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Research Article

Possible Zones of Submarine Groundwater Discharge (SGD) and Seawater Intrusion (SWI) along the West Coast of Kanyakumari, India

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The possible zones of submarine groundwater discharge (SGD) and seawater intrusion (SWI) along the west coast of Kanyakumari in the southernmost Indian Peninsula were identified by integrating the surface temperature anomaly, water table fluctuation, and water quality analysis. Temperature map of the sea surface from Landsat 8 satellite data, which helped to demarcate SGD in areas with significant thermal contrast, exists between the seawater and discharging groundwater. Monitoring data of 2019–2021 illustrated patchy, diffuse, and temporally variable groundwater seepage. The spatial distribution map created from groundwater level, and water quality parameters depicted high SGD in areas of high groundwater level and high chances of SWI in regions with low groundwater level. This study identified that the areas with low groundwater level, high EC, and high chloride contents are prone to SWI. Similarly, the regions with high thermal contrast, high groundwater level, and low EC have more SGD. These methods have the potential to be used as preliminary screening tools before implementing detailed studies about the mixing process.

1. Introduction

Submarine groundwater discharge refers to the transfer of water from a coastal aquifer to the ocean. SGD studies emphasize hydrogeochemical and biochemical influence in the coastal environment [1]. SGD occurs in regions where there is high groundwater gradient compared to the mean sea level. Though the SGD is volumetrically smaller compared to the surface water inputs (<10%), the chemical and nutrient fluxes associated with groundwater discharge can be comparable to the surface water fluxes. SGD and SWI are two complementary and interdependent processes [2] (Figure 1). SGD includes both fresh groundwater discharge (FSGD) and saline or recirculated groundwater discharge (RSGD). Saltwater intrusion is a major concern commonly found in coastal aquifers around the world. According to the Ghyben–Herzberg relation, saltwater intrusion occurs underground not at the sea level but at a depth below sea level about 40 times the height of freshwater above the sea level. SWI also falls under the important category of groundwater pollution.

There have been several reports on the detection and assessment of SGD from various segments throughout India's east and west coasts, as well as from islands. Thermal infrared remote sensing (TIR-RS) is used as an alternative method for locating suitable SGD locations because it allows

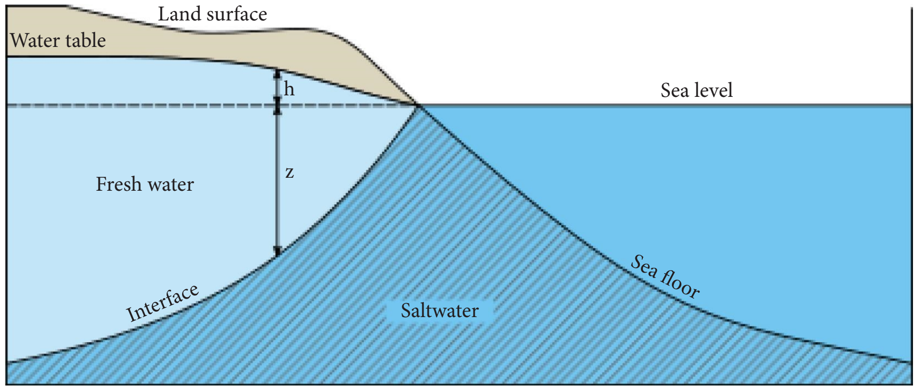

Figure 1: Illustration of groundwater-saltwater interactions along a transition zone in an idealized coastal aquifer (modified from Barlow Paul [3].

the screening and research of inaccessible zones or places with limited hydrogeological data [4, 5]. Submarine groundwater discharge (SGD) and seawater intrusion are crucial topics in the field of hydrogeology and coastal zone management. These phenomena have been studied extensively by researchers around the world to understand their impacts on coastal ecosystems, water quality, and groundwater resources. Temperature differences between inflowing groundwater and surface waters are detected using the same since groundwater is less dense than seawater it forms buoyant water plumes in the seawater. The thermal anomaly reveals the possible locations of submarine groundwater discharge over large spatial scales [6]. The temperature of the groundwater is typically steady and serves as an average temperature for the area, whereas the temperature of the surface water varies with the seasons [7]. Recent studies have used the data obtained from the Landsat 8 thermal infrared sensor (TIRS) to identify and characterize SGD sites. In comparison to SST products, Landsat 8 provides high spatial resolution images (30–100 m) and a robust quality/cloud mask [8]. Natural sources, such as rivers or streams, or civilian structures, such as ports, thermal power plants, fish farms, or wastewater treatment plants, can also create anomalies. These thermal anomalies may mislead or mask some SGD springs when the discharge occurs in shallow areas with high seawater residence. However, the TIR in conjunction with geochemical tracers can better determine the high flux SGD locations [9].

Groundwater level and quality data play an important role in assessing the locations of SGD and SWI. Groundwater level monitoring helps to observe the changes in the quantity of groundwater level and plays a crucial role in understanding the mixing process (SWI and SGD) along the coastal areas while determining the water quality certain measurements needs to be made in order to determine whether the quality is suitable for a particular use. These measurements include comparing the concentrations of various chemicals to the concentration of water that are natural. The concentrations of these particles in the water indicate the water quality. The key components that act as water quality indicators are dissolved oxygen, temperature, pH, nutrients, industrial chemicals, metals, and organic and inorganic materials. The electrical conductivity (EC) of water is one of the most important parameters to determine the quality of the sample of water. The salinity of the groundwater is higher in the regions where electrical conductivity is high [10].

Thermal infrared (TIR) imagery is a valuable tool used in submarine groundwater discharge (SGD) studies to identify and map areas of groundwater discharge into the coastal ocean. TIR imagery measures the thermal radiation emitted by objects, including water, at different wavelengths in the infrared spectrum. As groundwater discharges into the ocean, it can have a different temperature compared to the surrounding seawater, resulting in thermal anomalies that can be detected using TIR imagery. TIR imagery can be acquired from satellite sensors or airborne sensors, depending on the scale and resolution needed for the study. TIR imagery can be a valuable tool in submarine groundwater discharge (SGD) studies, allowing for the identification of potential SGD hotspots, mapping of SGD plumes, estimation of SGD rates, and monitoring changes in SGD patterns over time. TIR imagery can also be integrated with other data sources for a more comprehensive understanding of SGD processes, aiding in the development of a holistic approach to SGD studies and groundwater management. However, it is important to validate TIR imagery results with ground truth data and use them in conjunction with other methods and techniques for accurate interpretation and analysis. However, it is important to note that TIR imagery has limitations and should be used in conjunction with other data sources and field measurements for accurate interpretation and analysis. Factors such as cloud cover, atmospheric conditions, and instrument limitations can affect the accuracy and reliability of TIR imagery. Therefore, it is crucial to validate TIR imagery results with ground truth data and use them as a complementary tool in SGD studies along with other methods and techniques.

