Chapter 22
Groundwater Contamination due to Saline Water Encroachment in Coastal Andhra Pradesh, with Particular Emphasis on the Morphological Units

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22.1 Introduction

The younger coastal plains of Holocene to Recent-subrecent sediments in Andhra Pradesh are geomorphologically and lithologically prone to saltwater ingression into the coastal aquifers like other states of the eastern coast of India. As a result of the composition of unconsolidated alluviums, over extraction of groundwater for irrigating the delta plains as well as coastal plains, spread of coastal urbanization, reduction in freshwater flows into the downstream sections of coastal plain river systems, climate change reworking of the coastal landscapes by sea level rise threats, coastal erosion, and impacts of storm surge inundations, the groundwater is contaminated by such events of saline water encroachments. The sand-silt-clay and gravel beds with deltaic and marine alluviums provide favourable conditions for percolation and seepage flow at the land-water interface if the region is over pumped for groundwater uses and the gradient of the hydraulic head is reduced in the aquifer along the younger coastal plain of the coastal state.

The study demonstrates lithological and morphogenetic regions, rainfall diversity zones, land use and land cover types, sea level rise threats, storm surge inundation vulnerabilities, and groundwater quality of a few sections of the coastal. Using

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geospatial techniques, existing secondary data on groundwater conditions, other physical components of the coastal zones, and surface runoff characteristics with drainage systems and climate change threats, a spatial index of saltwater encroachments is prepared to delineate the boundaries of saltwater contamination zones into the coastal aquifers of the state. Such a method of study as well as the database will provide the ingredients for sustainable water uses and the management of contamination zones in the coastal belts of regional settings. Similarly, the method of spatial indexing for saltwater contamination would also be applicable for other coastal regions along the eastern shoreline of India. Coastal urbanization will be threatened by such aquifer contamination from saltwater encroachments influenced by sea level rise threats and over-extraction of groundwater resources in the near future. Many researchers studied on various aspects of groundwater quality in coastal urban areas (Rao et al., 2002), saltwater intrusion into coastal aquifers through model studies (Datta et al., 2009), sources of saltwater intrusion in Koleru lake (Harikrishna et al., 2012), investigation of saline water intrusion in Godavari delta (Naidu et al., 2013) using an integrated approach, effect of aquaculture practices in the groundwater in east Godavari district (Penmetsa et al., 2013), groundwater contamination types in Srikakulam (Rao et al., 2011) because of saline water intrusion, types of saltwater intrusion pathways using remote sensing techniques (Dhakate et al., 2016), seawater intrusion in Visakhapatnam (Mamatha et al., 2022), and investigation of groundwater quality using geostatistical techniques (Sangadi et al., 2022) for the Andhra Pradesh coast.

To reduce the contamination level of groundwater quality, the following measurements may be recommended for the coastal parts of the state. Restricted use of groundwater in the coastal urban centres, construction of artificial recharge pits, sharing of freshwater discharges into the downstream sections of the coastal streams, and rainwater harvesting should be practised immediately to reduce the rate of saltwater ingression into the coastal groundwater aquifers.

22.2 Materials and Method

The present work is carried out in the coastal tracts of Andhra Pradesh to find out the physical, environmental, and human factors as per their importance in the assessment of groundwater contamination potentials with saltwater ingression (Fig. 22.1a). A total of 10 factors are assessed for the selective coastal sections with the weighted sum method to set the integrated scores according to the importance of the factors in the regional settings. All the factors are analysed using Shuttle Radar Topography Mission (SRTM) DEM, Landsat 8 Operational Land Imager (OLI) satellite data, Google Earth Images, and other aspect data from India Meteorological Department (IMD), Indian National Center for Ocean Information Services (INCOIS), the Intergovernmental Panel on Climate Change (IPCC), the Survey of India, the Central Ground Water Board (CGWB) report, and the Central Water Commission (CWC) handbook for calculating the scores to identify the potential contamination zones.

