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Seawater intrusion in the coastal aquifers of India - A review

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ABSTRACT

Massive withdrawal of groundwater resources due to population growth and rapid industrialization has led to seawater intrusion into the coastal aquifers across the globe. The problem is an emerging challenge as the coastal areas host ≈40% of the total global population. Impacts of the seawater intrusion on the health of the local community, economic and socio-cultural developments in the coastal areas have led to a wide variety of research being conducted. The objective of the present study is to provide a detailed review of the processes that control the seawater intrusion into the coastal aquifers and the necessary measures to mitigate the same. Various methods of investigation and their applicability are explained. Finally, the status of seawater intrusion in India has been discussed in greater detail.

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1. Introduction

Coastal zones contain some of the most densely populated areas and have an average population density of about 80 persons per sq. km, which is twice the world's average population density (Kantamaneni et al., 2017). Apart from an increase in population, continuous improvement in living standards is further enhancing the water demand in these areas (Neumann et al., 2015). In coastal areas, groundwater being the primary source of freshwater is exploited indiscriminately to fulfill the increasing water demands for domestic, agricultural as well as industrial usages (Hamed et al., 2018). The excessive withdrawal of groundwater disturbs hydrodynamic equilibrium that exists between the freshwater – seawater in the aquifer and causes upward movement of the seawater (van Camp et al., 2014). This causes depletion in the available fresh groundwater resources in coastal areas (Alfarrah and Walraevens, 2018; Werner et al., 2013). The upward or downward movement of seawater into the coastal aquifer is governed by a well-established mathematical relationship known as the "Ghyben-Herzberg relationship" (Narayan et al., 2007). The relationship indicates that for a one-meter increase in the water table, the thickness of seawater reduces by 40 m. A decline in groundwater level below the mean sea-level leads to a reversal of hydraulic gradient and causes inland movement of seawater in the coastal aquifer (Lee and Cheng, 1974; Nair et al., 2013). The inland movement of seawater into the coastal aquifer is called seawater intrusion, which has been the major cause of deterioration of the coastal groundwater resources (Fig. 1). Seawater intrusion not only affects the industrial and agriculture growth in the area but also hampers the living standards of people (Demirel, 2004).

The extent of seawater intrusion varies widely from regional to global scale. A significantly large number of studies have been conducted in coastal areas across the globe to understand the problem of seawater intrusion (Abdalla, 2016; Allow, 2011; Barlow and Reichard, 2010; Felisa et al., 2013; Garing et al., 2013; Manivannan and Elango, 2019; Rajaveni et al., 2016; Shammas and Jacks, 2007; Shi and Jiao, 2014; Suhartono et al., 2015; Werner and Gallagher, 2006; Zghibi et al., 2013). However, limited attempts have been made to connect these individual studies for a broader understanding of the seawater intrusion process and its remedial measures. In the present work, an attempt has been made to explain various factors controlling seawater intrusion and the mitigation strategies. The scope of different methodologies for the investigations of seawater intrusion has been discussed in detail. Finally, the status of seawater intrusion in the coastal aquifers of India has been thoroughly reviewed.

2. Factors controlling seawater intrusion

Coastal aquifers are highly sensitive to both regional and global phenomena that include sea-level rise, storm surges, change in climatic condition, shoreline erosion, coastal flooding, etc. (Barlow, 2003). Additionally, human activities are enhancing the salinization process in coastal regions (Rapti-Caputo, 2010). Apart from the coastal aquifers, surface water sources also get affected due to their interaction with the seawater. The rivers and estuaries allow the natural inflow of seawater due to the backwater from the sea and make the surface water saline (Oude Essink, 2001; Vijay et al., 2011). Various factors affecting the coastal aquifer and their effects are summarized in Fig. 2 (Kumar, 2006). A synoptic view of the factors affecting the hydrodynamic equilibrium between the freshwater and seawater with the causes of seawater intrusion in coastal aquifers has been explained in the proceeding paragraphs.

