International Journal of Membrane Science and Technology, 2023, Vol. 10, No. 1, pp 1833-1850

Evaluation of Seawater Intrusion and Groundwater Quality in the Coastal Aquifers in Srikakulam District, A.P., India Using Electrical Conductivity Property

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Abstract: Seawater intrusion into coastal aquifers has emerged as a significant environmental threat that imperils water resources, especially groundwater resources, ecosystems, and human health. It is widely acknowledged that water plays an indispensable role in the maintenance of life. Groundwater is an important source, particularly in arid and semi-arid regions where surface water and precipitation are limited. Management of a safe and renewable supply of groundwater for drinking and agricultural purposes is one of the crucial aspects of sustainable development for any Nation. But the groundwater quality faces threats from urbanization, agricultural practices, industrial activities, climate changes, and groundwater parameters such as p^H, Electrical Conductivity (EC), Total Dissolve Solids (TDS), fluoride, chloride, calcium, sulfate, and iron. In the present study, 13 coastal mandals *viz*., Ranastalam, Laveru, Etcherla, Srikakulam, Gara, Polaki, Santhabommali, Vajrapukotturu, Mandasa, Sompeta, Kanchili, Kaviti and Ichapuram in Srikakulam district, A.P., India, have been considered. The quality of the groundwater in these mandals has been assessed based on seawater intrusion into the coastal aquifers considering the EC and TDS parameters which help identifying seawater intrusion. Among all the 13 coastal mandals, the Gara, Polaki, Sompeta, Santabommali, and Ichapuram mandala are much influenced by seawater intrusion. The geology, geomorphology, climate, rainfall, and soil types of the study areas have been discussed. 61 water samples from bore wells of the 13 mandals have been collected for the present study. All the water samples were analyzed to determine the groundwater quality based on the EC and TDS of the water.

Keywords: Seawater intrusion, Coastal aquifers, EC, TDS, Groundwater quality parameters, and aquicludes.

1. INTRODUCTION

The movement of seawater into freshwater aquifers because of groundwater development is referred to as saline water intrusion, seawater intrusion, or seawater encroachment (Cherry, 2020). According to Nagaraja and Sukumar (2018), any coastal aquifer that has a hydraulic link to the ocean is at risk of being contaminated by saltwater. Du Commun (1982) is the first person to identify the interface between freshwater and saltwater in coastal aquifers (Abd-Elaty et al., 2019 & Du Commun, 1982). This discovery was made a half-century prior to the Ghyben-Hertzberg ratio/equation, which is more commonly referenced (Abd-Elaty et al., 2019; Eissa et al., 2019). This ratio or equation is thus: $bg_s = (a + b) g_f$ where "a" is elevation of water table above sea level, "b" is the depth of freshwater below sea level, and g_s and g_f are the specific gravity of seawater and freshwater respectively. The above researchers provided an explanation of the seawater and freshwater equilibrium that always exists in coastal aquifers. They came up with an equation which states that the depth of the interface below the sea level is roughly forty times that of the groundwater level above the sea level. This information was acquired from their observations (Gopinath et al., 2019 & Muller et al., 2021). A series of benchmark publications on the topic was produced by a systematic investigation of seawater intrusion in the 1950s in South Florida (Gopinath et al., 2019). According to the findings of these investigations, the transition zone between freshwater and saltwater is not as abrupt as predicted by the Ghyben-Herzberg ratio/equation. Rather, it generates a zone of mixed water that can be referred to as a mixing zone (Ali et al., 2021; Gopinath et al., 2019). The brackish water that is present in this mixed zone is carried to the ocean along with the freshwater. It is referred to as a submarine groundwater discharge when the groundwater release takes place beneath the waters of an overlying estuary or marine environment. On the other hand, the position and extent of this mixed zone, in addition to the flux of the associated brackish groundwater discharge, are governed by several different factors (Ritter et al., 2019). Relating to freshwater, these factors include rainfall, groundwater withdrawals, irrigation, and evapotranspiration while with respect to the seawater, these factors include tides, waves, and changes in sea level.

The tides of the ocean, the rise and fall of the water table because of variations in the amount of recharge, and other forces, including pumping, contribute to the mixing of seawater and freshwater. Palmer (1927) and Wentworth (1948) proposed that the zone of dispersion is produced by a motion that is back and forth between two points (Paldor et al., 2019). If the static situation is the only one that exists, the body of freshwater will narrow to a razor's edge at the beach, and there will be no route for the freshwater to leave. When the dynamic aspect is considered, it is discovered that freshwater flows through a small space that exists between the freshwater and saltwater interface and the water table at the beach (Paldor et al., 2019).

If it is assumed that the constant piezometric head exists on a vertical line, then the position of the interface can be approximated as a function of the discharges of freshwater using the approach proposed by Dupuit (1963) for a gravity seepage in a two-dimensional aquifer. This method was developed for gravity seepage in an aquifer (Costall et al., 2020; Dupit, 1963). The boundary is not clearly defined in natural settings. The seawater and the freshwater progressively combine because of a process called dispersion which is helped by chemical diffusion. The pore properties of the aquifer play a major role in determining the width of the dispersion zone, as does the amplitude of the fluctuation that occurs because of recharge and/or discharge and tidal activity. If this zone is small, the assumption of a sharp interface can be applied to the field conditions to make a preliminary approximation of the flow pattern.

Origin of Salinity in the Unconfined Aquifer:

With the field studies that are currently available, the cause of the area's high salinity has not been identified up to this point. This salinity might be the result of palaeo-salinity leaking from the bottom saline aquifer or seawater intrusion.

Palaeo-salinity:

The concept of paleo-salinity suggests that the groundwater that is extracted from the aquifer at the present time is the same water that was encased in the geological formation at the time of deposition. Because it is a common fact that the location being investigated was formerly covered by water at some point in the geological past, the salinity may be caused by seawater that was trapped there. This conclusion ca be drawn through observation of the strandlines in the study area. If the groundwater in the unconfined aquifer in the study area is ancient water, then the salinity of the groundwater in the past when it had just come out of the sea should have been the highest, and the salinity should follow a trend of decreasing year by year as it is being recharged by rainfall and canal water. This is the case if the groundwater in the unconfined aquifers in the study area. Because of the revitalized hydraulic gradient, most of the seawater would have been able to flow away. However, it was discovered when conducting field research that the salinity of the water in the region does not steadily decrease from day to day in the same manner. Instead, it varies from place to place according to the amount of groundwater that is being extracted from the ground in that location. This might have caused the variations in the hydraulic gradient and inducing flow either from the sea or from the bottom aquifer. It was also discovered that salinity had a relationship with the distance from the sea. If it is palaeo-salinity, the groundwater's proximity to the ocean would not have had an impact on its salinity. Therefore, it is possible to conclude that the salinity in the study area does not correspond to paleo-salinity.

Leakage from Bottom Aquifer:

The study area contains three types of aquifers: The deep aquifers which occur at a depth of 111 meters below sea mean level (MSL), the shallowest of which is only 34 meters below MSL and are free flowing in nature and contain fresh water. The second type of aquifers are in constrained conditions and contain seawater. They are located between 22 and 63 meters below MSL. Normally, in multi-aquifer systems, it is possible that these aquifers may not be totally confined, and there may be a flow or leakage between the top unconfined and the bottom (semi-) confined aquifer. This is because the top unconfined aquifer is more permeable than the bottom (semi) confined aquifer. However, the long duration pumping tests that were carried out by Central Ground Water Board (CGWB) in this region at the Amalapuram and Munganda well-fields suggest that the second type of aquifers in this region are totally confined and that the intervening clay bed is an aquiclude. Even when one aquifer is pumped, there is no discernible effect on the water level in the other aquifers. It suggests that the salinity in the unconfined aquifer is not caused by the vertical leaking of saltwater from the bottom aquifers.

Seawater Intrusion:

The reversal of the hydraulic gradient is the most important and primary indicator of seawater intrusion. Consequently, there should not be any discharge of fresh groundwater into the sea. The groundwater that comes from the coastal aquifers typically has a positive hydraulic gradient towards the ocean and discharges directly onto the ocean floor. As a result, there is no possibility of any kind of irreversible seawater intrusion if there are freshwater discharges into the sea. During the pre-monsoon and post-monsoon seasons, the researchers calculated the amount of freshwater which was discharged into the sea in the study area. The freshwater head drops below MSL because of human activity, which causes the gradient to flip in the opposite direction.

According to the Ghyzen-Hertzberg ratio/equation, the freshwater column that is found below MSL at any site will be equivalent to 40 times the freshwater column that is found above MSL at the same point. As long as the level of freshwater remains higher than the MSL, there will be a lens of freshwater below the MSL that is floating on top of seawater. When the freshwater column above MSL falls to zero, the freshwater column below mean sea level will also fall to zero at that time. If the freshwater column above MSL is diminished because of human activities, the seawater front will advance upwards toward the surface. The quality of the groundwater decreases because of a transient change in the fresh groundwater column that is located above mean sea level. This change will produce an upward migration of salt water, which is the primary cause of this movement.

The Study Area

The thirteen coastal mandals *viz*., Ranastalam, Laveru, Etcherla, Srikakulam, Gara, Polaki, Santhabommali, Vajrapukotturu, Mandasa, Sompeta, Kanchili, Kaviti and Ichapuram in the Srikakulam district (Figure 1) have been chosen for the present study.

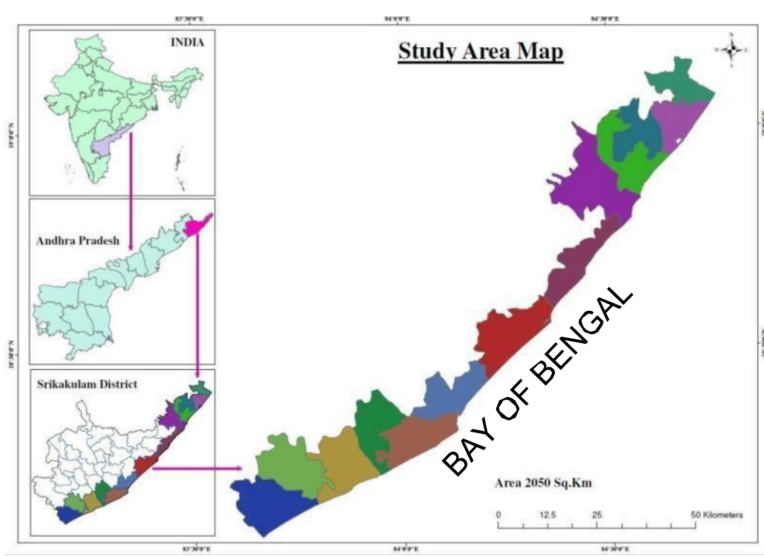

Figure 1. Map of the Study Area in the Srikakulam District.

