Vol. 4, No. 1 (2023); 18–30

Journal of Earth Sciences and Technology

http://www.htpub.org/Journal-Of-Earth-Sciences-And-Technology/

Numerical Modeling of Geophysical Data in Resolving the Saline and Fresh Water Aquifers in West Coast Maharashtra

Khan Tahama[a], Gautam Gupta[b]*, Flawiya More[a]

[a]*Indian Institute of Geomagnetism, New Panvel (W), Navi Mumbai 410218, India*
[b]*Dr. KSK Geomagnetic Research Laboratory, IIG, Prayagraj 221505, India*

Article Information

Article History
Received: 18/05/2023
Accepted: 10/08/2023
Available online: 28/08/2023

Keywords
Electrical resistivity
Magnetic
Groundwater
Saline water
Lineaments
Maharashtra

Abstract

Electrical resistivity and ground magnetic methods are widely used for identification of groundwater potential zones and in delineating the lateral and vertical distribution of sub-surface. Electrical resistivity technique can also differentiate the ingress of sea water into inlands thereby getting mixed up with fresh water bodies. The present studies are an attempt to delineate the saline water-fresh water interface and to demarcate the faults and lineaments in parts of Kudal-Vengurla and surrounding coastal region of western Maharashtra. A total of 30 vertical electrical soundings were carried out using the Schlumberger configuration with AB/2= 100m. The IPI2WIN algorithm based on automatic as well as manual interpretation of electrical sounding curves was used for analyzing the resistivity data set. The pseudo cross-sections of resistivity data over five profiles in the study region show the flow of saline water from the coastal side, partly controlled by the lineaments. A total of 122 ground magnetic data points were also acquired from the study region and the analysis was performed using SURFER software. From the observed magnetic anomaly map it appears that NW-SE trend are parallel to the present day coast line and can be associated with the coastal tectonics. The structural elements and magnetic sources within and below the trap covered region are delineated.

1. Introduction

Groundwater is a major source of clean drinking water all over the world. It has been an important resource especially in the arid to semi arid part of the world. Increased demands for water have stimulated development of underground water resources. As a result, techniques for investigating the occurrence and

---

* Corresponding author
E-mail address: gautam.g@iigm.res.in.

movement of groundwater have improved, better equipment for extracting has been developed, concepts for resource management have been established, and the research has contributed to a better understanding of the subject.

Saline water incursion is a common problem in coastal areas of the world (Bear et al., 1999, Park et al., 2005, Song et al., 2007, Gupta et al., 2010, Maiti et al., 2012). Groundwater contamination in coastal regions occurs when seawater mixes with freshwater aquifers. This process can be natural and human-induced. With growing industries and urbanization, this problem aggravates when excessive pumping of freshwater from an aquifer reduces the water pressure and thus draws seawater into the aquifers (Adeoti et al., 2010). Water resources in such coastal areas thus assume significance since any developmental activity will depend upon the availability of drinkable freshwater to meet industrial, farming, and other household requirements.

There are several factors that may explain the seawater intrusion into freshwater pockets. Lineaments play a major role and may act as a pathway for seawater invasion into the mainland. Also, seawater contamination may occur through any rivers flowing in the vicinity of the coastline (Benkabbour et al., 2004). Of all non-intrusive surface geophysical methods, the electrical resistivity profiling and vertical electrical sounding (VES) methods have been applied most widely to detect and monitor saline water/freshwater transitions in different coastal areas in the last several years with proven efficiency (Sherif et al., 2006; Omosuyi et al., 2008; Hermans et al., 2012; Mondal et al., 2013).

The VES and ground magnetic methods has been successfully used by a number of researchers for various applications which include groundwater investigations (Hamzah et al., 2007; Gupta et al., 2012; Goud and Mathur, 2018; Oni et al., 2020; Tahama et al., 2022), groundwater contamination studies (Frohlich et al., 2008; Karlik and Kaya, 2001; Kundu and Mandal, 2009; Park et al. 2005; Khalil, 2012; Naidu et al., 2021), saltwater intrusion problems (Edet and Okereke, 2001; Hodlur et al., 2006; Gupta et al., 2010; Al-Garni 2010; Oladele et al. 2015; Adeyemo et al. 2017; Goebel et al. 2017; Naidu et al., 2020), and geothermal explorations (El-Qady et al., 2000; Majumdar et al., 2000; Kumar et al., 2011; Saibi et al., 2022).

With the available database in the northern part of DVP, CGWB (http://cgwb.gov.in/CR/achi_geo_stu.html) suggested the following probable resistivity ranges for different litho units vis-à-vis water-bearing zones in the Deccan basalts:

20-40 Ω-m - weathered/fractured vesicular basalt saturated with water
40-70 Ω-m - moderately weathered/fractured basalt/vesicular basalt saturated with water
> 70 Ω-m -hard and massive basalts

These ranges may slightly vary either side from place to place depending on the proportion of clay, joints/fractures.

Water resources in coastal regions of Maharashtra, India assume a special significance because of rapid strides in developmental activities thereby depleting the available groundwater. Not much information is available on the role of lineaments in the hydrogeological set up as well as their role in the occurrence and movement of groundwater in the coastal region of Konkan Maharashtra. The ingress of saline water through inland drains due to tidal influence also makes the potable water unfit for consumption. In such areas, exploration and differentiation of fresh water aquifers from saline water aquifers becomes the primary objective (Bear et al., 1999). An attempt is made here to carry out geoelectrical and ground magnetic studies along the coastal tract of western Maharashtra to analyze the effects of sea water intrusion, in locating fresh groundwater pockets and to decipher the subsurface faults and lineaments.