The future prediction of the saltwater ingression limit into the groundwater aquifers is estimated in this work using the Analytical Hierarchy Process (AHP) method
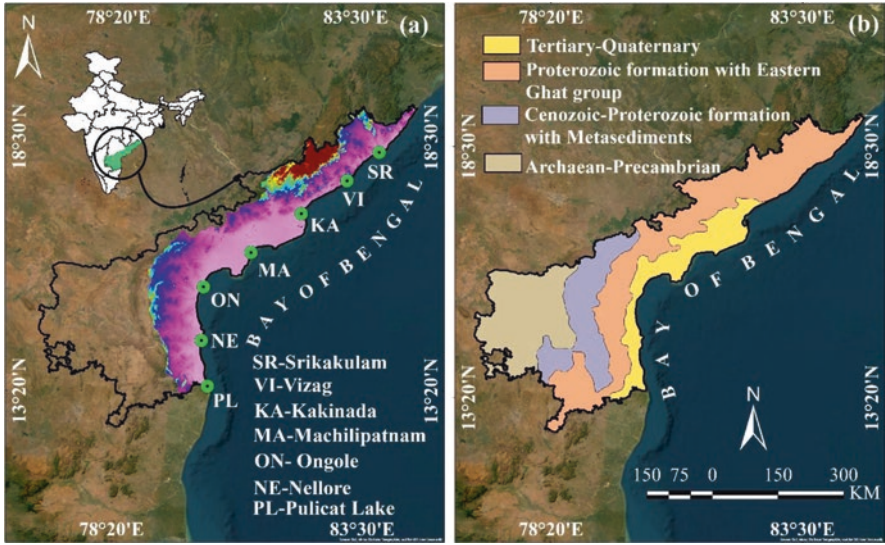
Fig. 22.1 (**a**) Coastal Andhra Pradesh and (**b**) Coastal geology of the state of Andhra Pradesh

and the fuzzy membership method to develop index values for zonal concentrations of saltwater contamination in the groundwater. However, the validation of such a prediction model is conducted using the receiver operating characteristic curve (ROC), and their accuracy level is tested with the AUC and AHP methods for the output of significance. The calculation shows that the AUC is more accurate at the 85.5% level than the AHP method is at the 81.0% for application in the region. Finally, the result of the AHP method and fuzzy membership method denotes the future trend and regional diversity in saltwater encroachment in Andhra Pradesh coastal tracts.

The multi-criterion decision matrix (AHP method) is used in weighted overlay tools to identify the hotspot areas of the saltwater ingression zones in the present study area considering the following Eq. 22.1. A few researchers have applied this equation in investigating the groundwater potential zones and their mapping in other areas of the country (Parimala & Lopez, 2012):

$$S = \sum_{i=1}^{n} W_i \times X_i \tag{22.1}$$

where, S refers to the suitability index for each pixel map. W_i is the assign weight of the ith layer and X_i score of the ith each criteria layer. n refers to the number of suitability layer. The future prediction of the model is calculated using the following Eq. 22.2:

$$Gp = \frac{1}{K} \sum k^{th} v^{response} \tag{22.2}$$

where, Gp refers to the groundwater prediction and *k* indicates the separate trees in the method. The performance of the model accuracy has been evaluated in the validation of the saltwater ingression using the following Eq. 22.3:

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \tag{22.3}$$

where, TP refers to the true positives, TN indicates true negatives, FP refers to the false positives (error type I), and FN refers to the false negatives (error type II). TP and TN are the numbers of pixels that are correctly grouped.

22.3 Results and Discussion

This section represents ten factors and their characteristics in influencing the groundwater contamination potentials by saltwater ingression. The future potential areas and their characteristics are also calculated to highlight the environmental crisis of the region related to saltwater encroachments.

22.3.1 Coastal Geology and Geomorphology

Coastal Andhra Pradesh comprises four major groups of rocks that extend gradually from the shoreline to the hinterland areas. They belong to (i) the Quaternary-Tertiary group of rocks constituting thick alluviums, laterites, and sandstones along the Bay of Bengal coastal zones; (ii) the crystalline sediments, on the other hand, represent thick deposits of sediments in the Cuddapah basin from the upper Precambrian to early Precambrian group of rocks; (iii) the Deccan traps with basalt and other intrusive rocks in combination with Intertrappean bed materials belong to the Cretaceous. Infratrappean beds of Rajahmundry areas comprise limestone and sandstones that underlie the lava trap flows. (iv) However, the Archaean-Precambrian group of rocks includes Granite, Gneiss, Schists, the Bended Gneissic Complex, Khondolites, and Charnockites in the western margin of Andhra Pradesh, particularly along the eastern ghat exposures. Among the geologic units, the Tertiary-Quaternary groups are considered potential aquifers of the groundwater quality (Figs. 22.1b and 22.2a).