Drainage of the Study Area

As the study area is a part of the Srikakulam district, it is influenced by the drainage of the Srikakulam district. The Vamsadhara and Nagavali are the two major rivers that drain the Srikakulam district. The other significant rivers include the Bahuda, Suvarnamukhi, Vegavathi, and Mahendra Tanya rivers (Figure 2). The stream order which is determined by the number of tributaries of a stream is represented in Figure 2. The stream order is an important concept in hydrology and is used to understand the hydrological processes in a watershed, and to estimate the flow rate and sediment transport capacity of a stream as well as the size of the stream channel. This information is important to understand the dynamics of a watershed and for managing water resources (Satyanarayana et al., 2017)

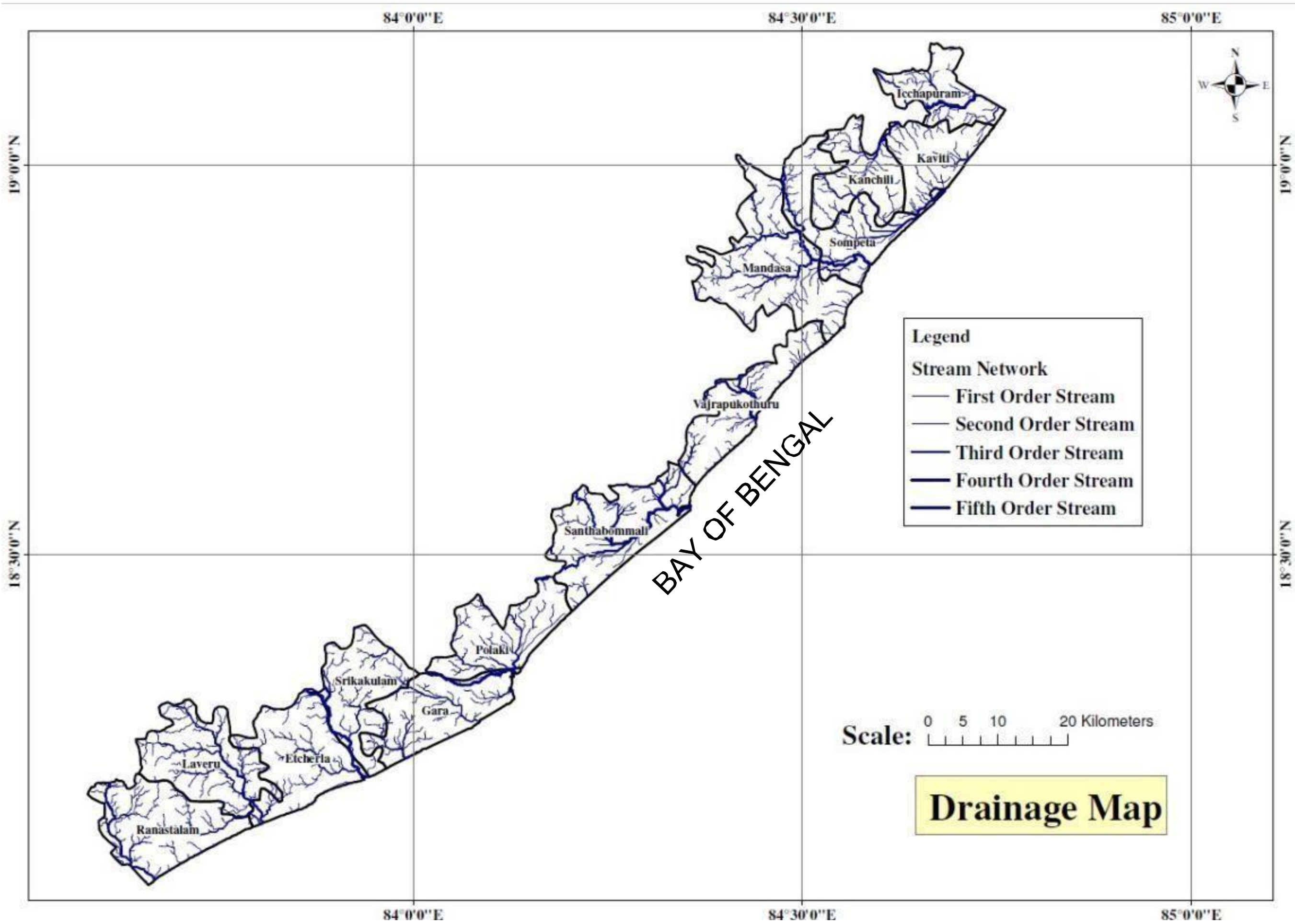

Figure 2. Drainage Map of the Study Area.

Climate and Rainfall in the Study Area

The study area is influenced by a mild climate with high humidity throughout the year, and by hot summers and abundant seasonal rains. The area receives an average of 1,067 mm of rainfall annually. The average seasonal rainfall is 745 mm during the southwest monsoon (June to September), 214 mm during the northwest monsoon (October to December), 18 mm during the winter (January to February), and 90 mm during the summer (March to May). Seasonally, rainfall is distributed as 70% during the southwest monsoon, 20% during the northwest monsoon, 2% during the winter, and 8% during the summer.

Geology of the Study Area

The geological strata that may be found in the Srikakulam district including the study area are classified as Precambrian - Upper Gondwanas, Tertiary, Recent, and Eastern Ghats Super group. Granulite makes up most of the topography of the Eastern Ghats Super Group, which is located on the east coast of India (Figure 3). However, this region also consists of granites, migmatites, anorthosites, and alkaline rocks. This granulite band has a long history of mountain formation, stretching back to the late Archaean and continuing into the late Proterozoic. Khondalites and charnockites occur abundantly in the area.

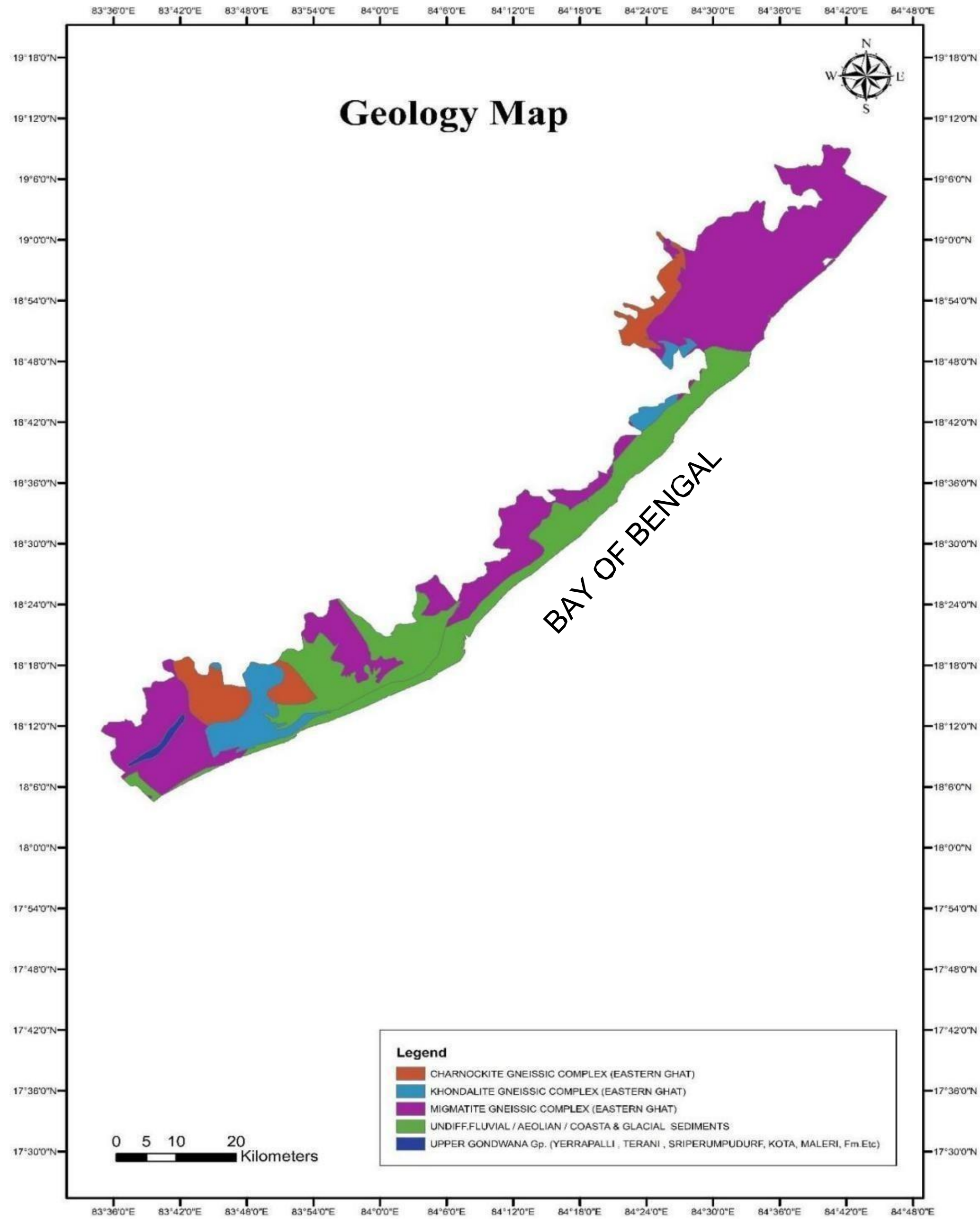

Figure 3. Geology Map of the Study Area

Geomorphology of the Study area:

The geomorphology of the steady area is represented by that of Srikakulam. On a scale of:50,000, a thorough geological, morphological, and structural map of the study area was produced using satellite data from the Geological Society of India (GIS). This map was prepared in accordance with the standards of the Rajiv Gandhi National Drinking Water Mission (RGNDWM). This is done on a scale of 1:50,000 so that the lithology, geomorphology, and structural properties of an area may be mapped and integrated to discover prospective ground water prospect zones and recommend suitable structures for ground water recharging. As part of this research, several distinct hydrogeomorphic units were mapped, and suitable recharge structures are suggested for the communities whose drinking water might be negatively impacted. The various geomorphic units that have been mapped in the study area are shown in Figure 4.

