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Effect of Sea Level Changes on the Groundwater Quality along the Coast of Ernakulam District, Kerala

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Abstract: Sea Level Rise (SLR) is considered as one of the effects of climate change that leads to Salt Water Intrusion (SWI) into the coastal areas around the world, thereby contaminating the groundwater and making it unusable for household and irrigation purposes along the coastal areas. Therefore, this paper is an attempt to analyze the change in sea level and shoreline and the consequent changes on the quality of groundwater in lowland and midland areas of Ernakulam district, Kerala. The tidal gauge data were sourced from the Permanent Service for Mean Sea Level (PSML) to assess the changes in sea level during 1971-2007. Remote sensing data was utilized for estimating the shoreline changes along the coast of the district using Digital Shoreline Analysis System (DSAS). The physical and chemical properties of groundwater were sourced for 27 locations from Central Ground Water Board (CGWB). Ionic ratios were computed to assess the salinity levels in the sampling locations. Sodium percentage (Na %) and potential salinity were computed for determining SWI and the suitability of the groundwater usage for domestic and irrigation purpose. Spatial variation of pH, EC, TDS and ionic ratios were assessed in the GIS environment through IDW interpolation. Findings indicate a rising trend in sea level at the rate of 1.8 mm/yr along the coast of the study area. Shoreline accretion and erosion was also observed at different locations along the coast during 2002-2012, though the rate of change varied across the shoreline. In general, water has shown slight alkaline nature, with pH varying from 7.2 to 8.2 at some locations, particularly along the coast. Higher values of EC and TDS were also observed along the coastal aquifer and may be ascribed to SWI. Sodium percentage (Na %) and potential salinity suggest presence of salt water. However, groundwater in majority of the areas especially away from the coast is good for domestic and irrigation uses. This study showed the groundwater quality deterioration, mainly due to the intrusion of sea water, particularly along the coastal areas of the Ernakulam district.

Keywords: Sea Level Rise; Shoreline changes; Salt Water Intrusion; Digital Shoreline Analysis System; Groundwater quality.

Introduction

Global warming has become a confronting issue around the world since last few decades. One of the consequences of global warming is the shriveling up of glaciers and melting of the polar ice sheets. They, together with the thermal expansion of ocean water, are leading to Sea Level Rise (SLR) across the world (IPCC, 2013). It is reported that rate of global mean SLR during the 21st century will exceed the rate observed during 1971-2010 due to accelerated ocean warming and loss of mass from glaciers and ice sheets. The coastal areas, that occupy less than 15 percent of the Earth's land surface (Feng et al., 2015) support about 60 percent of the world's population, are vulnerable to salt water intrusion (SWI) due to SLR. A rise in mean

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sea level in the last few decades with variations in the rate of rise has been reported from around the world (Menendez and Woodworth, 2010; Mudersbach et al., 2013; Weisse et al., 2014; Feng et al., 2015).

Rise in the mean sea level (MSL) is observed by studies in India also (Unnikrishnan et al., 2006; Kumar et al., 2006; Church et al., 2006; Palanisamy et al., 2014; Chowdhury et al., 2015). The estimated SLR at Mumbai, Kochi and Vishakhapatnam stations over a 120-year period found a rise of 0.78, 1.14 and 0.75 mm/year, respectively, whereas Chennai showed a decrease (–0.65 mm/year) in sea level (Unnikrishnan et al., 2006). A higher rise in sea level of 170 mm (2.66 mm/yr) along the coastal area of Cochin during the period 1939-2003 was reported by Kumar et al. (2006). Rise in mean sea level at different locations in the Eastern Indian Ocean was found at the rate varied between 0.5 and 1.5 mm/year (Church et al., 2006). The SLR in the Indian Ocean region, at a rate of 1.5 mm/yr over 60 years, is less than the global mean SLR over the same period (Palanisamy et al., 2014). The tide gauge data showed both rise and fall of sea level. The SLR was detected at few stations, a rise between 1 to 8 mm/year and a fall in sea level by as much as 3 mm/year in certain other tide gauge stations of Indian coast (Chowdhury and Behera, 2015). These studies highlighted the need to understand the increasing/decreasing trend in sea level at different tide gauge records to derive regional sea level variation. Hence, it is imperative to carry out regional studies in order to ascertain regional SLR and the impact of such changes along the coastal areas, especially coastal aquifers.

SLR has several impacts on the coastal areas such as accelerated erosion, extreme marine flooding, or SWI (Nicholls and Tol, 2006; Nicholls et al., 2007; Nicholls and Cazenave, 2010). The regions of SLR witnessed a higher coastal erosion and it also caused the episodic inundations (Cooper et al., 2008). Increasing erosion and changes in the sedimentation would cause disturbance to sandy beaches and dunes (Leatherman et al., 2011). The chemical transformation of the groundwater along the coast occurs due to the interaction with the parent rock initiating geochemical process like ion exchange (Johnson, 1979), contamination by pollutants from various sources (Polemio and Limoni, 2006; Naik et al., 2007; Keesari et al., 2014) or through SWI (Barlow and Reichard, 2010). The former is a natural process and have least human control. On the other hand, SWI can occur even without interference with local systems. Most of the transformations in groundwater chemistry and its isotopic changes occur at the fresh-saline water interface (Wicks and Herman, 1996; Barker et al., 1998; Ivan, 2005). Over the years SWI, especially consequent upon SLR, is a biggest challenge faced by coastal region of India (Prasanna et al., 2010, Singaraja et al., 2014, Senthilkumar et al., 2017). Salinity in aquifers has been reported from a few coastal locations of India (Kumar et al., 2015). These are either due to SLR induced SWI or over exploitation of groundwater (Chachadi, 2005) along the coastal aquifers. The SWI is impacting the groundwater quality and its use for drinking and agricultural operations over the time (Elango et al., 2007; Mondal et al., 2011; Sajil Kumar et al., 2014; Didar-UlIslam et al., 2017; Nair et al., 2015; Singaraja et al., 2014).

Groundwater quality deterioration usually occurs due to initiation of geochemical process like ion exchange and prolonged contact of groundwater with the aquifer material. The mixing of the sea water with the groundwater triggers many chemical reactions such as ion exchange, redox reactions, sorption, dissolution and precipitation (Hem, 1989; Srinivasamoorthy et al., 2008; Prasanna et al., 2010; Chidambaram et al., 2011; Srinivasamoorthy et al., 2014; Cary et al., 2015; Saravanan et al., 2015; Nagaraju et al., 2016). These processes are studied to determine the dominant process in an area and its consequences on groundwater quality which in turn determines its usability. Hence, analyzing the chemical constituents of groundwater is imperative in deciding its suitability for human consumption. It is essential to examine the suitability of groundwater quality on a regular basis because water quality deterioration will influence the human wellbeing (Schoeller, 1977; Hem, 1989; Nickson et al., 2005; Subramani et al., 2005, Garg et al., 2009). It is more important along the low lying coastal locations where the density of the population is very high. A simple measure of SWI into coastal aquifers is the degree of salinity in observation wells. Many studies focus on selected groundwater quality parameters to assess the level of SWI. The physical parameters and ionic ratios of groundwater samples proved to be a preliminary indicator of SWI (Elango et al., 2007; Nair et al., 2015; Singh et al., 2015).

The present study aimed to analyze the changes in sea level to understand the influence of SLR and shoreline changes on groundwater quality in the study area. In this regard, the study has focused on the indicators of groundwater quality in the lowland and the midland area of Ernakulam district, Kerala. It is also aimed to identify the areas of SWI and to understand the suitability of groundwater for domestic and agriculture purpose in the study region. A scientific understanding on the effect of sea level changes in the groundwater quality is essential for proper water resources planning and management.

Study Area

The study has been carried out in the lowland and midland areas of the Ernakulam district of Kerala, India (Figure 1). The study covered an area of about 1894 sq.km which is around 61% of the Ernakulam district. Geomorphologically, the study region falls under the lowland coastal plain with most areas lying less than 20 m altitude in the extreme west and midland in the central part of the district. The lowland region is considered conducive for SWI owing to lower altitude (average elevation of 4 m). This region is at far or lower than sea level along the coast and creeks and experience ingress of tidal water during high tide. The district receives on an average 3450 mm of annual rainfall. South-west monsoon contributes about 67.4% to annual rainfall. The groundwater occurs in the phreatic zone in the coastal sediment. It also occurs in semi confined to confined crystalline rock of midland and tertiary sediment of the coastal belt.

The major hydro-stratigraphy of coastal belt comprises Warkali bed, Vaikom bed, and Laterite and alluvial formation. The Warkali bed, mainly present in the southern part, is of tertiary formation and has aquifer in confined to semi confined state. The Vaikom bed, underlying the Warkali formation separated by Quilon bed, has very coarse sand, gravel, and pebble with clay intercalation (CGWB, 2009). Laterite, mainly found in midland region and also in patches in the sedimentary formation of coastal belt, has highly porous and permeable character. Along the coastal belt the alluvial formation having sand, silt and clay are found with thickness ranging from 1 to 54 m. The coastline length of Ernakulam district is about 46 km. Vypin, located along the northern coast of Ernakulam district, is a barrier island formed between the Arabian Sea and the mainland.