In geomorphology, the coastal state may be classified as (i) rocky coast; (ii) coastal plain and delta plain alluviums; (iii) basinal structure of the west central highlands; and (iv) elevated ridges of south western tracts. The coastal plains and delta plains of Godavari R., Krishna R., and Pennar R. sections extend along the Bay of Bengal shoreline towards the east, and the rocky coast, backed by hills and valleys, extends in Vishakhapatnam, Vijaynagaram, and Srikakulam districts of the state towards the northeast. Topographically, the coastal tracts
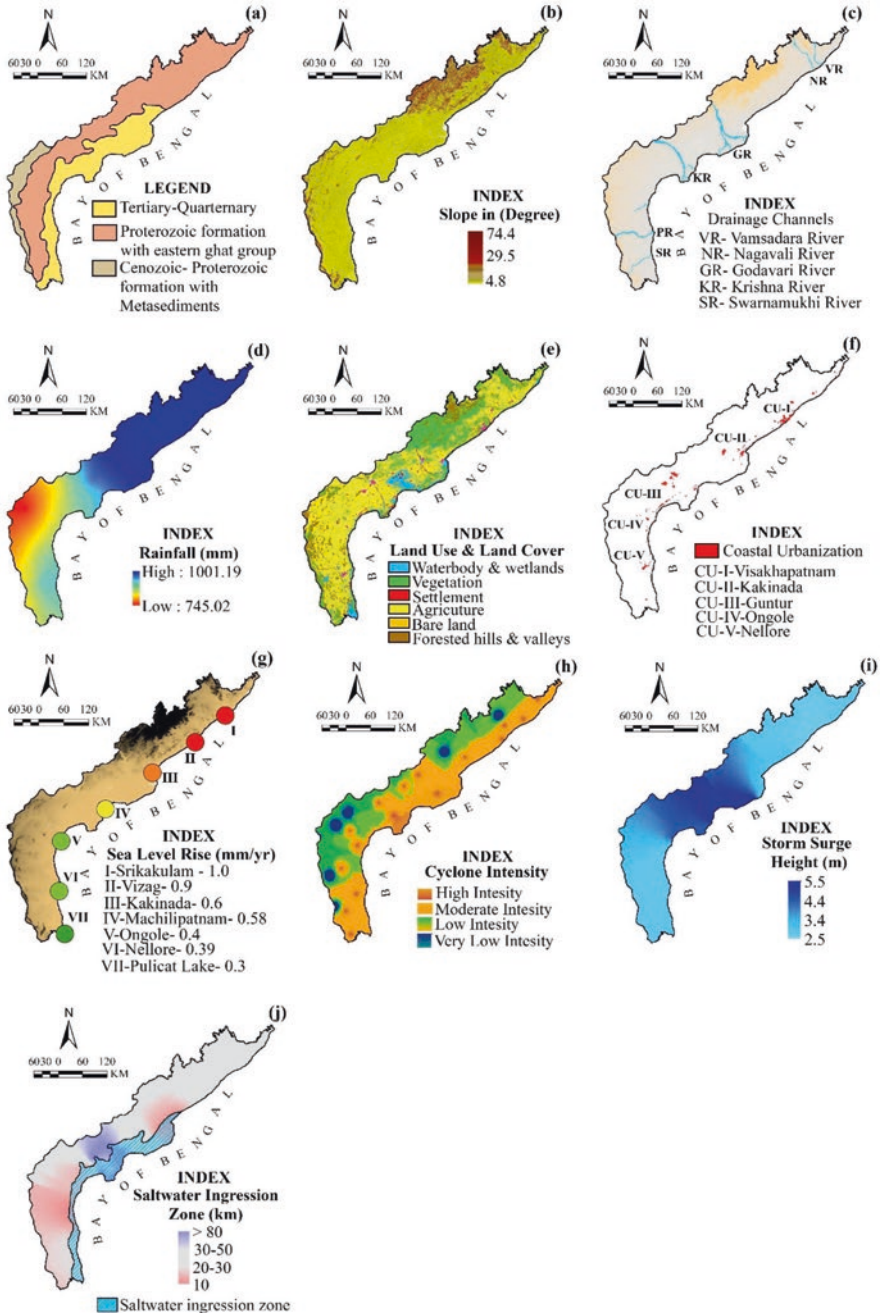
Fig. 22.2 Various aspects of physical, environmental, and human factors of the coastal Andhra Pradesh showing (**a**) Coastal Geology, (**b**) Slope, (**c**) Drainage, (**d**) Rainfall, (**e**) Land Use and Land Cover, (**f**) Coastal urbanization, (**g**) Rates of sea level rise rate, (**h**) Cyclone intensity, (**i**) Storm surge, and (**j**) Saltwater ingression zone