2. Geological setting of the study area

Sindhudurg district is located in the Konkan region of Maharashtra State and covers a geological area of 5087 sq. km. The district is bounded in the north by Ratnagiri district, west by the Arabian Sea and in the east by Kolhapur district, and in the south by Goa State and Belgaum district of Karnataka State.

These beaches are microtidal and are under the influence of semi-diurnal tides, which has morphological features distinct from those of the rest of the Indian coast (Chandramohan et al., 1992). The entire coastal stretch of Konkan was tectonically active during the Miocene-Pliocene period. The study area has three stretches of beach: Mochemad beach, Shiroda beach, and Redi beach. The rainfall ranges between 300 and 470 cm/y, and wave height reaches up to 1.0 m, with an average wave period of 5 to 6 seconds. The predominant wave activity is of plunging type with multiple breakers. The district lies in the Survey of India degree sheets 47H, 48E and 48I. The district is located between north latitude 15°37’ and 16° 40’ and east longitude 73° 19’ and 74° 13’ (figure 1). This district is covered by the Deccan volcanic rocks, most of the soils are derived from lateritic rocks and the groundwater is circulated through a network of voids, conduits, joints and fractures. Hence monitoring the shallow distribution of true resistivity pattern and the magnetic anomalies in the area is vital for mapping the faults, fractures, joints, conduits and lineaments for groundwater exploration.

Different rock formations exist in the Sindhudurg district and within the study area. Each formation generally has different petrophysical properties, which will impart different capacities to store and transmit water. The Archaean and the Cuddapah formations are found only in the southern part of the district, while the entire northern portion is occupied by lava flows referred to as Deccan traps. The Dharwars are the most ancient formations in the area and are represented by banded hematite quartzite, varieties of schist, and granitic rocks. Vengurla has a moderate to bold relief with hills and deep valleys. It has a coastline on its western side with an NNW-SSE trend (Deshpande, 1998). The coastline of Vengurla is rocky, but it is not so in the south. River Karli flows from east to west and borders the northern part. River Talvada flows from north-east to south-west and joins the sea at Mochemad. River Redi, which marks the southern border of Vengurla, has a north-south flow on the eastern side and abruptly changes to east-west direction near Shiroda, to join the sea. The general trend of the major rivers in the area is from east to west. Two more rivers join the sea at the Vengurla port hill, situated on the northern and southern sides of the hill. These rivers have a major east-west trend. The important rock units in the region are banded hematite quartzite, quartzite, and schist (amphibolites and garnet), as well as granitic rocks. The area is structurally disturbed and influences the geology and the drainage pattern to a large extent (Deendar, 2003). Faulting is a major factor influencing the deformation and rock alterations, facilitating the formation of residual ore deposits and iron ore-containing rocks in the area. The sustainable iron ore deposit of Redi, thus formed, has supported large-scale mining operations over a long period, with the workable reverse of about 48 metric tons (Hiremath, 2003).

Geological conditions, on which the occurrence of groundwater depends, vary in different parts of Maharashtra. Nearly 82% of the total area of the state is occupied by Deccan basalt flow. Dharwarian metasediments (Archean), Kaladgi formation (Precambrian), Deccan Trap lava flows (Upper Cretaceous to Lower Eocene age), Laterite (Pleistocene), and Alluvial deposits (Recent to Sub-Recent) are the water-bearing formations observed in Sindhudurg district (CGWB, 2009). However, Kaladgi formation occurs in very limited patches and does not form a potential aquifer in the district. The Alluviums also have a limited areal extent found mainly along the coast.

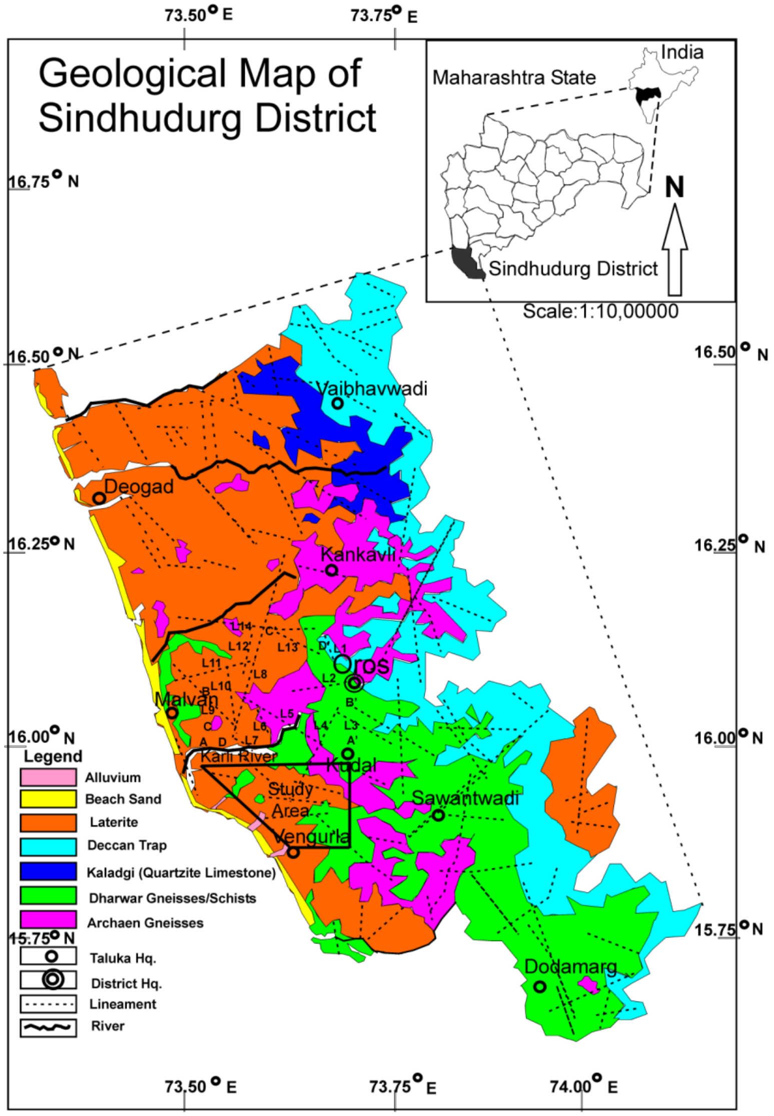

Fig. 1. Geological map of the Sindhudurg district, showing the study area.