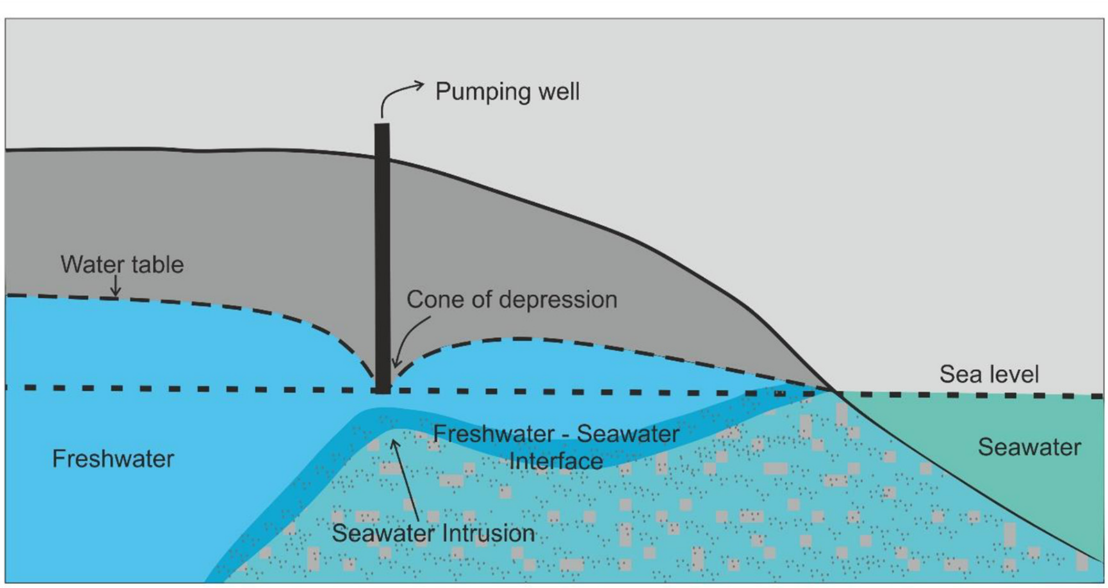

Fig. 1. Schematic diagram of seawater intrusion into the coastal aquifer.

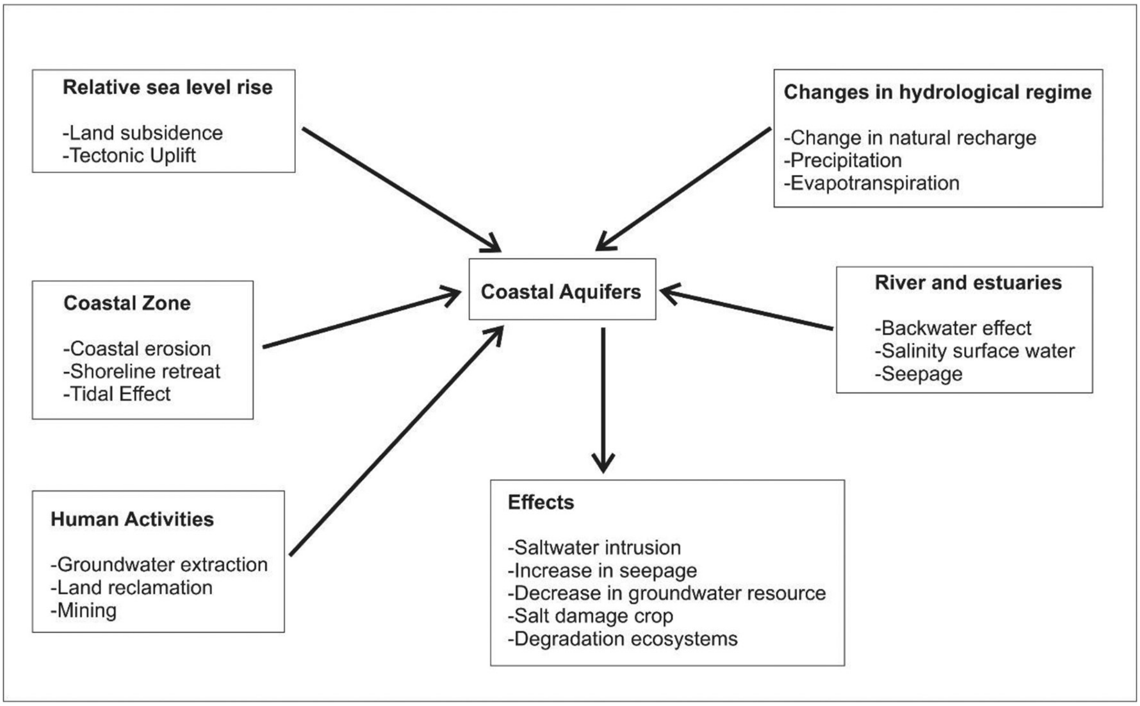

Fig. 2. Factors affecting the coastal aquifer and their effects (Kumar, 2006).

2.1. Geological factors

Geological factors such as lithology, geomorphology, structural features, etc. play important roles in controlling the seawater intrusion into the coastal aquifers. The inland flow of water in the coastal aquifer depends on the nature of geological formations, i.e., aquifer lithology (Michael et al., 2013). The geological history of water-bearing formation, hydraulic gradient, rate of groundwater extraction, and its replenishment directly affect the extent of seawater intrusion (Ammar et al., 2016; Barlow, 2003; Choudhury et al., 2001). Geologic formations with varying porosity and permeability have different water-holding capacities. The seawater flooding into the inland areas may get trapped in the under-saturated pore spaces and form paleo-seawater (Werner and Gallagher, 2006). Clayey layers usually occur in small patches in coastal regions, which act as barriers and help to preserve the paleo-seawater (Barrett et al., 2002; Cary et al., 2015). In contrast, these clay patches may develop perched aquifers and accumulate the freshwater in non-seawater flooding areas (Yousif and Bubenzer, 2012). Under such circumstances, the distribution of freshwater and seawater depends upon the distribution of clay patches in coastal aquifers. However, the interaction of freshwater with the old trapped seawater and saltpans can lead to much higher salinity in the coastal groundwater (Ayolabi et al., 2013; Nair et al., 2016).

Studies have reported that structural features such as fractures, deep-seated faults, and lineaments act as potential pathways for the seawater to intrude into the coastal aquifer and mix with the fresh groundwater (Gupta et al., 2010). Besides, coastal landforms and land use patterns play a vital role in controlling the surface and subsurface runoff. They affect the seawater migration in the inland areas and can explain the salinity distribution in the coastal soils (Liu et al., 2008; Yu et al., 2014). Various fluvial, marine, fluvio-marine, and aeolian landforms work as the potential fresh groundwater zones down to 10 m in the coastal areas (Central Ground Water Board, 2014). It has been found that the beach dunes, which generally occur as narrow strips along the coast, have not been affected by the seawater and have formed potential perched freshwater aquifers locally (Prusty et al., 2020).