are backed by highland surfaces elevated up to 800 m in height and slope towards the east and southeast directions. The flat, low-lying delta plain surface is composed of fluvio-marine depositional alluviums with beach ridges, levee deposits, paleo channels, and estuarine deposits. Geomorphological surfaces from the west to the east have been documented from the Polarimetric Phased Array L-band Synthetic Aperture Radar (PALSAR) DEM. The hills, ridges, highlands, basins, and plain lands are descending at the steps from west to east and cut by drainage systems following the regional surface gradients of the coastal state. The river systems of Godavari, Krishna, Pennar, Vamshadhara, Gosthani, and Nagavali are flowing to the Bay of Bengal, cutting transversely to the shoreline from west to east. Wider delta plains are produced by the Godavari, Krishna, and Pennar rivers in the southeastern tract and lie 10–20 m in heights above the mean sea level. Several palaeo channels, beach ridges, and levees provide the conditions for transporting sea waters inland in the region of coastal plain alluviums (Figs. 22.2b and 22.3).

Fig. 22.3 Sandy and Graveliferous materials of the coastal tracts prone to saline water intrusion into the groundwater in Visakhapatnam and Bheemunipatnam areas along the Bay of Bengal shoreline

22.3.2 Coastal Drainage Features

Freshwater flow into the downstream sections declined rapidly along the drainage systems due to human-controlled water and sediment discharges and reduced rainfall due to climate change impacts in the previous decades. Several studies by the researchers and the CWC database of river discharges in the peninsular drainage channels demonstrated a 40% reduction after 1960 (Das, 2021; Das et al., 2022). Due to a significant reduction of fresh water flow in the lower courses, the river beds are silted up and filled with the deposition of bars, shoals, and islands (Fig. 22.2c). The encroachment of tidal flows into the upstream channels transported sea waters and occupied the floodplain wetlands across the channels in the region. Deltaic distributary channels, Paleo channels, and low-lying wetlands are usually influenced by marine environments and saltwater flooding, particularly during the landfall of cyclones and the impacts of storm surges. As the gradient of downstream sections is very low in the coastal plain drainage channels, the saltwater encroachment advanced landward sections at high sea levels. The six major river systems of the coastal tract are used as passage for transporting saltwaters into the landward sections of the state.

22.3.3 Land Use and Land Cover Types

The delta plains and coastal plains of Godavari R., Krishna R., and Pennar R. are intensively cultivated by multiple cropping patterns using groundwater irrigation. A number of settlement sites and urban centres have emerged in the coastal plains in expanses of wetlands and alluvium tracts in the west Godavari, east Godavari, Krishna, Guntur, Nellore, and Prakasham districts. Similarly, urbanization processes expanded in Vishakhapatnam, Vijaynagaram, and Srikakulam districts of the highlands coast of Andhra Pradesh. The municipality's towns and other urban water supplies are also overly dependent on the pumping of groundwater in the region. Various land use practices like salt manufacturing pans, aquaculture ponds, and placer mining sites occupy the coastal fringes of estuary banks, lagoons, backwaters, bay side areas, sand dunes, beach ridges, and delta plains. Coastal wetland habitats such as mangroves, saltmarshes, tidal flats, spits, beaches, sand dunes, and river mouths are under stress due to an overdependence on natural land cover resources. Such a rapid rate of land use conversion and over-extraction of the groundwater is causing fluctuating aquifer levels in the region (Figs. 22.2e and 22.3). Kakinada and Visakhapatnam cites have occupied the coastal fringe landscapes and modified their habitats.