The district has very high density of population of about 1072 persons per sq. km. About 30 percent of the area is urban where about 49 percent of district's population live (Census, 2011). The majority of the households in district have a very high dependency on groundwater (through open wells) for drinking and

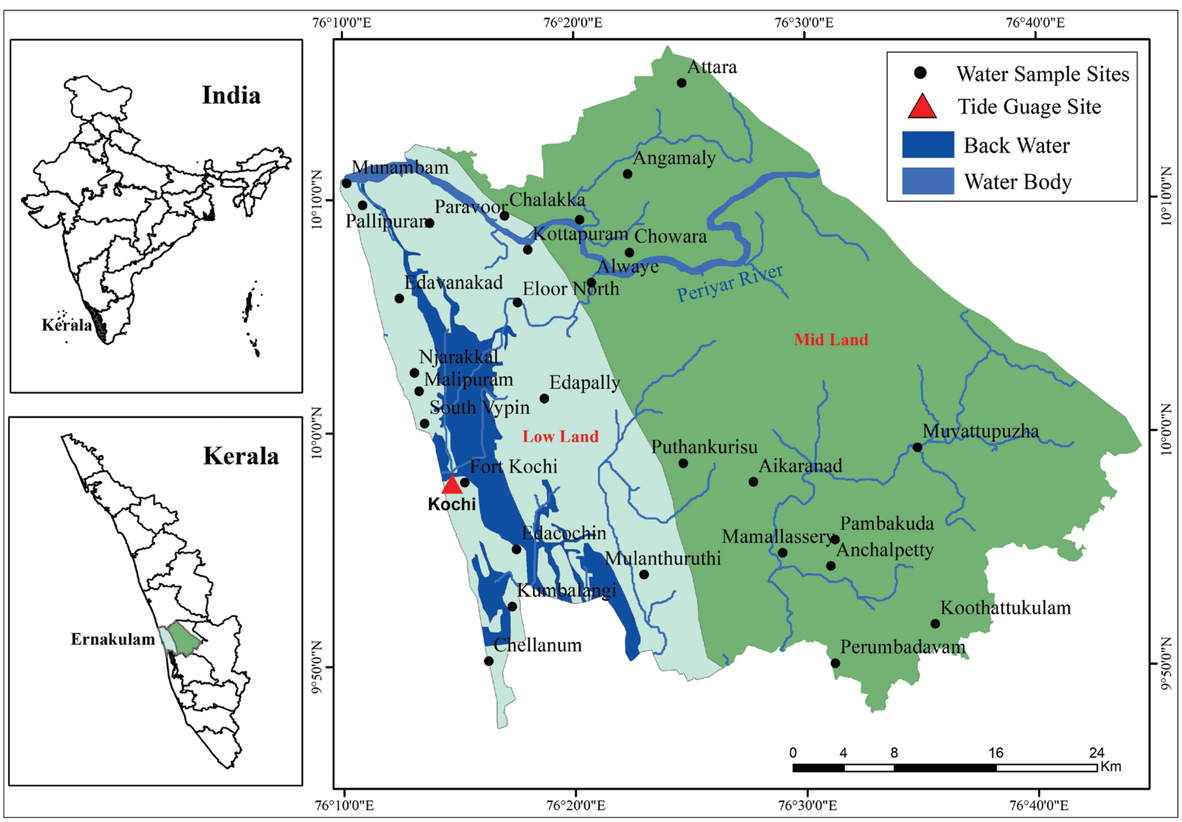

Figure 1: Study area showing coastal and midland areas of the Ernakulam district of Kerala.

other household requirements (Census, 2011). The groundwater quality and hydrochemistry in this district was analyzed and found deteriorated over space and time, especially in and around industrial and coastal locations (Gopinath and Seralthan, 2006; CGWB, 2009; Balakrishna, 2009; Priju et al., 2012). Nonetheless, a detailed investigation of the relationship between shoreline changes and groundwater quality is lacking.

Materials and Methods

In order to study the sea level change, tide gauge data of Kochi (station id 438) for the period 1971-2007 has been collected from the Permanent Service for Mean Sea Level (PSMSL), at the Proudman Oceanographic Laboratory, United Kingdom, which has been widely used for SLR studies (Woodworth and Player, 2003; Church et al., 2004; Kumar et al., 2006). This station is located at Kochi estuary (Figure 1), at the middle portion of the coastline of Eranakulam district. The tide gauge data has been collected at monthly time scale, which is the average of daily observations. The data is reduced to a common datum in order to construct a time series data and avoid negative values in model analysis. The anomalies and trend in mean sea level (MSL) of the study area have been analyzed using standard statistical summaries and ordinary least squares (OLS).

The shoreline changes were analyzed through the PAN and multispectral bands of Landsat 7 satellite images of the dates 18/02/2002 and 14/02/2012. Scanline drop in these images were filled using the algorithm available within ENVI image processing software. The multispectral images having 30 m spatial resolution were sharpened with PAN (15 m resolution). The shoreline of the study area was digitized from the PAN sharpened image. In the present study, the shoreline was demarcated by considering the mean intertidal line. The level of uncertainty due to spatial resolution of satellite images were given due consideration while interpreting the results of the shoreline changes. Changes in shoreline through processes of accretion and erosion was analyzed in GIS environment by measuring differences in the past and present shoreline locations for the coast of Ernakulam district. In order to accomplish this, the Digital Shoreline Analysis System (DSAS), an application developed by USGS, has been used in the study (DSAS version 4.3) (Thieler et al., 2017). This application works within the ArcGIS environment, to assess the spatial changes in shoreline. DSAS has been extensively used in detecting shoreline changes and rate of change (Ford, 2003; Mahapatra et al., 2014). The change in sea level, indicated by the advance or retreat of shoreline, was determined based on transects laid at fixed intervals across the shoreline. Total 719 transects with a spacing of 50 m were used to estimate the shoreline change of the Ernakulam district. The DSAS tool basically estimates the Shoreline Change Envelope (SCE) and End Point Rate (EPR) which were used to derive the shoreline change of the study area. The SCE calculates the distance between the past and recent shoreline for each transect and the EPR is obtained by dividing the SCE by the number of years elapsed between the two shoreline positions. EPR indicates the average rate of change per year. The linear extent with negative SCE or EPR values indicate erosion whereas those with positive values indicate accretion. Correspondingly, they respectively indicate rise and fall in sea level.

In order to study the hydrogeochemistry and groundwater quality, a total of 27 wells locations were considered (Figure 1) and the data of 2010 were compiled from CGWB (2013). The groundwater quality data of the area were obtained from pre-monsoon season because the groundwater is least recharged by rainfall during this season. Salinity is one of the primary factors used to identify the presence of SWI. It is measured either as total dissolved solids (TDS), or as Electrical Conductivity (EC). The ionic ratios—Cl^-/HCO_3^-, Mg/Ca and Na/Cl were also calculated to assess the salinity levels of the groundwater samples. To examine the suitability of water for different uses, sodium percentage (Na %) (Wilcox, 1948) and potential salinity (PS) (Doneen, 1964) were determined. pH, EC, TDS and ionic ratios were spatially interpolated using Inverse Distance Weighted (IDW) method in GIS environment (Naoum and Tsanis, 2004) to understand the spatial variations in groundwater quality. In order to understand the effect of SLR on groundwater quality, the relationship of shoreline change with EC and TDS was assessed in ArcGIS through overlay technique using the combine function. Subsequently correlation coefficient of EPR with EC and TDS was computed in SPSS.

Results and Discussion

Sea Level and Shoreline Changes

The analysis of tide gauge data of Kochi showed rise in sea level along the coast of Ernakulam district of Kerala for the period 1971-2007 (Figure 2). Rise in sea level in the study area has occurred, particularly since 1989 and this rise became more consistent since 2004 as seen in the anomalies (Figure 2).The rate of rise in

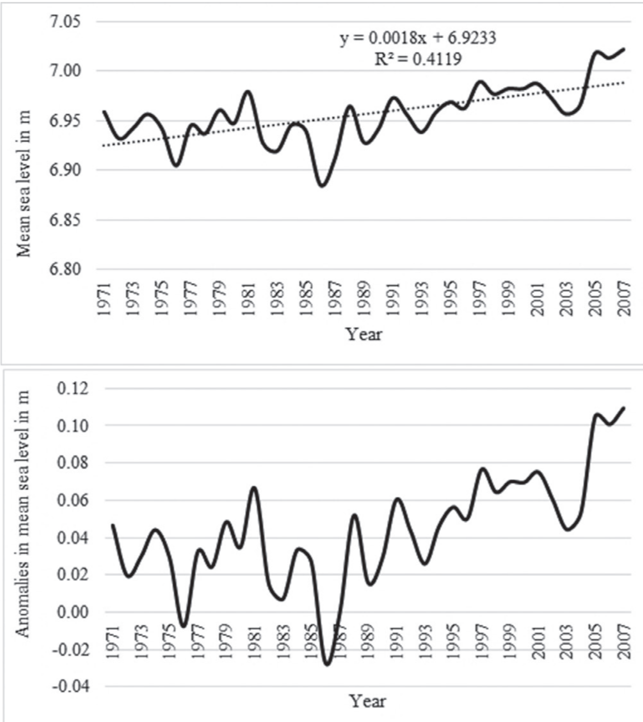

Figure 2: Sea level changes along the coast of the Ernakulam district of Kerala.

the annual sea level was estimated to be 0.0018 m/year (1.8 mm/yr) during the study period, which is lower than the IPCC (2013) estimated global average value probably due to variation in coastal morphology and consequent differences in sea-level. Compared to annual mean sea level data of the period 1936-1970, the annual sea level has shown a marginal rise during the period 1971-2007. Previous studies have reported comparable rise in mean sea level for this location (Unnikrishnan et al., 2006) and at different locations in the Eastern Indian Ocean at the rate that varied between 0.5 and 1.5 mm/year (Church et al., 2006). Obtained mean sea level changes through the trend analysis may be attributed to global warming or vertical land movements near the instrument (Unnikrishnan et al., 2006). Appreciable vertical land movement has not been reported along the southwest coast of India (Kailasam, 1975). Hence, it can be concluded that the observed rise in sea level is due to global warming.