This study evaluated the aerial thermal infrared (TIR) imageries of LANDSAT 8 to locate the possible SGD sites along the west coast of the Kanyakumari district in south India. Data about the groundwater levels (GWL) and water quality parameters between 2019 and 2021 helped to demarcate the locations of saline water influx and groundwater discharge. Both the data sets covered 38 monitoring wells of the Kanyakumari district and were procured from the groundwater division (PWD) in Chennai.

2. Materials and Methods

2.1. Study Area. Kanyakumari district is located at the southernmost tip of the Indian peninsula. Its coastal area is approximately 68 kilometres long [11]. A ten-kilometre buffer zone is created along the coastline for the detailed analysis of the groundwater-seawater interactions. On the north and east, it is bordered by Tirunelveli district. The Gulf of Mannar forms the eastern border. The Indian Ocean and the Arabian Sea form the southern and western boundaries. Kerala state borders it in the west and north-west. This area falls between the north latitudes 08°02′ and 08°22′ and east longitudes 77°04′ and 77°35′ (Figure 2). The average maximum and minimum temperatures are 35.93 and 23.85°C, respectively [12, 13]. There are five coastal blocks in the district which include Munchirai, Killiyoor, Kuruthankode, Rajakkamangalam, and Agatheeswaram. The western Kanyakumari district has a rocky coast in many places and is largely overlain by red Teri sands over basement rocks, which represents the semiarid climate that was experienced by the area in the recent past. The major river draining in this zone is Kothayar. Sandy beaches are also visible at many locations. The coastal zone of Kanyakumari has a low EC beach at different segments [14].

2.2. Geology and Hydrogeology. The Survey of India's toposheets of scale 1 : 50,000 were used to create a base map of the study area, and it falls under 58H/12, 58H/8, 58H/4, and 58H/3. Physiographically, it has the Western Ghat mountain, coastal plain, and some undulating regions. Charnockite, gneiss, granite, alluvium, sandy clay, and marine deposits form the basement [15]. The charnockites are exposed around Rajakkamangalam, and calcareous lime shell is noticed at Kanyakumari. The west coast is covered by thick lateritic soil [16]. The major rivers flowing in the region include Pazhayar river, Valliyar river, and Thamiraparani river. Groundwater occurs under unconfined conditions. Weathered and fractured rocks serve as the zones of groundwater occurrences. Unconsolidated to semi-consolidated formations and weathered, fissured, and fractured crystalline rocks are the major hydrogeological formations of the study area. Figures 3 and 4 show the elevation, drainage pattern, and geology of the Kanyakumari district, respectively.

2.3. Landsat 8 Thermal Data Acquisition. A preliminary examination has been carried out using remote sensing techniques through the analysis of thermal data collected by the Landsat 8 data. Satellite data products over the Kanyakumari coast for the past three years are used for preparing and comparing the sea surface temperature. Anomalies in sea surface temperature were detected using Landsat-8 operational land imager (OLI) and thermal infrared sensor (TIRS) with a cloud cover of less than 20% [17]. All the data sets were resampled using the closest neighbour approach and projected to the WGS84 datum and zone 44 of the Universal Transverse Mercator (UTM) coordinate system. All the required satellite data are acquired from the USGS Earth Explorer web portal. The steps involved in the preparation of SST maps are given as follows in detail.

2.4. Estimation of Sea Surface Temperature. The sea surface temperature maps can be prepared from Landsat 8 satellite images. Several steps are involved in the preparation of the SST maps. At first, the satellite images of the study area are downloaded from the USGS earth explorer portal. For this study, mainly bands 4, 5 10, and 11 were used. Then, the digital numbers of the TIRS bands are converted to TOA spectral radiance (Table 1). Later, the spectral radiance values are converted to brightness temperature (BT) using the constant thermal values from the satellite metadata file adopting the formula [18]. In order to calculate the temperature in °C, absolute zero is added that approximates −273.15. The Landsat visible and near-infrared bands may be used to compute the normal difference vegetation index (NDVI). Land surface emissivity is calculated using NDVI data, which indicate the average values of emissivity from various elements on the surface of the planet (LSE). To determine emissivity, the NDVI and proportional vegetation are considered. Finally, the SST is calculated using TOA, BT, wavelength of the emitted radiance, and LSE. Calculated SST was then used to delineate the probable SGD zones of the study area. The final SST map shows the temperature variation in the sea surface along the coastline.

2.5. Data Collection and Analysis. The periodic groundwater level monitoring provides valuable data about variations of hydrologic stresses on recharge, discharge, and storage [19]. The water quality assessment provides information about subsurface geological environments [20, 21]. The groundwater level and quality data of the Kanyakumari district were gathered from the groundwater division (PWD), Chennai. In the past 3 years (2019, 2020, and 2021), water quality and water level maps of the study area were prepared for identifying the possible locations of SWI and SGD. The IDW interpolation methods are carried out using Arc GIS software for preparing the spatial distribution maps of the study area. The factors that affect groundwater level changes are carefully examined, and the effects of those factors on the coastal zone have been thoroughly covered. Seawater intrusion is caused by the low groundwater level or by the high seawater level, and the reverse phenomenon gives rise to SGD.

