological contacts or discontinuities and act as good conduits for the flow of groundwater (Prost 1994, Singhal and Gupta 2010) and have very good water reservoirs. Elewa and Qaddah (2011) mentioned that fractures in a rock enhance the secondary porosity that increases water percolation to the aquifer. Lattman and Parizek(1964) first adopted the linear feature called “lineaments” for groundwater potential in a folded and faulted hard rock terrane. The lineaments generally show the tonal, textural, relief, drainage and vegetation linearity, etc. in a satellite image (Lillesand 1989, Drury 1990, Gupta 1991, Kumar *et al.* 2014). The structural lineaments were mapped with the help of satellite image and field studies for identifying different faults, fractures, and lithological contacts that control the groundwater occurrence. From the satellite data and field mapping, the detected linear features with different sizes, orientations, and distributions were exported and plotted on a map (Elewa and Qaddah 2011). Furthermore, not all linear features in the satellite image are lineaments; hence, there need to be ground truth verification by field visits. The straight course of streams or vegetation linearity may be due to faulting and fracturing, therefore inferred as the areas of high porosity and permeability in hard rock terrane (Shekhar and Pandey 2015). The areas around lineaments and crisscrossed lineaments are considered the most favorable site for groundwater occurrence due to high infiltration and transmitting capacity. Solomon and Quiel (2006) studied that high chance for getting groundwater bearing zones are close to the structural lineaments as the intensity of fractures are decreased with increasing distance from lineaments. For the present study, lineaments were prepared from Resource Sat2 LISS IV satellite imagery through visual interpretation based on the existence of linear features and tonal contrast followed by field verifications. The study area comprises numerous criss-crossed lineaments in the northern part and north-western part due to transtensional settings (Pradhan and Biswal 2020, Pradhan *et al.* submitted). Yeh *et al.* (2009) computed lineament density of an area as follows:

$$Ld = \frac{\sum_{i=1}^{i=n} Li}{A} \text{ -------------------------- } (5)$$

Where Ld is termed as lineament density, $\sum_{i=1}^{i=n} Li$ is refers to the total length of lineaments, and A is the unit area.

Lineament density is one of the important aspects prepared from the lineament map, which is critically used in groundwater studies especially in hard rock terrane. The importance of the lineament density study is to calculate the frequency per unit area (Narendra *et al.* 2013). Based on the lineament density analysis, concentrations of the lineaments have been prepared for the study area (Figure 4d). The higher lineament density areas are considered excellent aquifer zones for groundwater resources. Based on the lineament density of a region higher to lower weightage has been assigned. In the map (Figure 4d), it has been observed that a high density of lineaments falls in areas of granitic gneiss, granite, and basic granulites/gabbroic rocks. On the other hand, lower to moderate lineament density is observed in the alluvium and sandy zones in the central and southwestern corners of the study area. Using the Euclidean method, the distance from lineaments was calculated in ArcGIS 10.1. The lineament proximity (Figure 4g) was further categorized into five class viz. 0 – 91.764, 91.764 – 229.411, 229.411 – 416.470, 416.470 – 645.882, and 645.882 – 900 m (Table 6) using natural break methods (Jenks 1967).

4.1.5 Drainage density and drainage proximity

Drainage is the pattern formed mainly by streams and rivers in a particular drainage basin. These are mainly controlled by topography dominated by crystalline hard rocks or unconsolidated rocks and the gradient of the land surface. The drainage transmitted water from the hilly regions to the plains (Balamurugan *et al.* 2017). Drainage density has a major role in exploring groundwater resources for a particular region**.** The drainage systems in hard rock terrane are mainly controlled by different structural entities, i.e. faults and fractures, and hence drainage systems act as a medium for water movement into the subsurface (Balamurugan *et al.* 2017). The drainage of the Ambaji basin was extracted from the SOI toposheet and ASTER DEM and verified with an acquired satellite image.

The drainage density is measured as the closeness of channels and higher the drainage density of a basin, lower the infiltration rate. This implies that the drainage density is an inverse function to permeability. Dinesh Kumar *et al.* (2007) mentioned that higher drainage density is not favorable for groundwater prospects. The drainage density and drainage type provide useful information about the runoff, runoff rate, infiltration, and permeability of a particular watershed. The dendritic drainage pattern indicates homogenous rocks, whereas the trellis, rectangular, and parallel drainage patterns indicate structural and lithological controls. The drainage density of the study basin was calculated by the total length of all the rivers and streams in the basin divided by the total area (Figure 4e). The drainage density percentage is computed through the line density tool in ArcGIS 10.1 (Agarwal and Garg 2016). Further, the drainage proximity (Figure 4h) was calculated using the Euclidean method and categorized into five different classes viz. 0 – 88.235, 88.235 – 215.294, 215.294 – 409.411, and 409.411 – 900 m (Table 6) based on the natural breaks method (Jenks 1967).