3. Analysis and computational techniques

3.1 Analysis of vertical electrical sounding data

The vertical electrical sounding (VES) studies is based on measuring the potentials between one electrode pair while transmitting direct current (DC) between another electrode pair. The depth of penetration is proportional to the separation between the electrodes, in homogeneous ground, and varying the electrode separation provides information about the stratification of the ground (Dahlin, 2001). This method is carried out to decipher problems of saline water intrusion into freshwater in the hard formation such as the Deccan Trap region.

The VES was carried out in the study area with the SSR-MP-ATS resistivity meter supplied by IGIS, Hyderabad. The location of electrical soundings is shown in figure 2. Electrical resistivity soundings were conducted at 30 different locations by employing the Schlumberger array for delineating vertical distribution of water bearing zones, constituting the aquifer bodies in this region and to delineate the zones of seawater intrusion (Song et al., 2007). The Schlumberger soundings were carried with maximum current electrode spacing (AB) of 200 m (AB/2=100 m). The field data acquisition was generally carried out by moving two or four of the electrodes used, between each measurement. The resulting geoelectrical layer succession was used for identifying various conducting zones based on true resistivities.

The data obtained from the field was processed and modeled using IPI2WIN software, version 3.0.1.a7.01.03 (Bobachev, 2003) for interactive semi-automated interpretation. IPI2WIN is designed for automated and interactive semi automated interpreting of vertical electrical sounding and induced polarization data obtained with any of a variety of the most popular arrays used in the electrical prospecting. It is presumed that a user is an experienced interpreter willing to solve the geological problem posed as well as to fit the sounding curves. Targeting at the geological result is the specific feature distinguishing IPI2WIN among other popular programs of automatic inversion. Due to handy controls the interpreter is able to choose from a set of equivalent solutions the one best fitting both geophysical data (i.e. providing the least fitting error) and geological data (i.e. geologically sensible resistivity cross section). Comparing various concepts of the geological structure along the surveyed observation line rather than independent formal sounding curves, inversion is the approach implemented in IPI2WIN. This approach provides the opportunity to use a priory geological data and extract information to the greatest possible extent in the complicated geological situations. For viewing curves and models, the pseudo cross- section of a specified value and resistivity cross section are displayed (VES-IP mode: or chargeability cross section) in the pseudo cross section and resistivity cross section window, which can be used for interpretation.

IPI2Win is capable of solving resistivity electrical prospecting 1 D forward and inverse problems for a variety of commonly used arrays for the cross section with resistivity contrast within the range of 0.001 to 10000 ohm-m. The forward problem is solved using the linear filtering. These thoroughly tested filters and filtering algorithm implementation provide fast and accurate direct problem solution for a wide range of models, covering all reasonable geological situations.

The inverse problem is solved using a variant of the Newton algorithm of the least number of layers or the regularized fitting minimizing algorithm using Tikhonov’s approach to solving incorrect problems. A-priory information on layer depths and resistivites can be used for regularizing the process of the fitting error minimizing. The inverse problem is solved separately for each sounding curve. One-dimensional inversion results of VES sounding curves in the area are H-type and the rest are of Q-type and A-type. The apparent resistivity vs. half of the current electrode separation (AB/2) on log-log graph suggests three to four layered structures in this study area.