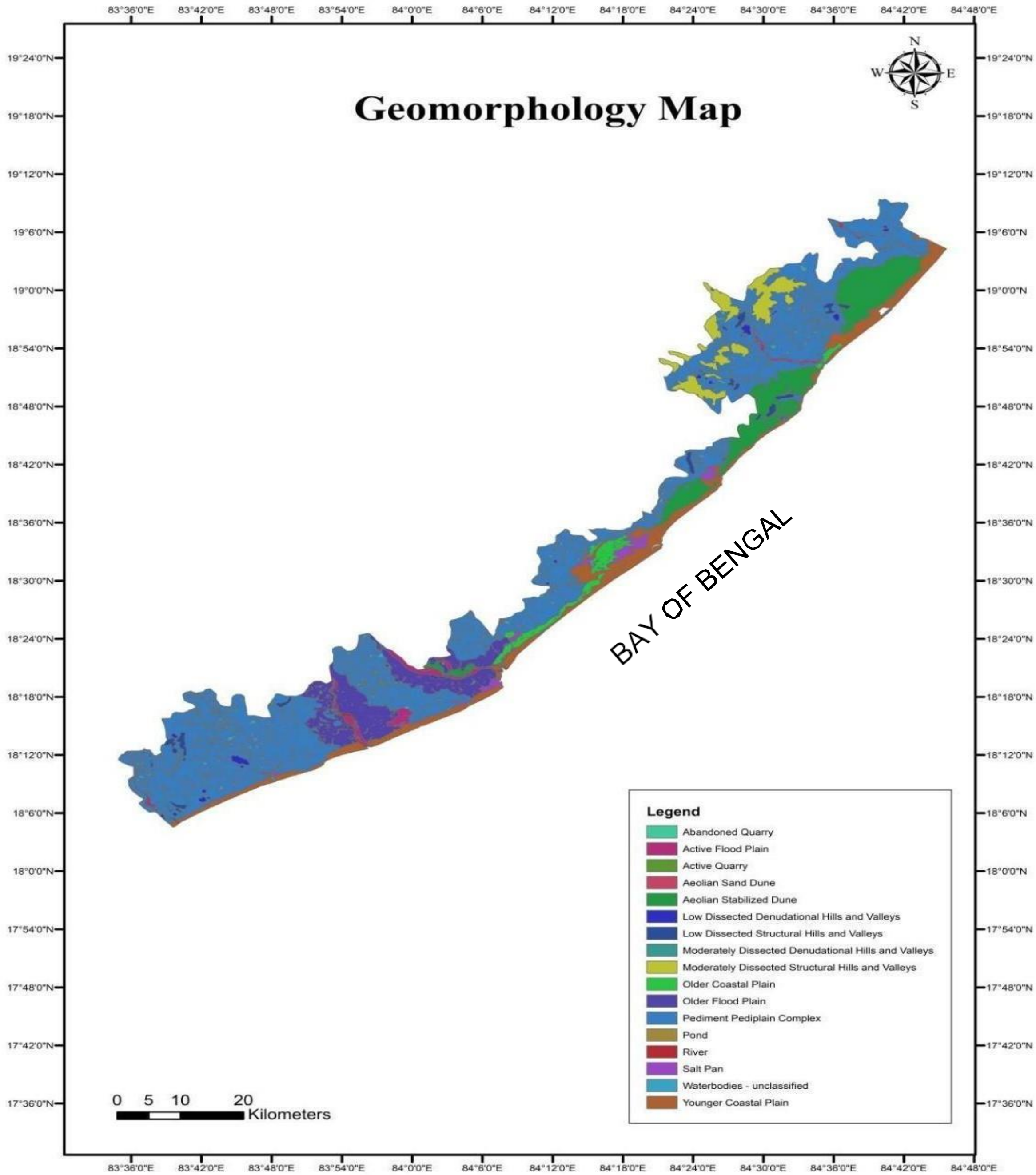

Figure 4. Geomorphology of the Study Area

Soil Types of the Study Area

The study area consists of different types of soils, the most common of which are red, sandy, black, and alluvial soil and red and sandy loam (Figure 5). Most of the time, hill slopes are the sites where red soils are found due to the weathering of khondalites and gneisses. The red loamy soil can also be found in the confined valleys and low-lying areas that are found between the hills. It has been observed that sandy soils are present in the southern and eastern regions of the study area. Along the banks of the rivers Vamsadhare and Nagavalli, as well as their tributaries, one can find a distribution of deltaic alluvial soil which is transported to the coastal regions. Coastal alluvial soils are found in areas of Ichapuram, Sompeta, and Tekkali mandals in the Srikakulam district. Most of the area is composed of red sand and lateritic soils.

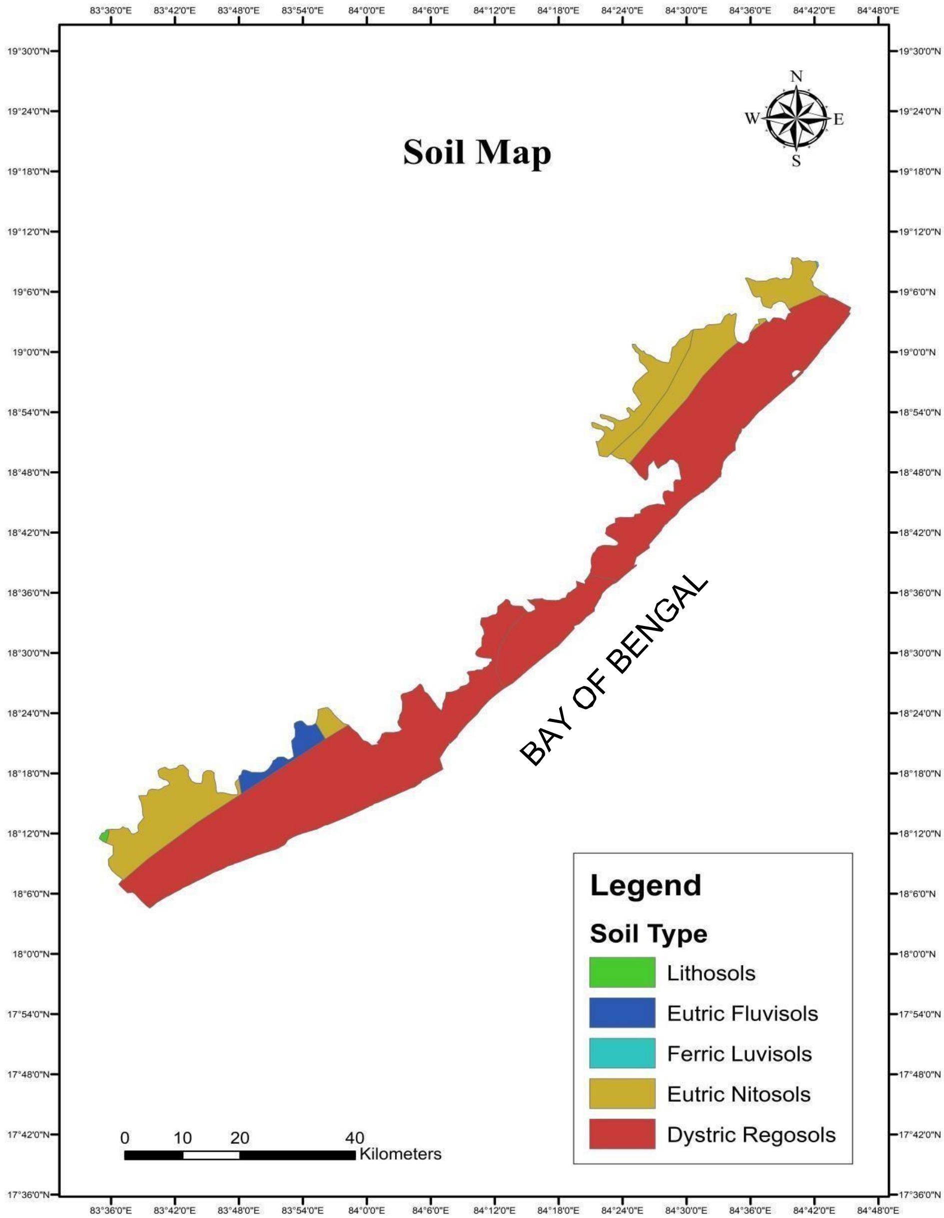

Figure 5. Soil Types in the Study Area

2. METHODOLOGY

Remote Sensing (RS) Methods

Remote Sensing (RS) technology has become a highly effective method in the scientific community for analyzing various Earth ressources and the related features. It offers vast potential for exploring large land areas quickly, aided by the introduction of multi-spectral satellite imagery. Parameters such as spatial resolution, spectral bandwidths, repeated coverage, and radiometric sensitivity are crucial due to the unique nature of the data they provide. Remote Sensing (RS) and Geographic Information Systems (GIS) are widely employed in various studies to examine diverse land features and the changes that have occurred. The ability of Remote Sensing technology to provide a synoptic (big area) view along with spectral data to represent and monitor information on topographical characteristics makes the technique more valuable. Meaden et al. 2013; Aboelnour and Engel (2018) and Patra et al. (2018) devoted to examining diverse land features and the changes that have occurred. The ability of Remote Sensing technology to provide a synoptic view along with spectral data to represent and monitor information on topographical characteristics makes the technique more valuable. Both RS and GIS have been used in the present study.

Data Used

Field data collected includes geology, soils, geomorphology, land use and land cover, groundwater levels and groundwater quality. CGWD has provided some data for the present study.

Elements of Image Characteristics

Essential photo-elements or image properties that were observed during the visual interpretation of satellite images included tone or color, size, shape, texture, pattern, location, association, shadow, aspect, and resolution. These image characteristics played a significant role in the visual interpretation process.

Groundwater Sample Collection

A total of 61 groundwater samples were collected from 13 mandals adjoining the seacoast of Srikakulam district to determine water quality (Figure 6). Samples were collected in both pre-monsoon and post-monsoon periods from 61 different open wells in pre-cleaned one-liter water bottles, and their precise locations were recorded using handheld GPS devices. Electric Conductivity (EC), and Total Dissolved Solids (TDS) were assessed in the field from the years 2020 to 2022.