SLR can drive changes in shoreline position, particularly due to the absence of the river system (Muhs et al., 2004). Therefore, changes in the shoreline along the Ernakulam district was also analyzed for the period 2002-2012 using satellite images. Total coastline length of the district is about 46 km and the digitized shoreline in the present study was only 42.75 km excluding the estuary area. The length of artificial shoreline is 5.45 km, which has not been included in the change analysis, that makes 12.74 percent of the total digitized shoreline. The artificial shoreline along the Ernakulam coast was constructed at Vallarpadom Island, skirting the Vembadnad Lake, for development of International Container Transshipment Terminal of the port of Kochi. Results indicate that about 83.1 percent of the shoreline of the study area over a length of 29.9 km with the rate of 1.57 m/year is under erosion and remaining shoreline is under accretion with a rate of 0.9 m/year during the study period 2002-2012. Net change in the shoreline is about 0.67 m/year indicating the predominance of sea level rise in the Ernakulam coast. Area under accretion and erosion was estimated about 0.054 sq.km and 0.47 sq.km respectively.

Changes in the shoreline of the study area were categorized into five broad classes. These are high erosion (≤ 3 m/year), low erosion (≥ 1 to ≤ 3 m/year), stable (− 1 to 1 m/year), low accretion (>1 to < 3 m/year) and high accretion (> 3 m/year). The shoreline of about 0.56% of the study area over a length of 0.2 km (Figures 3 and 4) is under high erosion mostly along the coast of Fort Kochiin Ernakulam district. About 25 km long coastal segment which accounts for 69.68% of the total length is under low erosion category mostly along the Munambam, Edavanakkad, Thamaraparambu and Kannamaly area in the district. Stable coastal length of the study area is 8.3 km i.e., 23.23% of the total length of the study area and mostly found in Cherai, Perumpilly and Cheriakadavu. Low accretion was found along 2.3 km length of the coast which is around 6.4% of the total shoreline, mostly around Njarackal, Kuzhupilly and Sandipilly. High accretion is very marginal and distributed near South Vypin (Figure 1) in the study area. Net shoreline movement in the study area under accretion and erosion was estimated to be 9.2 m and 15.6 m respectively during the period of study. Coastal vulnerability index (CVI) assessment of India was carried out by the Indian National Centre for Ocean

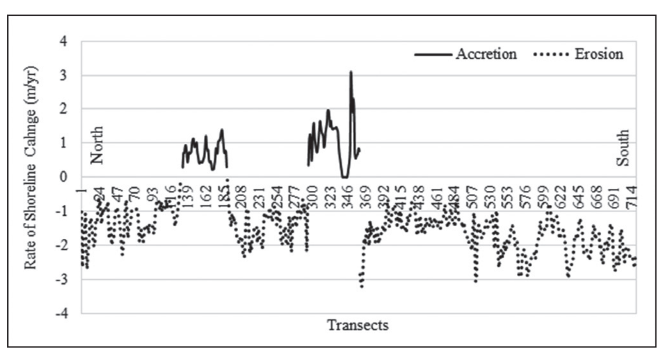

Figure 3: Erosion and accretion in the shoreline of the Ernakulam district of Kerala.

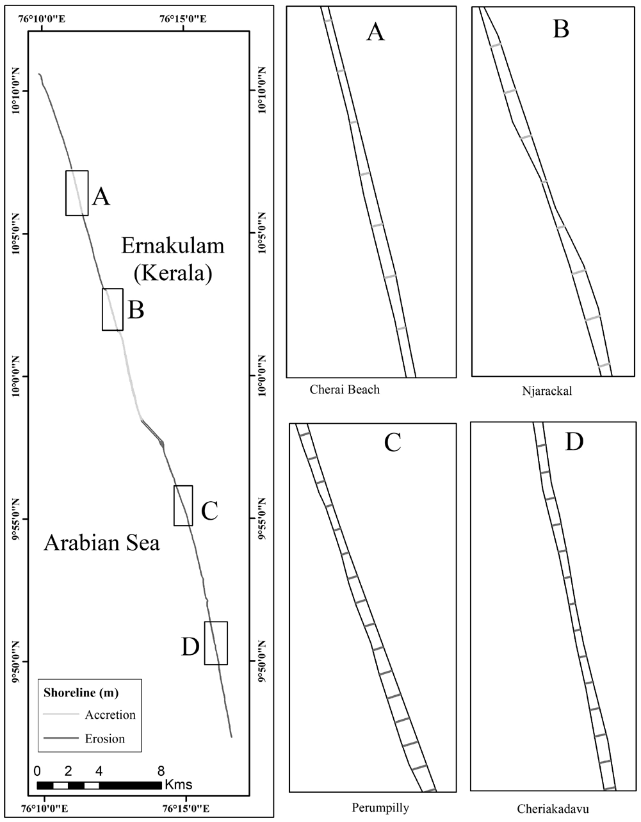

Figure 4: Spatial pattern of erosion and accretion in the shoreline of the Ernakulam district of Kerala.

Information Services (INCOIS, 2012). It expressed relative vulnerability of the coast to physical changes because of future SLR. As per the report, the shoreline change along the Kerala coast on an average experienced a maximum erosion of 6 m/y and accretion of 8 m/y (INCOIS, 2012). The difference in the rate of shoreline change between the report and present study is due to difference in time period, spatial extent of the study, criteria for shoreline demarcation and spatial resolution of the remote sensing data. A shoreline change atlas of Indian coast was prepared by Space Application Centre ISRO (SAC ISRO 2014). As per the report, about 50% (294 km) and 37% (218 km) of the total Kerala coast is observed to get accreted and eroded respectively while 13% (73.6 km) is more or less stable in nature (SAC ISRO, 2014). The total accreted and eroded area along the coast of Kerala is estimated around 9.54 sq.km and 5.31 sq.km respectively. Large area of the shoreline is under erosion indicating the influence of SLR. Changes in shoreline can make the area vulnerable to SWI that deteriorate the aquifer quality (Nicholls and Tol, 2006; Nicholls et al., 2007; Nicholls and Cazenave, 2010).

Groundwater Quality Assessment

The study assessed whether the SLR has an effect on coastal aquifer systems through an assessment of physical parameters of water quality, namely EC, TDS and pH for understanding the level of salinity in the groundwater of the study area. These parameters also change in concentrations with other environmental conditions (Himida, 1981; Olson, 2012; Oyem et al., 2014; Kura et al., 2014). The EC value of the groundwater in the study area ranging from 26 to 3080 µs/cm (Figure 5). The lowest value of EC was found at Aikranad located in the southern midland area of the district and highest value was observed at Chellanum which is located in south of Kochi (Figure 5). The EC level of water can be classified into three categories (Sarath Prasanth et al., 2012) as type I – low salts, if EC is less than 1,500 µmhos/cm; type II – medium salts, if EC is between 1500 and 3000 µmhos/cm; and type III-high salt, if EC is more than 3000 µmhos/cm. As per the above EC classification, 92 percent of the total groundwater samples of the study area, come under the type I and remaining samples at Eloor North and Chellanum come under type II and III indicating medium and high enrichment of salts respectively. CGWB (2009) also reported high levels of EC during different assessment periods indicating high ionic concentration. A high value of EC at Eloor North was attributed to the leaching of industrial effluents or backwater intrusion (Umadevi et al., 2010). The high value of EC at Chellanum, a coastal location, can be attributed to SWI (Priju et al., 2012; Sajil Kumar et al., 2014) because higher the EC means more solute salts and ions are present in the water, the source of which can only be sea at this location. Southeast part of the district (Puthankurisu, Aikaranad, Pambakuda, Anchalpetty, Koothattukulam etc.) has shown low level of EC, indicating the better quality of groundwater.

As per Bureau of Indian Standards (BIS, 2012) standard, 90 percent of the groundwater sample in the study area is useful for domestic and irrigation purpose. Only less than eight percent of the samples, with conductivity ranges between 750 and 2250 µs/cm, is usable for irrigation but requires good management and well-developed drainage condition.