4.1.6 Slope

Slope defines the difference in elevation for a specific area and has a direct influence on the surface and subsurface runoff (Naghibi *et al.* 2016, Balamurugan *et al.* 2017). The slope gives critical information about the regional geologic and geodynamic processes functioning in the subsurface of the earth (Arulbalaji *et al.* 2019). In general, gentler the slope, slower is the movement of water and in turn more percolation into the subsurface (Balamurugan *et al.* 2017). On the other hand, a higher or steeper slope promotes an increase in surface runoff and in turn decreases the percolation capability into the subsurface. The slope map was generated from ASTER DEM (30 m resolution) (Figure 4i). The slope degree ranges from 1 to 30 and is classified into seven classes, i.e. <1, 1-3, 3-5, 5-10, 10-15, 15-30, and >30° based on the natural breaks method (Jenks 1967). The high weightage has assigned to a flat slope or gentle slope (<1°) while lower weightage has given to a steep slope (>30°) based on their importance in groundwater recharge and discharge (Table 6).

4.1.7 Depth to the water table

The depth to the water table or groundwater level mainly depends on the hydrogeological conditions, rainfall pattern, and topography of an area (Eleswa and Qaddah 2011). Groundwater level represents the top surface of the saturated zone. Rainfall and heavy pumping play a major role in groundwater fluctuations of water level and variations in groundwater recharge-discharge. The groundwater level data were collected through fieldwork during the pre- and post-monsoon period (2017-18) and from CGWB, Ahmedabad. The groundwater levels were measured from 58 observed wells (Dug wells/ Bore wells). The groundwater level in this region varies from 2.5 to 20.22 m (Figure 4f). These data were used for plotting the groundwater level map and then classified into five classes, i.e. 2.50-7.92, 7.92-9.59, 9.59-11.26, 11.26-13.27, and 13.27-20.22 m (Table 6) below the groundwater level. The weightage was assigned based on the groundwater level values. Generally, shallower the groundwater table higher the groundwater potential and deeper the groundwater level indicates less groundwater potential.

4.1.8 Groundwater quality (total dissolved solids)

The groundwater quality of an aquifer system mainly depends on the local geological formation, anthropogenic activities, and drainage networks (Freeze and Cherry 1979). While accessing groundwater resources quantitatively, it is also essential to check the water quality for a healthy society. World Health Organization (WHO) set a different permissible limit for different ion for drinking and domestic uses. The water sample consists of major and minor ions. A total of 42 groundwater samples were collected from different dug well/bore well/hand pumps for water quality study. The total dissolved solids (TDS) of the water samples are calculated by multiplying 0.45 with electrical conductivity (EC). The existence of dissolved solids in groundwater may affect the taste and WHO suggested a scale of limits for domestic use (excellent, <300 ppm, good, 300 - 600 ppm, fair, 600 - 900 ppm, poor, 900 - 1200 ppm, and unacceptable, >1200 ppm). The ranks are assigned based on WHO limits of the TDS level to identify and map the quality of the groundwater in the study area. The results show that most of the area falls in good quality of water (301-600 ppm) zone except for some samples with a higher value in the central part of the basin(Figure 4j) (Table 6).

5 Discussions

5.1 Groundwater potential zone (GWPZ) mapping

Groundwater is considered as a natural resource, but due to anthropogenic activities through aquifer overexploitation for irrigation and domestic use, the life-sustaining resource has been deteriorated considerably day by day. Therefore, a proper understanding of the groundwater resources is required for effective planning and management for sustainable use. The hydrogeological setting of the Ambaji basin shows that the groundwater occurs in top unconfined zones, fractured aquifer zones especially in weathered and fractured granitic rocks, and alluvial/sand, and recent sediments. Also, groundwater occurs in semi unconfined aquifers in the deep-seated fractured rock aquifers (Pradhan and Biswal 2020). The groundwater availability is varied with space and time; hence, a detailed assessment of the groundwater resources is required. For the present study, ten groundwater influencing parameters (geology, hydrogeomorphology, LULC, lineament density, lineament proximity, drainage density, drainage proximity, slope, groundwater quality, and groundwater level) are considered for GWPZ mapping. The weightage overlay method has been employed for the generation of GWPZ in the Ambaji basin (Table 5). These are further classified as very-high, high, moderate, moderately-low, low, and very-low potential zones (Figure 5) and the aerial spread percentage of these categories are 4.29, 12.86, 19.67, 24.98, 25.81, and 12.40 respectively (Table 7). In the groundwater potential map, very high and high GWPZ are concentrated in the northern and eastern end of the basin. Very high to high potentials zones are predominantly found in large-scale faults and fractures-prone areas, which helps the infiltration ability to aquifer systems. The moderate potential zones were found mainly in the north-western and south-eastern zones of the study basin. The low to very-low potential zones fell in the central part and the eastern end of the study area. The general flow direction of groundwater in the Amabji basin is from north-east to south-west. All the wells are agreed with the GWPZ categories in the study area.

