



# Spatial behavior of the Dar-Zarrouk parameters for exploration and differentiation of water bodies aquifers in parts of Konkan coast of Maharashtra, India

Suneetha Naidu<sup>1</sup> · G. Gupta<sup>1</sup> · G. Shailaja<sup>1</sup> · K. Tahama<sup>1</sup>

Received: 24 November 2018 / Revised: 2 January 2021 / Accepted: 5 January 2021 / Published online: 14 January 2021  
© The Author(s), under exclusive licence to Springer Nature B.V. part of Springer Nature 2021

## Abstract

Demarcation of aquifer boundaries and hydro-geologic characterization can help in proper management and conservation of groundwater resources of a coastal region. The objective of the present study is to identify and delineate the groundwater-bearing zones and protection of freshwater aquifers from saltwater ingress in the northern parts of Sindhudurg district, western Maharashtra, India. A total of 86 vertical electrical soundings (VES) were carried out by Schlumberger electrode arrangement to infer the sub-surface lithology around Kankavali, Vijaydurg, and Malvan. The Dar-Zarrouk parameters were computed to generate the spatial variation maps of transverse resistance (T), longitudinal conductance (S), transverse resistivity ( $\rho_t$ ), and longitudinal resistivity ( $\rho_l$ ), to decipher the resistivity contrast of fresh water and salt water-bearing formations. The results demonstrate that these parameters provide a better resolution in delineating the seawater intrusion in coastal aquifers. The overburden aquifer protective capacity computed from the longitudinal conductance suggests that 59% of the area has poor aquifer protection, while 23% has weak, 11% has moderate and 7% falls in good protective capacity rating. This parameter reveals the infiltration of contaminants and the health of the aquifer. The electrical anisotropy ( $\lambda$ ) value ranges from 0.9 to 5.1, suggesting an increase from SW to NE and also from SE to NW. The fracture porosity ( $\varphi_f$ ) ranges from  $10^{-6}$  to 0.65, which corroborates with the high and low  $\lambda$  values, reflecting that fracturing is due to anisotropy and significant reserves of groundwater could be exploited in this coastal region.

**Keywords** Seawater intrusion · Vertical electrical sounding · Aquifer · Dar-Zarrouk parameters · Sindhudurg · India

## Introduction

Groundwater is the primary source of freshwater used for domestic, irrigation, and industrial purposes in coastal regions. As a result of population density, urban development, and agricultural activities in such region, groundwater withdrawal developed rapidly to meet the water demand. Therefore, an assessment of this resource is extremely significant for its sustainable management and conservation. The over-use of groundwater resources in recent years has generated several environmental problems such as groundwater depletion, water stress, pollution of groundwater, etc. However, contamination of freshwater aquifers by seawater intrusion is

among the critical phenomena which primarily affect the region.

Usually, the coastal regions are endured to a strong incidence of human activities like agriculture and tourism, which has a bearing on its environmental, economic, social, and cultural aspects. Therefore, conservation and management of coastal aquifers are critical which is inextricably linked to poverty alleviation, food and health security, environmental sustainability and overall human development and prosperity. Exploration of freshwater bodies and differentiation between fresh and contaminated aquifers in the coastal areas thus becomes the primary objective.

The earth's shallow subsurface is an extremely vital geological zone that provides information on the subsurface, preferential pathways, and estimation of petro-physical relationships. This dynamic zone yields groundwater resources, supports agriculture and ecosystems, has a bearing on the climate, and serves as a storehouse for various contaminants. The coastal areas are usually thickly inhabited, as they support good living conditions and are a repository for economical

---

✉ G. Gupta  
ggupta@iigs.iigm.res.in

<sup>1</sup> Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai 410218, India

development. However, such areas are vulnerable to the scarcity of fresh groundwater arising out of seawater intrusion into coastal aquifers. Excessive groundwater extraction and other human activities disturb the balance between freshwater and saline water in coastal aquifers thereby diminishing the fresh groundwater flow towards coastal waters and finally that causes the saltwater intrudes on coastal aquifers. Therefore, the need to develop sustainable water resources for an increasing population, agriculture, energy needs along with the associated threat of climate and land-use change on ecosystems causes urgency for understanding the occurrence, flow, and transport processes in the shallow subsurface.

To study the aquifer properties, such as its thickness and dimensions, the use of geological sequence, exploration, and subsequent drilling is used globally. Nonetheless, these procedures are both time consuming and very expensive. Therefore, geophysical techniques play a vital role in identifying and understanding the aquifers and advocating a superior correlation with geology and existing boreholes, if any (Maillet 2005).

The electrical resistivity technique is a very popular geophysical tool for groundwater exploration and contamination studies and its impact on the environment in the coastal aquifers (Loke 2000; Mondal et al. 2013; Maiti et al. 2013; Suneetha et al. 2020). This technique has been employed for salinity mapping and delineation of fresh-saline water interface (Lee et al. 2002; Batayneh 2013; Ali Kaya et al. 2015). This paper enlightens the use of Dar-Zarrouk (D-Z) parameters (viz. total longitudinal unit conductance (S) and total transverse unit resistance (T)) along with other important indices (average longitudinal resistivity ( $\rho_l$ ), average transverse resistivity ( $\rho_t$ ), electrical anisotropy ( $\lambda$ ), and fracture porosity ( $\varphi$ )) derived from D-Z parameters to shed different groundwater characteristics and geological conditions.

## Geology and hydrogeology of the study region

The Sindhudurg district is bordered by Goa state to the south. To its east is Kolhapur district, the north is bounded by Ratnagiri district, and the Arabian Sea to its west. It is the smallest district in Maharashtra state with an area of 5207 sq. km. Sindhudurg district is located between 15°36' to 16°40' North latitudes and 73°19' to 74°18' East longitudes. The eye-pleasing seashore, hills, rare flatlands, and Sahyadri mountain ranges are the distinctive features of this district.