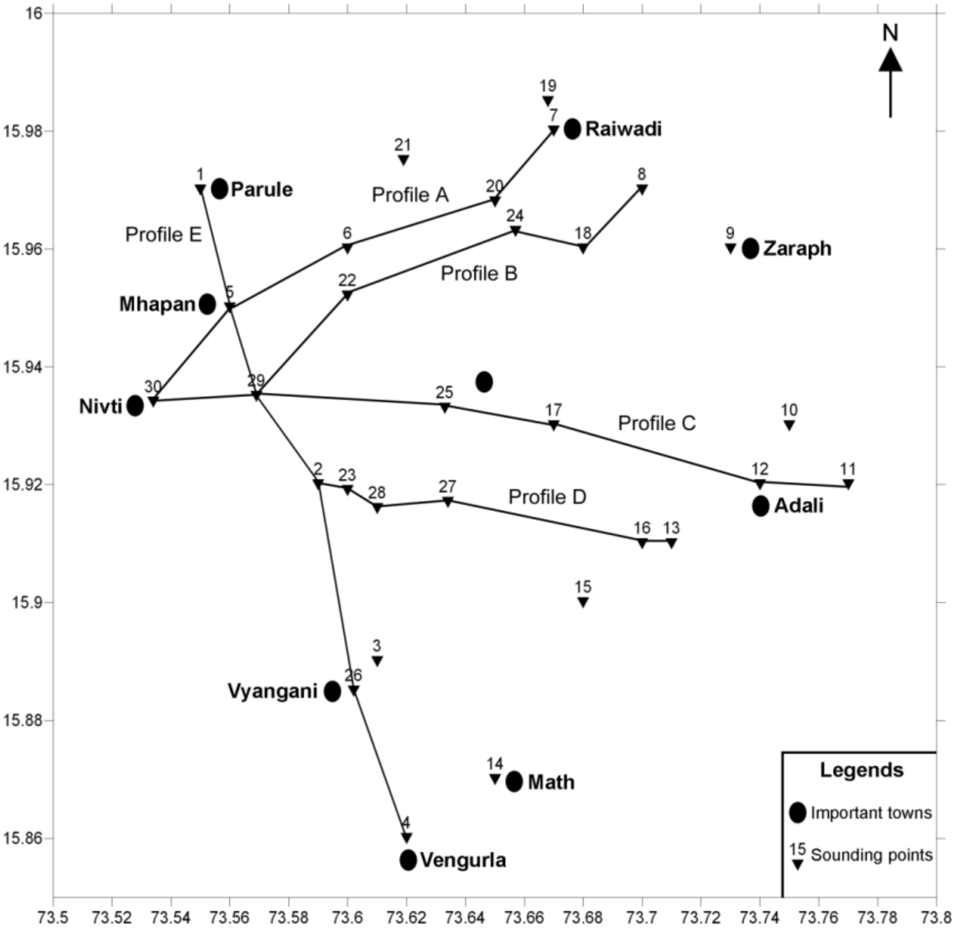

Fig. 2. Location map of vertical electrical soundings.

3.2 Analysis of ground magnetic data

Proton precession magnetometer was used to measure the total field (F). The measurements were taken at an interval of around 1 km and were dictated by the access to roads. Such large station spacing was chosen, as long wavelength (deep-seated), structures are to be deciphered. At each observation point ten to twelve readings were taken and the average value computed. A total of 122 observation points covered the area and their distribution is shown in the data distribution map. To obtain crustal anomaly map, the contributions due to the main core field and external current contribution must be removed. Data reduction concerns mainly with the removal of the effect due to main field i.e. removal of IGRF and the reduction of the effect due to the external field.

The total field (F) data was collected from the field, which contain contributions from the Main core field, the crustal field and the external current systems. Hence to isolate the crustal anomaly, the contributions due to the main core field and the external current systems have been removed. IGRF-2010 (Olsen, 2009) was used to represent the main field at each observation point. For the representation of the external field variations, the gridded anomaly values were plotted with the SURFER software against the latitude and longitude to obtain the anomaly maps.

Surfer is a grid-based mapping program that interpolates irregularly spaced XYZ data into a regularly spaced grid. Grids may also be imported from other sources, such as the United States Geological Survey (USGS). The grid is used to produce different types of maps including contour, vector, image, shaded relief, 3D surface and 3D wireframe maps. Many gridding and mapping options are available allowing us to produce the map that best represents the data.

An extensive suite of gridding methods is available in Surfer**.** The variety of available methods provides different interpretations of the data, and allows choosing the most appropriate method for specific needs. In addition, data metrics allows gathering information about the gridded data. Surface area, projected planar area and volumetric calculations can be performed quickly in Surfer**.** Cross-sectional profiles can also be computed and exported.

The grid files themselves can be edited, combined, filtered, sliced, queried and mathematically transformed. For example, create an isopach map from two grid files. The original surface grid file and the surface grid file are required after a volume of material was removed. This is subtracted from the two surfaces to create an isopach map. The resulting map displays how much material has been removed in all areas.

4. Results and discussion

4.1 Geoelectrical modelling

The 2-D geoelectrical section has been generated over five selected profiles in the study region. The profiles A and B are oriented in SW-NE direction while the profiles C and D are from west to east. The profile E is trending from north to south direction. The directions of the profiles are chosen in order to understand the geometry of the aquifer developed and the extent of saline water intrusion in and around the study area. The 2-D geoelectrical model is shown in figure 3a-e.

Profile A:

The profile A covers the sounding points 30, 5, 6, 20 and 7, from west to east. VES 30 is barely 200 m away from the coast at Nivti. The apparent resistivity cross-section (figure 3a) shows a wide low resistivity zone at VES 30 having resistivities below 5 Ω-m. This is a clear indication of saline water ingress. The resistivity values are highly influenced by the proximity of the Arabian Sea. Further east, below VES 5, 6 and 20 the resistivity value ranges from 500-2000 Ω-m. This region is at a higher elevation and hard and compact laterites are the main rocks types present. It is thus possible that this zone is acting as a barrier to groundwater or saline water flow from western side. However, below VES 7 the resistivities are of the order of 20-100 Ω-m indicating development of an aquifer. Further sounding points to the east of this station would have brought out the complete aquifer body.

Profile B:

The sounding points 29, 22, 24, 18 and 8 comprise profile B (figure 3b). A low resistivity (about 150 Ω-m) zone is delineated at depths of 3m below station 29. This station is about 5 km away from the coast and the resistivity values suggest that there is no saline water intrusion in this area. Sounding points 22, 24 and 18 lies over hard rocks reflecting resistivities of the order of 300-600 Ω-m. Below station 8, an aquifer body is developed which has resistivities of about 50-100 Ω-m up to depths of 20 m. This point is a potential groundwater zone and further suggests that groundwater recharge is towards west.

Profile C:

The profile C is more or less the central profile of the study area from Nivti in the west to Adali in the east. This profile covers the stations 30, 29, 25, 17, 12 and 11 (figure 3c). As discussed earlier, sounding point 30 is affected with saline water intrusion, which is seen here as a very low resistivity feature (below 5 Ω-m) from shallow depths to greater than 100 m. The intrusion of saline water is obvious at least 4 km inland, though the station 29 is not affected by saline water ingress. The resistivities are of the order of 150 Ω-m below station 29. Further east at stations 25, 17 and 12, the resistivities ranges from 500-2000 Ω-m, reflecting laterites and hard rocks. Below station 11, a small shallow aquifer body seems to develop. The resistivities here are in the range of 50-100 Ω-m.