The study of buried paleochannels is of scientific interest to understand the hydrogeology of an area as they contain permeable sediments to form excellent aquifers (Shirke et al., 2005). Studies have reported that paleochannels form freshwater zones in a seawater dominated environment in the coastal areas (Prusty et al., 2020; Samadder et al., 2011; Sharma et al., 2016). Paleochannels, filled with high permeable sediments, provide preferred pathways for the movement of groundwater and seawater in coastal regions (Daniel et al., 1996; Falls et al., 2005). The sub-marine groundwater discharge through paleochannels restricts the landward movement of the saline front. However, these paleochannels may support seawater intrusion with the increase in the groundwater abstraction on land (Mulligan et al., 2007). In such cases, the increased salinity indicates that the same routes that transported freshwater to the ocean have been turned into pathways for seawater intrusion (Gallardo and Marui, 2007). By simulation of coastal aquifers, Mulligan et al. (2007) confirmed that the paleochannels permit both inflow and outflow of the seawater.

2.2. Tidal activity

Effects of tidal activity on coastal groundwater quality have been studied by several researchers involving experimental studies, field studies as well as simulation studies. Using time series analysis, Kim et al. (2005) found that the groundwater quality in the coastal regions of Kimje, Korea reflects periodic changes in the tidal activities. In another study, the effects of tides on the coastal groundwater system have been traced up to 3 km inland from the coastline of Jeju Island, Korea (Kim et al., 2006). Studies have shown that the oscillation in tidal movement fluctuates the groundwater head in coastal regions, which causes periodical changes in the groundwater table (Carr and van der Kamp, 1969; Nielsen, 1990). Such fluctuations in the groundwater head have a direct effect on the freshwater – seawater mixing zone (Bear, 1972; Strack, 1976; Wang and Tsay, 2001). Shalev et al. (2009) have reported that this fluctuation in freshwater – seawater interface causes an inflow of the seawater into the pumping wells during the high tide period. Einsiedl (2012) stated that the natural conduits supplying water to the tube wells could also act as pathways to transport the tide-induced seawater into inland areas. Further, studies have found that tides not only influence the freshwater – seawater mixing zone but also affects the rate of groundwater discharge into the sea (Robinson and Gallagher, 1999; Uchiyama et al., 2000; Urish and McKenna, 2004).

Simulation studies have identified tidal fluctuations as one of the primary causes of freshwater – seawater mixing in the Atoll Islands (Underwood et al., 1992). Simulation of tidal activity by Ataie-Ashtiani et al. (1999) highlighted that the tidal activity enhances the seawater intrusion process and causes thickening of freshwater – seawater interface. The study also indicated that the tidal fluctuations affect the water table severely in the shallow aquifer, while the beach slope plays a vital role in groundwater discharge into the sea (Ataie-Ashtiani et al., 2001; Li et al., 2002). In contrast, the integration of laboratory experiments with numerical simulations found that the tidal action is negatively related to the seawater intrusion in the inter-tidal zone (Kuan et al., 2012). It is found that the tide-induced seawater circulation develops a saltwater plume in the inter-tidal zone, which reduces the freshwater discharge into the sea, and in turn, reduces the seawater intrusion considerably.

2.3. Climate change and sea-level rise

Climate change and sea-level rise are the most important climatic factors that control seawater intrusion in coastal regions. The atmospheric precipitation is the primary source of groundwater recharge; however, its quantity changes in terms of both space and time. Further, atmospheric precipitation shows a high degree of inter-annual variability. During the rainy season, the groundwater level increases with the increase in precipitation, while in the summer season, a many-fold increase in evapotranspiration coupled with a decrease in precipitation results in a decline of groundwater level (Rapti-Caputo, 2010). Thus, during non-rainy seasons even relatively lesser withdrawal of groundwater may result in seawater intrusion. Therefore, the chances of seawater intrusion remain higher during non-rainy seasons as compared to the rainy season. Meteorological drought, storm surges, and coastal erosion are some of the other factors associated with climate change that are explicitly linked to seawater intrusion (Terry and Falkland, 2010). Storm surges threaten the coastal aquifers by flooding the low-lying coastal areas with seawater, which salinizes the coastal groundwater and causes deposition of salts on soil (Central Water Commission, 2017; Rezaie et al., 2019). This makes the groundwater and soil unusable for agricultural and other usages.

Rise in the atmospheric temperature due to global warming accelerates glacial melting and supplies large quantities of water to the ocean, which in turn results in sea-level rise. A rise in sea-level leads to an increase in the seawater head at the ocean boundary, causing migration of the freshwater – seawater mixing zone to inland areas (Custodio, 1997). Simulation studies indicated that a decrease in the slope of shoreline increases the land-surface inundation, which causes inland advancement of the freshwater – seawater interface with the sea-level rise (Ataie-Ashtiani et al., 2013; Hussain and Javadi, 2016; Ketabchi et al., 2016). Chen et al. (2015) have predicted that there will be an increase in the salt content as well as the length of seawater intrusion in the Tamsui River, Taiwan due to a rise in the sea-level. This will also increase the salinity of the river due to delayed transport of dissolved contents to the sea. In another study by Shi and Jiao (2014), sea-level fluctuation is shown to cause paleo-seawater intrusion in the coasts of Laizhou Bay, China.