3. Results

3.1. Seawater Temperature Anomaly. The identification of SGD zones was based on thermal maps derived from the Landsat 8. Each material, depending upon the emissivity property, has thermal radiation in different proportions. The thermal imagery separates the warm objects from the cold ones. The cold-water plumes are more evident in high-

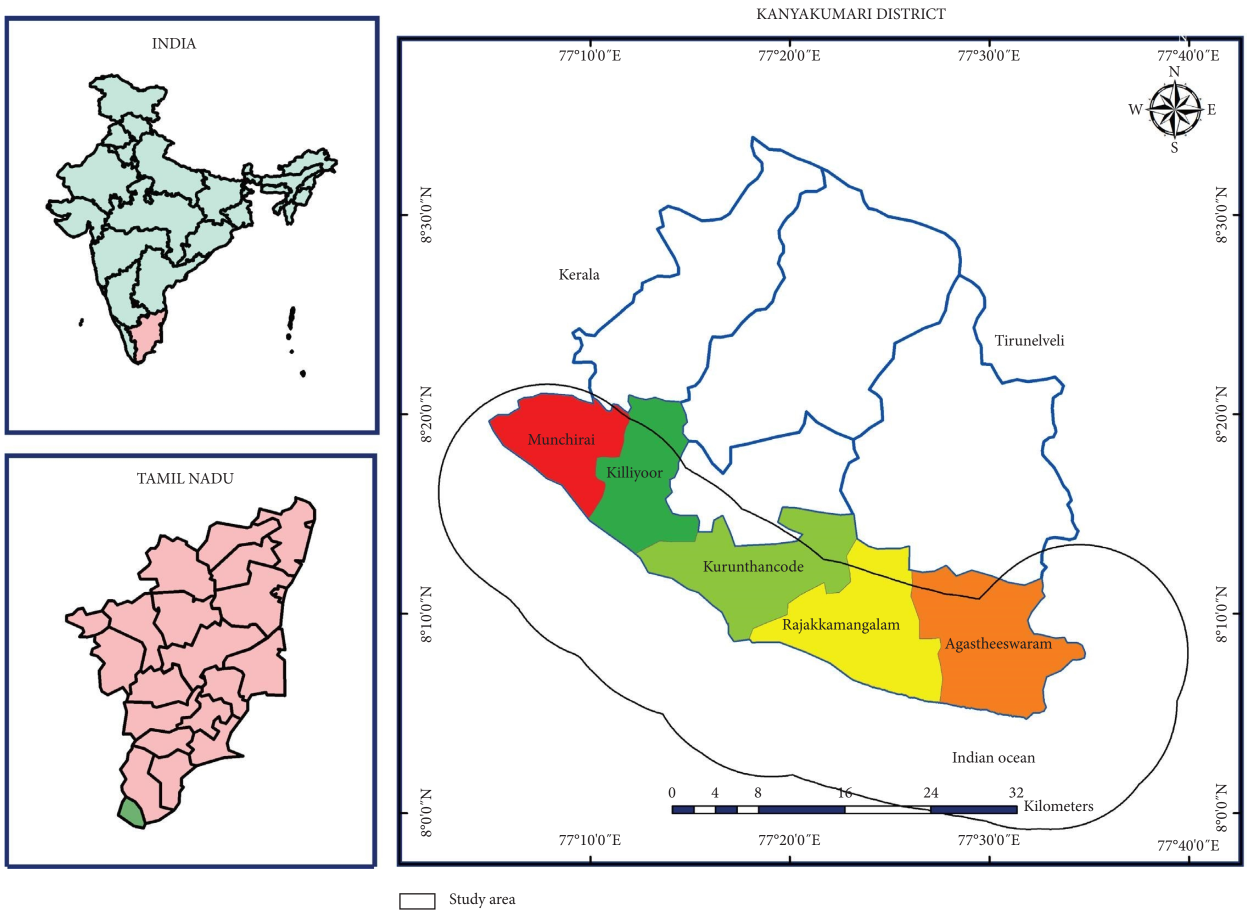

Figure 2: Map showing the west coast of Kanyakumari district in the southern Indian state of Tamil Nadu that is located at the confluence of Indian Ocean, Arabian Sea, and Bay of Bengal.

temperature surrounding areas, and it is treated as a notable provenance for SGD. Hence, from the map, it is clear that certain regions especially towards the southern portion (blue) exhibit the SGD phenomenon. These locations include Kovalam, Puthalam, and Muttam. Also, the groundwater seepage is found to be patchy, diffuse, and temporally variable. The probable locations of SGD are marked in red circles (Figure 5).

3.2. Groundwater Level Monitoring. The resulted groundwater level map is reclassified into different classes which indicate regions of high and low water levels (Figure 5). In the year 2021, the groundwater level in post-monsoon and pre-monsoon was similar, and Killiyoor and Rajamankkalam show prominent zones of SGD. In the year 2020, the groundwater level in post-monsoon was as low as 0.06 m and as high as 16.46. Similarly, in pre-monsoon, values range between 1.56 and 18.36. In 2019, the groundwater level varies between 0.82 and 13.28 during post-monsoon, and it varies between 1.68 and 18.99 in pre-monsoon. From Figure 6, we can conclude that there are regions where GWL continues to be greater than MSL (mean sea level), implying that the potential of SGD occurrence is high in those areas. The high groundwater table depth observed in many parts of the study area can be influenced by various hydrological factors, including precipitation, geology and soil properties, topography, vegetation and land use, groundwater abstraction, and climate change. Understanding these factors is crucial for managing groundwater resources and mitigating potential impacts on hydrogeology and water availability in the study area.

3.3. Groundwater Quality Analysis. The hydro-geo-chemical parameters helped to identify brackish or saline waters. The spatial distribution map of EC, Cl^-, SO_4, and NO_3 revealed the sites of saline water intrusion along the Kanyakumari coastline between 2019 and 2021 (Figures 6–8). The pH of water samples varied between 7 and 8.2, the minimum amount of pH is 7 found in Kalkulam, and the maximum is 8.2 in the Vilavangode region. The 2021 data show that the TDS falls under the range of 29 mg/l to 1793 mg/l. Most of the regions in the study area come under freshwater quality except the sample from Nagercoil (Veppamoodu). The range of EC during the year 2021 is about 50–3190 mg/L. High EC is exhibited by seawater, and low EC values indicate SGD zones. The presence of bicarbonates, sulfates, chlorides, and nitrates may increase the hardness of water. Hardness values ranged between 15 (Kalkulam) and 600 mg/L (Vilavangode)