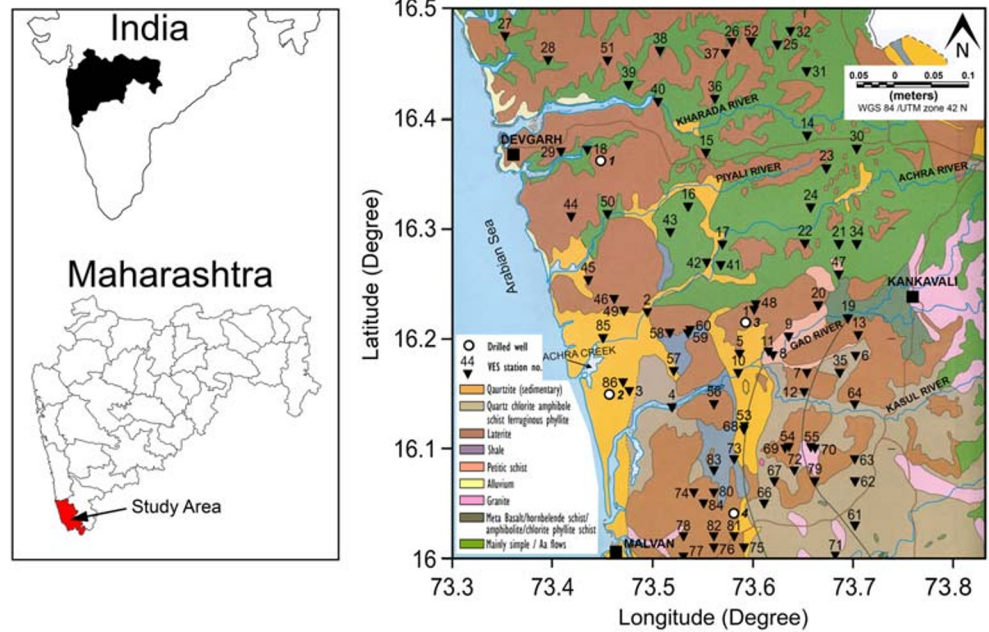
Geologically, the age of the study area is in the range of Archaean to Quaternary period along with different petro-physical properties, which imparts different capacities to store and transmit water. The general geological map of the Sindhudurg district is illustrated in Fig. 1. The Konkan region is characterized by the Archaean complex, Kaladgi

Supergroup, Deccan trap, laterite, and alluvium (Deshpande 1998). The Archaean granites and gneisses are medium to coarse-grained and consist of quartz, hornblende, orthoclase biotite, and microcline (CGWB 2014). The water-bearing geological formations in this region are the Deccan Basalts, Kaladgi formation, shale with peat and pyrite nodules, laterites, Dharwarian meta-sediments, and alluvial deposits. However, the coverage of Kaladgi formation and alluviums are limited, while Dharwarian schists lack primary porosity and permeability (CGWB 2014) and therefore not prospective for aquifer formation. In the Deccan trap basalts, the primary porosity is insignificant and therefore secondary porosity plays a vital role in groundwater circulation because of jointing and fracturing (Deolankar 1980). Laterites are more porous than the Deccan trap basalt, and hence are likely to be potential for groundwater in the study area. The groundwater occurs in inter-granular pore spaces of sands, gravels, and silts, under phreatic/unconfined aquifer at relatively shallow depths of 2–10 m below ground level (bgl) and their yield varies from about 2 to 5 m<sup>3</sup>/day. The groundwater level in the study area fluctuates from 2 m to 20 m bgl (CGWB 2014). The physiography of the region is undulating throughout the expanse, except in coastal plains. The area displays a dendritic drainage pattern. A major amount of soils are derived from lateritic rocks. The rainfall varies from 2300 mm to about 3205 mm annually, with the north-east recording very high rainfall.

## Materials and methods

In the resistivity method two pairs of electrodes are used to measure the resistivity; one pair of current electrodes is used to transmit current into the ground and another pair measures the potential difference between two potential electrodes. In the present study, a total of 86 vertical electrical soundings (VES) were carried out using the Schlumberger electrode array with AB = 200 m separation (Fig. 1). The investigation was carried out with the aid of an SSRMP-ATS resistivity meter supplied by IGIS, Hyderabad. In Schlumberger configuration, the current electrode is symmetrically increased while the potential electrode is fixed at its initial distance until the resistance measured becomes too small. At any point, the condition  $AB/2 \geq 5(MN/2)$  was satisfied. The apparent resistivity ( $\rho_a$ ) is plotted against the corresponding half electrode spacing (AB/2) on a bi-logarithm graph to generate the sounding curves. The sounding curves were interpreted by computer-assisted 1-D forward modeling scheme IPI2WIN software (Bobachev 2003). VES field data is plotted on a double log graph sheet with apparent resistivity versus electrode spacing to obtain geo-electrical parameters (layer resistivity and layer thickness) which suggested 3–5 layered structure in the study area. One-dimensional inversion results of some