Climate change and land-sea elevation contrast can enhance the effects of sea-level rise on seawater intrusion. This has been well-explained by Sherif and Singh (1999) in Nile delta, Egypt and Madras aquifer, India with the help of numerical simulations. Scare rainfall and high-temperature conditions prevail in the Nile delta region due to its occurrence within a desert and arid belt. Besides, it has low land-sea elevation, which results in higher seawater intrusion with an increase in the sea-level. It has been predicted that a sea-level rise of 0.5 m in the Mediterranean sea will result in 9 km more inland movement of seawater in the Nile delta aquifer, while the same sea-level rise in the Bay of Bengal can only cause an increase in seawater intrusion $\approx$0.4 km along the east coast of India. Simulation studies further indicated that sea-level rise causes severe coastal flooding issues (Loáiciga et al., 2012; Shrivastava, 1998). Interestingly, Chang et al. (2011) identified a self-reversing process in the confined aquifer, which causes natural reversal of the seawater intrusion process induced by sea-level rise.

2.4. Human-induced factors

Human activity is the foremost important factor that is directly or indirectly related to all other factors controlling seawater intrusion. Overexploitation of groundwater resources is the most crucial human-induced process that enhances the seawater intrusion in coastal regions. Groundwater is primarily used for domestic, agricultural, and industrial purposes in coastal areas. With the increase in the water demand, the groundwater sources are over-exploited, causing seawater intrusion. Excessive withdrawal of groundwater has been reported as the main cause of seawater intrusion in many parts of the world, for example in Africa (van Camp et al., 2014), Australia (Narayan et al., 2007), China (Shi and Jiao, 2014), Europe (Daliakopoulos et al., 2016; Einsiedl, 2012), India (Kanagaraj et al., 2018), USA (Misut and Voss, 2007), Vietnam (Ngo et al., 2015), etc. Periodic fluctuation in freshwater – seawater interface exposes the aquifer sediments to freshwater and seawater alternately. This differential flow of water severely affects the hydraulic properties of the aquifer (Barlow, 2003). Additionally, extensive withdrawal of groundwater develops stress conditions in the aquifer and causes a reduction in the pore pressure of the aquifer sediments, which may lead to land subsidence (Gambolati and Teatini, 2015). Severe effects of groundwater extraction induced subsidence on buildings and coastal structures have been reported from many coastal regions across the globe (Feng et al., 2008; Minderhoud et al., 2017).

Other human activities such as large-scale groundwater usage for agriculture, land reclamation, unplanned shrimp culture, inland saltpans, insufficient or poorly maintained infrastructure, and inadequate water management systems can encourage salinization of the coastal aquifer (Mahmuduzzaman et al., 2014). At places where freshwater is under severe stress, the groundwater with relatively higher salt content is used in agricultural fields, which over time, makes the soil saline (Han et al., 2011). The removal of salts from the soil is a difficult task and is not beneficial; thus, the saline soil becomes unusable for agricultural activities. In some of the coastal regions, shrimp farming is adopted to raise income and employment. However, extensive shrimp culture has several negative impacts on the coastal environment, such as depletion of water resources, loss of biodiversity, seawater intrusion, environmental pollution, etc. (Hossain et al., 2013; Nguyen et al., 2019). Studies have further shown that the development of an extensive drainage system in the river's upstream direction may lower the groundwater level in the coastal areas and may facilitate the seawater intrusion (Barlow, 2003; Barlow and Reichard, 2010). Several infrastructures have been developed in many of the coastal regions to prevent the inflow of seawater and supply of water to the coastal population. However, improper maintenance and management tactics may lead to leakage of water, contamination from surficial activities leading to failure of their purposes.

3. Methods of investigation

Over the years, a large number of studies have been conducted on coastal aquifers to understand the various aspects of the seawater intrusion process. Investigation of seawater intrusion includes determining the spatial distribution of physicochemical properties of the subsurface, such as electrical conductivity (EC), salinity, water quality, total dissolved salts (TDS), seawater mixing, etc. (Bear et al., 1999). The methods applied to achieve this can be broadly divided into two types: (i) direct method and (ii) indirect method. The direct techniques involve collection and analysis of water samples for various physio-chemical parameters, while in indirect method, the hydrologic properties are interpreted from the measurement of bulk conductivity, bulk resistivity, and seismic velocities of the aquifer material. Measurement of groundwater levels and the geochemical analysis of groundwater samples are some of the examples of the common direct methods used in seawater intrusion studies. Additionally, in many cases, remote sensing and geographical information systems (GIS) have also been used in combination with direct or indirect methods to monitor the coastal aquifers. A brief description of the common direct and indirect methods used for seawater intrusion studies are given below.