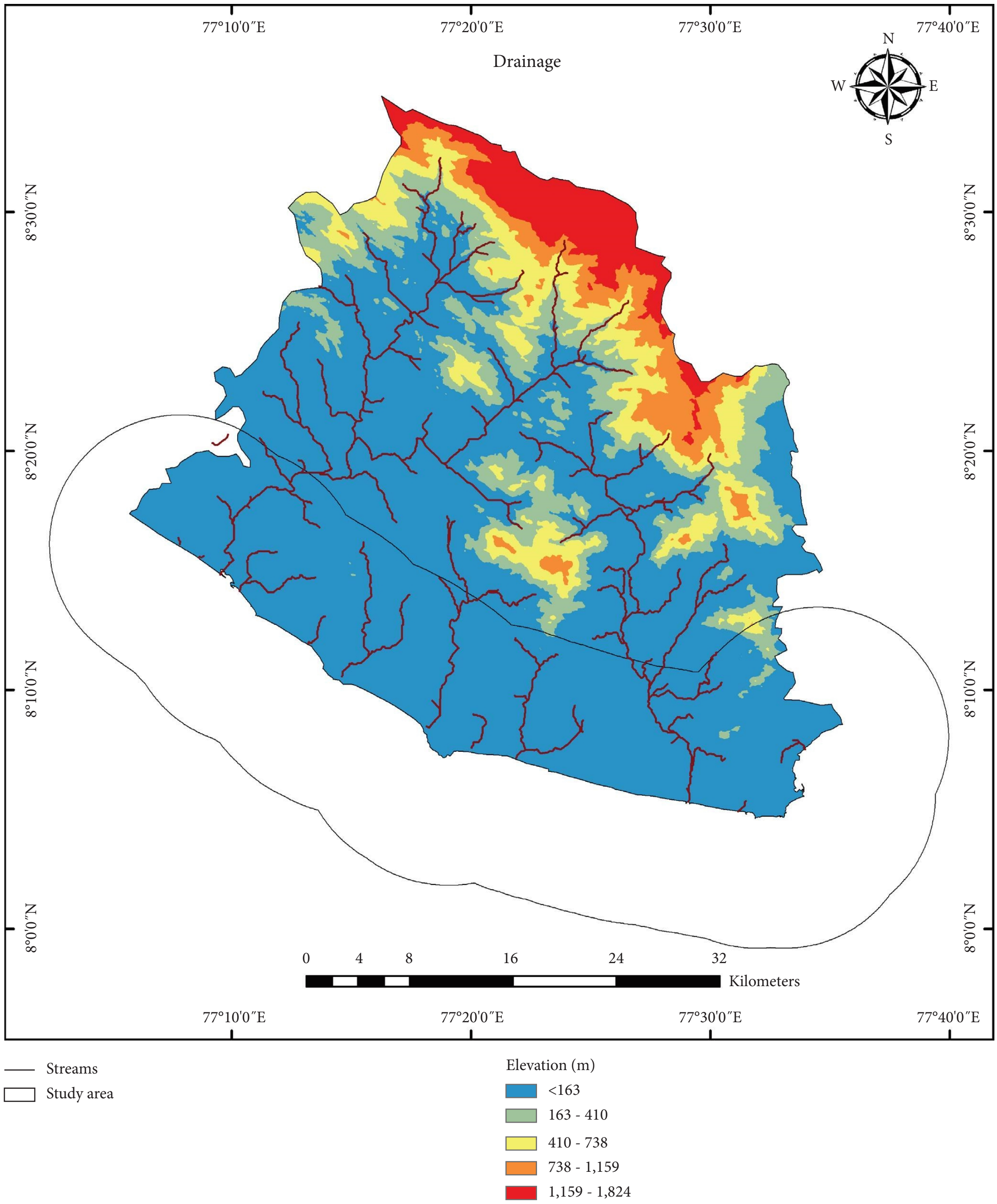

Figure 3: Elevation and drainage map of the study area.

in the study area. Chloride concentrations rise dramatically when groundwater is contaminated with seawater. High chloride concentration in the study area indicates saline water intrusion. Nutrients, such as sulfate, nitrate, and phosphate, are indications of SGD.

4. Discussions

Sea surface temperature, groundwater level, and groundwater quality are considered as a very essential parameter for estimating the probable zones of SGD and SWI. Surface water discharge forms an important channel for freshwater and material inflow to the sea. Apart from the surface water discharges, certain locations are characterized by thermal anomalies which indicate submarine groundwater discharge zones. The identification of SGD zones from the thermal maps is derived from Landsat 8. Based on the emissivity property of materials, each material gives off thermal radiation in different proportions. The warm and cold objects stand out in the thermal imagery. SGD may lower the SST of the region around the discharge zones in the summer, but in the winter, the open water of the sea is colder, and the water