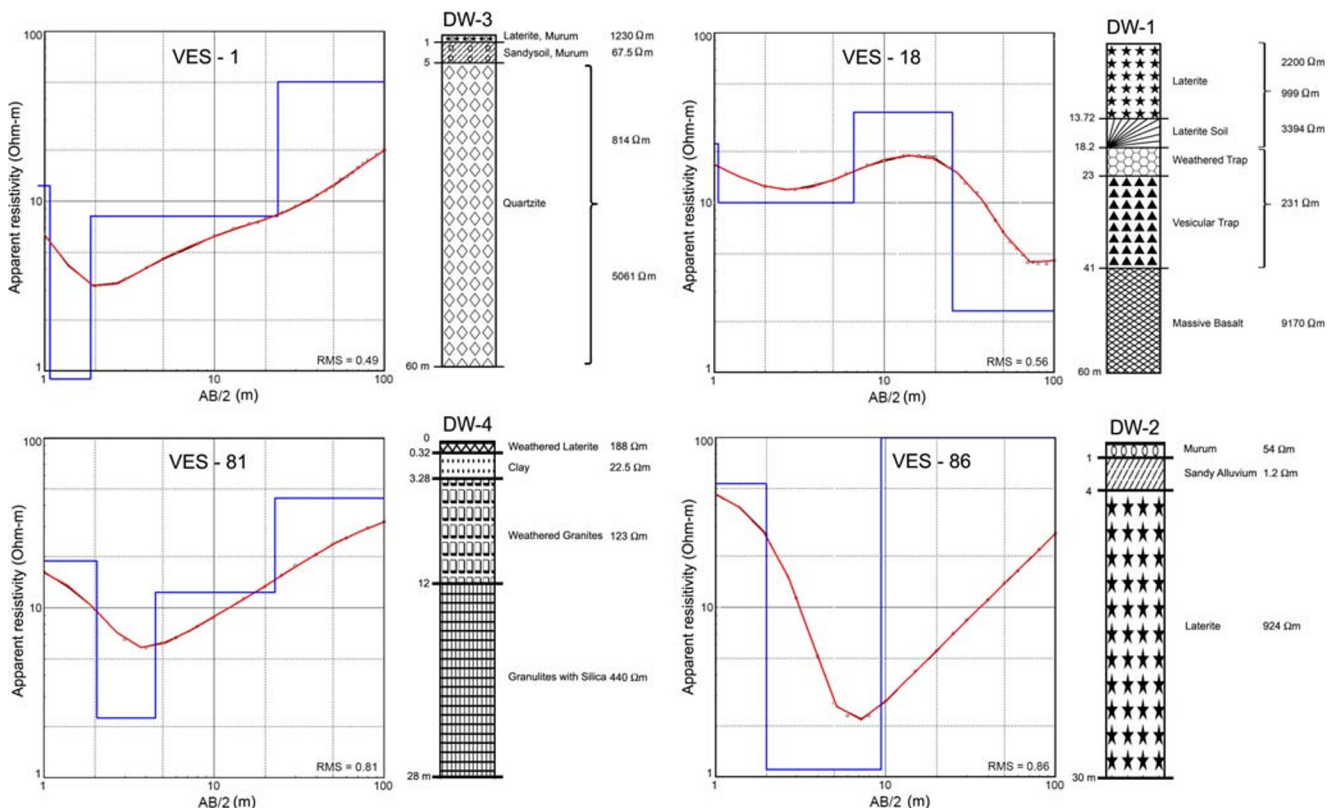
**Fig. 1** Geological map of the study area. Also shown are the vertical electrical sounding points and drilled well points



representative stations are shown in Fig. 2. Also shown is the correlation between borehole logs consisting of 3–5 different geological formations corresponding to the true resistivity values obtained from 1-D inversion at these stations.

There are several analytical tools for resistivity data interpretation which are being widely used for exploration studies

(Bhattacharya and Patra 1968; Zohdy 1989). However, the resolution is often hindered and the stigma of uncertainty dominates due to some geophysical similarities in the behavior of different layers of the subsurface. To overcome uncertainty in resistivity data interpretation, some other geophysical indices other than the primary elements (resistivity and



**Fig. 2** Borehole logs of geological formations corresponding to the true resistivity values obtained from 1-D inversion

thickness) are necessary to provide additional, more practical, and confident support that can lead to reliable solutions, both in terms of interpreting and understanding the geoelectrical model. These parameters are associated with different combinations of layer thickness and layer resistivity in the model (Orellana and Mooney 1966; Singh 2005). Dar-Zarrouk (D-Z) parameters (also called secondary geophysical indicators), termed by Maillet (1947), play a crucial role in electrical resistivity soundings. D-Z parameters (transverse resistance and longitudinal conductance) are ample for computing the distribution of surface potential and therefore, electrical resistivity plots (Henriet 1976). The significance of D-Z parameters for obtaining hydrological properties of the aquifers has been studied by several workers (Niwas and Singhal 1981; Gupta et al. 2014). A flowchart showing the methodology of resistivity sounding is depicted in Fig. 3.

The D-Z parameters (S and T) along with other indices like transverse resistivity ( $\rho_t$ ), longitudinal resistivity ( $\rho_l$ ), coefficient of anisotropy ( $\lambda$ ) and fracture porosity ( $\varphi_f$ ) have been calculated to analyze the data further.

The D-Z parameters are defined as,

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \dots + \frac{h_n}{\rho_n} = \sum_i^n \frac{h_i}{\rho_i} \quad (1)$$

$$T = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \dots + \rho_n h_n = \sum_i^n \rho_n h_n \quad (2)$$