3.1. Direct methods: geochemical methods

Seawater intrusion is the main cause of higher salinity in coastal water. However, the salinity in coastal water could also be contributed by several other sources like entrapped fossil seawater, sea-spray accumulation, evaporite rock dissolution, anthropogenic pollution (from sewage effluents, industrial effluents, mine water, road deicing salts, etc.) (Alcalá and Custodio, 2008; Davis et al., 1998). The changes in the salinity in coastal groundwater are generally found to be associated with four geochemical processes, namely (i) freshwater – seawater mixing, (ii) carbonate precipitation, (iii) ion exchange, and (iv) redox reactions (Bear et al., 1999). For the purpose to determine the dominant processes that control the groundwater salinity at a particular location, concentrations of major ions such as Na, Cl, Ca, and Mg, and some minor ions such as Br, F, and I are widely used (Alcalá and Custodio, 2008; Manivannan and Elango, 2018; Nair et al., 2013). Additional parameters such as EC and TDS are incorporated to precisely locate the major intrusion plumes in the coastal areas (Sylus and Ramesh, 2015; Zghibi et al., 2013). Molar ionic ratios such as Na/Cl, Cl/Br, Ca/Mg, Cl/HCO_3, Ca/($HCO_3 + SO_4$), etc. have also been used as tracers for seawater intrusion. In many studies, stable isotopes of oxygen ($\delta^{18}O$), hydrogen (δ^2H), and boron ($\delta^{11}B$) are used to determine the origin of water and trace the contribution of seawater mixing in modulating the groundwater quality in coastal regions (Han et al., 2015; Nair et al., 2015). Werner et al. (2013) have also used the strontium isotopic ratio ($^{87}Sr/^{86}Sr$) to differentiate past and recent seawater intrusion. Utilizing EC, Na, and Cl concentrations, seawater intrusion has been identified in the coastal areas of south India (Kumar et al., 2014). Tomaszkiewicz et al. (2014) have calculated the groundwater quality index for seawater intrusion from the geochemical parameters. Excessive Cl over Na concentrations with the molar ratio of Na/Cl equals to 0.86 and excessive Mg over Ca concentrations with the molar ratio of Mg/Cl varying between 4.5 and 5.2 has been reported to indicate seawater intrusion (Bear et al., 1999).

3.2. Indirect methods: geophysical methods

Seawater intrusion causes higher Na and Cl concentrations in the coastal groundwater, which is reflected in the form of higher EC values. Thus, measurement of EC or resistivity of aquifer fluids can be used to understand the water quality in the coastal aquifer. Usually, groundwater has high resistivity values (low EC), and lower resistivity values (high EC) in coastal regions are indicative of saline groundwater (Manivannan and Elango, 2018). Electrical methods (resistivity and electromagnetic) have commonly been used in coastal areas to delineate the subsurface brackish or seawater bodies from the freshwater. In the resistivity method, an electric current is passed into the ground through current electrodes, and resistivity is measured from electrical potential between the current electrodes. Vertical electrical sounding (VES) and electrical resistivity tomography (ERT) are the most common electrical resistivity methods used for the study of seawater intrusion in coastal regions (Kumar et al., 2016). In electromagnetic methods, a magnetic field is developed on the surface, which induces an electric current in the subsurface, and the secondary magnetic field produced by the induced current is measured to know the subsurface condition. Very low frequency (VLF), an electromagnetic method is used to locate the freshwater – seawater interface in the coastal aquifer (Bear et al., 1999). Seismic methods are also used to demarcate the lithological boundaries that may provide hydrological information of the geological formations. In this method, changes in seismic velocity are measured and interpreted in terms of the mechanical properties of the geological formations. The technique has been very successful in understanding the subsurface information in remote areas and gives very reliable results in combination with electrical methods. Ground-penetrating radar (GPR) includes both seismic reflection and electromagnetic methods and can be used to locate the freshwater – seawater interface in a coastal aquifer (Bear et al., 1999; Kumar et al., 2016). However, these methods are limited to investigate the subsurface depth of a few meters to a few hundred meters. For the investigation of deeper subsurface, borehole logging methods can be applied. The integration of various geophysical methods may provide a piece of clear information about the subsurface hydrological condition. Sathish et al. (2011) have adopted high resistivity electrical tomography technique to precisely locate the freshwater – seawater mixing zone in the Indian city of Chennai. Melloul and Goldenberg (1997) have used a time-domain electrical resistivity method to study the penetration of seawater into the coastal aquifers of Israel. Further, VES and shallow seismic refraction methods are explicitly applicable in evaluating the seawater intrusion in the coastal alluvial terrain with thick clay formations (Choudhury et al., 2001; Majumdar and Das, 2011).

3.3. Remote sensing and GIS

Remote sensing of the surface features can provide information about the subsurface geological structures. This technique is useful for quick groundwater mapping, especially in large and inaccessible areas. The surficial features associated with groundwater, such as vegetation and runoff, can be recognized easily in the satellite imageries based on their spectral signatures (Elbeih, 2015). Remotely sensed imageries could also be utilized for the identification of the surface water bodies like streams, lakes, wetlands, seepage areas, recharge zones, etc., which help in predicting the subsurface water flow. Fang et al. (2010) have identified seawater intrusion in the Pearl River Estuary, China using Earth Observing-1 (EO-1) Advanced Land Imager (ALI) satellite imagery. In another study, Astaras and Oikonomidis (2006) have used high-resolution Landsat and Thematic mapper (TM) satellite images to delineate the seawater affected coastal areas in central Greece. Nguyen et al. (2018) have also predicted seawater intrusion in the Mekong Delta, Vietnam based on Landsat reflectance. Later, the Landsat images have also been used to assess the soil salinity of the region (Nguyen et al., 2020). GIS techniques have been proved to be very powerful tools in understanding the spatial distribution of water quality parameters (Elbeih, 2015; Prusty et al., 2020; Rao et al., 2008). It is a common practice to use remote sensing and GIS techniques in conjunction with other studies like VES and geochemical surveys to identify various pathways for seawater intrusion (Dhakate et al., 2016). With the application of GIS techniques, high salinity hazards zones have been demarcated in Maharashtra, India (Anbazhagan and Nair, 2004).