22.3.4 Variation in Rainfall

There is a significant variation in average annual rainfall distribution patterns between northeastern districts and other eastern and southeastern districts of the coastal state. The national average annual rainfall map shows that Srikakulam, Vijaynagaram, Visakhapatnam, West Godavari, East Godavari, Krishna, and parts of Nellore districts received above 1000 mm of rainfall during the year 2021. Guntur and other areas of Nellore district received 900–1000 mm of rainfall. However, the coastal districts of Guntur, Prakasam, Chittoor, and the eastern parts of Kadappa received 800–900 mm of rainfall during this time. The coastal districts were affected by the seasonal variation of rainfall, for example, the high rainfall (62.6–174.1 mm) in the southwest monsoon months (May–November) and low rainfall in the northeast monsoon months (December–April), when only 6.5–23.2 mm of rainfall were recorded in the region (Fig. 22.3d). The amount of such rainfall plays a significant role in recharging the groundwater and surface runoff towards the Bay of Bengal following the surface gradient.

22.3.5 Population and Urbanization

Population concentration, density, and coastal urbanization play a significant role in the consumption of water from the groundwater aquifers. Intensity of cropping and prolific urban growths, as well as urban sprawling and irrigation of the productive alluviums, need water.

Thus, over-extraction or overpumping of groundwater is practised to support the population and urbanization in the coastal plains of Andhra Pradesh. Major urban centres of the region include Vishakhapatnam, Kakinada, Machilipatnam, Guntur, Nellore, Chirala, Srikakulam, etc., and population density ranges from 500 to 700 persons per square kilometre in the rural settlements (2011 Census of India) of the coastal tracts (Fig. 22.2f). As the Godavari delta, Krishna delta, and adjacent coastal plains are noted for agricultural activities, the river waters and groundwaters are heavily used for irrigating the lands to feed the enormously growing population of the region. During the months of February, March, and April, the region receives very less amount of rainfall, and over-extraction of groundwater is the only solution to supply the agricultural needs.

22.3.6 Climate Change Threats

Dynamic stream flow and reductions in freshwater flow or river runoff in the Godavari, Krishna, and Penner River basins are caused by climate change impacts and human activities. During the past five decades, the changes have been

associated with variations in precipitation in the catchment areas of the river basins of the Godavari and Krishna (Das, 2021). However, the average annual temperature is increased in the northern districts of Andhra Pradesh than it was during the previous two decades (2001–2021). Similarly, the coastal districts of the state were affected by a series of cyclone landfalls with encroaching storm surges in the low-lying coastal plains from 1970 to 2022. The increased SST of the Bay of Bengal, the reduction in stream flow into the coastal zones, and the change in salinity gradients caused the intensification of cyclones in the Bay of Bengal in the previous decades (Fig. 22.2h). The low-lying areas liable to saltwater inundations during the tidal surges and storm surges promoted salt encrustation over the coastal plain alluviums, and vertical translocation by rainwater solution and percolation injected the saline waters into the groundwater aquifers. Such processes of saltwater ingression are enhanced by repeated cyclone impacts on the coast caused by climate change threats.

22.3.7   Sea Level Rise Effects

The IPCC working committee report 2021, and the tide gauge data of Kakinada port and Visakhapatnam port reveal the current status of sea level rise rate in the Bay of Bengal fringed Andhra Pradesh coast, which is ranging from 0.93 to 1.03 mm/year. Thus, the increasing rate of sea level rise threats will enhance the saltwater ingression into the coastal aquifers across the freshwater–saltwater interface zones into the coastal tracts (Fig. 22.2g). The alternate sand layers trapped between the clay blankets are vulnerable to saltwater ingression, with an increasing rate of sea level rise threat along the coastal plains in Andhra Pradesh.