Profile D:

Profile D covers sounding points 2, 23, 28, 27, 16 and 13 (figure 3d). The central part of the profile is highly saturated with groundwater as is shown by the resistivities ranging from 50-150 Ω-m. The aquifer body at station 28 has depth extension up to about 50m. The flow of groundwater is towards east covering stations 27 and 16. Stations 2 and 23 lies over laterites as is evidenced by the high resistivity values of 250-1000 Ω-m.

Profile E:

Profile E is trending in north-south direction covering stations 1, 5, 29, 2, 26 and 4 (figure 3e). It is seen from the figure that there is no saline water intrusion over this region. This profile is about 3-4 km away from the coast. The resistivity values over this profile ranges from 100-1000 Ω-m. Below station 1, a shallow aquifer is observed with resistivities of about 100-200 Ω-m. Another potential aquifer zone is obtained below station 29 having resistivities of the order of 100-200 Ω-m. A high resistivity feature obtained at station 5 demarcates these two aquifer bodies. It has been reported by Sarkar and Soman (1986); Hanamgond and Mitra (2008) that an N-S trending lineament passes from this region. It seems that this lineament is acting as a barrier between the two aquifer zones observed at stations 1 and 29. The aquifer zone at station 29 extends from depths of about 5m up to 100m. It can also be seen that the flow of groundwater is towards south at deeper levels. At station 26, another localized aquifer body is delineated at very shallow levels.

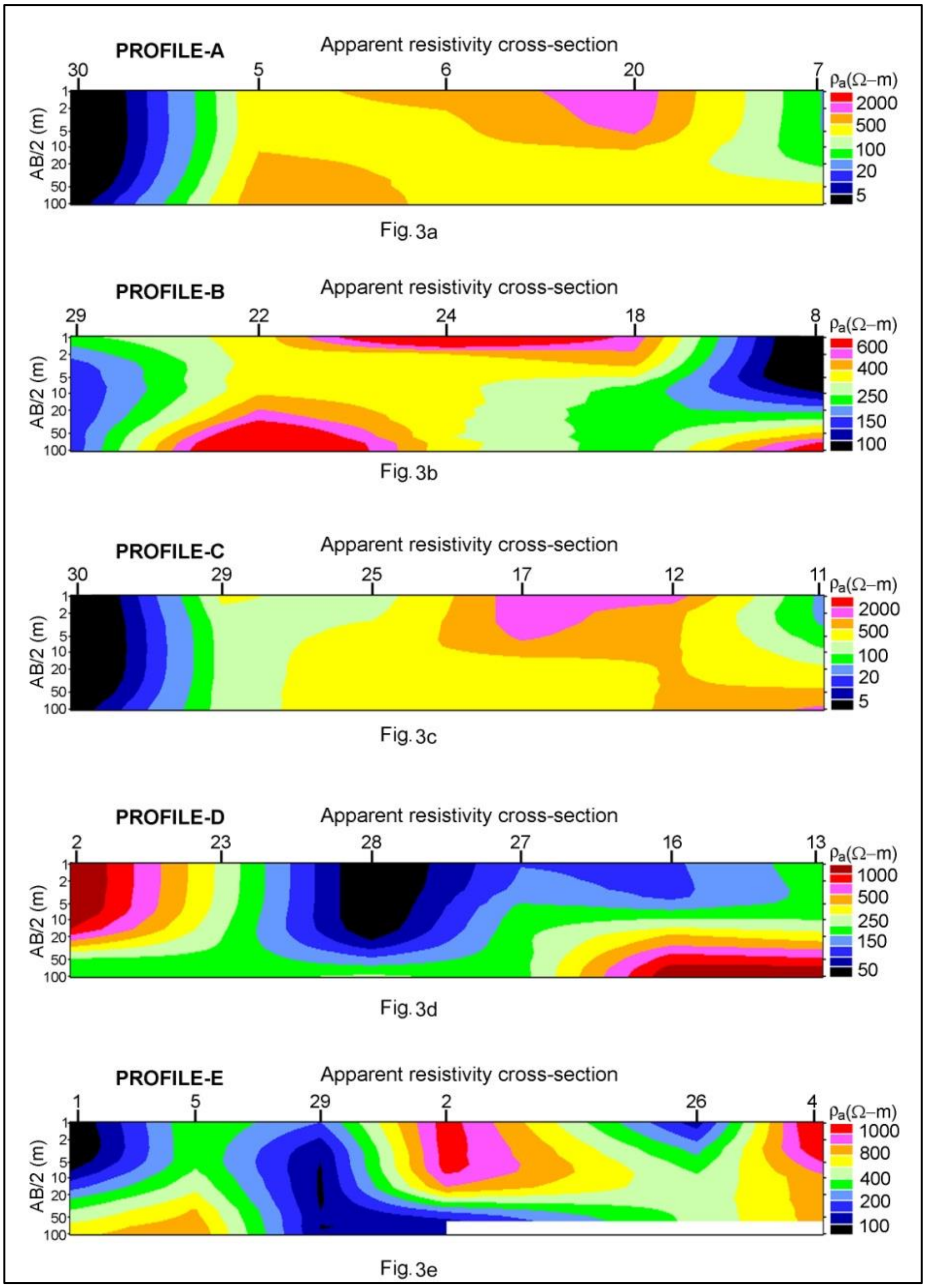

Fig. 3. Longitudinal geoelctrical cross section over profiles A, B, C, D and E.

4.2 Ground magnetic data

The ground magnetic data of Sindhudurg Distict was plotted against the latitude and the longitude with the respective magnetic value (figure 4). As mentioned earlier, a total of 122 data points were collected.