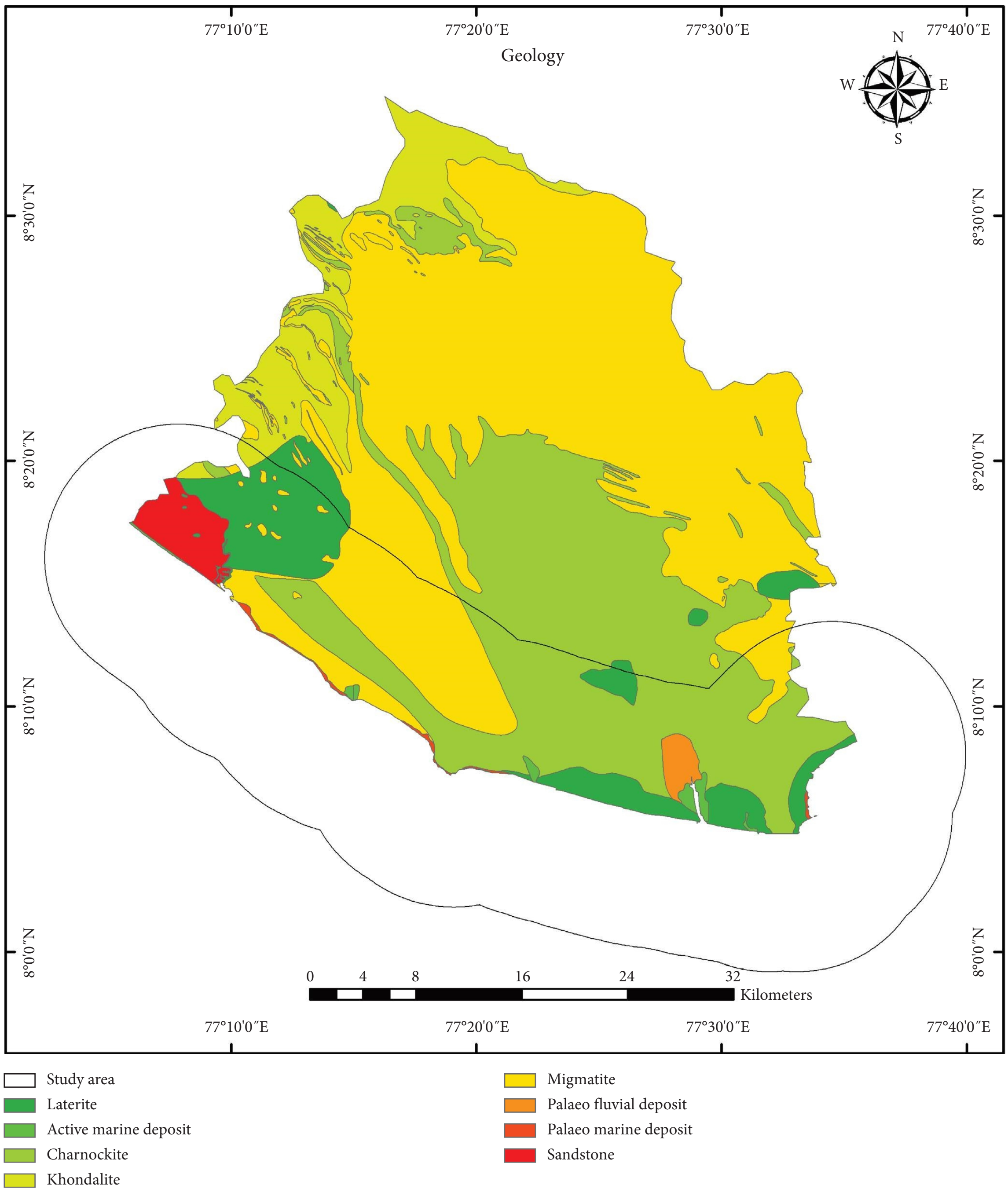

Figure 4: Geology map of the study area.

Table 1: Statistics of Landsat 8 SST maps of the Kanyakumari coastal zone.

Acquisition date	Time	Path	Row	SST (min)	SST (max)	SST (mean)
01-01-2019	05:05:45.62	143	054	21.80	28.53	25.16
07-04-2019	05:05:24.02	143	054	20.32	27.8	24.06
20-01-2020	05:06:02.49	143	054	17.88	26.68	22.28
09-04-2020	05:05:31.65	143	054	22.44	26.14	24.29
07-02-2021	05:05:59.96	143	054	21.66	28.81	25.23
28-04-2021	05:05:27.76	143	054	18.25	27.84	23.04

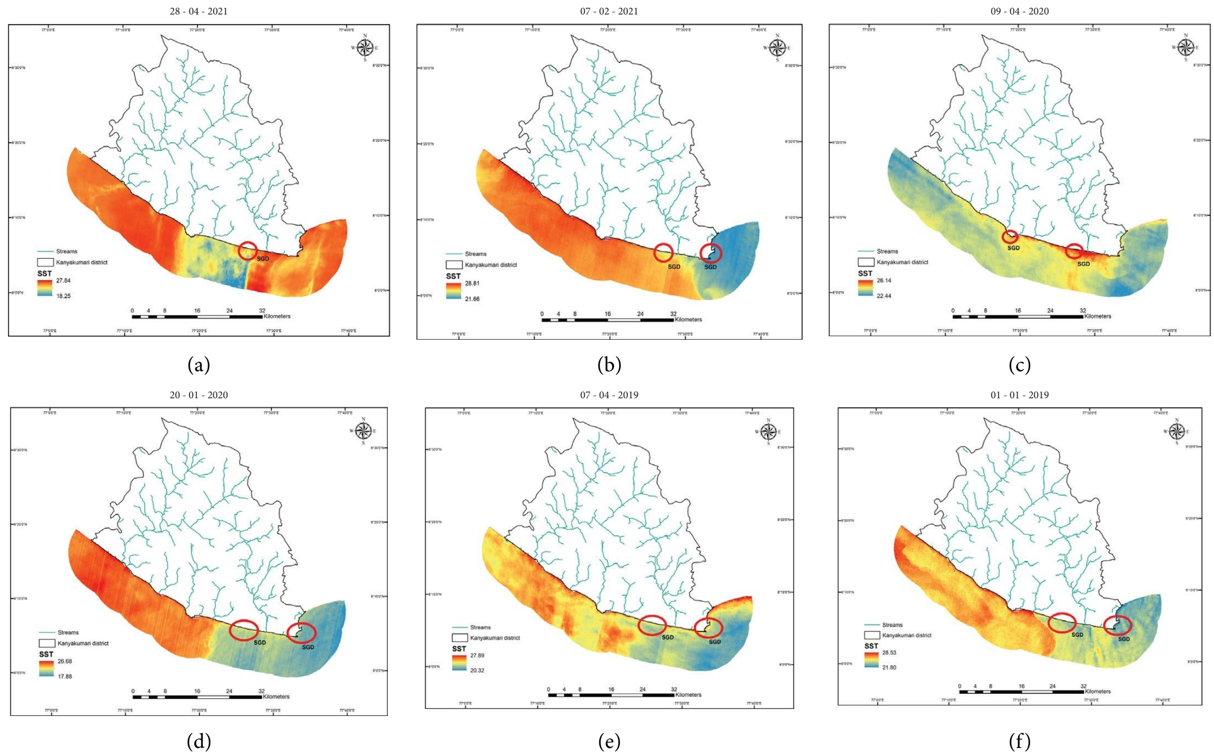

FIGURE 5: The SST map of the study area for the past three years 2021, 2020, and 2019, respectively.