Further, the transverse resistivity ( $\rho_t$ ), longitudinal resistivity ( $\rho_l$ ) and coefficient of electrical anisotropy ( $\lambda$ ), have been computed from S and T as,

$$\rho_l = \frac{H}{S} \quad (3)$$

$$\rho_t = \frac{T}{H} \quad (4)$$

$$\lambda = \sqrt{\frac{\rho_t}{\rho_l}} \quad (5)$$

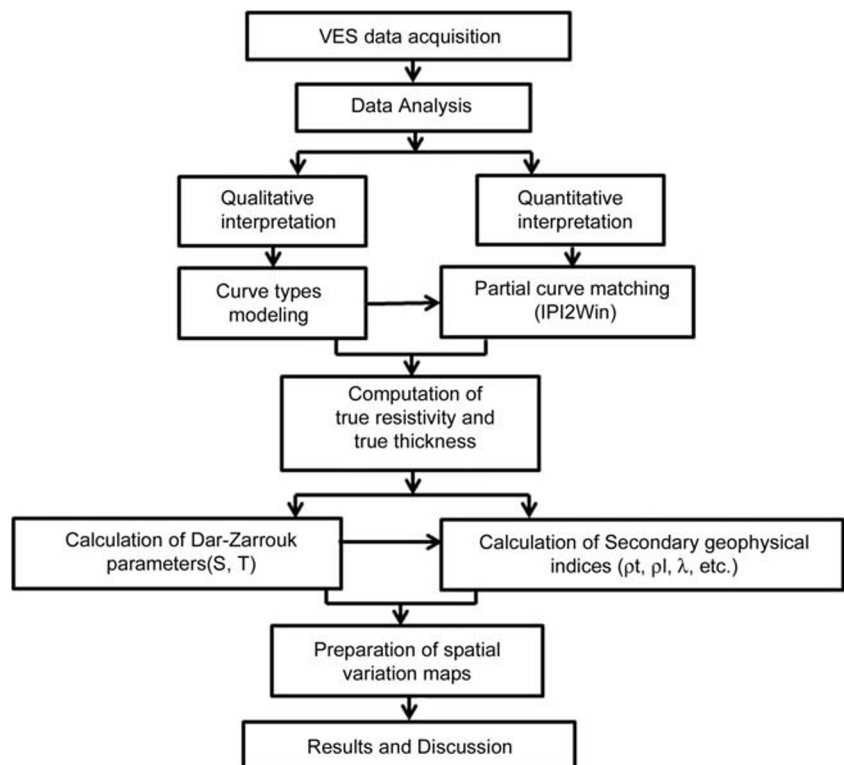
These indices were used to delineate the sub-surface saline and freshwater zones in the study area.

The fracture porosity was calculated in the study area using eq. (5), to understand the water saturation condition using the following equation (Lane et al. 1995),

$$\varphi_f = \frac{3.41 \times 10^4 (N-1)(N^2-2)}{N^2 C(\rho_{max} - \rho_{min})} \quad (6)$$

where  $\varphi_f$  is the secondary or fracture porosity, N is the vertical anisotropy corresponding to the coefficient of electrical anisotropy  $\lambda$ ,  $\rho_{max}$  and  $\rho_{min}$  are the maximum and minimum apparent resistivity ( $\Omega m$ ) respectively and C is the specific conductance of groundwater (371  $\mu S/cm$ ).

Fig. 3 Flowchart of the methodology for electrical resistivity technique



## Results and discussion

The data from 86 VES sites were used to calculate the secondary geophysical indicators (D-Z parameters, i.e. S and T, which is the combination of layer resistivity and thickness). Spatial variation maps for longitudinal conductance (S), transverse resistance (T), transverse resistivity ( $\rho_t$ ), longitudinal resistivity ( $\rho_l$ ), anisotropy ( $\lambda$ ) and fracture porosity ( $\varphi_f$ ) were generated to demarcate the saline water-fresh water bodies and to delineate the groundwater potential zones in the study region. In the present study, the spatial variation maps of the above parameters were plotted using the ordinary kriging technique, which is a linear stochastic method using semi-variogram model fitting schemes to evaluate values at unknown sites using the values at known VES sites (Webster and Oliver 2001).

### Longitudinal conductance map (S)

Spatial variation map of longitudinal conductance (S) of the study area was prepared by using the 86 soundings points with contour interval 0.2 S. The S map ranges from 0.0001–3.78 S (Fig. 4) and reveals the changes in the cumulative thickness of low resistivity features from one place to another. It is observed that there is a distinct boundary between the southwestern part and the rest of the study area. The variation reveals distinct boundaries without any overlapping characteristics. The low S values (0.0001 to 0.2 S) are located towards the central and northern parts of the study region. Moderate values (0.2 to 0.7) are observed at VES 15, 18, 27, 32, 58, 66, 75, 84, and 85 while high S values varying from 0.7 to 3.78S