Most of the anomalies are trending in a NW-SE direction and are in accordance with the regional Dharwar trend. A clear change in the amplitude of the anomalies can be seen on either side of a NW-SE fault/lineament/contact starting from approximately 73.46°E and 16.00°N. This may possibly represent a change in metamorphic grades of the Achaean rocks on either side of this linear feature. The moderate amplitude magnetic highs towards the north of the study area suggest Achaean rocks at shallow levels below the laterities. The continuation of these anomalies towards south is restricted by a NE-SW trend coinciding with the Karli river fault. Short wavelength signatures found associated with trap flows (Anand and Rajaram, 2003) is not evident in the anomaly map.

From the foregoing, the significant utility of the geoelectrical profiles illustrate the intrusion of sea water into inland areas and the influence of fracture zones and lineaments on the movement and occurrence of groundwater. Figures 3a-d reveal that the top layer in the study region is thinner over elevated land compared to low-lying areas. Additionally, resistivity values are lower towards the north-western side of the study area (near Parule, Nivti, and Vyangani) than towards the eastern part. A significant resistivity low (1-5 Ωm) is observed below station 30, Nivti, indicating the potential presence of saline water intruding into fresh water zones, with its impact extending about 4 km inland in that area. Figure 3d further suggests the existence of a notable groundwater reservoir below station 28 (resistivities of 30-100 Ωm).

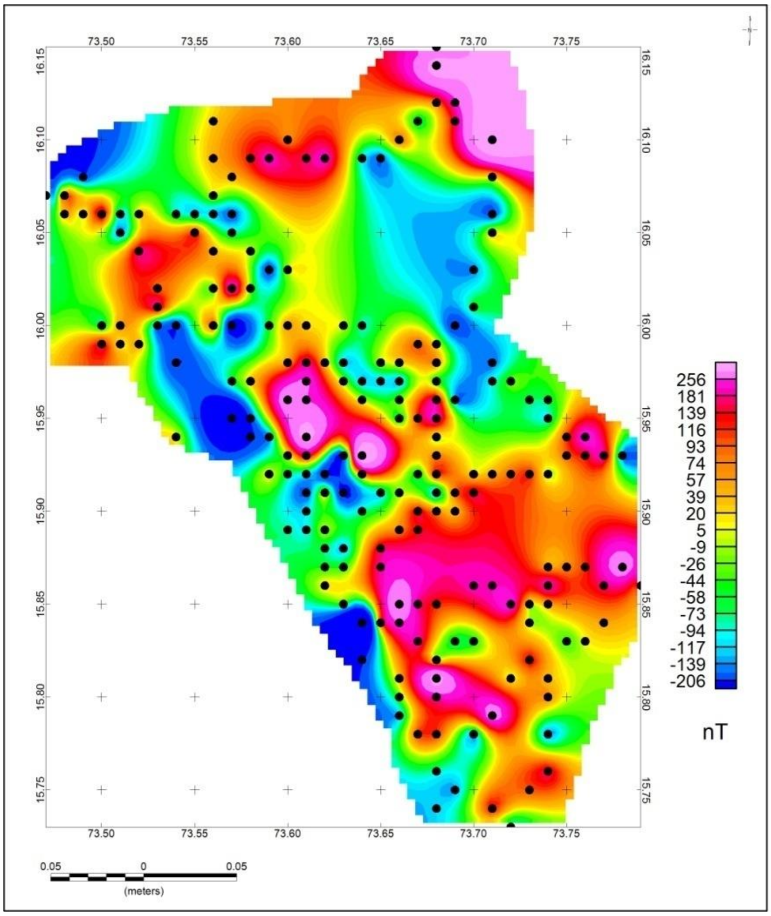

Fig. 4. Total Field Magnetic Anomaly with data distribution superposed.

Lineament-like features aligned in the NW-SE and NE-SW directions, with some intersecting points showing promise for groundwater recharge in the area, as is seen from the magnetic anomaly map. From the ground magnetic data, it is seen that most anomalies trend in a NW-SE direction. A NW-SE fault/lineament observed in the coastal side of the study area indicates a metamorphic grade variation in the Achaean rocks on either side of this linear feature, which is reflected as very low resistivity feature due to saline water intrusion. The moderate amplitude magnetic highs in the northern study area suggest Achaean rocks at shallow depths below the laterites, which are revealed as high resistivity values in the geoelectrical profiles. The major lineament trend in the NW-SE direction is associated with regional folding, forming folds whose axes strike in the same direction. On the other hand, the minor lineament system trends in the NE-SW direction and is related to a cross-folding episode. The NW-SE folding episode indicates compressive stress, with the principal axis oriented in the NE-SW direction. Hence, the dominant NW-SE trending lineaments are perpendicular to the direction of the regional stress field. It is pertinent to mention here that LANDSAT imageries in and around Katta, Sindhudurg district, revealed numerous lineaments trending NNW-SSE to NE-SW (figure 5) (Sarkar and Soman, 1986). Additionally, there are parallel en echelon lineaments running from Malvan in the north to Nivti and Math in the south near the coast. These lineaments show intense fracturing, brecciation, and silicifaction.

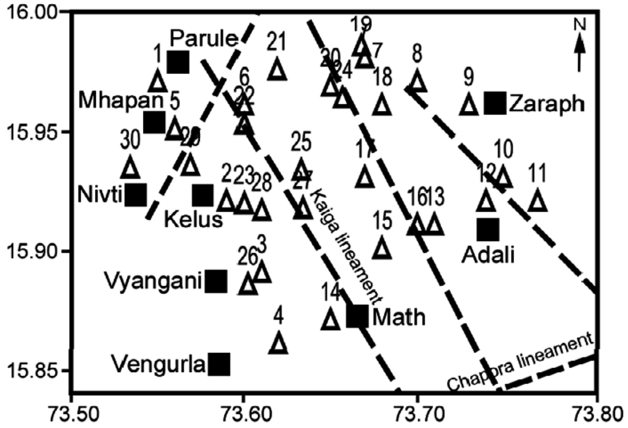

Fig. 5. Lineament map of the study area showing the vertical electrical sounding locations and major towns.