22.3.8   CGWB Report (2014)

The Central Ground Water Board (CGWB) of India, by their experimental wells along the Andhra Pradesh coast, prepared the report on groundwater status in 2018. From the status report, it is observed that southeastern and eastern districts of the coastal plain are affected by saltwater ingression into the aquifers up to 10 km inland from the shoreline position (Fig. 22.2j). The groundwater quality index is prepared by assigning weightage to the physiographic environmental, hydrologic, lithologic, and human factors of the coastal tracts for the estimation of integrated scores and to find out the landward extension of the saltwater contaminated zones. The potential for contaminated groundwater aquifers due to encroachment and ingression of saltwater from the sea may extend further inland in the near future.

22.3.9   Surge Water Heights and Tidal Inundations

The factors of surge heights and tidal inundations are considered as potential reasons for ingression of saltwaters into the coastal aquifers. Surge water heights and tidal inundations vary from place to place on the basis of coastal topography, intensity of surges, tidal bores, storm waves, and the location of funnel-shaped estuaries along the coast. Occurrences of the surge heights and tidal inundation encroachments are estimated by the researchers (Babu et al., 2015; CGWB, 2014) in coastal Andhra Pradesh. The surge height is relatively higher in Machilipatnam, Ongole, and Kakinada (3.0–5.5 m) than the areas of Kalingapatnam, Vishakhapatnam, and Nellore (2.6–2.8 m). However, the landward encroachment of tidal inundation zones is very high in Godavari, Eluru, Machilipatnam, and Guntur (50–80 km inland) in comparison to the areas of Pulicat, Nellore, Ongole, and Kakinada (10–30 km inland) in the coastal plains (Fig. 22.2i).

The composition of the coastal plain alluviums, paleo channels, beach ridge Cheniers, and marshy wetlands allows and invites the saltwaters to percolate into the aquifers if the groundwater piezometric pressure is depleted in the region of surge and tidewater inundation.

22.4   Assessment of Potential Areas of Groundwater Contamination

The shorelines of coastal Andhra Pradesh are categorized into four different sections for the assessment of potentially contaminated aquifers by encroachment or ingression of saltwater. They are classified on the basis of topographic contrasts and physiographic settings of the coast, for example, (i) northeastern coastal tracts; (ii) Godavari Krishna delta plains; (iii) southeastern coastal plains; and (iv) the Penner Delta and Pulicat Lake Province. A total of ten factors are considered, including the landward extension of the 2014 contaminated coastal aquifers (CGWB, 2014), and weightage are assigned from 0 to 10 for each parameter as per their importance to identify their role in determining the saltwater ingression limit in the coastal tracts (Table 22.1).

Similarly, the future encroachment limit of saltwater into the coastal aquifer is also predicted in this work using the AHP method and the fuzzy membership method. The SRTM Dem (2022) and Landsat 8 (2022) data are used in the assessment of Land Use Land Cover (LULC), drainage characteristics, physiographic settings, slope, and finally rainfall diversity (2021) data, which are integrated to get the current status of the saltwater ingression limit in comparison with the CGWB (2014) report on groundwater contamination with saltwater encroachment into the aquifers of the Andhra Pradesh coastal plains.

Thus, the current status as well as future prediction of the shifting of groundwater contamination zones towards inland with saltwater ingression are estimated in

Table 22.1 An integrated approach of ten parameters with four different coastal sections of Andhra Pradesh using weightage sum method to calculate the integrated score to identify the saltwater contamination potential zones