4. Mitigation methods

The investigation, monitoring, and management of seawater intrusion is a tedious task since it has large spatio-temporal variations. The groundwater quality in two wells located just a few tens of meters apart can be drastically different on account of local and regional scale variations in hydrogeological conditions and anthropogenic activities. Such variations make it challenging to manage the coastal groundwater resources sustainably and cost-effectively. There are many coastal groundwater management techniques. However, there is no strait-jacket formula to determine which method can be applied to a particular region to protect the coastal groundwater. A poor management technique may lead to the loss of freshwater resources. For the determination of best-suited groundwater management techniques, the current status of groundwater quality and seawater intrusion, hydrogeological characterization of the region, recharge and utilization estimation, etc. must be taken into consideration. Some of the important management strategies are discussed below.

4.1. Reduction in pumping rate

Reduction in over-draft and rate of groundwater abstraction are some of the most effective and free of cost mitigation measures to prevent further ingress of seawater into the coastal aquifer (Manivannan and Elango, 2018). The reduction in over-draft can be achieved by the utilization of surface water and rainwater through artificial drainage channels for agricultural activities (Central Water Commission, 2017). It has been reported by Hussain et al. (2019) that periodic changes in crop patterns and avoiding high water demanding crops like rice, wheat, soya, etc. can significantly reduce groundwater pumping in coastal regions. The construction of major commercial structures that require huge quantities of water should be restricted in the coastal areas. The installation of desalination plants can also reduce groundwater usage by making saline groundwater meet the industrial requirement of water (Shalev et al., 2009; Soni and Pujari, 2010). Additionally, the wastewater and the water used in industrial processes can be reused for some other purposes after appropriate treatment. The facilitation of water supply to the coastal areas from far inland areas can reduce the pumping activity to a great extent. However, high population growth creating high water demand is the main barrier for the deployment of this method. In some cases, an alternate usable water source is limited, and the supply of good quality water is not cost-effective; thus, the method fails to achieve its goal.

4.2. Rearrangement of pumping wells

Intense pumping activities close to the seashore will cause rapid inland movement of seawater. Generally, the freshwater – seawater interface is located at a shallow depth close to the sea, while it occurs at greater depths in inland areas. Thus, the shifting of sea-side pumping wells towards the inland areas could minimize the seawater intrusion (Manivannan and Elango, 2018). Reduction of pumping activities in the seawater affected area helps in re-establishing the natural hydraulic gradient between the seawater and freshwater, which can prevent the landward movement of the seawater (Hussain et al., 2019). This method is especially suitable for coastal aquifers with high lateral heterogeneity. However, in many cases, the cost of the relocation of wells may not be beneficial. A well-planned strategy needs to be adopted while deciding the location of the shifted wells.

4.3. Artificial recharge and rainwater harvesting

Natural replenishment of the groundwater reservoir is a slow process. Generally, the rate at which groundwater withdrawal occurs oversteps the natural recharge. Under such conditions, the groundwater head decreases and causes the landward migration of the seawater. The acceleration of natural recharge in coastal areas may prove to be an effective strategy to deal with the seawater intrusion problem. In this process, the surface water is connected to the groundwater reservoir through various artificial constructions. Renovation of old ancestral structures like ponds/tanks and installation of different recharge structures may prove to be very effective in facilitating the groundwater recharge in over-exploited and critical regions (Central Ground Water Board, 2013a). Sakthivadivel (2007) has suggested that the construction of a series of check dams may also help in groundwater recharge in the coastal areas and slow down the seawater intrusion process. The development of thick forests along the shorelines can increase the water holding capacity of the aquifer sediments, which can prevent the inundation of seawater. The process is not only environment-friendly but also cost-effective. Further, it does not require much land and displacement of the population. However, the unavailability of good quality water for recharge, especially during dry periods, is the major issue associated with this strategy. There are also chances of groundwater contamination from the surface water recharge. The cost of the development of subsurface structures is another limitation.

Rainwater, a renewable water resource, can be quite helpful in dealing with water scarcity and related problems if stored and appropriately utilized. The storing of rainwater can prevent the risks associated with storm-water runoff. The collected rainwater can be used for groundwater recharge, domestic and agricultural usages, and other purposes subsequently. With the depletion of groundwater level in fluctuating climate conditions, especially during the non-rainy seasons, harvested rainwater can play a major role in meeting the groundwater demands. The collection of rainwater not only reduces urban flooding but also helps in recharging the local aquifers and supplying water to water-scarce areas (Kumar et al., 2005; Rekha, 2002). The recharge of groundwater increases the water table, and the chances of seawater intrusion are minimized. Datta (2019) has reported several consequences of rainwater harvesting such as overcoming water shortage, supplementing existing supplies, stopping seawater intrusion, auto-filtration through soils, storing water for agricultural usage in dry periods, controlling floods by storing excess runoff, mitigating drought effects, recharging groundwater, dry and dead rivers, etc. Since rainwater harvesting is rainfall dependent, the abrupt change in rainfall pattern is the major challenge of this management practice.