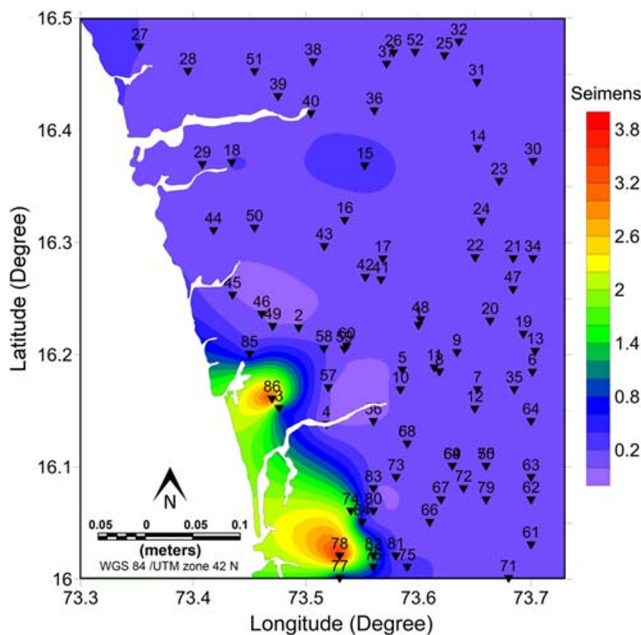


Fig. 4 Spatial variability of longitudinal conductance map (S) of the study area

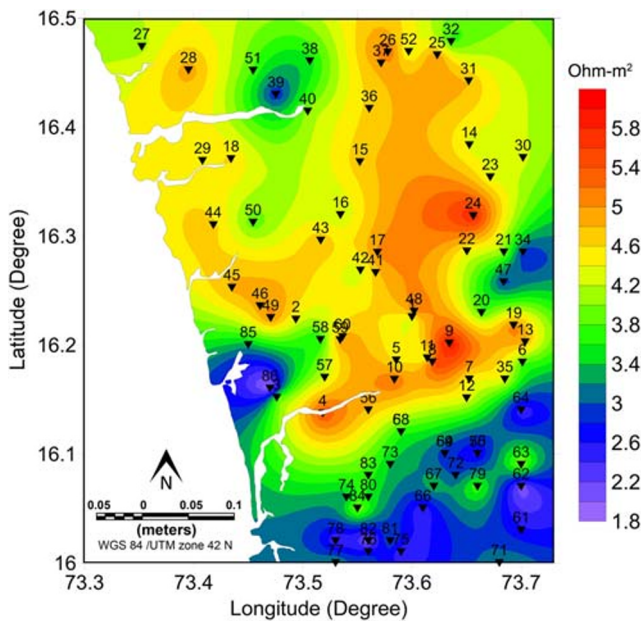
are revealed at the VES stations 3, 74, 76, 78, 82, 86 towards the western part of the study area, suggesting saline water ingress due to the environs of Arabian Sea. A relatively high S value is also seen at inland station VES 15 (0.4 Siemens), possibly due to enrichment of fertilizers and anthropogenic activity, which increases the TDS, and in turn, increases the electrical conductivity at this site.

It is pertinent to mention here that water samples collected from 36 wells in the study area (Suneetha and Gupta 2018) indicate that the electrical conductivity (EC) value ranges from 170 to 94,920  $\mu\text{S}/\text{cm}$ . Well numbers 7, 14, and 15 are located in close vicinity of VES sites 3, 78, and 86, which reveals very high EC values ( $> 5000 \mu\text{S}/\text{cm}$ ), indicative of saline water intrusion. Similarly, the total dissolved solids (TDS) at these stations are also beyond the permissible limit as prescribed by WHO (2011). The  $\text{Na}^+$  and  $\text{Cl}^-$  concentration at these locations record high values ( $>200 \text{ mg}/\text{l}$ ). The high amount of these ions is mainly due to saline water intrusion. Also, the influence of discharged agricultural and domestic wastewaters is responsible for such high  $\text{Cl}^-$  content. Sounding points 3, 78, and 86 show high S values ( $>3.5$  Siemens), thereby corroborating with the geochemical results. From the above, it can be advocated that the anomaly of fresh/saline water is distinctly reflected by the S values (Fig. 4) and thus it becomes easy to differentiate the region of saline water aquifers from that of the freshwater aquifers without any overlapping nature.

It is suggested that the earth acts as a natural filter to the percolating fluid and that its capacity to hold back fluid is a measure of its protective capacity. Higher S values generally indicate a relatively thick sequence of overburden and offer protection to the underlying aquifer from contaminants to permeate. To classify the aquifer protective capacity, Oladapo et al. (2004) categorized an area into poor, weak, moderate, good, very good, and excellent protective capacity zones. In the present study, the longitudinal conductance map (Fig. 4) reveals 59% of the surveyed area falls under poor aquifer protective capacity rating. About 7% of the area falls within the good protective capacity, while about 11% signifies moderate protective capacity rating and the remaining 23% exhibits weak protective capacity. This means that a major part of the study area is characterized by relatively poor to weak capacity rating, and thus is more prone to percolating contaminants. The areas with moderate to good aquifer protective capacity correspond with zones of significant clayey overburden, which are adequate to protect the aquifer from contamination.

### Transverse resistance map (T)

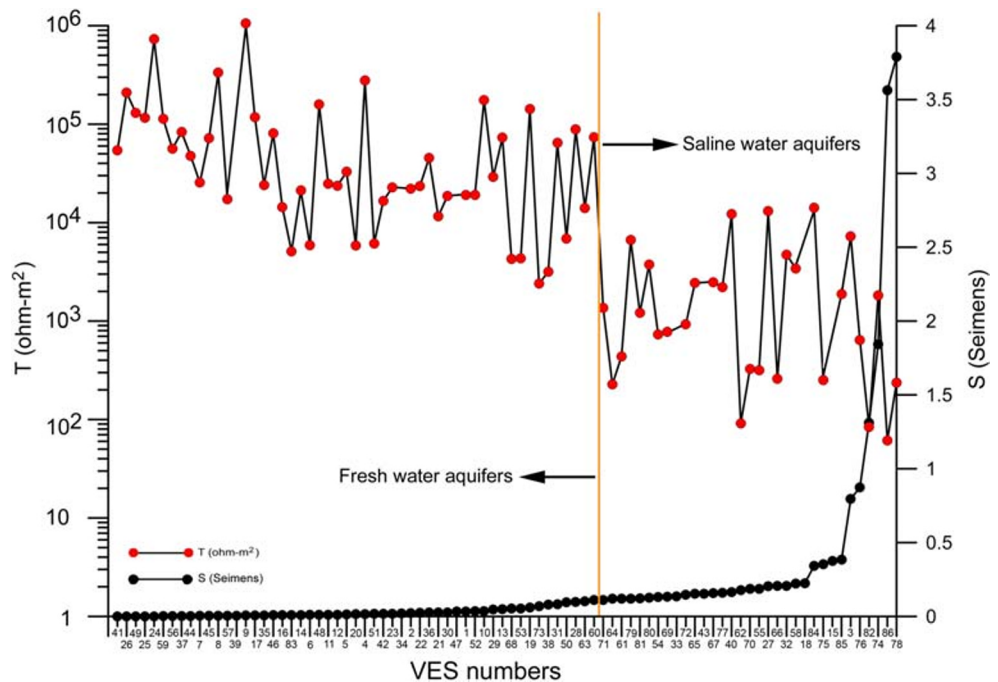
The spatial variation map of transverse resistance (T) is prepared for 86 VES locations with a contour interval of 50,000  $\Omega\text{m}^2$  (Fig. 5). Increasing T values are indicative of an increase