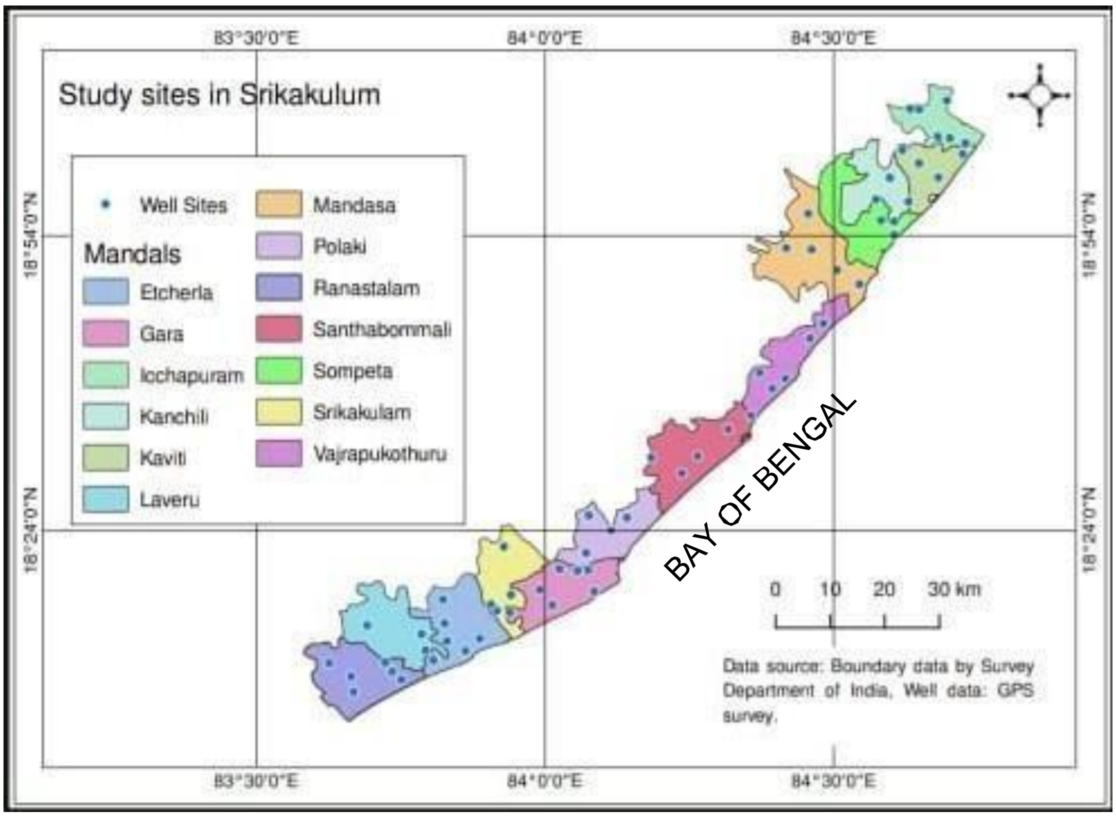

Figure 6. Sample Location Map

3. RESULTS AND DISCUSSION

Electrical Conductivity in Pre-Monsoon and Post-monsoon Seasons in the 13 Coastal Mandals in the Years 2020, 2021 and 2022

The maximum and minimum values of the EC in the pre-monsoon and post-monsoon seasons in the years 2020, 2021, and 2022 are given in Tables 1 to 6.

The highest values of EC are recorded in the Polaki, and Sompeta mandals in the pre-monsoon season in 2020 and the lowest values were recorded in Ranastalam, Laveru, Etcherla, Santabommali, and Kaviti mandals (Figure 7). Swathi (2020, 2022) has recorded approximately the same EC values in the Ranastalam, Laveru, and Etcherla mandals. In the post-monsoon season, the highest value is recorded in the Gara mandal, and the lowest values are recorded in the Mandasa and Kaviti mandals (Figure 8). In the year 2021, in the pre-monsoon season, the highest values of EC are recorded in Gara, Polaki and Santabommali mandals (Figure 9), and in the post-monsoon season the highest values are recorded in the Srikakulam, Gara, Polaki and Santabommali mandals (Figure 10).

Table 1. Maximum and Minimum Values of Groundwater Parameters in the Pre-monsoon Season in the Year 2020

Parameter	Sample No	Maximum	Mandal Name	Sample No.	Minimum	Mandal Name
EC	1	1876	Itchapuram	26	295	Polaki
TDS	13	2688	Sompeta	46	296	Etcherla

Table 2. Maximum and Minimum Values of Groundwater Parameters in the Post-monsoon Season, in the Year 2020

Parameter	Sample No.	Maximum	Mandal Name	Sample No.	Minimum	Mandal Name
EC	30	5898	Gara	5	253	Kaviti
TDS	50	2051.2	Ranastalam	9	96	Kanchili

Table 3. Maximum and Minimum Values of Groundwater Parameters in the Pre-monsoon Season, in the Year 2021

Parameter	Sample No	Maximum	Mandal Name	Sample No	Minimum	Mandal Name
EC	56	4587	Srikakulam	48	313	Ranastalam
TDS	34	3467	Gara	58	373	Mandasa

Table 4. Maximum and Minimum Values of Groundwater Parameters in the Post-monsoon Season, in the Year 2021

Parameter	Sample No.	Maximum	Mandal Name	Sample No	Minimum	Mandal Name
EC	33	3560	Gara	48	444	Ranastalam
TDS	32	2278	Gara	7	341	Kaviti

Table 5. Maximum and Minimum Values of Groundwater Parameters in the Pre-monsoon Season in the Year 2022

Parameter	Sample No	Maximum	Mandal Name	Sample No	Minimum	Mandal Name
EC	2	3587	Itchapuram	45	329	Etcherla
TDS	2	2296	Itchapuram	60	222	Mandasa

Table 6. Maximum and Minimum Values of Groundwater Parameters in the post-monsoon Season, in the year 2022

Parameter	Sample No	Maximum	Mandal Name	Sample No	Minimum	Mandal Name
EC	32	3174	Gara	53	329	Etcherla
TDS	31	1521	Srikakulam	57	222	Manadasa

In the year 2022, in the pre-monsoon, the highest values of are recorded in the mandals Srikakulam, Gara, Polaki and Santabommali (Figure 11), and in the post-monsoon season the Gara mandalam, and to some extent in the Ranastalam, Laveru, Etcherla, and Polaki mandals (Figure 12) and the lower values in the other mandals. Swathi (2020, 2022) observed the same results in the Ranastalam, Laveru and Etcherla mandals with respect to the EC properties. The higher values of EC represent larger quantities of seawater intrusion. The Electrical Conductivity values are high in the Gara, Polaki and Santabommali mandals in both the pre-monsoon and post-monsoon seasons in the years 2020, 2021 and 2022 as per the data represented in Figures 7 to 12. This interpretation represents that the higher values of EC indicate that the seawater intrusion is more in the Gara, Sompeta and Santabommali mandals and to some extent in the Srikakulam, Laveru, Etcherla, Kaviti and Ichapuram mandals. These higher EC values correspond to the higher values of Total Dissolved Solids (TDS). The higher TDS values also support the higher quantity of seawater intrusion along with the other parameters of groundwater quality as described in the next paragraphs.