Total dissolved solids (TDS) is considered as another indicator of the amount of contaminant present in the groundwater which is directly proportional to EC. The value of TDS decides the portability of groundwater for domestic use. Heath (1983) uses five categories of TDS as type I (0-1000 mg/l-fresh water), type II (1000-3000 mg/l-slightly saline), type III (3000-10000 mg/l-moderately saline), type IV (10000-35000 mg/l-very saline) and type V (more than 35000 mg/l-briny). As per the above classification of TDS, 78 percent of the samples lie in type I mostly in midland and eastern part of lowlands and remaining samples come under the type II (Chellanum, Edacochin, Eloor North, Njarakkal, Pallipuram and Paravoor) suggesting slightly saline groundwater (Figure 6). Value of TDS in the groundwater samples of the district, varying between 17.4 and 2063 mg/l, indicates the acceptable as well as unacceptable limits of groundwater usage (Figure 6). TDS data for Eloor North has a relatively high TDS which is also reported by Umadevi et al. (2010) who attributed it to leaching of industrial waste. Similarly, Chellanum has an exceptionally high TDS and not good either for the domestic use or for irrigation. The highest value of TDS around Chellanum village which has also shown the high value of the EC, is possibly due to SWI because it is located on the coast and highly vulnerable to SWI. Priju et al. (2014) also observed higher value of TDS at Chellanum and Vypin coasts and attributed this to SWI. Besides these two locations, Pallipuram (1254 mg/l), Paravoor (1548 mg/l), Njarakkal (1658 mg/l) and Edacochin (1450 mg/l), which are located in the lowland area of the district away from the coast, have also shown higher TDS. As per the BIS (2012), acceptable limit of the TDS for drinking purpose is less than 500 mg/l and permissible up to 2000 mg/l in absence of alternate source. TDS between 500 and 2000 mg/l is poor for drinking use and unacceptable if it is greater than 2000 mg/l. Around 94 percent of the sample locations in the study area have values that fall within the acceptable limits and can be used for both domestic and irrigation purposes.

pH of the groundwater in the study area ranges from 6.8 to 8.7 with an average value of 7.8 (Figure 7). Among 27 samples, about 44 percent of the samples (Edacochin, Edapally, Edavanakad, Eloor, Kumbalangi, Malipuram, Munambam, Muvattupuzha, Njarakkal, Pallipuram, Paravoor and Perumbadavam) along the coastal areas have shown alkalinity indicating the influence of salt water in some of these locations. Two locations (Edavanakad 8.62 and Pallipuram 8.7), near the coastal area have shown highest alkalinity in the groundwater may be due to SWI. The high value of pH in the coastal area of the Ernakulam district was also observed in a previous study (Priju et al., 2014). The high value of pH at Eloor North was attributed to the presence of chemical industries in the area (Umadevi et al., 2010). Many locations (Alwaye, Anchalpetty, Angamaly, Chalaka, Chellanum, Chengamanad, Chowara, Koothattukulam, Kattapuam, Mulanthuruthi and Pambakuda) have pH values within the permissible limit and it can be used for domestic and irrigation purpose as per BIS (2012) guideline. These locations are away from the coast, indicating less effect of the sea water on the groundwater quality. The problem of salinization of coastal aquifers has been reported from Ernakulam district in Kerala (CGWB, 2007).

Groundwater quality assessment has shown that some parts of the coastal region of Ernakulam district are under the influence of SWI. It is imperative to study the ionic ratio to identify the seawater intruded region. Mixing of seawater with coastal groundwater led to the development of the distinct groundwater quality system. Seawater is enriched with sodium and chloride compared to clean groundwater. When these two water systems come together and mix with each other, there starts an ion exchange process. The groundwater salinization can be detected using Cl^-/HCO_3^- ratio (Revelle, 1941). If the value of this ratio is greater than 1, it indicates region is affected by SWI and if it is less than1, it suggests region is unaffected by SWI (Sajil Kumar et al., 2014). According to Simpson (1946), if Cl^-/HCO_3^- ratio is greater than 2.8 then it is highly contaminated groundwater. Likewise, if the values of the Mg/Ca ratio are greater than 1, it indicates SWI and vice versa (Sajil Kumar et al., 2014). In contrast, if Na/Cl ratio is greater than 1, the ground water is fresh and low Na/Cl ratio (< 0.8) indicates salinization of groundwater resource which is mainly happening when fresh water mixes with brackish water or saline water.

In the present study, Cl^-/HCO_3^- of the groundwater varied between 0.07 and 30.97 with an average of 2.55 (Figure 8). About 4 percent of the total samples have Cl^-/HCO_3^- more than 1 suggesting salinity in water. Cl^-/HCO_3^- of six samples (Anchalpetty, Angamaly, Chellanum, Chengamanad, Eloor North and Mamallassery) out of 27 has a value greater than 1 suggesting an elevated Cl concentration over HCO_3 (Sajil Kumar et al., 2014) (Figure 8). These are located proximal to the sea (e.g. Chellanum, Edavanakad etc.) indicating the intrusion of sea water into groundwater. On the other hand, some locations have high Cl^-/HCO_3^- due to salinization by industrial waste or agrochemical waste e.g. Eloor North is located in close proximity to Periyar River, the reach of it is under the influence of tidal action. At this location effect can also be due to SWI along the Periyar River during the high tide periods. Chowara, Alwaye, Muvattupuzha and Perumbadavam have low Cl^-/HCO_3^- ratio showing the occurrences of good groundwater quality. These are

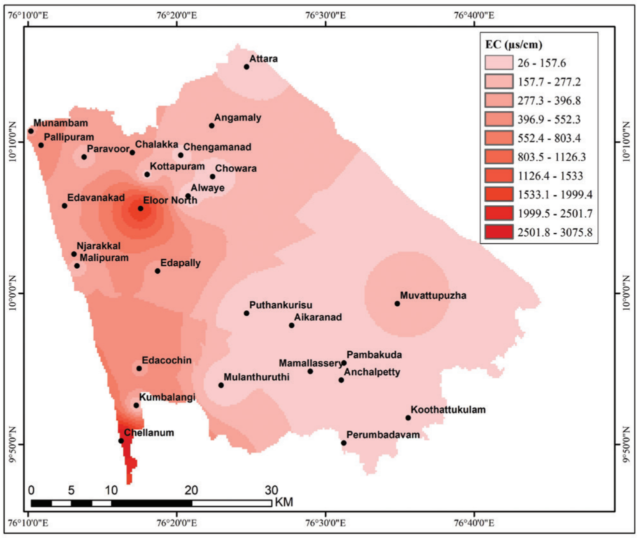

Figure 5: Distribution of EC in the Ernakulam district of Kerala.

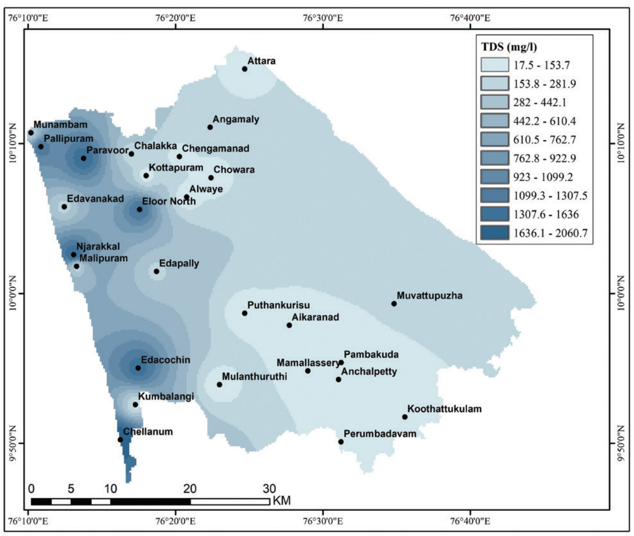

Figure 6: Distribution of TDS in the Ernakulam district of Kerala.

located in the Midland area of the district and are not under the influence of sea water.

Mg/Ca ratio of groundwater in the district varied from 0.04 to 1.39 with an average of 0.38. In the study area, 96 percent of the samples have Mg/Ca ratio less than 1 suggesting the presence of better groundwater quality. However, the Mg/Ca ratio of one sample (Eloor North) has a value greater than 1 demonstrating the presence of salinity in the groundwater (Figure 9) due to tidal effect since the area is located near to the mouth of Periyar River which is under the tidal influence. The seawater has a higher Mg concentration than Ca and those wells influenced by seawater intrusion will have

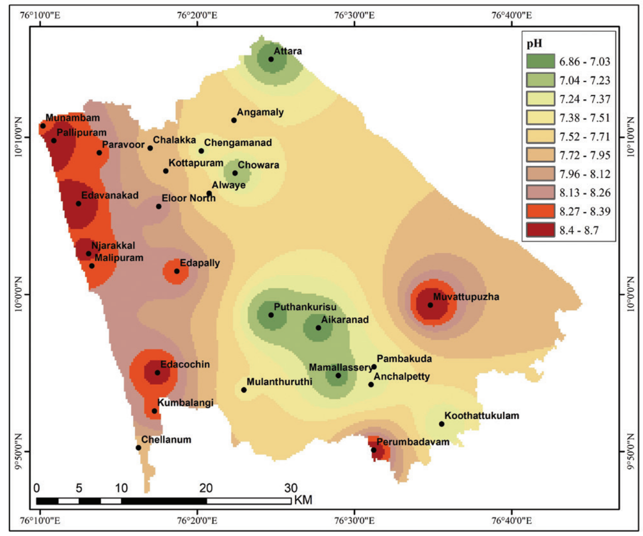

Figure 7: Distribution of pH in the Ernakulam district of Kerala.