**Fig. 5** Spatial variability of Transverse resistance map (T) of the study area. Units are expressed in log10

in the thickness of the high resistivity materials. The T value varies from a minimum of 61.42  $\Omega\text{m}^2$  at VES 86 to a maximum of 1,055,955  $\Omega\text{m}^2$  at VES 9. It is evident from Fig. 5 that low T values ( $<700 \Omega\text{m}^2$ ) encompass several sounding stations in the south, south-east and south-west parts of the study area. It may be noted that the very low T values observed at VES 78, 82, and 86 correspond to a very high S value (1.3–3.8 S), characterizing saline water aquifers. It can be observed from Fig. 5 that several sites in the study area are characterized by moderately high T values (700–8000  $\Omega\text{m}^2$ ), signifying

**Fig. 6** Discerning saline and fresh groundwater aquifers using S and T plots corresponding to VES points



freshwater zones. It is further revealed that the southern part is more potential than the northern part of the study area. The remaining parts of the study area reveal very high T values ( $>8000 \Omega\text{m}^2$ ) suggesting hard rock terrain. It can be surmised that the line of contact between saline and freshwater is distinct and they do not mix.

Transverse resistance values are generally linked with zones of high transmissivity and therefore highly permeable to fluid movement. This indicates that the potential aquifer zones in the study area increase with increasing transverse resistance, which is most likely due to changes in hydraulic conductivities and electrical anisotropy (Salem 1999).

To demarcate the boundary between saline and freshwater, the D-Z parameters are sorted out and interpreted based on true resistivity values, constrained with available borehole lithology and geochemical data (Fig. 6). The graphical plot of S and T values of the soundings reflects a significant distinction for saline and freshwater aquifers. In the present case, the S and T values range from 0.12 to 3.8 S and 61 to  $<2000 \Omega\text{m}^2$  for saline water; and 0.00014 to 0.111 S and  $>2000$  to about 30,000  $\Omega\text{m}^2$  for freshwater aquifers, respectively.

**Transverse resistivity ( $\rho_t$ ) and longitudinal resistivity ( $\rho_l$ )**

The transverse resistivity ( $\rho_t$ ) has a similar trend to that of the spatial variation seen in the T map. Low values are observed at N-W and S-E parts of the study area, moderate resistivity of the order of 2000–5000  $\Omega\text{m}$  were seen at distinct places and very high resistivity values ( $>5000 \Omega\text{m}$ ) are revealed around the central-eastern part, which

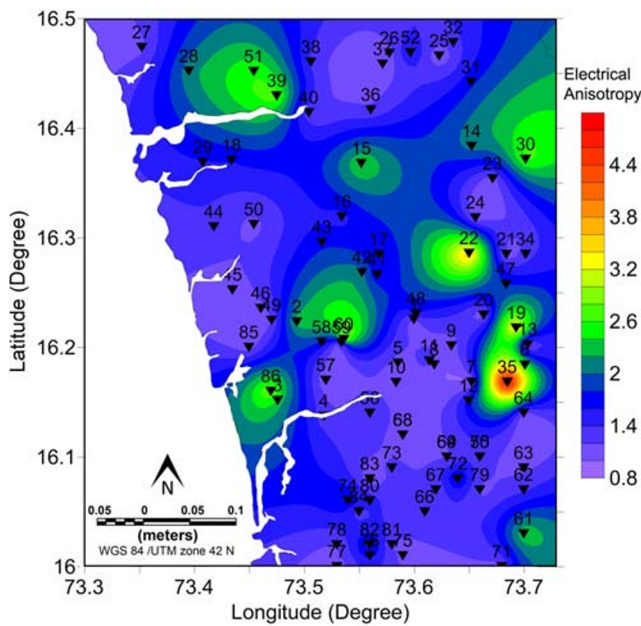
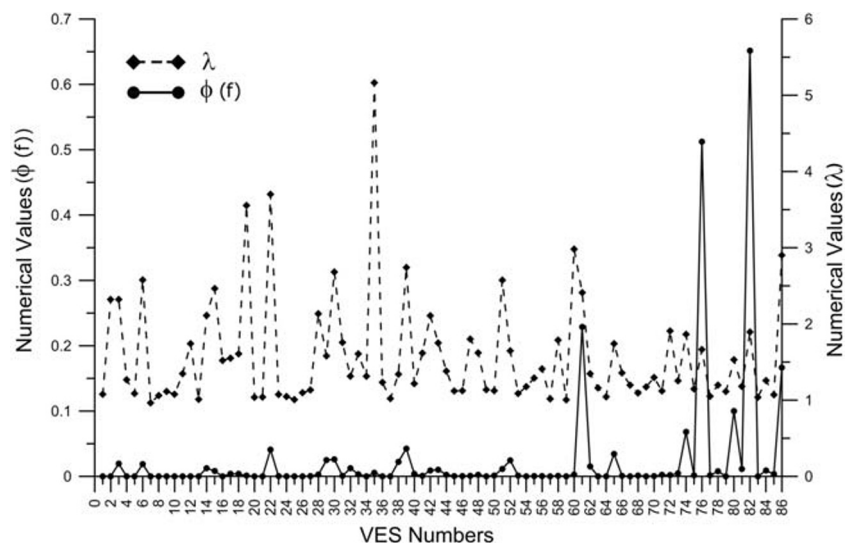


Fig. 7 Spatial variability of Anisotropy map ( $\lambda$ ) of the study area

is presumably due to the lateritic and hard rock formation. Similar trends are also observed in the longitudinal resistivity ( $\rho_l$ ) values. The transverse resistivity is usually more than the longitudinal resistivity in case the medium is heterogeneous (Flathe 1955), else the two parameters will be equal. This implies that the current flow and average hydraulic conduction along the longitudinal boundary are greater than those normal to the boundary plane (Ayolabi et al. 2010). Further, Keller (1982) was of the view that longitudinal resistivity is subjugated by the more conductive layers (in the present case, clay and weathered/fractured basalts) whereas transverse resistivity increases quickly even if a small fraction of resistive layers are present.