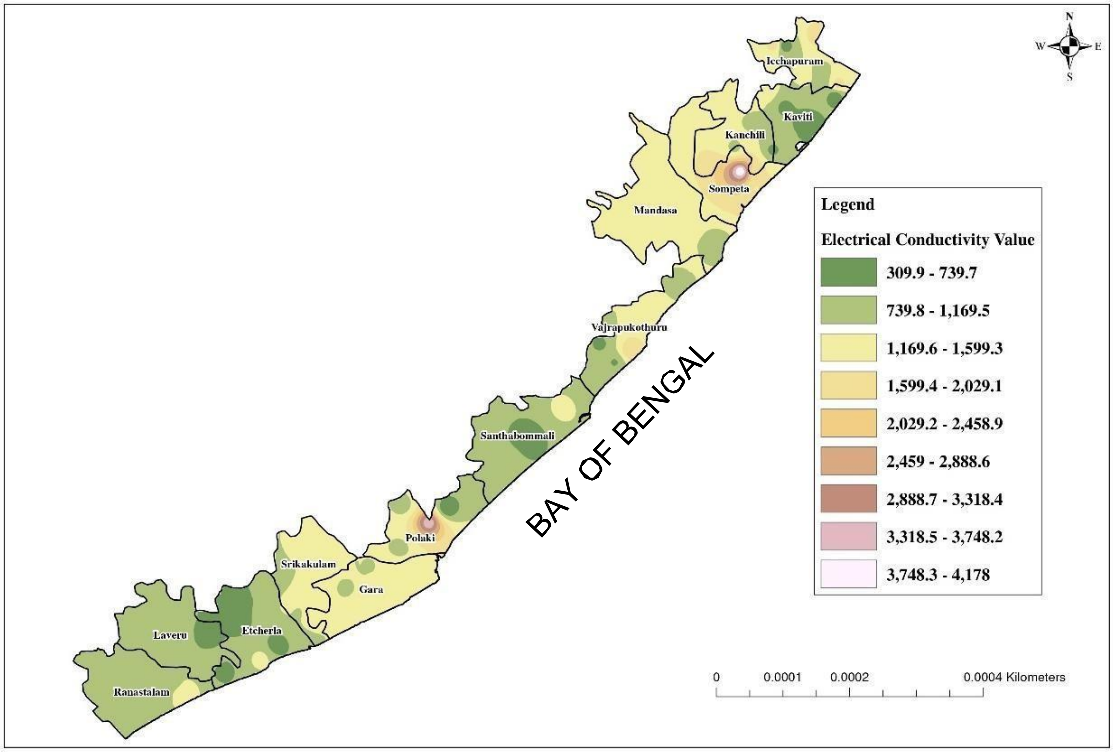

Figure 7. Electrical Conductivity (µS/cm) Map for Pre-monsoon Season, 2020

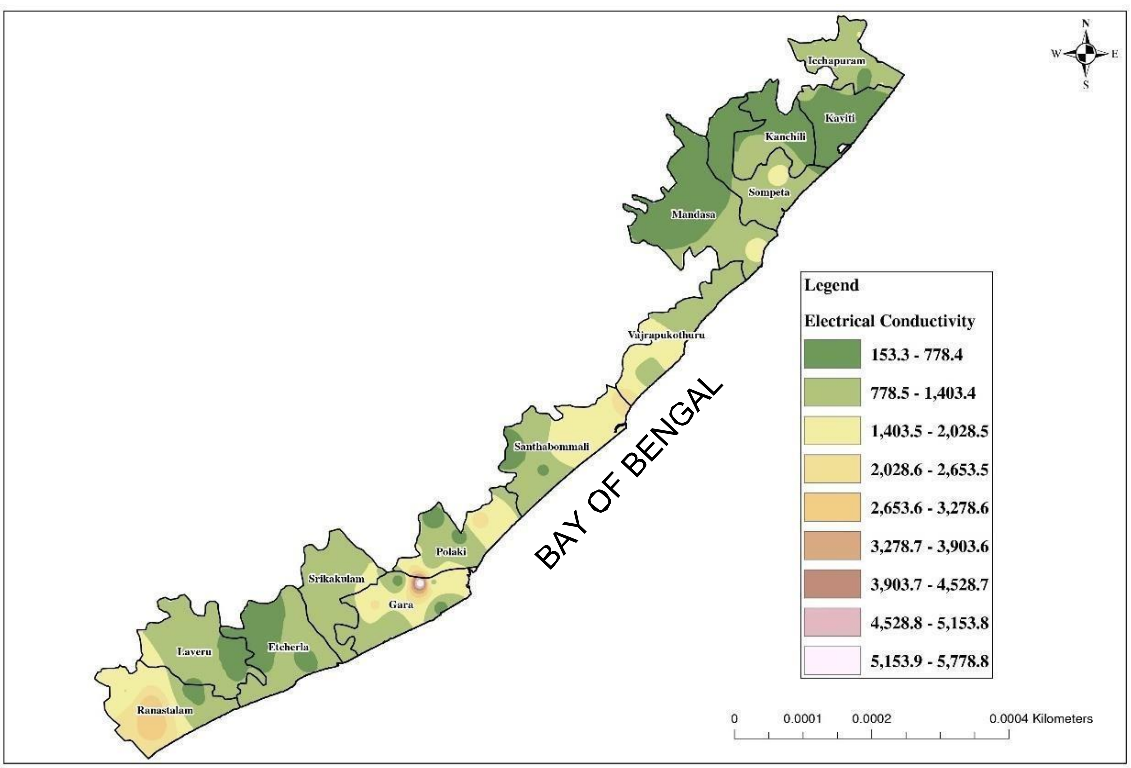

Figure 8. Electrical Conductivity (µS/cm) Map for Post-monsoon Season, 2020

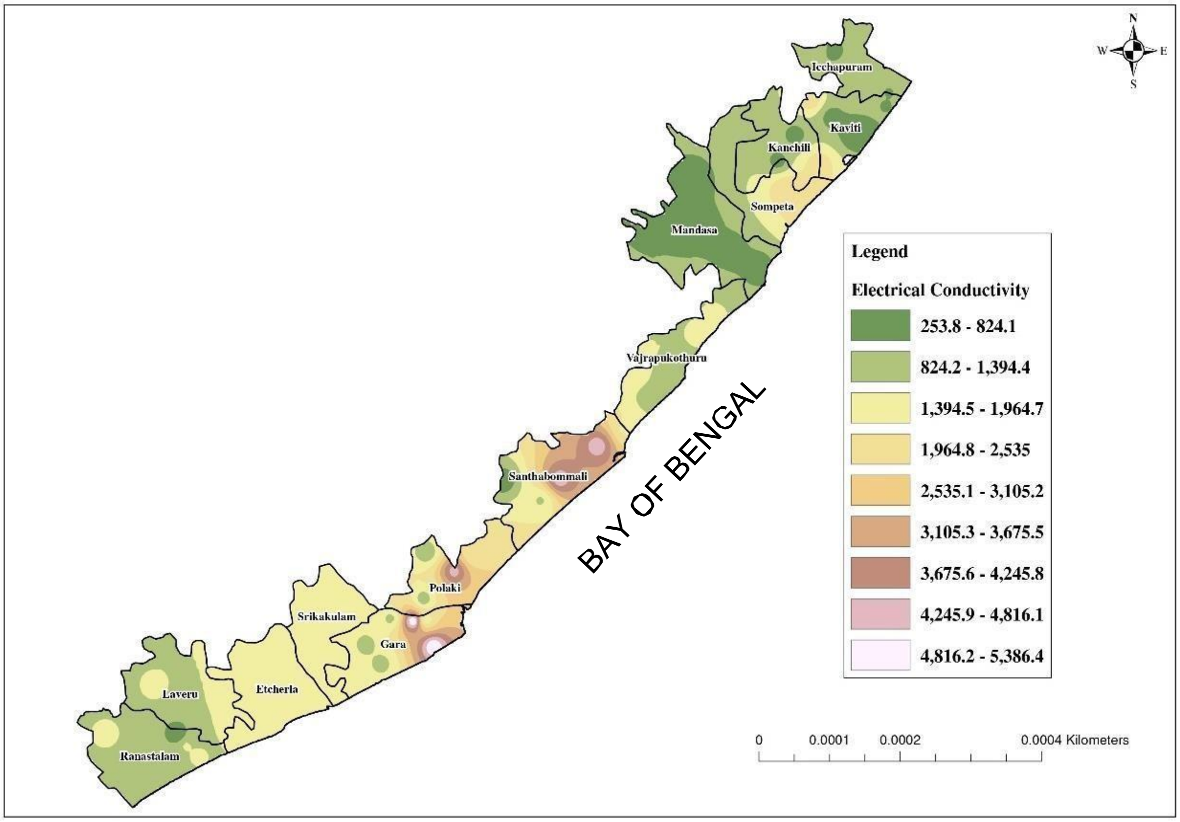

Figure 9. Electrical Conductivity (µS/cm) Map for Pre-monsoon Season, 2021

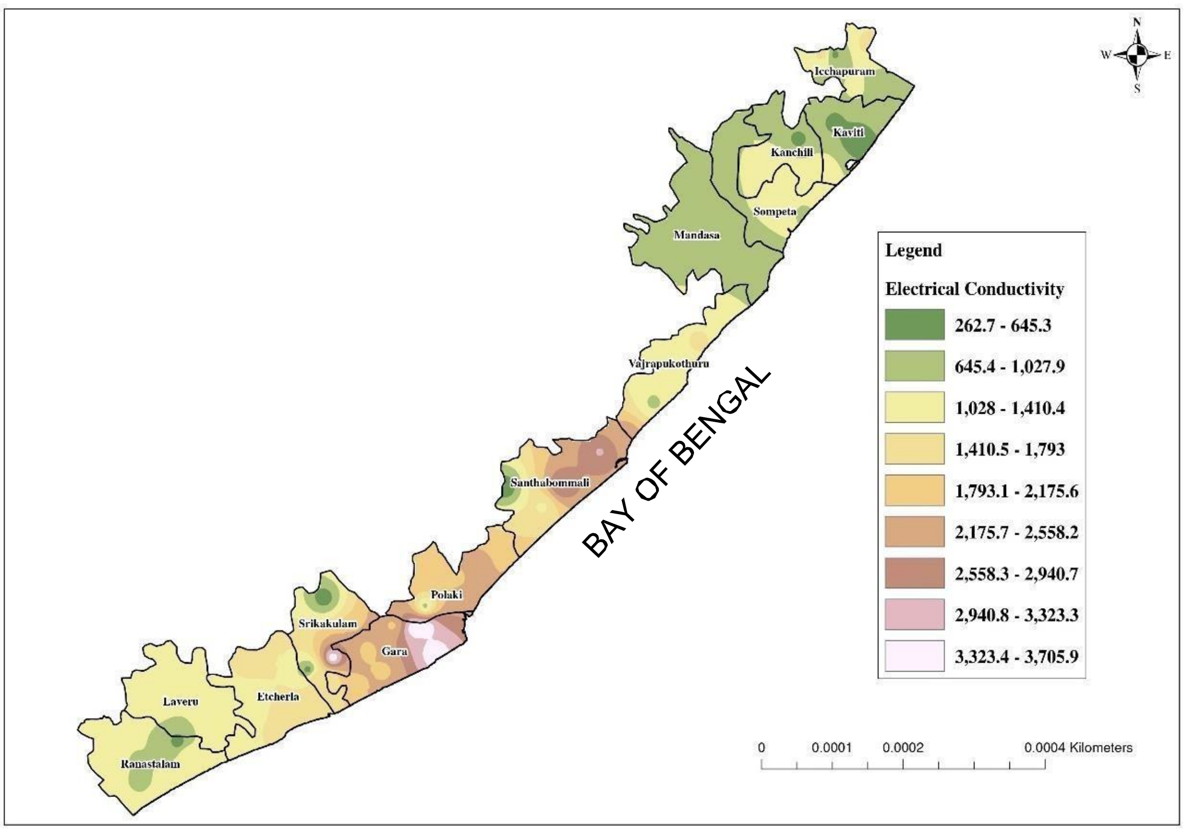

Figure 10. Electrical Conductivity (µS/cm) Map for Post-monsoon Season, 2021

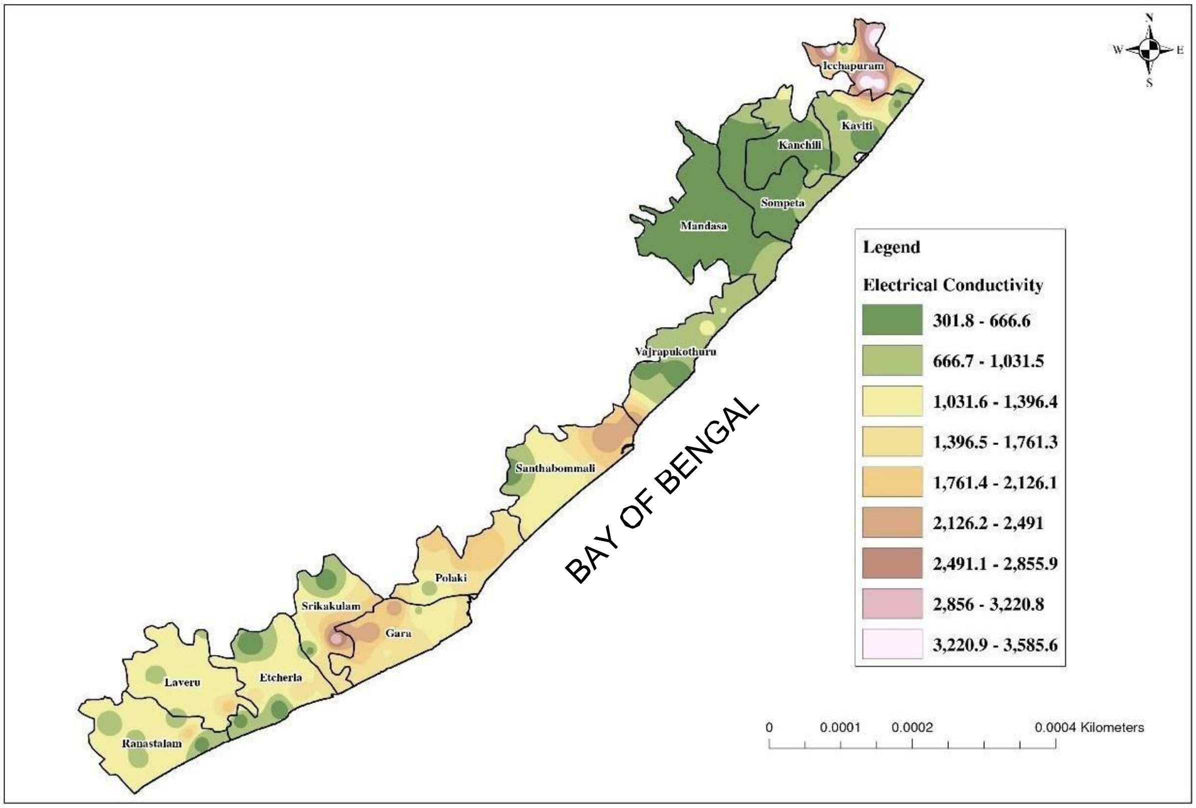

Figure 11. Electrical Conductivity (µS/cm) Map for Pre-monsoon Season, 2022

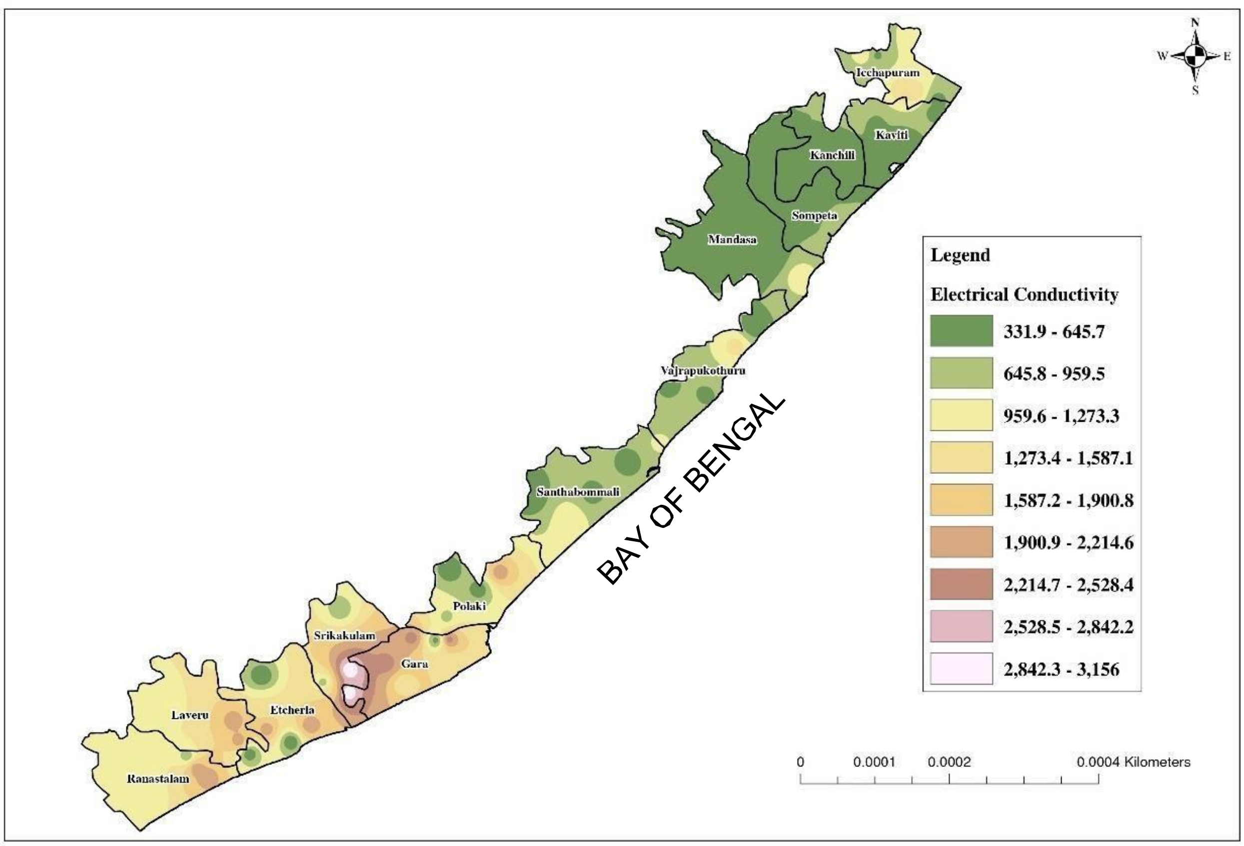

Figure 12. Electrical Conductivity (µS/cm) Map for Post-monsoon Season, 2022

Total Dissolved Solids (TDS) in Pre-Monsoon and Post-monsoon Seasons in the 13 Coastal Mandals in the Years 2020, 2021 and 2022:

The maximum and minimum values of TDS in the pre-monsoon and post-monsoon seasons in the years 2020, 2021, and 2022 are given in Tables 1 to 6.

The maximum value (2688 mg/l) of the Total Dissolved Solids in the pre-monsoon season in the year 2020 occurred in the Sompeta mandal and the minimum value (296 mg/l) was in the Etcherla mandal. Swath (2020, 2022) has reported the same values here with respect to TDS. In the post-monsoon season, the maximum (2051 mg/l) and minimum (96 mg/l) values occurred in the Ranastalam and Kanchili mandals. In the year 2021 in the pre-monsoon and post-monsoon mandals, the maximum (3467 mg/l & 2,278 mg/l) and minimum 931 mg/l & 341 mg/l) values of TDS occurred in the Gara and Mandasa mandals, and Gara and Kavit mandals respectively. In the year 2022 in the pre-monsoon and post-monsoon mandals, the maximum (2,296 mg/l & 1521 mg/l & 222 mg/l & 222 mg/l) and minimum values of TDS occurred in the Ichapuram and Mandasa mandals, and Srikakulam and Mandasa mandals respectively. The TDS values represent the corresponding EC values. Wherever the TDS values are high, the EC values increase representing the intrusion of saltwater into the coastal aquifers. The concentration of TDS in both the seasons in the years 2020, 2021 and 2022 are shown in Figures 13 to 18.