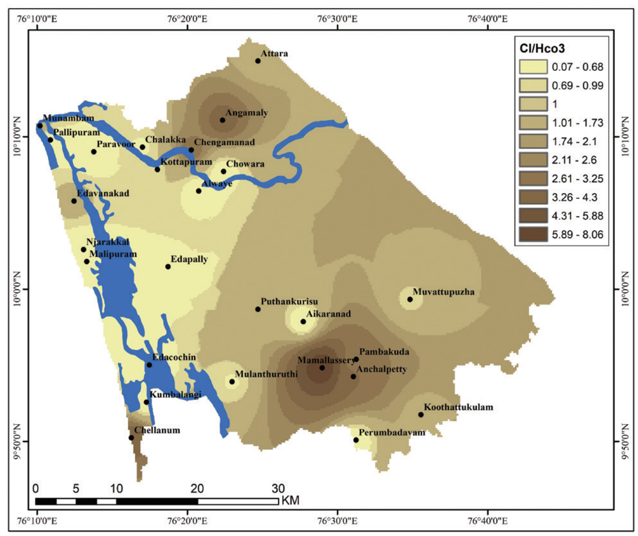

Figure 8: Distribution of Cl/HCO_3 in the Ernakulam district of Kerala.

Mg/Ca ratio greater than 1 (Sajil Kumar et al., 2014). The lower reaches of the Periyar River are affected by sea-water ingression during the non-monsoon season (Maya et al., 2010). Tidal constituents near the sea and nearby shallow water were reported by Srinivas et al. (2013) and Arjun et al. (2015). The high value of Mg/Ca at Eloor North is partially due to induced salinization by industrial and agrochemical waste. Southern areas in the midland of the district have shown low value of Mg/Ca.

Na/Cl ratio in the study area varied between 0.01 and 2.4 with an average of 0.92 (Figure 10). As per the Na/Cl ratio, 96 percent of samples indicate the salinity in the groundwater. Alwaye Chalakka, Chowara, Edavanakad, Kumbalangi, Paravoor and Puthankurisu have Na/Cl greater than 1 suggesting the better quality of groundwater. Most of the locations (Njarakkal, Malipuam, Edacochin, Chellanum, Munambam and Pallipuram) in the lowland area near the coast have shown value of Na/Cl less than 1 indicating SWI has taken place into the aquifer. The highest value of Na/Cl was found around Chowara in the midland area of the district suggesting the availability of fresh groundwater.

The present study has shown that groundwater quality in the Ernakulam district has deteriorated, particularly along the coastal areas due to salt water intrusion. In order to assess the effect of SLR on groundwater quality in the study area, relation of shoreline change by considering EPR (indicates the rate of change in shoreline) with EC and TDS was computed using

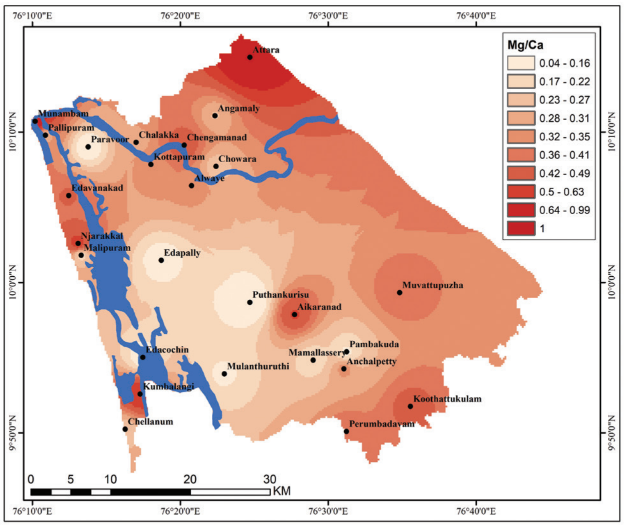

Figure 9: Distribution of Mg/Ca ratio in the Ernakulam district of Kerala.

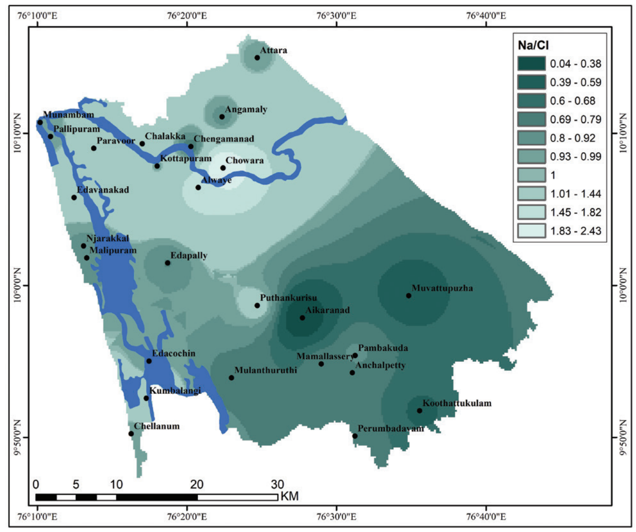

Figure 10: Distribution of Na/Cl ratio in the Ernakulam district of Kerala.

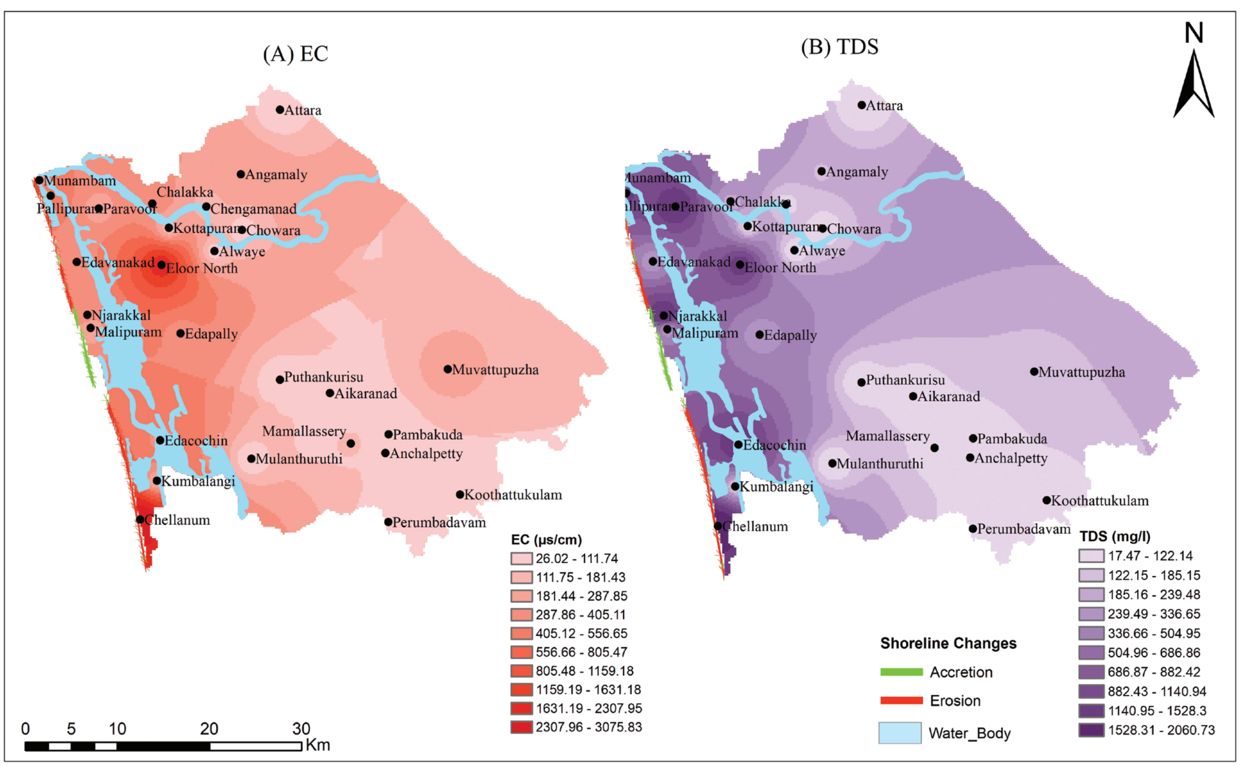

Figure 11: Spatial relation of shoreline change with EC (a) and TDS (b) of the study area.

overlay technique in GIS environment as well as using Pearson correlation coefficient. Overlay analysis showed that the erosion prone coasts, an indication of SLR, have high EC and TDS values (Figure 11). Similar to this, the correlation analysis also showed significant negative relationship of shoreline changes i.e. EPR with EC and TDS (Table 1), suggesting that the eroded shoreline (area of SLR) has high values of EC and TDS. It means SLR is adversely impacting the groundwater quality along the coast of the Ernakulam district through SWI. Many studies have pointed out the effect of SWI on groundwater quality at different coastal areas (Elango et al., 2007; Mondal et al., 2011; Sajil Kumar et al., 2014; Didar-Ul Islam et al., 2017; Nair et al., 2015; Singaraja et al., 2014). Deteriorated groundwater quality can be attributed to SWI, leaching of industrial or domestic waste and overexploitation of groundwater due to urbanization (Umadevi et al., 2010; Priju et al., 2014; Sajil Kumar et al., 2014). However, there is need to understand the dominant processes as well as spatial cause-effect relationship of the above factors in detail for proper planning and management of coastal aquifer systems.