Fig. 8 Plot between the coefficient of anisotropy ( $\lambda$ ) and fracture porosity ( $\phi_f$ ) with VES numbers



### Electrical anisotropy ( $\lambda$ )

The variation in electrical anisotropy ( $\lambda$ ) within the subsurface is mainly caused by the fracturing of rocks and the direction of the scattered grains in the rock (Habberjam 1972; Watson and Barker 1999). The value of this parameter lies between 1 and 2. However, if  $\lambda$  value exceeds 2.0, it could usually be due to high resistive intrusive bodies, and thus, create an unconformity in resistivity resulting in very high values of coefficient of anisotropy (Isife and Obasi 2012).

The spatial variation in anisotropy was prepared using 86 VES in the study area and the value ranges from 0.9 to 5.1 (Fig. 7). As hardness and compaction of rocks increases,  $\lambda$  also increases. In the present case, the coefficient of anisotropy increases from SW to NE and also from SE to NW. It is not uniform in all directions and therefore anisotropy plays a major role in fracturing. These sections are thus more fractured suggesting a prospective groundwater zone. Also, several lineaments are traversing the study area and the intersection points of the lineaments are potential zones for groundwater. The fracture porosity ( $\phi_f$ ) observed in the study area ranges from  $10^{-6}$  to 0.65. A correlation between electrical anisotropy and fracture porosity was plotted to visualize the water saturation of the study area. A positive correlation is observed between the fracture porosity and the electrical anisotropy (Fig. 8), implying well-connected fractures in the subsurface. The high value of fracture porosity identifies the zone of high potential within the water-bearing formation. This is because of the occurrence of alluvium type of lithology since the formation over this area contains very fine grain size and unlithified sediments/materials which results in high porosity content (Maiti et al. 2013).

From the foregoing, it can be deduced that several parts of the study area in coastal Sindhudurg rely heavily on local water supplies, including groundwater and local storage.

Therefore the availability and suitability of this resource are of utmost importance. It is also inferred that there is wide-spread saline water ingress in the western part of the study area characterized by high longitudinal conductance and high electrical conductance values, thus polluting the coastal freshwater aquifers. To conserve sustainability, there should be improved water use and management in place to increase water supply reliability while decreasing the effects of contamination. This will lead to improving both the ecosystem and water supply resiliency to impacts of climate change, protecting the aquifers from contamination, increase groundwater recharge, etc. These initiatives will help in coastal conservation wherein coastal agriculture is a significant economic driver. Unregulated agricultural water use and excessive pumping of water from coastal aquifers may impact water quality thereby degrading the aquifers and in turn affecting the health of the populace of that region.

## Conclusion

Vertical electrical sounding (VES) studies were carried out at 86 sites and were corroborated with geochemical results to understand the ingress of saline water into the mainland, to delineate aquifer zones, and characterize the conditions of the underground flow in terms of fracture porosities of the aquifers. The spatial distribution of D-Z parameters revealed the demarcation between saline and fresh water in the study area.

High longitudinal conductance (S) values (0.7–3.78 S) are observed in the western part of the study area presumably due to the ingress of saline water. This finding is further corroborated by the fact that very high electrical conductivity (EC) values ( $> 5000 \mu\text{S}/\text{cm}$ ) of groundwater samples are observed from the VES sites having high S values. This suggests wide-spread saline water ingress in the coastal aquifers. The protective capacity of aquifers also suggests a predominantly poor to weak rating in the study area thus offering less protection to the underlying aquifer from contaminants to infuse. Further, very low transverse resistance (T) values were seen at VES stations corresponding to a very high S value suggesting that the coastal aquifers at these sites are characterized by saline water intrusion.

Electrical anisotropy ( $\lambda$ ) is a crucial parameter in understanding the fracturing of a region. In the present study the  $\lambda$  values ranging between 0.9 to 5.1. Two prominent high trends are observed in SW-NE and SE-NW directions and these are potential groundwater zone. Several lineaments are criss-crossing the study area and the intersection points of these lineaments are also prospective groundwater zones. A positive correlation has been drawn between electrical anisotropy and fracture porosity wherein the high porosity zones confirm the high  $\lambda$  values, suggesting that fracturing is due to anisotropy

and a significant amount of usable groundwater may be explored.

The analysis of DZ parameters reveals a clear and striking contrast and suggests a reliable solution in demarcating the saline and freshwater aquifers in this coastal terrain. These indices also provide a dependable elucidation, particularly when the resistivity data analysis is inhibited by the intermixing of resistivities of saline and fresh waters, clayey and sandy layers in any coastal aquifer system. Demarcation of aquifer boundaries and hydro-geologic characterization can help in proper management and conservation of groundwater resources of a coastal region.

**Acknowledgments** The authors are thankful to the Director, IIG, for the kind permission to publish this paper. They are also grateful to Shri B.D. Kadam, Dr. V.C. Erram, and Dr. M. Laxminarayana for their keen interest in data acquisition. The first author (SN) is obliged to IIG, Panvel for the financial support in the form of a research fellowship. The authors are highly indebted to Shri B.I. Panchal for drafting the figures.