5.2 Validation of results

5.2.1Depth to water table data

Validation of scientific outputs is the most crucial part as far as groundwater prospect is concerned. For validation of the GWPZ map, we have analyzed a total of 58 groundwater level data with GPS locations (Figure 6). The groundwater level ranges from 2.5 m to 20.65 m in this region. These are classified into six categories, i.e. 2.5-6.4, 3.5-9.0, 8.2-12, 9.3-13.5, 9-18.3, and 11.5-20.6m and were referred as very-high (6 wells), high (14 wells), moderate (11 wells), moderately-low (3 wells), low (12 wells) and very-low (12 wells) water table. These observed data sets were used as a reference point to calculate and compare the accuracy in the classifications. Using the Kappa index method, the water level data overlay on the GWPZ map for comparison of accuracy. The Kappa method suggests a valid and reliable result between collected depths to water table data sets with calculated GWPZ (Balamurugan*et al.* 2017). Based on the Kappa method we have obtained 83.3% accuracy for very-high GWPZ, 85.7% accuracy for high GWPZ, and 90.1% accuracy for moderate GWPZ. Moreover, the field well data also shows the average accuracy of GWPZ of the study area as 86.6%. The overlay analysis shows that water level with shallower to a moderate depth well is within high to moderate GWPZ and water table with higher depths well is within low to very-low GWPZ.

5.2.2 Well yield data and electrical resistivity tomography (ERT) profiles

In addition to the depth to groundwater table data, the delineated GWPZ map has also been validated with two more important field-based data sets i.e. electrical resistivity imaging (ERT) profiles and limited well-yield data (collected from CGWB, GWRDC, and through fieldwork) (Figure 7). The well-yielding capacity of a specific region mainly relies on the permeability and availability of subsurface water in the aquifer system. A total of 9 well yield data (Table 8) were analyzed for this study. The results show that very high to high GWPZ have a yield capacity of 120-200LPM and moderate to moderately low GWPZ have 90-110 LPM yield capacity. However, low to very low GWPZ have a yielding capacity of less than 90 LPM. Out of 09 observation well, 08 wells has a good correlation with the AHP based GWPZ map and observation wells. A total of 01 well (i.e. PW-7) does not match with the

GWPZ map due to one or more other reasons. The application of electrical resistivity tomography (ERT) is considered to be one of the important geophysical surveys for groundwater exploration to demarcate groundwater bearing zones, especially in water-scarce hard rock terranes. To validate with geospatial data, ERT (combined Wenner-Schlumberger configuration) profiles have been used to delineate the weathered and fractured zones in the Ambaji basin. Generally, the subsurface resistivity values depend on the lithological units and fracture systems present in an area (Pradhan *et al.* 2019 accepted). For this study, instead of traditional four-electrode systems (1D) resistivity survey, electrode resistivity tomography (2D and 3D imaging) traverses were conducted as it produces more realistic models to understand a complex hard rock aquifer system like Ambaji basin (Aravalli terrane). A combined inversion Wenner-Schlumberger (WS) mode has been arranged for this study as it provides a very good resolution (signal-to-noise-ratio) of the lateral and vertical resistivity variations of the subsurface (Loke 2004, Chandrasekhar *et al.* 2014, Cardarelli and De Donno 2019, Pradhan *et al.* 2019 accepted). The 2D resistivity section (Figure 8) shows that the study area mainly consists of weathered zones, fractured, and fresh basement zones. The weathered zones may be divided into upper and lower units as it shows a variation in resistivity values due to different mineral composition and the degree of weathering of rocks. The results show that all the resistivity models have approximately 1-15m thick layer of weathered zones in the top and followed by fractured zones (5-40 m) and basement rocks (35m onwards). The ERT sections (Figure 8P1-P7) show the electrical resistivity with three different zones (labeled with X: soil and weathered granites, Y: fractured zones, and Z: massive hard rock or basement rocks). The upper zone has low resistivity ranges from 5 to 120 Ω.m and a thickness of 20 to 30 m, indicating a water-bearing fractured and weathered zone. The lower zone (labeled as Z) has a higher resistivity, indicating a massive basement and granitic body. Vertical or steeply fractured zones (Figure 8P2-P5) are identified in Surela and Bhedla areas. These zones can be targeted for pinpointing borehole sites. Generally, groundwater storativity in basement rocks increases with an increase in overburden weathered zones and fractured zones. The weathered zones represent basement rocks that are relatively high porosity and permeability and can be used for sitting large-diameter dug wells. A borehole was drilled up to a depth of 65 m encountering soil layer, weathered granite, fractured zone, and fresh granite basement as incurred from the lithology of the well (Figure 9) in Surela area (Figure 8P4). This shows a good pact between resistivity values, well yield data, and GWPZ map.