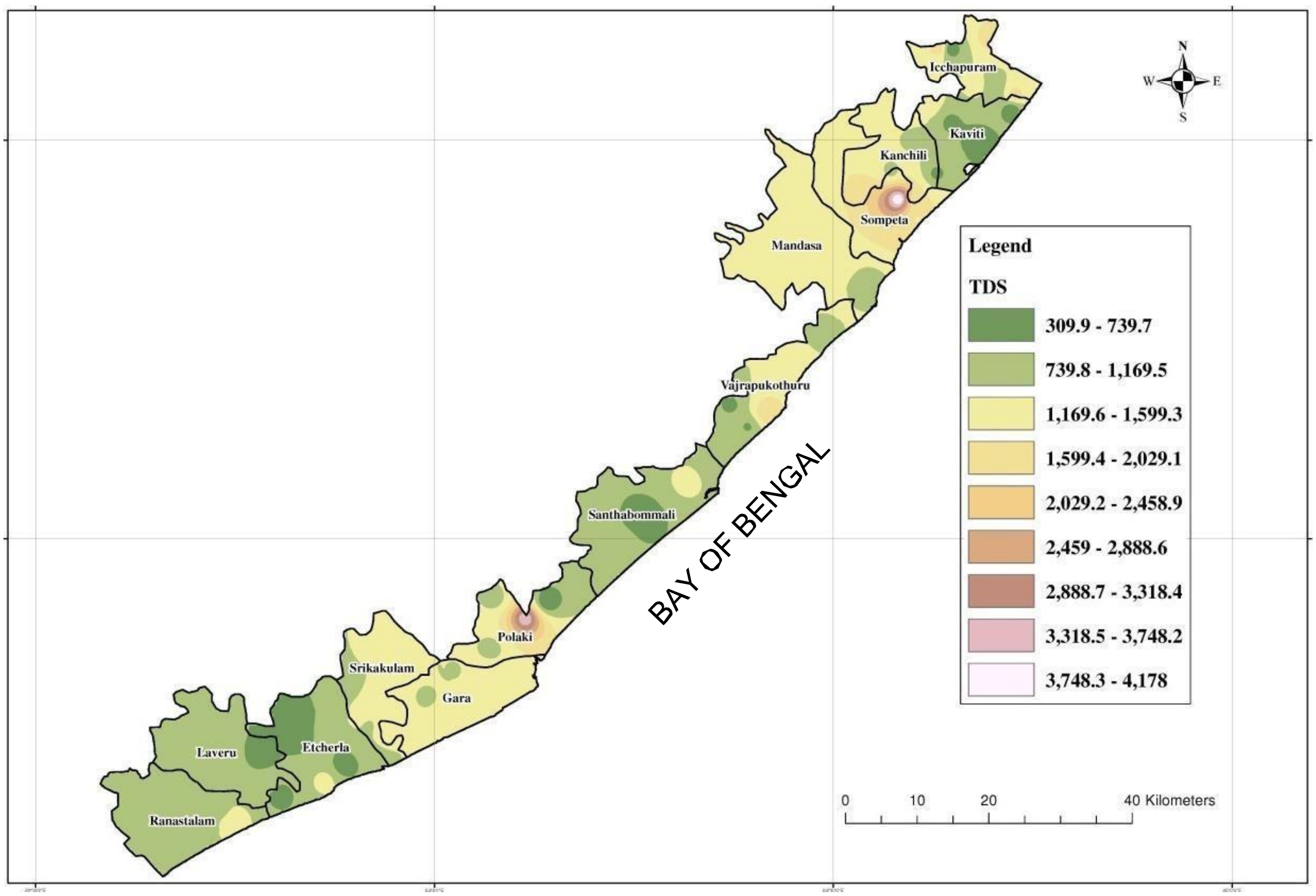

Figure 13. Total Dissolved Solids (mg/l) Map for Pre-monsoon Season, 2020

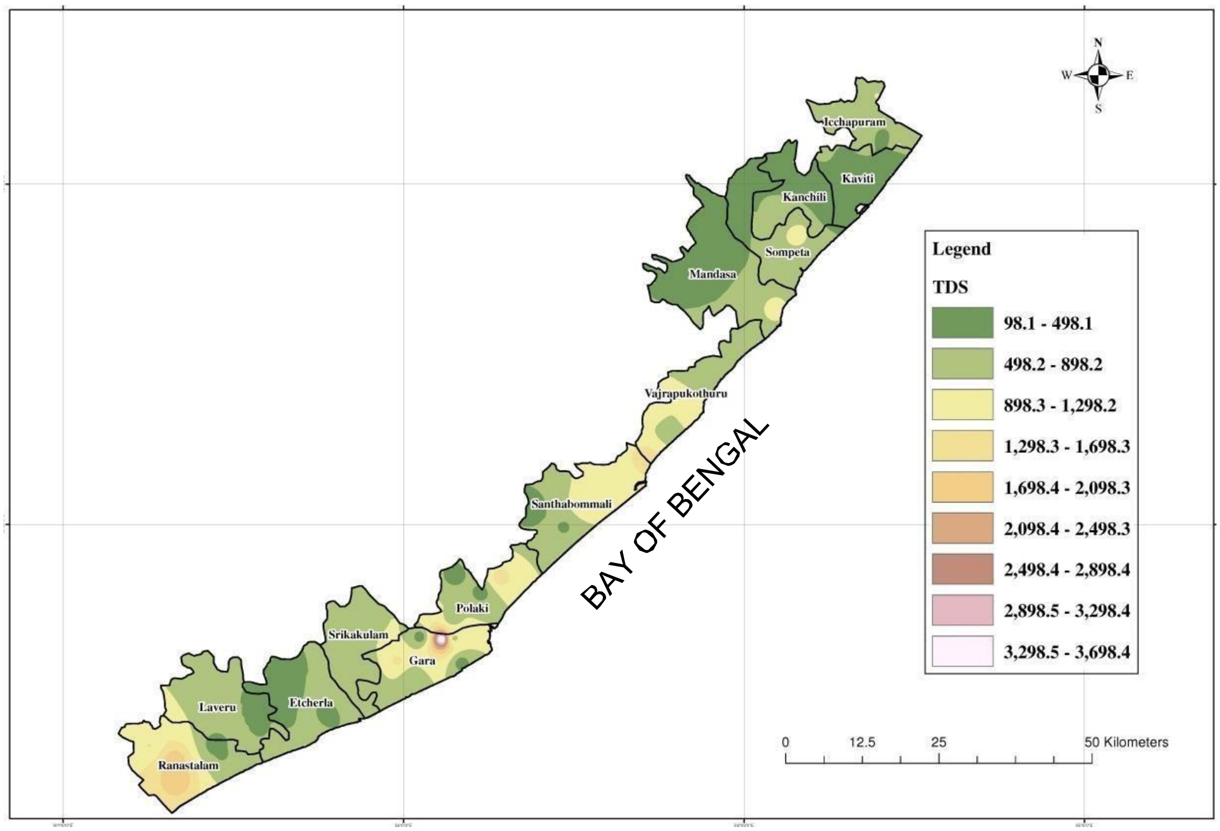

Figure 14. Total Dissolved Solids (mg/l) Map for Post-monsoon Season, 2020

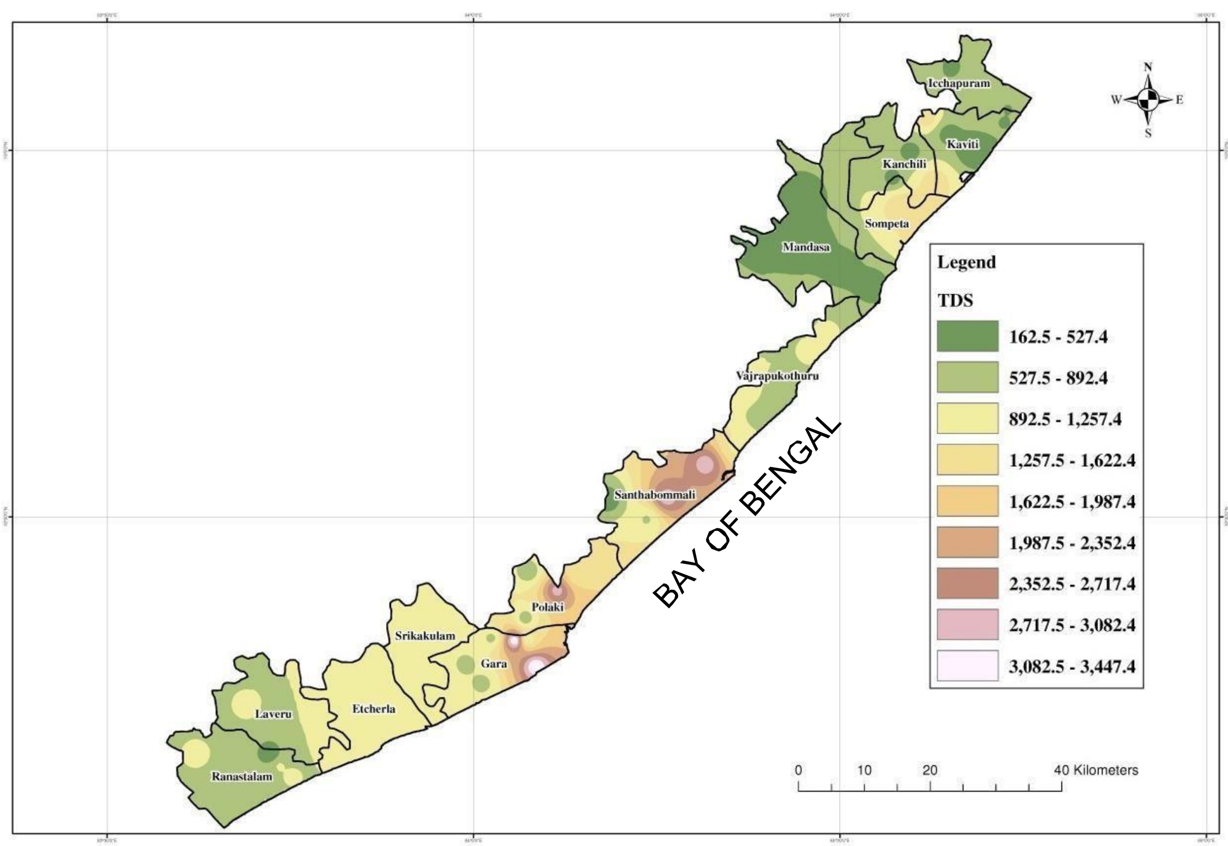

Figure 15. Total Dissolved Solids (mg/l) Map for Pre-monsoon Season, 2021

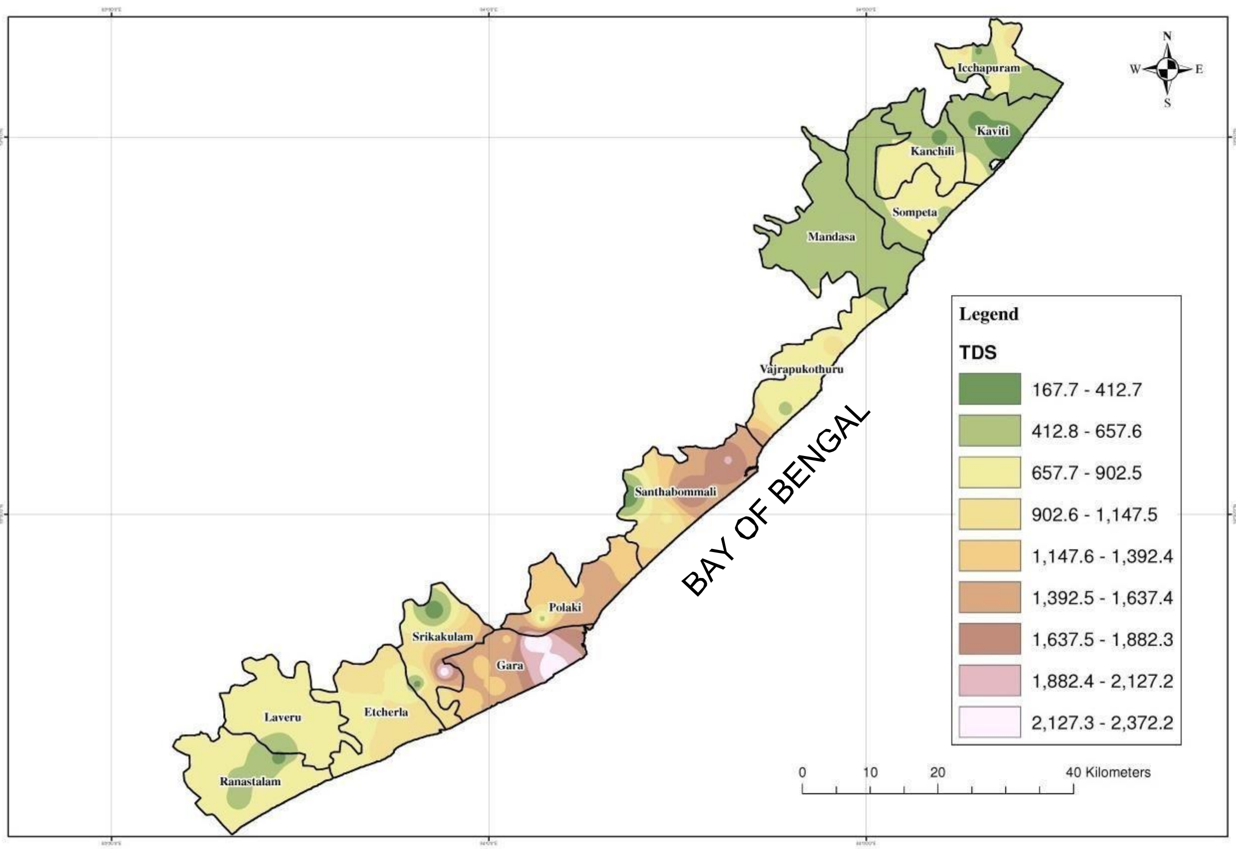

Figure 16. Total Dissolved Solids (mg/l) Map for Post-monsoon Season, 2021

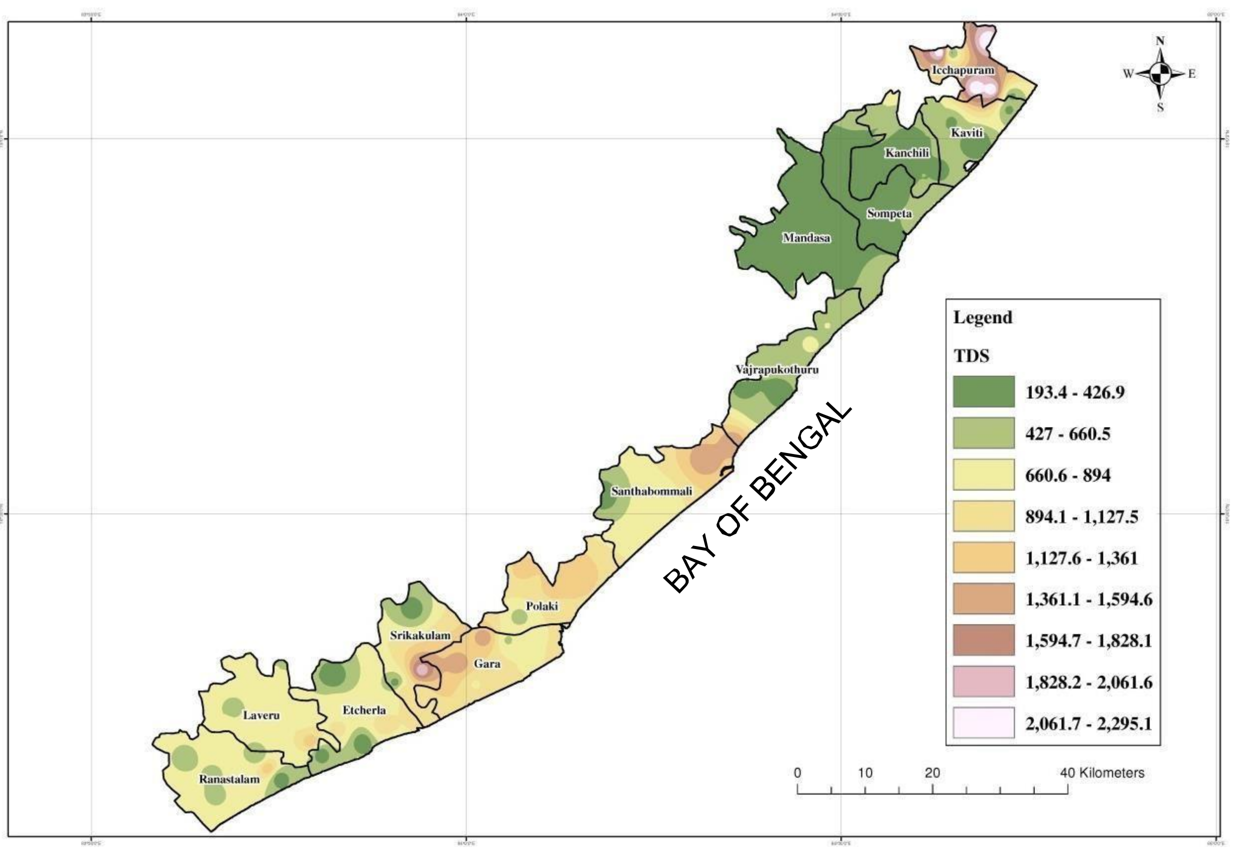

Figure 17. Total Dissolved Solids (mg/l) Map for Pre-monsoon Season, 2022

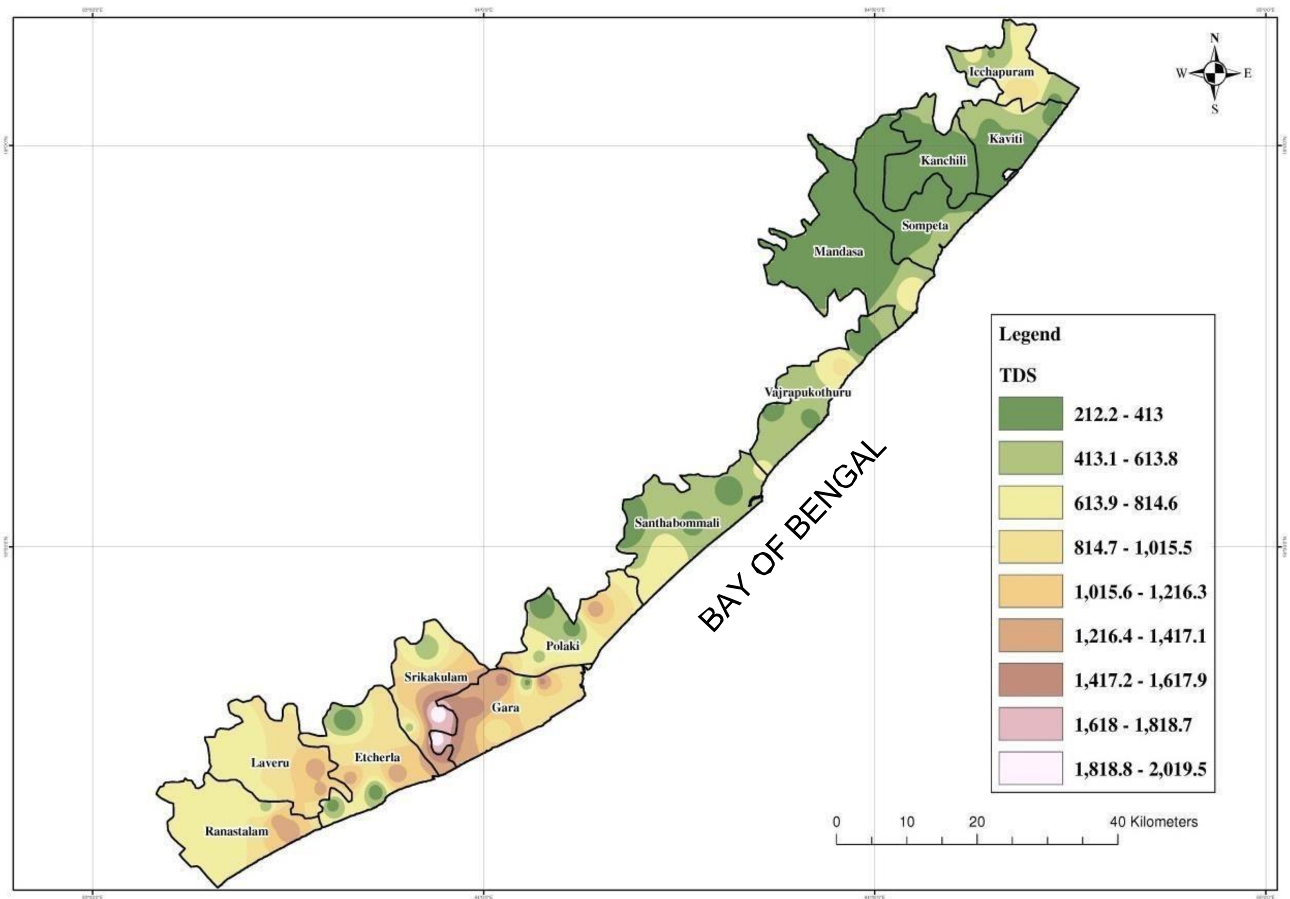

Figure 18. Total Dissolved Solids (mg/l) Map for Post-monsoon Season, 2022

4. CONCLUSION

Groundwater is an important source, particularly in arid and semi-arid regions where surface water and precipitation are limited. Management of a safe and renewable supply of groundwater for drinking and agricultural purposes is one of the crucial aspects of sustainable development for any Nation. But the groundwater quality faces threats from urbanization, agricultural practices, industrial activities, climate changes, and groundwater parameters such as p^H, Electrical Conductivity (EC), Total Dissolved Solids (TDS), fluoride, chloride, calcium, sulfate, and iron. In the present study, 13 coastal mandals viz., Ranastalam, Laveru, Etcherla, Srikakulam, Gara, Polaki, Santhabommali, Vajrapukotturu, Mandasa, Sompeta, Kanchili, Kaviti and Ichapuram in Srikakulam district, A.P., India, have been considered to evaluate the seawater intrusion and groundwater quality. The quality of the groundwater in these mandals has been assessed based on seawater intrusion