## References

- Ali Kaya M, Özürlan G, Balkaya Ç (2015) Geoelectrical investigation of seawater intrusion in the coastal urban area of Çanakkale, NW Turkey. *Environ Earth Sci* 73:1151–1160
- Ayolabi EA, Folorunso AF, Oloruntola MO (2010) Constraining causes of structural failure using electrical Resistivity tomography (ERT): a case study of Lagos, southwestern, Nigeria. *Mineral Wealth* 156: 7–18
- Batayneh AT (2013) The estimation and significance of Dar-Zarrouk parameters in the exploration of quality affecting the Gulf of Aqaba coastal aquifer systems. *J Coast Conserv* 17:623–635. <https://doi.org/10.1007/s11852-013-0261-4>
- Bhattacharya PK, Patra HP (1968) *Direct Current Electric Sounding*. (Methods in Geochemistry and Geophysics, 9) Elsevier Publishing Co., Amsterdam, ix + 135, 47
- Bobachev A (2003) Resistivity sounding interpretation. IPI2WIN:version 3.0.1, a 7.01.03 Moscow State University
- Central Groundwater Board (CGWB) (2014) Groundwater information, Sindhudurg district, Maharashtra. Technical Report 1835/DB/2014
- Deolankar SB (1980) The Deccan basalt of Maharashtra, India- their potential as aquifers. *Ground Water* 18(5):434–437
- Deshpande GG (1998) *Geology of Maharashtra*. Geological Society of India, Bangalore, 223p
- Flathe H (1955) Possibilities and limitations in applying geoelectrical methods to hydrogeological problems in the coastal area of Northwest Germany. *Geophys Prospect* 3:95–110
- Gupta G, Maiti S, Erram VC (2014) Analysis of electrical resistivity data in resolving the saline and fresh water aquifers in west coast Maharashtra, India. *J Geol Soc India* 84:555–568
- Haberjam GM (1972) The effect of anisotropy on square array resistivity measurements. *Geophys Prospect* 20:249–266
- Henriet JP (1976) Direct application of the Dar-Zarrouk parameters in ground water surveys. *Geophys Prospect* 24:344–353
- Isife FA, Obasi RA (2012) Electrical anisotropy of crystalline basement/sediment rock around Ifon, South-Western Nigeria: implications in geologic mapping and groundwater investigation. *ARPN J Eng Appl Sci* 7:634–640



- Keller GV (1982) Electrical properties of rocks and minerals. In: Carmichael RS (ed) Hand book of physical properties of rocks. CRC Press, pp 217–293
- Lane JW Jr, Haeni FP, Watson WM (1995) Use of a square array direct current resistivity method to detect fractures in crystalline bedrock in New Hampshire. *Ground Water* 33(3):476–485
- Lee S, Kim K, Ko I, Lee S, Hwang H (2002) Geochemical and geophysical monitoring of saline water intrusion in Korean paddy fields. *Environ Geochem Health* 24:277–291
- Loke MH (2000) Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys
- Maiti S, Erram VC, Gupta G, Tiwari RK, Kulkarni UD, Sangpal RR (2013) Assessment of groundwater quality: a fusion of geochemical and geophysical information via Bayesian neural networks. *Environ Monit Assess* 185:3445–3465
- Maillet R (1947) The fundamental equation of electrical prospecting. *Geophysics* 12:529–556
- Maillet GM (2005) Recent and current sedimentary relationships between a river and its delta in micro tidal area: example from Rhône River mouth. Unpubl. Ph. D. Thesis, University of Provence, Aix-Marseille 1, 301
- Mondal NC, Singh VP, Ahmed S (2013) Delineating shallow saline groundwater zones from southern India using geophysical indicators. *Environ Monit Assess* 185:4869–4886
- Niwas S, Singhal DC (1981) Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *J Hydrol* 50:393–399
- Oladapo MI, Mohammed MZ, Adeoye OO, Adetola BA (2004) Geoelectrical investigation of Ondo state housing Coperation estate, Ijapo, Akure, South Western Nigeria. *Jour Mining Geol* 40(1):41–48
- Orellana E, Mooney HM (1966) Master Tables and curves for Vertical Electrical Sounding over layered structures Intercientia Madrid Spain. 193
- Salem HS (1999) Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurements. *Hydrol Earth Syst Sci* 3(3): 421–427
- Singh KP (2005) Nonlinear estimation of aquifer parameters from surficial resistivity measurements. *Hydrol Earth Syst Sci Dis* 2:917–938
- Suneetha N, Gupta G (2018) Assessment of groundwater quality for irrigational use: a case study from the coastal tracts of Sindhudurg district, Maharashtra. *Indian J Mar Sci* 47(10):2013–2020
- Suneetha N, Gupta G, Tahama K, Erram VC (2020) Two-dimensional modelling of electrical resistivity imaging data for assessment of saline water ingress in coastal aquifers of Sindhudurg district, Maharashtra, India. *Model Earth Syst Environ* 6:731–742. <https://doi.org/10.1007/s40808-020-00725-w>
- Watson KA, Barker RD (1999) Differentiating anisotropy and lateral effects using azimuthal resistivity offset Wenner soundings. *Geophysics* 64(3):1–7
- Webster R, Oliver MA (2001) *Geostatistics for environmental scientists*. Wiley, Chichester
- WHO (2011) *Guidelines to drinking water quality*. World health organization 4<sup>th</sup> Edn Geneva Switzerland
- Zohdy AR (1989) A new method for automatic interpretation of Schlumberger and Wenner sounding curves. *Geophysics* 54:245–253

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.