Table 1: Correlation coefficient of shoreline change with EC and TDS of the study area

Groundwater parameters	*Shoreline changes EPR (m/yr)*
EC (µm)	-.299*
TDS (mg/l)	-.247*

* Correlation is significant at the 0.05 level (2-tailed).

Suitability of Groundwater Usage for Domestic and Irrigation Purpose

The study has indicated the effect of sea level changes in the groundwater quality of the study area. Hence, it is essential to check how far this sea level change has influenced the suitability of groundwater, particularly for domestic purpose. Groundwater is the main source of water for domestic use in the area. Suitability of the groundwater usage in the study area was assessed by two parameters, namely sodium percentage (Na%) and potential salinity. The Na percentage of the groundwater samples of the study area range from 8.45 to 82.76 with an average of 43.78 (Figure 12). About 48 percent of the sample falls in permissible category and 33 percent of the samples fall into good and excellent category. About 15 percent of the samples had Na% between 60 and 80 (Chellanum, Edapally, Malipuram and Mulanthuruthi) suggesting doubtful category. Out of total samples, 3.7 percent have shown Na percent above 80 namely Chalakka indicating unsuitability of the groundwater use for irrigation. Excess of Na percentage in water leads to sodium hazard and makes water unsuitable for irrigation. The remaining areas in the midland have Na percentage varied between 20 and 60 indicating that majority areas have good quality of water. The presence of soluble salts proportionally increases the salinity of soil media. On the other hand, the insoluble or low soluble salt precipitate on the soil. Potential salinity indicates the chloride concentration plus half of the sulfate concentration (Ogunfowokan et al., 2013). In the present study, the potential salinity of the groundwater varied between 0.62 and 22 with an average concentration of 2.5 (Figure 13). High

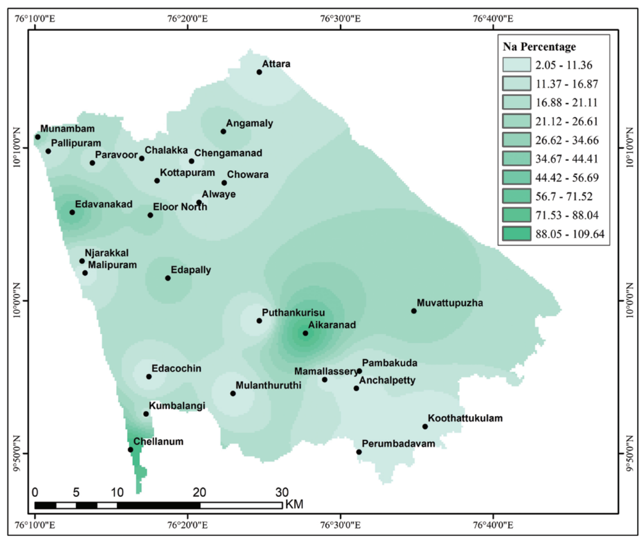

Figure 12: Distribution of Na percentage in the Ernakulam district of Kerala.

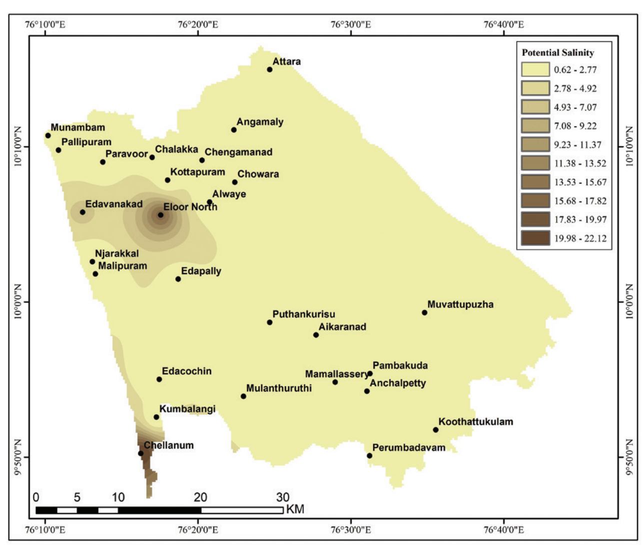

Figure 13: Distribution of PS in the Ernakulam district of Kerala.

potential salinity was found in and around Eloor North and Chellanum. The high value of potential salinity at former place may be attributed to the presence of agrochemical and industrial waste (Umadevi et al., 2010) while at the latter, it may be because of the intrusion of sea water (Priju et al., 2014).

Conclusions

The present study analyzed the SLR and its effect on groundwater quality in the lowland and midland areas of Ernakulam district in Kerala. It infers a rise in mean sea level in the study area particularly after 1993 though the magnitude of change is marginal. The observed rise in sea level has been more consistent since 2004. The rate of rise in the sea level was estimated to be about 1.8 mm/year during the study period.

SLR has driven changes in shoreline position in an area. Results indicate that about 83.1 percent of the shoreline of the study area over a length of 29.9 km with the rate of 1.57 m/year is under erosion and remaining shoreline is under accretion with a rate of 0.9 m/year during the study period 2002-2012, suggesting a large area under erosion which is also an indication of SLR. The shoreline of about 0.5% and 69.68% of the study area is respectively under high and low erosion in the district. Stable coastal length of the study area is about 23.23% of the total length while low accretion was estimated about 6.4% of the total shoreline. High accretion is very marginally distributed near South Vypin in the study area.

Shoreline changes influenced the groundwater quality through SWI. It was studied by assessing the physical parameters of the groundwater in the district. The lowest and highest values of EC were found in Aikranad and Chellanum respectively. The high value of EC along the coast of Ernakulam district is an indicator of SWI during the study period. About 90 percent of the groundwater samples in the study area have EC within permissible limits and are useful for domestic and irrigation purpose. Moreover, the highest value of TDS was also observed around the Chellanum village (located along the coast) which is a sign of SWI in the area. Around 96 percent of the TDS value at many locations in the midland falls within the permissible limits. The effect of SLR on groundwater quality is also shown in the spatial analysis as well as the correlation analysis. Both showed that SLR has been adversely affecting the EC and TDS along the coastal stretch of Ernakulam. Similarly the pH values were also high, indicating alkalinity of the groundwater and the influence of SWI. Cl^-/HCO_3^-, Mg/Ca and Na/Cl ratios along the coast of the district have also shown signs of SWI. Cl^-/HCO_3^-, Mg/Ca and Na/Cl at Eloor North is a matter of concern as the water is very saline in the area and not suitable for domestic use. This may be attributed to industrial waste or agrochemical waste and its proximity of Periyar River that brings sea water during the high tide periods.

The sixty percent of the samples have shown that the Na percentage falls in permissible category and the remaining samples fall into good and excellent category. Few locations have shown Na percent above 80 indicating unsuitability of the groundwater use. Highest potential salinity was found in Eloor North and Chellanum. All the indicators of groundwater quality point towards SWI along the coast of Chellanum. The observed value of Na percentage and potential salinity indicates that groundwater sample data from most of the locations in the midland areas is suitable for domestic and irrigation purposes. However, groundwater quality along the coastal areas has deteriorated due to SWI which is the major driver of salinity in the coastal region. It requires immediate attention of the planners. This research work will be useful to monitor the groundwater quality on a regular basis and identifies the vulnerable regions along the coastal stretch of Ernakulam.

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References

Arjun, S.L., Nair, S., Shamji, V.R. and Kurian, N.P., 2010. Tidal Constituents in the Shallow Waters of the Southwest Indian Coast. *Marine Geodesy*, **33(2-3):** 206-217.

Balakrishnan, P., 2009. Hydrogeological and Hydrochemical Studies of the Periyar River Basin, Central Kerala. (Unpublished Ph.D.) Department of Marine Geology and Geophysics, Cochin University of Science and Technology, Kochi (India). Retrieved from https://www.researchgate.net/profile/Arvind_Singh56/.../Dyuthi-T0508.pdf.

Barker, A.P., Newton, R.J., Bottrell, S.H. and Tellam, J.H., 1998. Processes affecting groundwater chemistry in a zone of saline intrusion into an urban sandstone aquifer. *Applied Geochemistry*, **13:** 735-749.

Barlow, P.M. and Reichard, E.G., 2010. Saltwater intrusion in coastal regions of North America. *Hydrogeology Journal*, **18(1):** 247-260. https://doi.org/10.1007/s10040-009-0514-3.

BIS (Bureau of Indian Standards) (2012). Drinking Water Specification (Second Revision), IS: 10500: 21012. Bureau of Indian Standards, New Delhi.