Parameter	Northeastern coastal tracts (A)	Godavari-Krishna delta plains (B)	Southeastern coastal plain (C)	Penner delta and Pulicat lake (D)	Total Score	Integrated Score
Coastal geology	4	9	7	8	28	7
Coastal geomorphology (slope and elevation)	3	7	5	6	21	5.25
Coastal drainage features	4	9	6	8	27	6.75
Land use and land cover types	5	9	6	6	26	6.5
Variation in rainfall	6	6	4	5	21	5.25
Population and urbanization	6	7.5	6	6.5	26	6.5
Climate change threats	3	9	6.5	7	25.5	6.375
Sea level rise effects	3	4	3.5	3.5	14	3.5
Surge water height and tidal encroachment	2.5	7.5	6.5	6	22.5	5.625
Saltwater ingression (CGWB)	3	9.5	7.5	8	28	7
Total score	39.5	77.5	58	56		
Integrated score	9.875	19.375	14.5	14		

this study, and it will provide additional information to the coastal managers and administrators for implementing sustainable groundwater management (Fig. 22.4a, b). The CGWB (2014) data is used to validate our present work based on geospatial techniques and field surveys in Andhra Pradesh coastal zones from time to time (2003–2018). Result of the Integrated Scores assessed on ten environmental factors for the four physiographic settings of Andhra Pradesh demonstrated very high scores (Rank-I) for the Godavari-Krishna delta plains (19.38); a high to moderate score (Rank-II) for the southeastern coastal plain (14.50) and the Penner delta with Pulicat lake region (14.00); and finally, a low score (Rank-III) for the northeastern coastal tracts (9.88) of the region fringed with the Bay of Bengal (Fig. 22.5a, Table 22.1). Thus, the result shows that there is a strong similarity between such an assessment of potential groundwater contamination zones and the actual impacts of saltwater ingression into the coastal aquifers of the region studied by the Central Ground Water Board during 2011–2014 (CGWB, 2014) in Andhra Pradesh.
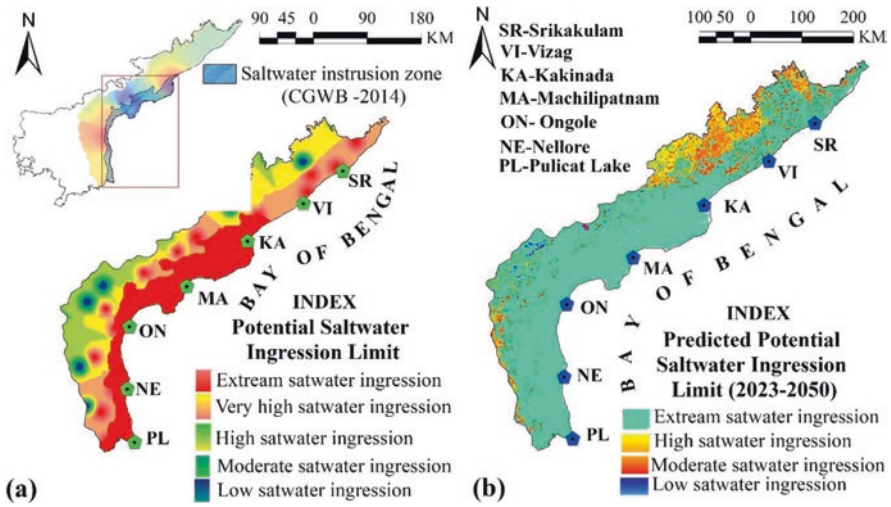
Fig. 22.4 (**a**) The current status (2022) of saltwater intrusion zones in the coastal aquifers estimated with the AHP method and (**b**) The future predictive potential zones of saltwater intrusion investigated using Fuzzy Membership method applied for coastal Andhra Pradesh to find out the landward shifting of the contaminated zones
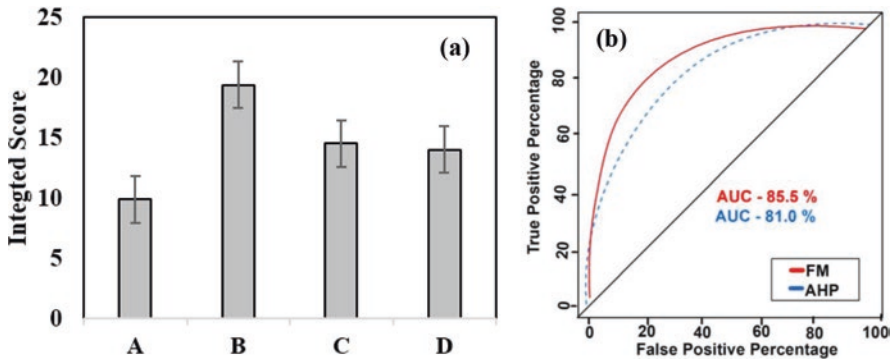