4.4. Injection and abstraction wells

Construction of a series of freshwater injection wells close to the sea may help in maintaining the freshwater – seawater equilibrium. The high-pressure freshwater injection forces the freshwater – seawater interface back towards the sea (Manivannan and Elango, 2018). Loáiciga et al. (2012) have succeeded in groundwater recharge by this method in California, USA. This method is most suitable for coastal areas that have restricted land availability with a good network of rivers. These rivers may act as local sources of freshwater to be injected. High volume injection of freshwater will increase the water level, and thus will push the seawater front away from the land (Abdalla, 2016). However, the injection of inferior quality of freshwater may lead to deterioration of groundwater quality. Further, injection under high pressure may change the pore pressure and alter the aquifer properties.

Another method to push back the freshwater – seawater interface towards the sea involves the construction of a series of seawater abstraction wells close to the sea. The abstracted seawater can either be utilized in desalination plants or discharged directly into the sea (Hussain et al., 2019). The excessive withdrawal of seawater can develop a seaward hydraulic head that may direct the water flow towards the sea and protect the coastal aquifer from seawater intrusion. It is of utmost importance to calculate the seawater abstraction rate carefully to avoid any freshwater extraction. In most cases, it is neither economic nor practically possible to remove the seawater entirely by pumping.

4.5. Construction of subsurface barriers

The construction of physical subsurface barriers can restrict the inland flow of seawater into the coastal aquifers. These barriers are usually constructed with concrete, grout, slurry walls, etc. on impermeable strata to prevent seepage from beneath. They have a longer lifetime and minimal maintenance (Hussain et al., 2019; Werner et al., 2013). The construction of physical barriers prevents not only seawater intrusion but also the mixing of seawater with the fresh groundwater (Dey and Prakash, 2020). The method has successfully been adopted at the Okinawa island in the Pacific Ocean, where the subsurface barriers prevent seawater intrusion into the limestone coastal aquifer (Sugio et al., 1987). This method may prove to be cost-effective and yield good results in shallow coastal aquifers. In the case of deeper aquifers, high costs associated with the construction of the retaining wall (or similar subsurface structure) may pose a challenge. Further, in the absence of impervious strata at a shallower depth, diffusion of seawater may occur beyond the barrier depth.

4.6. Groundwater monitoring network

Various water laws and policies have been implemented nationally and at state levels across the globe for effective management and protection of coastal water resources. It has been stressed that high-resolution water quality data is crucial to determine the current state of seawater intrusion, which can only be possible through a carefully designed monitoring network. Regular monitoring of water resources also helps in indicating the shrinking surface water bodies due to siltation and clearance of watershed in the catchment areas (Central Ground Water Board, 2014; Central Water Commission, 2017). Additionally, to provide crucial data for mitigation planning, these agencies develop awareness among the people through various awareness and training programs. Periodic publication of reports appraises people about the impact of their efforts on local groundwater quality and seawater intrusion.

5. Status of seawater intrusion in India

The problem of seawater intrusion is predominant in Asian countries, especially in the Indian subcontinent, which falls under medium vulnerability (Fig. 3a; Fuchs, 2010). A vast coastline of approximately 7500 km surrounds the Indian subcontinent on its three sides: the Bay of Bengal in the east, the Arabian Sea in the west, and the Indian Ocean to the south (Fig. 3b; Central Ground Water Board, 2014). According to Chachadi (2005), the Indian coastline stretches over nearly 53 coastal districts in nine coastal states. These nine maritime states from west to east include Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Odisha, and West Bengal. Besides, there are four coastal union territories, two located in the mainland (Daman and Diu, and Puducherry) and two islands (Andaman and Nicobar Islands, and Lakshadweep Island). The coastal zones of India comprise extensive fertile delta plains, industries, harbors, airports, land ports, tourism, etc. They have diverse ecosystems, including mangroves, coral reefs, salt marshes, mudflats, estuaries, and lagoons (Central Water Commission, 2017). A number of major rivers, including the Ganga, Brahmaputra, Mahanadi, Krishna, Godavari, Cauvery, Narmada, Tapti, etc. discharge their water into the sea through the coastal tract of India (Mukhopadhyay and Karisiddaiah, 2014). The geological formations of the coastal tract vary from Archean crystalline rocks to recent fluvial and marine sediments (Manivannan and Elango, 2019). The Quaternary sediments cover a major portion in the southeast coast with the Deccan traps in the west and the Archean rocks in the southwest.

In recent times, enormous developments and rapid increase in coastal populations have stressed the coastal freshwater resources leading to water scarcity issues and seawater intrusion into the coastal aquifer. Various coastal districts of India that are under the direct influence of the seawater are shown in Fig. 3b (MoEF and CC, 2016). A study from Central Soil Salinity Research Institute (Karnal, India) indicates that there are about 70 thousand sq. km salt-affected soils in India, out of which about 21 thousand sq. km comprise saline soils in the coastal tracts (Farooqui et al., 2009). A detailed explanation of the available coastal groundwater resources, state-wise seawater intrusion status, and adopted mitigation measures are presented in the following subsections.