into the coastal aquifers considering the EC and TDS parameters which help identifying seawater intrusion. Among all the 13 coastal mandals, the Gara, Polaki, Sompeta, Santabommali, and Ichapuram mandala are influenced by more seawater intrusion and the other mandals are influenced by saltwater intrusion to some extent. The geology, geomorphology, soil types, climate, and rainfall of the study areas have been discussed to evaluate the seawater intrusion in the coastal aquifers in the above mandals. 61 water samples from bore wells of the 13 mandals have been collected in the pre-monsoon and post-monsoon seasons in the years 2020, 2021 and 2022 for the present study. All the water samples were analyzed to determine the groundwater quality based on the EC and TDS. The EC of the waters of the coastal aquifers mostly depends on the TDS property which is proved in our investigations. Our investigations may be useful in the groundwater management by the CGWB and the State Ground Water Department (SGWD).

ACKNOWLEDGEMENTS

The authors are thankful to the Central Ground Water Board (CGWD), Hyderabad, and the State Ground Water Department of Srikakulam branch for providing some data which is useful in our investigations. We are very grateful to Prof. R. Kaladhar, a retired Professor, Department of Geology, Andhra University, Visakhapatnam, for his help in drafting the MS of this paper. We are also thankful to Dr. M. Srinivasa Rao, a faculty member in the Mechanical Engineering Department, ANITS, Visakhapatnam, for his help in drawing up the necessary diagrams.

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DOI: https://doi.org/10.15379/ijmst.v10i1.3469