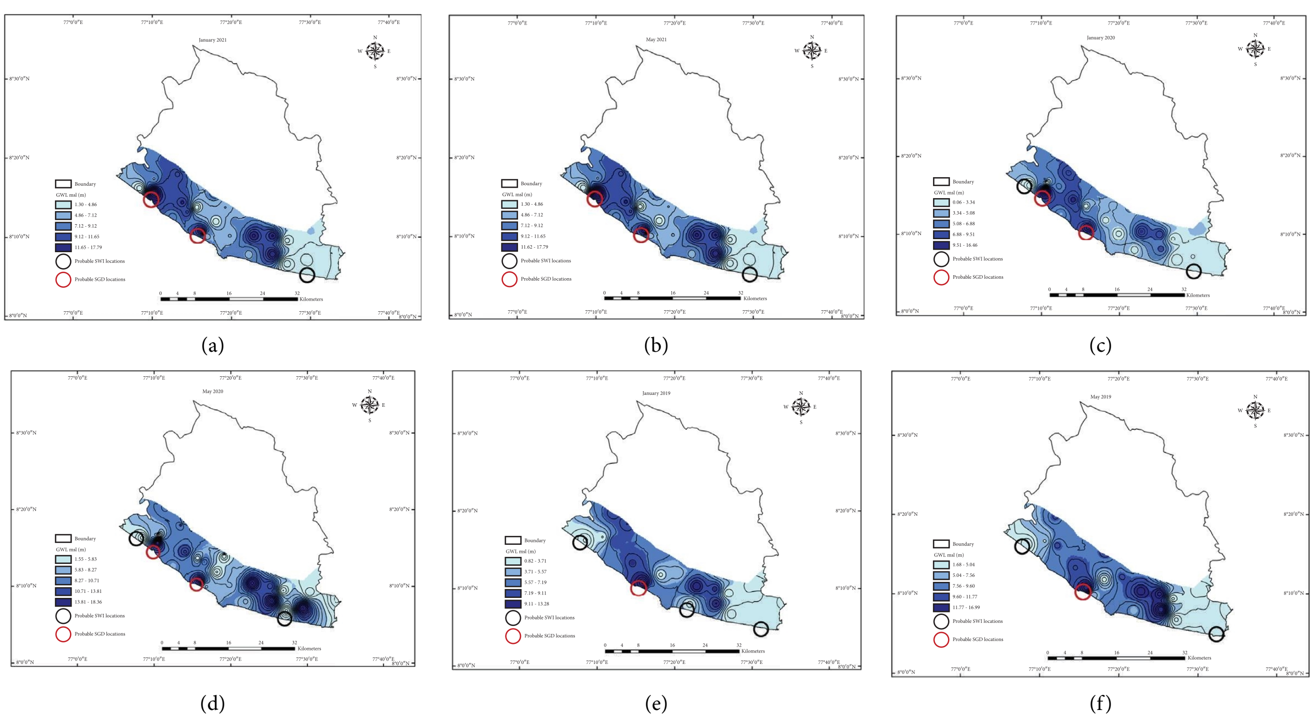

FIGURE 6: The water level map for the past three years (2021, 2020, and 2019, respectively). Both SWI and SGD are defined and marked with black and blue colours.

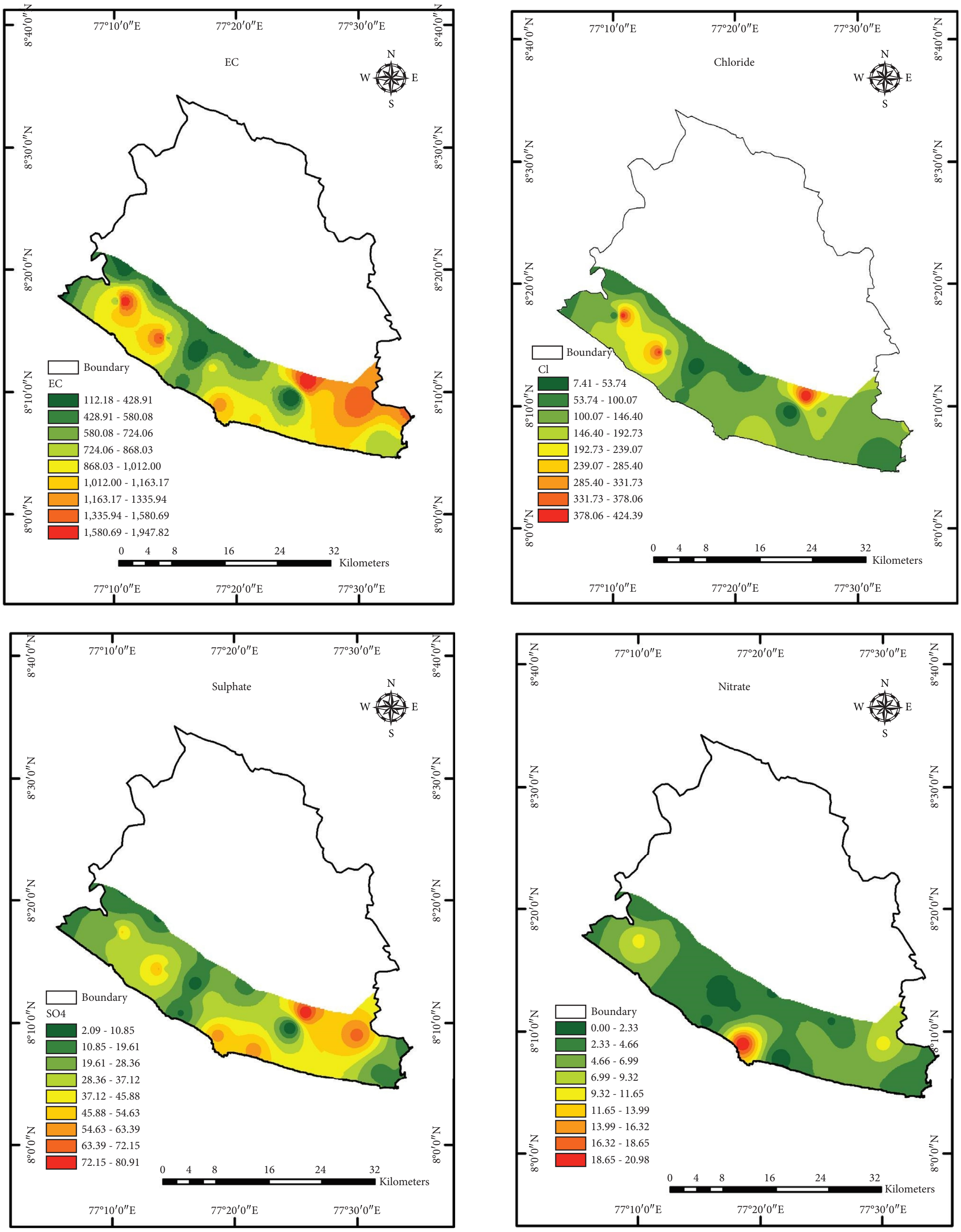

Figure 7: Different groundwater parameters of the west coast of Kanyakumari of Southernmost India for 2021.

discharged as SGD may be warmer [22]. From this point of view, the SST map serves as an excellent tool in the SGD identification. The probable zones of SGD based on SST are marked in figures (Figure 9) in red circles.