Based on the results, it can be inferred that AHP and GIS-based methods are powerful methods for mapping GWPZ qualitatively and quantitatively from a local to regional scales. Further, this method could be applied for better planning and management for long term groundwater sustainability, especially in water-scarce Precambrian hard rock terranes.

6 Conclusions

In this study, groundwater potential zones (GWPZ) have been delineated through integrated multi-criteria approach (AHP and GIS techniques) in water-scarce Precambrian terranes of the Ambaji basin (North Gujarat), India. The results show that combinations of both techniques are effective tools for understanding the groundwater occurrence and behaviors of the study area. A total of ten groundwater influencing parameters (geology, hydrogeomorphology, lineament density, lineament proximity, drainage density, drainage proximity, LULC, slope, groundwater level, and groundwater quality) were taken into considerations to delineate the GWPZ. Besides other influencing parameters, water quality data, which is very crucial for qualitative as well as quantitative studies of groundwater resources, are considered for this study. The GWPZ map was classified into six categories, such as very-high, high, moderate, moderately-low, low, and very low. The very-high zone indicates the most favorable zone, whereas the very-low zone indicates the least favorable zone for groundwater prospects. Very-high and high GWPZ mostly located in the upper catchment of the basin and covers an area of 4.29% and 12.86% respectively of the total area. Moderate and moderately low GWPZ spreads about 44.65% of the total catchment area. Very-low and low GWPZ located in the lower catchment of the basin and covers an area of 12.4% and 25.81% of the study area. The validation of the observed depth to water table data sets shows a strong agreement with the GWPZ map. Also, for validation, well yield data and electrical resistivity imaging based on multi-electrode Wenner-Schlumberger (WS) configuration have been used to understand the groundwater system. The basement feature has been delineated through WS configuration that involves saprolites, weathered-, fractured-, steeply contact zones, and fresh basements. These indicate that the WS configuration for resistivity imaging is sensitive to vertical features such as faults and fractured zones and steeply contacts which has a significant role for sitting bore-holes/dug wells for sustainable groundwater use. Further, for a rigorous validation with AHP outputs, a large number of pumping test (well yield) data will be much more needed for the sustainable management of groundwater resources. Further, the proposed methodology is found to be an important and effective method that can be applied to arid- and semi-arid regions, especially in the water-scarce Precambrian hard rock terranes. Finally, the output of the GWPZ map will be useful for local communities as well as decision-makers for planning and management for sitting hand pumps/bore wells/dug wells to meet the groundwater requirements qualitatively and quantitatively.

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Figure captions:

Figure 1. Location map of the study area (Amabji Basin, Aravalli terrane).

Figure 2. Rainfall distribution in the study area.

Figure 3. Flowchart of the methodology used for groundwater potential zone (GWPZ) map.

Figure 4. Thematic layers of the Ambaji basin a. geology, b. hydrogeomorphology, c. land use/land cover, d. lineament density, e. drainage density, f. water level, g. lineament proximity, h. drainage proximity, i. slope, j. Groundwater quality (TDS-total dissolved solids).

Figure 5. Groundwater potential zone (GWPZ) map of Ambaji Basin

Figure 6. Validation of the GWPZ map.

Figure 7. Validation of GWPZ map with well yield data and ERT profiles.

Figure 8. Resistivity profiles in the Ambaji regions (P1; AjapurMota, P2; Surela-1, P3; Surela-2, P4; Surela-3, P5; Bhedla, P6; Kansara, P7; Ghoda), X; weathered and unconfined zones, Y; fractured zones, Z; massive or basement rocks.

Figure 9. Subsurface lithology profile in the Surela area (Borehole B1; Refer in Figure 8P4).

Table captions:

Table 1. Recent groundwater studies using remotely sensed data and different statistical methods.

Table 2. Details of source data.

Table 3. The scale of preference between two parameters in AHP (after Saaty, 1980).

Table 4. Random Consistency Index (RI) (after Saaty, 1980).

Table 5. Weight criteria for different layers.

Table 6. Weightage of different thematic layers for groundwater potential zone mapping.

Table 7. Groundwater potential zone derived from AHP.

Table 8. Observation well locations and the yield data.

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