This study has provided a comprehensive understanding of the geological structures beneath the study area and valuable insights for conducting geoelectric studies essential for groundwater investigations. The magnetic method was employed to explore the potential structural influence on the origin of saline water, while the electrical resistivity method was used to map the subsurface sequence in the area and identify potential zones of saline water intrusion.

5. Conclusions

The sub-surface geoelectrical section over five profiles shows the ingress of sea water into inlands and the magnetic anomaly map depicts the role of fracture zones and lineaments which helps in the movement of groundwater. Water resources in coastal regions of Maharashtra assume a special significance because of rapid strides in developmental activities thereby depleting the available groundwater. The ingress of saline water through inland drains due to tidal influence makes the potable water unfit for consumption. In the present work the efficacy of geoelectrical and ground magnetic studies in such areas is demonstrated in locating fresh groundwater pockets to meet the water demands of society.

Acknowledgements

The authors are grateful to Director, IIG, for providing the necessary facilities and according permission to publish this work. Thanks are also due to Dr. Vinit Erram for data acquisition.

References

Adeoti, L., Alile, O. M., & Uchegbulam, O. (2010). Geophysical investigation of saline water intrusion into freshwater aquifers: A case study of Oniru, Lagos State. *Scientific Research and Essays*, 5(3), 248-259.

Adeyemo, I.A., Omosuyi, G.O., & Adelusi, A.O. (2017). Geoelectric Soundings for Delineation of Saline Water Intrusion into Aquifers in Part of Eastern Dahomey Basin, Nigeria. *Journal of Geoscience and Environment Protection*, 5, 213-232.

Al-Garni, M.A. (2010). Magnetic Survey for Delineting Magnetic Structures and Estimating Magnetic Sources Depth, Wadi Fatima, KSA. *Journal of King Saud University (Science)*, 22, 87-96.

Anand, S.P., & Rajaram, M. (2003). Study of aeromagnetic data over part of Eastern Ghat mobile belt and Bastar craton. *Gondwana Research*, 6, 859-865.

Bear, J., Ouazar, D., Sorek, S., Cheng, A., & Herrera, I. (1999). Seawater intrusion in coastal aquifers. Springer, Berlin Heidelberg New York, p 640.

Benkabbour, B., Toto, E.A., & Fakir, Y. (2004). Using DC resistivity method to characterize the geometry and the salinity of the Plioquaternary consolidated coastal aquifer of the Mamora plain, Morocco. *Environmental Geology*, 45, 518-526.

Bobachev, A. (2003). Resistivity Sounding Interpretation. IPI2WIN: Version 3.0.1, a 7.01.03. Moscow State University.

CGWB (2009). Groundwater Information, Sindhudurg district, Maharashtra. *Technical report No. 1625/DB/2009*.

Chandramohan, P., Anand, N.M., & Nayak, B.U. (1992). Surf zone dynamics of the Konkan Coast, India. In Desai, B.N. (Ed.), Oceanography of the Indian Ocean (pp. 751–759), New Delhi, India: Oxford and IBH.

Dahlin, T. (2001). The development of DC resistivity imaging techniques, *Computer Geoscience*, 27, 1019-1029.

Deendar, D.I. (2003). Structural controls in the formation of iron ore deposits and laterite in Vengurla area. In Sustainable Resource Management in Mining with Special Reference to Coastal Regions of Karnataka and Maharashtra. Mining Engineers Association of India, Belgaum Chapter Workshop, 8-10.

Deshpande, G.G. (1998). Geology of Maharashtra. Geological Society of India, Bangalore.

Edet, A., & Okereke, C. (2001). A regional study of saltwater intrusion in southeastern Nigeria based on the analysis of geoelectrical and hydrochemical data. *Environmental Geology*, 40, 1278-1289.

El-Qady, G., Ushijima, K., & El-Sayed, A. (2000). Delineation of a geothermal reservoir by 2D inversion of resistivity data at Hammam Faraun area, Sinai, Egypt. *Proceeding World Geothermal Congress*, 1103-1108.

Frohlich, R.K., Barosh, P.J., & Boving, T. (2008). Investigating changes of electrical characteristics of the saturated zone affected by hazardous organic waste. *Journal of Applied Geophysics*, 64, 25-36.

Goebel, M., Pidlisecky, A., & Knight, R. (2017). Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. *Journal of Hydrology*, 551, 746-755, 10.1016/j.jhydrol.2017.02.037

Goud, K. B., & Mathur, R.R (2018). Geochemical Signatures for the Identification of Seawater Intrusion in an alluvial aquifer in Palghar District, Maharashtra. *International Journal of Recent Scientific Research*, 9(3), 24779-24783.

Gupta, G., Kachate, N. R., Erram, V. C., Maiti, S., & Patil, S.N. (2010). Geoelectrical studies for delineating seawater intrusion in parts of Konkan coast, western Maharashtra. *International Journal of Environment and Earth Science*, 1(1), 62-79.

Gupta, G., Erram, V.C., & Kumar, S. (2012). Temporal geoelectric behaviour of dyke aquifers in northern Deccan Volcanic Province, India. *Journal of Earth System Science*, 121(3), 723-732.

Hamzah, U., Samudin, A.R., & Malim, E.P. (2007). Groundwater investigation in Kuala Selangor using vertical electric sounding (VES) surveys. *Environmental Geology*, 51, 1349-1359.

Hanamgond, P.T., & Mitra, D. (2008). Evolution of Malvan Coast, Konkan, West Coast of India—A Case Study Using Remote Sensing Data. *Journal of Coastal Research*, 24, 672-678.