The fluctuations in groundwater levels are due to both natural and artificial factors. The groundwater level map of the study area is reclassified into different classes which indicate regions of high and low water levels. Low groundwater levels are due to over extraction of groundwater from the coastal aquifer, and this may lead to seawater intrusion. Water always moves from a higher gradient area to a lower gradient area. A steeply dipping groundwater contour indicates a high groundwater level, and a gently dipping contour indicates a low groundwater level. From this, we can conclude that regions with low groundwater level (GWL-MSL < 0) indicate seawater intrusion, and regions with high groundwater level (GWL-MSL > 0) indicate SGD zones. SGD and SWI zones are

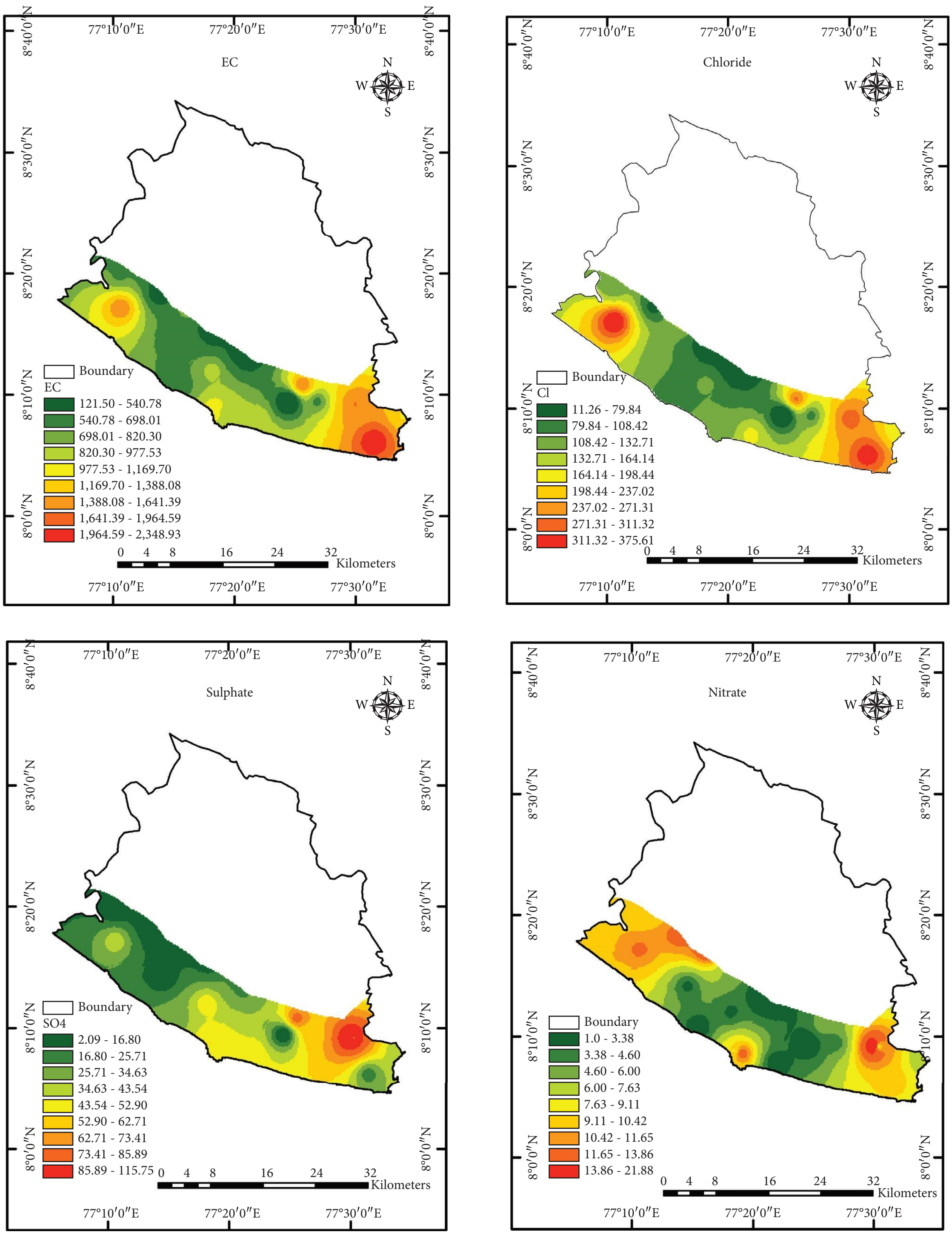

Figure 8: Different groundwater parameters of the west coast of Kanyakumari of Southernmost India for 2020.

noticeable in both seasons, and it seems that the marked locations are not stable and keep on fluctuating depending on the seasons.

In order to identify brackish or saline waters, hydro-geochemical parameters are used. There are several physio-chemical parameters that serve as excellent tracers for SWI and SGD. A spatial distribution map of various parameters such as EC, Cl, SO_4, and NO_3 for three years was used to reveal the signature of saline water intrusion along the Kanyakumari coastline. The increased conductivity values are caused by seawater influx into the coastal aquifers. High EC in groundwater signifies enrichment of salts. This may be due to the migration of seawater into the freshwater aquifer. This migration is mostly triggered by the excessive pumping of the groundwater from the coastal aquifers. Since fresh water is free of dissolved solids, it is having a low EC