Cary, L., Petelet-Giraud, E., Bertrand, G., Kloppmann, W., Aquilina, L., Martins, V., Hirata, R., Montenegro, S., Pauwels, H., Chatton, E., Franzen, M., Aurouet, A., the team, 2015. Origins and processes of groundwater salinization in the urban coastal aquifers of Recife (Pernambuco, Brazil): A multi-isotope approach. *Science of the Total Environment*, **530-531:** 411-429.

Census of India, 2011. Provisional Population Totals Paper 1 of 2011: Kerala. Retrieved from https://kerala.gov.in/census2011. Accessed on 20, May, 2015.

Central Ground Water Board (CGWB), 2007. Hydro Geological Conditions of Kerala. Ministry of Water Resources, Govt. of India, New Delhi. Retrieved from http://cgwb.gov.in/KR/

Central Ground Water Board (CGWB), 2009. Report: Ground water information booklet of Ernakulam district, Kerala state, India. Ministry of Water Resources, Govt. of India, New Delhi.

Central Ground Water Board (CGWB), 2013. Dynamic ground water resources of India. Ministry of Water Resources, Govt. of India, New Delhi.

Chachadi, A.G., 2005. Seawater intrusion mapping using modified GALDIT indicator model – Case study in Goa. *Jalvigyan Sameeksha*, **20:** 29-45.

Chidambaram, S. and Karmegam, U., 2011. Significance of saturation index of certain clay minerals in shallow coastal groundwater, in and around Kalpakkam, Tamil Nadu, India. *Journal of Earth System Science*, **120(5):** 897-909.

Chowdhury, P. and Behera, M.R., 2015. A study on regional sea level variation along the Indian coast. *Procedia Engineering*, **116:** 1078-1084. https://doi.org/10.1016/j.proeng.2015.08.348.

Church, J.A., White, N.J. and Hunter, J.R., 2006. Sea-level rise at tropical Pacific and Indian Ocean islands. *Global and Planetary Change*, **53:** 155-168.

Church, J.A., White, N.J., Coleman, R., Lambeck, K. and Mitrovica, J.X., 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *Journal of Climate*, **17:** 2609-2625.

Cooper, M.J.P., Beevers, M.D. and Oppenheimer, M., 2008. The potential impacts of sea level rise on the coastal region of New Jersey, USA. *Climatic Change*, **90:** 475. https://doi.org/10.1007/s10584-008-9422-0.

Didar-Ul Islam, S.M., Bhuiyan, M.A.H., Rume, T. and Azam, G., 2017. Hydrogeochemical investigation of groundwater in shallow coastal aquifer of Khulna District, Bangladesh. *Applied Water Science*, **7(8):** 4219-4236.

Doneen, L.D., 1964. Notes on water quality in Agriculture Published as a Water Science and Engineering Paper 4001, Department of Water Science and Engineering, University of California.

Elango, L. and Kannan, R., 2007. Rock–water interaction and its control on chemical composition of groundwater. *In:* Dibyendu Sarkar, Rupali Datta and Robyn Hannigan (eds). Concepts and Applications in Environmental Geochemistry. Developments in Environmental Science (Vol. 5). Amsterdam: Elsevier.

Feng, J., von Storch, H., Jiang, W. and Weisse, R., 2015. Assessing changes in extreme sea levels along the coast of China. *Journal of Geophysical Research: Oceans*, **120:** 8039-8051. doi:10.1002/2015JC011336.

Ford Murray, 2003. Shoreline changes interpreted from multi-temporal aerial photographs and high resolution satellite images: Wotje Atoll, Marshall Islands. *Remote Sensing of Environment*, **135:** 130-140.

Garg, V.K., Suthar, S., Singh, S., Sheoran, A., Meenakshi, G. and Jai, S., 2009. Drinking water quality in villages of southwestern Haryana, India: Assessing human health risks associated with hydrochemistry. *Environmental Geology*, **58(6):** 1329-1340.

Gopinath, G. and Seralthan, P., 2006. Chemistry of groundwater in the lateritic formation of Muvatterpuzha river basin, Kerala. *Journal of the Geological Society India*. **68:** 705-714.

Heath, R.C., 1983. Basic ground-water hydrology: U.S. Geological Survey Water Supply Paper 2220.

Hem, J.D., 1989. Study and Interpretation of Chemical Characteristics of Natural Waters. 3rd Edition, US Geological Survey Water Supply Paper 2254.

Himida, I.H., 1981. Groundwater in Kuwait and the Environmental Factors Affecting its Quality. *Studies in Environmental Science*, **17:** 121-124.

INCOIS, 2012. Coastal Vulnerability Atlas of India. Indian National Centre for Ocean Information Services (INCOIS). Hyderabad. Retrieved from http://www.incois.gov.in/portal/cvi/index.html.

IPCC, 2013. Climate Change 2013: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

IPCC, 2013. Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK.

Johnson, C.C., 1979. Land application of water—An accident waiting to happen. *Ground Water*, **17(1):** 69-72.

Johnson, Michael S. and Musterman, John L., 1979. Removal of sulfate by ion exchange. *Journal of American Water Works Assoc.*, **71(6):** 343-348.

Kailasam, L.N., 1975. Epeirogenic studies in India with reference to recent vertical movements. *Tectonophysics*, **29:** 505-521.

Keesari, T., Kulkarni, U.P., Jaryal, A., Mendhekar, G.N., Deshmukh, K.N., Hegde, A.G. and Kamble, S.N., 2014. Groundwater dynamics of a saline impacted coastal aquifer of western Maharashtra, India: Insights from a radiotracer study. *Journal of Radioanalytical and Nuclear Chemistry*, **300(1):** 1-6. https://doi.org/10.1007/s10967-014-2940-5.

Kumar, K.A., Priju, C.P. and Prasad, N.N., 2015. Study on saline water intrusion into the shallow coastal aquifers of Periyar River Basin, Kerala using hydro chemical and electrical resistivity methods. *Aquatic Procedia*, **4:** 32-40.

Kumar, P.K.D., 2006. Potential Vulnerability Implications of Sea Level Rise for the Coastal Zones of Cochin, Southwest Coast of India. *Environment Monitoring and Assessment*, **123:** 333-344. https://doi.org/10.1007/s10661-006-9200-2.

Kura, N.U., Ramli, M.F., Ibrahim, S., Sulaiman, W.N.A., Zaudi, M.A. and Aris, A.Z. (2014). A Preliminary appraisal of the effect of pumping on seawater intrusion and upconing in a small tropical island using 2D resistivity technique. *The Scientific World Journal*, 796-425. http://doi.org/10.1155/2014/796425.

Leatherman, Stephen P., Zhang, Keqi Douglas and Bruce, C., 2011. Sea level rise shown to drive coastal erosion. *Transactions American Geophysical Union*, **81(6):** 55-57.

Mahapatra, M., Ratheesh, R. and Rajawat, A.S., 2014. Shoreline Change Analysis along the Coast of South Gujarat, India, Using Digital Shoreline Analysis System. *Journal of the Indian Society of Remote Sensing*, **42(4):** 869-876.

Maya, K., Babu, K.N., Padmalal, D. and Seralathan, P., 2010. Hydrochemistry and dissolved nutrient flux of two small catchment rivers, south-western India. *Chemistry and Ecology*, **23(1):** 13-27.

Menendez, M. and Woodworth, P.L., 2010. Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research*, **115:** C10011, doi: 10.1029/2009JC005997.

Mondal, N.C., Singh, V.P. and Singh, V.S., 2011. Hydrochemical characteristic of coastal aquifer from Tuticorin, Tamil Nadu, India. *Environmental Monitoring and Assessment*, **175(1-4):** 531-550.

Mudersbach, C., Wahl, T., Haigh, I.D. and Jensen, J., 2013. Trends in high sea levels of German North Sea gauges compared to regional mean sea level changes. *Continental Shelf Research*, **65:** 111-120, doi: 10.1016/j.csr.2013.06.016.

Muhs, D.R., Wehmiller, J.F., Simmons, K.R. and York, L.L., 2004. Quaternary sea level history of the United States. *Developments in Quaternary Science*, **1:** 147-183.

Nagaraju, A., Muralidhar, P. and Sreedhar, Y., 2016. Hydrogeochemistry and Groundwater Quality Assessment of Rapur Area, Andhra Pradesh, South India. *Journal of Geoscience and Environment Protection*, **4(4):** 88-99.

Naik, P.K., Dehury, B.N. and Tiwari, A.N., 2007. Groundwater Pollution around an Industrial Area in the Coastal Stretch of Maharashtra State, India. *Environment Monitoring and Assessment*, **132(1-3):** 207-233. https://doi.org/10.1007/s10661-006-9529-6.

Nair, I.S., Rajaveni, S.P., Schneider, M. and Elango, L., 2015. Geochemical and isotopic signatures for the identification of seawater intrusion in an alluvial aquifer. *Journal of Earth System Science*, **124(6):** 1281-1291. https://doi.org/10.1007/s12040-015-0600-y.

Naoum, S. and Tsanis, I.K., 2004. A Multiple Linear Regression GIS Module Using Spatial Variables to Model Orographic Rainfall. *Journal of Hydroinformatics*, **6:** 39-56.