Hermans, T., Daoudi, M., Vandenbohede, A., Robert, T., Caterina, D., & Nguyen, F., (2012). Comparison of temperature estimates from heat transport model and electric resistivity tomography during a shallow heat injection and storage experiment. *Applications in Geothermal Monitoring, Berichte Geology*, B.-A. 93.

Hiremath, D.A. (2003). Iron ore deposits of Sindhudurg district Maharashtra state and their export potentiality. In Sustainable Resource Management in Mining with Special Reference to Coastal Regions of Karnataka and Maharashtra. Mining Engineers Association of India, Belgaum Chapter Workshop, 21–25.

Hodlur, G.K., Dhakate, R., & Andrade, R. (2006). Correlation of vertical electrical sounding and borehole-log data for delineation of saltwater and freshwater aquifers. *Geophysics*, 71(1), G11–G20.

Karlik, G., & Kaya, M.A. (2001). Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: A case study from Isparta, Turkey. *Environmental Geology*, 40, 725-731.

Khalil, M.H. (2012). Magnetic, geo-electric, and groundwater and soil quality analysis over a landfill from a lead smelter, Cairo, Egypt. *Journal of Applied Geophysics*, 86, 146-159. https://doi.org/10.1016/j.jappgeo.2012.08.004.

Kumar, D., Thiagarajan, S., & Rai, S.N. (2011). Deciphering geothermal resources in Deccan trap region using electrical resistivity tomography technique. Journal of the Geological Society of India, 78, 541-548.

Kundu, M.C. & Mandal, B. (2009). Assessment of potential hazards of fluoride contamination in drinking groundwater of an intensively cultivated district in West Bengal, India. *Environmental Monitoring Assessment*, 152, 97-103.

Maiti, S**.,** Gupta, G., Erram,V.C., & Tiwari, R.K. (2012). Delineation of shallow resistivity structure around Malvan, Konkan region, Maharashtra by neural network inversion using vertical electrical sounding measurements. *Environmental Earth Sciences.* doi:10.1007/s12665-012-1779-8.

Majumdar, R.K., Majumdar, N., & Mukherjee, A.L. (2000). Geoelectric investigations in Bakreswar geothermal area, West Bengal, India. *Journal of Applied Geophysics*, 45, 187-202.

Mondal, N.C., Singh, V.P., & Ahmed, S. (2013). Delineating shallow saline groundwater zones from southern India using geophysical indicators. *Environmental Monitoring Assessment*, 185, 4869-4886.

Naidu, S., Gupta, G., Tahama, K., & Erram, V.C. (2020). Two-dimensional modelling of electrical resistivity imaging data for assessment of saline water ingress in coastal aquifers of Sindhudurg district, Maharashtra, India. *Modeling Earth Systems and Environment*, 6, 731-742.

Naidu, S., Gupta, G., Singh, R., Tahama, K., & Erram, V.C. (2021). Hydrogeochemical processes regulating the groundwater quality and its suitability for drinking and irrigation purpose in parts of coastal Sindhudurg district, Maharashtra. *Journal of the Geological Society of India*, 97, 173-185.

Oladele, S., Ayolabi, E.A., Olobaniyi, S.B., & Dublin-Green, C.O. (2015). Structural Features of the Benin Basin, Southwest Nigeria Derived from Potential Field Data. *Journal of Mining and Geology*, 51 (2), 151-163.

Olsen, N., Mandea, M., Sabaka, T.J., & Tøffner-Clausen, L. (2009). CHAOS-2—A geomagnetic field model derived from one decade of continuous satellite data. *Geophysical Journal International*, 179, 1477-1487. doi:10.1111/j.1365 246X.2009.04386.x.

Omosuyi, G.O., Ojo, J.S., & Olorunfemi, M.O. (2008). Geoelectric Sounding to Delineate Shallow Aquifer in the Coastal Plain Sands of Okitipupa Area, South Western Nigeria. *Pacific Journal of Science and Technology*, 9(2), 562-577.

Oni, A.G., Eniola, P.J., Olorunfemi, M.O., Okunubi, M.O., & Osotuyi, G.A. (2020). The magnetic method as a tool in groundwater investigation in a basement complex terrain: Modomo Southwest Nigeria as a case study. *Applied Water Science*, 10, 190. https://doi.org/10.1007/s13201-020-01279-z.

Park, S.C., Yun, S., Chae, G.T., Yoo, I.S., Shin, K. S., & Heo, C.H. (2005). Regional hydrochemical study on salinization of coastal aquifers, western coastal area of South Korea. *Journal of Hydrology, 313*,182-194.

Saibi, H., Amrouche, M., Batir, J., Gabr, A, & Fowler, A.R. (2022). Magnetic and gravity modeling and subsurface structure of two geothermal fields in the UAE. *Geothermal Energy*, 10, 28. https://doi.org/10.1186/s40517-022-00240-4.

Sarkar, P.K., & Soman, G.R. (1986). Geology of the area around Katta, sindhudurg district, Maharashtra based on aerospace data. *Journal of the Indian Society of Remote Sensing*, 14, 43-51.

Song, S.H., Lee, J.Y., & Park, N. (2007). Use of vertical electrical soundings to delineate seawater intrusion in a coastal area of Byunsan, Korea. *Environmental Geology,* 52, 1207-1219.

Sherif, M.A., Mahmoudi, El., Garamoon, H., Kacimov, A., Akram, S., Ebraheemand, A., & Shetty, A. (2006). Geoelectrical and hydrogeochemical studies for delineating seawater intrusion in the Outlet of Wadi Ham, UAE, *Environmental Geology*, 49(4), 536-551.

Tahama, K., Gupta, G., Erram, V.C., Baride, A., & Baride, M.V. (2022). Electrical Resistivity Imaging in Parts of Nandurbar District, Deccan Volcanic Province, Maharashtra, India. *Journal of the Geological Society of India,* 98 (3), 305-313.