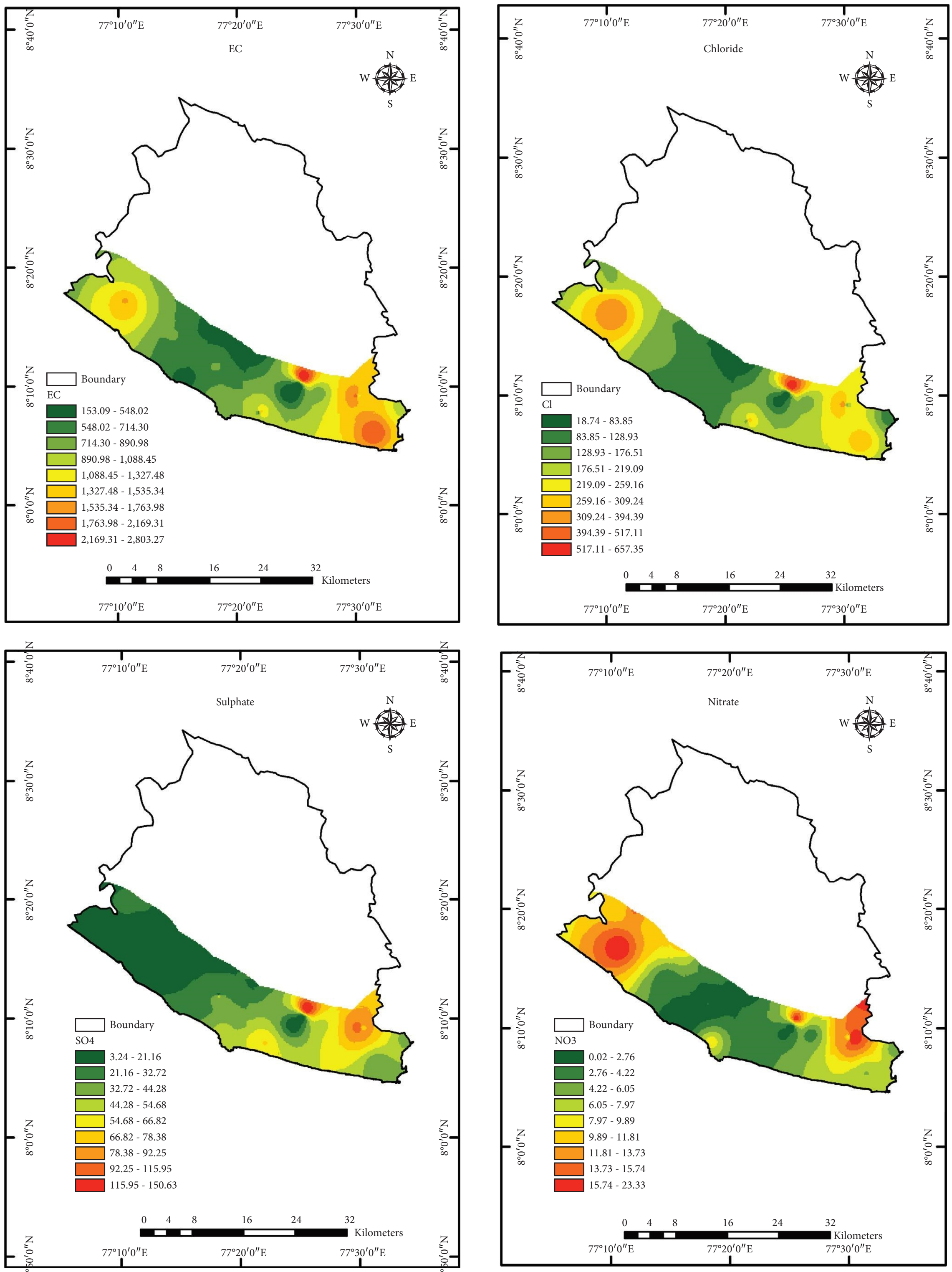

Figure 9: Different groundwater parameters of the west coast of Kanyakumari of Southernmost India for 2019.

value and is considered as an SGD zones in coastal areas. Therefore, regions with high EC value indicate SWI zones and low EC value indicates SGD zones. The concentration of chloride ions in seawater is much higher as compared to the fresh groundwater. Fresh groundwater is rich in nutrients as compared to the seawater. Hence, high discharge of fresh water into the sea causes large influx of nutrients to the ocean that can cause several ecological implications such as eutrophication, algal bloom, and red tide. Table 2 shows the outcome of the study, i.e., the variations of SGD and SWI

Table 2: Variations of SGD and SWI with respect to SST, GWL, and GWQ.

Criteria	Variations		Process
Sea surface temperature	Summer	Cold water plumes	SGD
	Winter	Hot water plumes	SGD
Groundwater level	High		SGD
	Low		SWI
Groundwater quality parameters			
EC	High		SWI
	Low		SGD
Cl	High		SWI
	Low		SGD
SO_4	High		SGD
	Low		SWI
NO_3	High		SGD
	Low		SWI

with respect to SST, GWL, and GWQ. Hence, the physiochemical parameters reveal the areas where SGD and SWI are prominent, and also, we can take measures to enhance the quality of the water where water quality parameters are weak.

5. Conclusions

The findings of this study provide valuable insights into the dynamics of submarine groundwater discharge (SGD) and seawater intrusion (SWI) in the study area and highlight the importance of considering various hydrological factors for classifying individual areas related to SGD and SWI. SGD and SWI are the two major phenomena in coastal aquifers. They are interrelated but reverse in nature. Several techniques are involved in their identifications, but here, we combined three approaches such as the sea surface temperature anomaly, groundwater level fluctuation, and groundwater quality analysis. An attempt was made to determine the likely sites of SGD by analyzing the temperature difference at the sea surface on the west coast of Kanyakumari in the southernmost Indian Peninsula between 2019 and 2021 using the Landsat 8 thermal data. Thermal contrast in SST maps demarcated the SGD zones along the coastline. The patches with a temperature lower than the surroundings were considered as SGD potential zones. The temperature anomalies were more pronounced towards the southern end at Kanyakumari, Kovalam, Puthalam, and Muttam. Groundwater seepage, possibly from multiple aquifers, appears uneven, dispersed, and temporally and spatially varied. The variations in groundwater level and groundwater quality of the past three years indicated SWI in regions with low GWL, high EC, and chloride (e.g., Agatheeswaram and Munchirai). The areas with high GWL, low EC, and high nutrient concentrations were the potential SGD zones (e.g., Killiyoor and Rajakkamangalam). This study highlights the importance of considering multiple hydrological factors, including geology and soil properties, topography, vegetation and land use, groundwater abstraction, and climate change, for accurately classifying areas related to SGD and SWI in the study area. Further research and monitoring of these factors can provide valuable insights into the dynamics of SGD and SWI, aid in developing effective groundwater management strategies, and contribute to the sustainable use of groundwater resources in the study area.

Future groundwater management in SGD and SWI zones should focus on enhancing groundwater recharge, managing groundwater abstraction sustainably, monitoring and managing land use practices, preventing further seawater intrusion, developing and implementing groundwater quality monitoring programs, optimizing groundwater abstraction practices, promoting alternative water sources, and raising awareness and promoting community engagement. These measures can contribute to the sustainable management of groundwater resources in SGD and SWI zones, ensuring their availability and quality for current and future generations.

Data Availability

The data supporting the current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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