Nicholls, R.J. and Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, **328(5985):** 1517-1520. doi:10.1126/science.1185782.

Nicholls, R.J. and Tol, R.S.J., 2006. Impacts and responses to sea-level rise: A global analysis of the SRES scenarios over the twenty-first century, Philos. Philosophical Transactions of the Royal Society A. *Mathematical, Physical and Engineering Sciences*, **364(1841):** 1073-1095. doi:10.1098/rsta-2006.1754.

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S. and Woodroffe, C.D., 2007. Coastal systems and low-lying areas, in Climate Change 2007: Impacts, Adaptation and Vulnerability. Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds). Cambridge University Press, Cambridge, UK.

Nickson, R.T., McArthur, J.M., Shresthn, B., Kyaw-Nyint, T.O. and Lowry, D., 2005. Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan. *Applied Geochemistry*, **20(1):** 55-66.

Ogunfowokan, A.O., Obisanya, J.F. and Ogunkoya, O.O., 2013. Salinity and sodium hazards of three streams of different agricultural land use systems in Ile-Ife, Nigeria. *Applied Water Science*, **3:** 19-28.

Olson, John R., 2012. The Influence of Geology and other Environmental Factors on Stream Water Chemistry and Benthic Invertebrate Assemblages. All Graduate Thesis and Dissertations. 1327. https://digitalcommons.usu.edu/etd/1327.

Oyem, H.H., Oyem, I.M. and Ezeweali, D., 2014. Temperature, pH, Electrical Conductivity, Total Dissolved Solids and Chemical Oxygen Demand of Groundwater in Boji-BojiAgbor/Owa Area and Immediate Suburbs. *Research Journal of Environmental Sciences*, **8:** 444-450.

Palanisamy, H., Cazenave, A., Meyssignac, B., Soudarin, L., Wöppelmann, G. and Becker, M., 2014. Regional sea level variability, total relative sea level rise and its impacts on islands and coastal zones of Indian Ocean over the last sixty years. *Global and Planetary Change*, **116:** 54-67.

Polemio, M. and Limoni, P.P., 2006. Groundwater pollution and risks for the coastal environment (southeastern Italy). *In:* Predictions in Ungauged Basins: Promise and Progress. Murugesu Sivapalan.

Prasanna, M.V., Chidambaram, S., Shahul Hameed, A. and Srinivasamoorthy, K., 2010. Study of evaluation of groundwater in Gadilam basin using hydrogeochemical and isotope data. *Environment Monitoring Assessment*, **168(1-4):** 63-90.

Priju, C.P., Karthick, P., Kumar, A., Abdul Hameed, E., Madhavan, K. and Narasimha Prasad, N.B., 2014. Electrical Resistivity Sounding and Hydrochemical Investigation for Delineating Saline Water Intrusion in Shallow Aquifers of Ernakulam-Alappuzha Coast. Proceedings of the International Symposium on 'Integrated Water Resources Management', CWRDM, Kozhikode, Allied Publishers Pvt. Ltd., New Delhi.

Priju, C.P., Athira, S.G., Neerajamol, T.P., Madhavan, K. and Narasimha Prasad, N.B., 2012. Groundwater Quality with Special reference to salinity intrusion in Cochin area, Kerala. *In:* Proceedings of the Fifth International Groundwater Conference (IGWC-2012). Vol 2. Water and environment. Retrieved from http://www.academia.edu/2316597/Groundwater_quality_with_special_reference_to_salinity_intrusion_in_cochin_area_Kerala_-_C.P.Priju_S.G.Athira_T.P.Neerajamol_K.Madhavan_and_N.B.Narasimha_Prasad

Rajawat, A.S., Chauhan, H.B., Ratheesh, R. et al., 2015. Assessment of coastal erosion along the Indian coast on 1:25,000 scale using satellite data of 1989–1991 and 2004–2006 time frames. *Current Science*, **109(2):** 347-353.

Revelle, R., 1941. Criteria for recognition of sea-water in ground water (M). *American Geophysical Union*, **22(3):** 595-596.

SAC ISRO, 2014. Shoreline Change Atlas of Indian Coast. Vol 3. Central Water Commission, Ministry of Water Resources. Govt. of India. Retrieved from https://vedas.sac.gov.in/vedas/downloads/atlas/Seashore/Vol-3-Full.pdf.

Sajil Kumar, P.J., Elango, L. and James, E.J., 2014. Assessment of hydrochemistry and groundwater quality in the coastal area of South Chennai, India. *Arabian Journal of Geosciences*, **7(7):** 2641-2653.

Sarath Prasanth, S.V., Magesh, N.S., Jitheshlal, K.V., Chandrasekar, N. and Gangadhar, K., 2012. Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha District, Kerala, India. *Applied Water Science*, **2(3):** 165-175. https://doi.org/10.1007/s13201-012-0042-5.

Saravanan, K., Srinivasamoorthy, K., Prakash, R., Gopinath, S. and Suma, C., 2015. An Evaluation of Hydrogeochemistry of Groundwater in Upper Vellar Sub-Basin using Mineral Stability and Solute Transport Modelling. *Aquatic Procedia*, **4:** 1119-1125.

Schoeller, H., 1977. Geochemistry of Groundwater. *In:* Groundwater Studies – An International Guide for Research and Practice. UNESCO, Paris.

Senthilkumar, S., Balasubramanian, N., Gowtham, B. and Lawrence, J.F., 2017. Geochemical signatures of groundwater in the coastal aquifers of Thiruvallur district, south India. *Applied Water Science*, **7(1):** 263-274.

Simpson, T.R., 1946. Salinas Basin Investigation. Division of Water Resources, State of California, Sacramento. *Bulletin*, **52:** 138-139.

Singaraja, C., Chidambaram, S., Anandhan, P., Prasanna, M.V., Thivya, C., Thilagavathi, R. and Sarathidasan, J., 2014. Hydrochemistry of groundwater in a coastal region and its repercussion on quality, a case study—Thoothukudi district, Tamil Nadu, India. *Arabian Journal of Geosciences*, **7(3):** 939-950.

Singh, S., Raju, N. and Ramakrishna, C. (2015). Evaluation of Groundwater Quality and Its Suitability for Domestic and Irrigation Use in Parts of the Chandauli-Varanasi Region, Uttar Pradesh, India. *Journal of Water Resource and Protection*, **7:** 572-587.

Sivan, O., Yechieli, Y., Herut, B. and Lazar, Boaz., 2005. Geochemical evolution and timescale of seawater intrusion into the coastal aquifer of Israel. Geochimicaet Cosmochimica Acta, **69(3):** 579-592. DOI:10.1016/j.gca.2004.07.023.

Srinivas, K., Revichandran, C., Maheswaran, P.A., Asharaf, T.M. and Murukesh, N., 2013. Propagation of tides in the Cochin estuarine system, southwest coast of India. *Indian Journal of Marine Sciences*, **32(1):** 14-24.

Srinivasamoorthy, K., Chidambaram, S., Prasanna, M.V., Vasanthavihar, M., Peter, J. and Anandhan, P., 2008. Identification of major sources controlling groundwater chemistry from a hard rock terrain—A case study from Mettur taluk, Salem district, Tamil Nadu, India. *Journal of Earth System Science*, **117:** 49-58.

Srinivasamoorthy, K., Gopinath, M., Chidambaram, S. and Vasanthavigar, M., 2014. Hydrochemical characterization and quality appraisal of groundwater from Pungar sub basin, Tamil Nadu, India. *Journal of King Saud University – Science*, **26(1):** 37-52.

Subramani, T., Elango, L. and Damodarasamy, S.R., 2005. Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India. *Environmental Geology*, **47(8):** 1099-1110.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L. and Ergul, Ayhan, 2017. Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change (ver. 4.4, July 2017): U.S. Geological Survey Open-File Report 2008-1278. Retrieved from https://pubs.er.usgs.gov/publication/ofr20081278.

Umadevi, A.G., George, M., Dharma Lingam, P., Jose, P.A., Rajagopalan, M., Dhanya B., Haridasan, P.P. and Pillai, P.M.B., 2010. An Investigation of the quality of underground water at Eloor in Ernakulam District of Kerala, India. *E-Journal of Chemistry*, **7(3):** 908-914.

Unnikrishnan, A.S., Kumar, K.R., Fernandes, S.E., Michael, G.S. and Patwardhan, S,K., 2006. Sea level changes along the Indian coast: Observations and projections. *Current Science*, **90(3):** 362-368.

Weisse, R., Bellafiore, D., Mendez, M., Mendez, F., Nicholls, R.J., Umgiesser, G. and Willems, P., 2014. Changing extreme sea levels along European coasts. *Coastal Engineering*, **87:** 4-14, doi:10.1016/j.coastaleng.2013.10.017.

Wicks, C.M. and Herman, J.S., 1996. Regional hydro-geochemistry of a modern coastal mixing zone. *Water Resources Research*, **32:** 401-407.

Wilcox, L.V., 1948. The quality of water for irrigation use. US Department of Agriculture. Technology Bulletin 962, Washington DC.

Woodworth, P.L. and Player, R., 2003. The permanent service for mean sea level: An update to the 21st century. *Journal of Coastal Research*, **19:** 287-295.