Fig. 22.5 (**a**) The error bars showing the 5% error for the assigned weightage value and their diversity in the four different coastal sections to investigate the potential zones of saltwater intrusion and (**b**) The ROC curves represent the accuracy levels for the validation of AHP and Fuzzy Membership methods in the study

In other ways, the result of the AHP method and fuzzy membership method applied for assessing the current status and future prediction of saltwater contamination zones indicated areas of Kakinada, Machilipatnam, Ongole, Nellore, and Lake Pulicat under the extremely high saltwater encroachment potential of Andhra Pradesh (Fig. 22.4a, b). Inland shifting of potential contaminated zones is reflected in the AHP method of the present study in comparison with the information received from the CGWB (2014) report for the coastal zones of the state. Result of the fuzzy membership method applied for the study shows, on the other hand, that Vishakapatnam, Vizayanagaram, and Srikakulam regions are of very high potential,

and western portions of the Delta Plain are of high to moderate potential for future ingression rates of saltwater into the aquifers. However, a few low patches of potential contamination zones are also demarcated in the western highlands of crystalline rocks and also along the western margins of the Eastern Ghat granulite terrains of Andhra Pradesh in the near future.

Finally, the validation of such a prediction model using the receiver operating characteristic curve (ROC) prepared with pixel-by-pixel calculation shows the accuracy validation for the AUC in the fuzzy membership method as 85.5% and the accuracy validation for the AHP model as 81.0% in the present study (Fig. 22.5b). From the accuracy point of view, the predictive model is highly justified with such a positive relationship between false positive percentage and true positive percentage ratio, and the fuzzy membership method is more significant than the AHP in the model's accuracy.

22.5   Conclusion

The coastal groundwater contamination caused by saltwater ingression is a major environmental issue in Andhra Pradesh along the three coastal sections fringed by the Bay of Bengal. Physiographically, the regional settings for the coastal tracts can be grouped as northeastern tracts of highland coast with rocky and alluvial materials; Godavari-Krishna delta plains backed by highlands with Quaternary alluviums; southeastern tracts of low land coast with the Penner delta and Lake Pulicat region; and elevated ridges of southwestern tracts. The unconsolidated alluviums of the coastal plains and semi-consolidated weathered materials of highland areas are liable to saltwater ingression if the saltwater–freshwater interface is affected by physical, environmental, and human factors. The CGWB estimated the groundwater quality of coastal Andhra Pradesh in 2014 using the data of groundwater monitoring wells and the application of geoinformatics to delineate the landward boundaries of saltwater contaminated aquifers, but spatial variation was not illustrated broadly in this output of information.

The present study highlighted a weighted sum approach in the integration of ten major factors as per importance in the coastal sections of four physiographic settings using SRTM DEM, Landsat 8 satellite data, Google Earth Images, and other aspect data on rainfall, cyclones, sea level rise rates, storm surge penetration distance, tidal encroachments, and CGWB water quality data at the first step. In the second step, the groundwater contamination zones due to saltwater ingression into the aquifers is estimated up to 2022 to explore the current status using satellite data with the AHP method. This study represents the further landward encroachments of the groundwater-contaminated zones in comparison with the CGWB (2014) study based on ground monitoring wells. Affected areas of contaminated potentials are ranked into extreme to very high contaminated zones, high to moderately contaminated zones, and low contaminated zones as per the spatial diversity of saltwater ingression in the physiographic settings of Andhra Pradesh.

Finally, the saltwater ingression into the groundwater aquifers is predicted using the fuzzy logistic approach with a future predictive model. This approach identified the newer sites of groundwater contamination with saltwater ingression in the inner

parts of entire coastal Andhra Pradesh. However, the CGWB (2014) data is used in the study for validation of contaminated sites, and ROC is applied to improve the accuracy of such model studies to identify the groundwater quality sites affected by saltwater ingressions. The data set and methods of study will provide attractive information for sustainable groundwater management in the coastal tracts of Andhra Pradesh.

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