5.1. Coastal groundwater resources of India

Uncertainty in rainfall, scarcity of surface water at a few places and the onsite availability of fresh groundwater have resulted in higher dependency on groundwater resources in India. Growing urbanization and changes in land usage patterns have largely reduced the natural groundwater recharge process, which has significantly decreased the groundwater level (Mishra et al., 2014; Mukherjee et al., 2018; Patra et al., 2018). The situation becomes worse during the summer season when there is a considerable decrease in the groundwater table due to very limited recharge (Dams et al., 2012). This leads to severe water crisis, especially in the coastal areas where over-exploitation of groundwater is prevalent. Various states and central government organizations have assessed the groundwater resources of India. The groundwater resources in the coastal states of India assessed by Central Ground Water Board (2017) are provided in Table 1. The annual replenishable

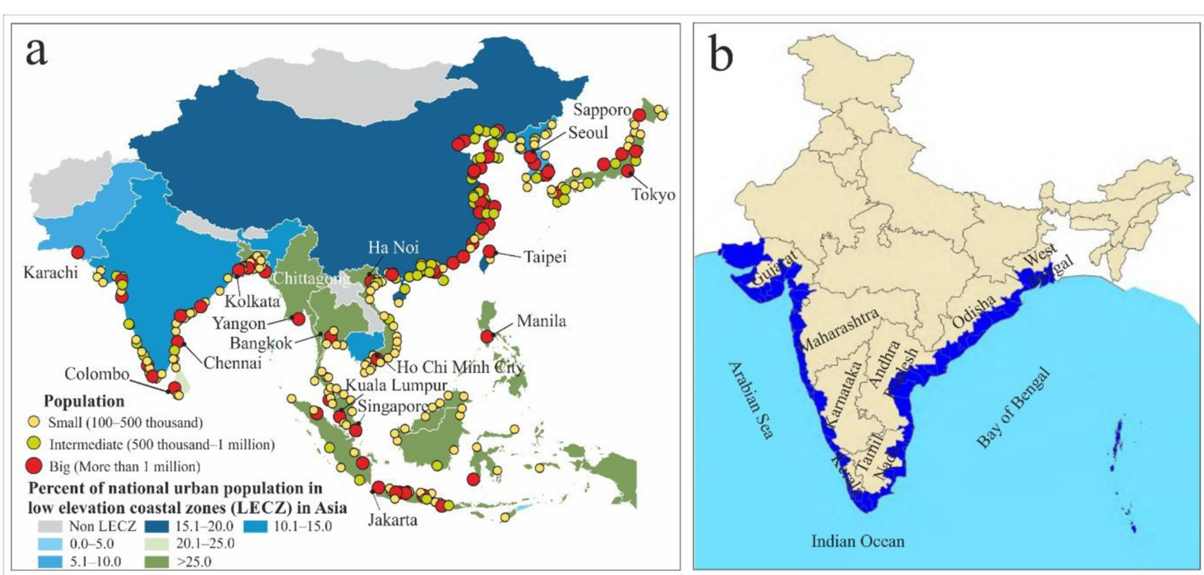

Fig. 3. (a) Map of Asia showing the risk of populated coastal cities due to sea-level rise (Fuchs, 2010), (b) map showing various coastal districts of India (blue coloured) under the influence of seawater (MoEF and CC, 2016).

Table 1
Groundwater resources in the coastal states of India as on March 2013.
Source: Central Ground Water Board (2017).

States of India	Annual replenishable groundwater resource					Natural discharge during non-monsoon season	Net annual groundwater availability	Annual groundwater draft			Net groundwater availability for future uses
	Monsoon recharge		Non-monsoon recharge		Total			Irrigation	Domestic and industrial uses	Total	
	Rainfall	Others	Rainfall	Others							
Gujarat	13.93	3.22	0.00	3.71	20.85	1.07	19.79	12.30	1.14	13.44	6.35
Maharashtra	21.96	1.64	1.83	7.76	33.19	1.71	31.48	15.93	1.14	17.07	14.41
Karnataka	6.74	4.18	2.67	3.40	17.00	2.16	14.83	8.76	0.99	9.76	5.07
Goa	0.15	0.01	0.01	0.08	0.24	0.10	0.15	0.02	0.03	0.05	0.10
Kerala	4.51	0.04	0.59	1.13	6.27	0.60	5.66	1.18	1.45	2.63	3.03
Tamil Nadu	7.12	9.87	1.52	2.15	20.65	2.07	18.59	12.98	1.38	14.36	4.23
Andhra Pradesh	8.97	4.25	3.21	3.97	20.39	1.91	18.48	7.29	0.81	8.10	10.38
Odisha	11.29	2.53	1.33	2.63	17.78	1.09	16.69	4.14	0.87	5.02	11.67
West Bengal	18.71	5.26	1.51	3.85	29.33	2.77	26.56	10.84	1.00	11.84	14.72
Total	93.38	31.0	12.67	28.68	165.7	13.48	152.2	73.44	8.81	82.27	69.96

All values are in billion cubic meters (bcm).

groundwater resource in the coastal states has been assessed as 165.7 billion cubic meters (bcm). The groundwater replenishment is mostly dependent on the rainfall recharge, which contributes about 64% of total groundwater resources (total 106 bcm; monsoon rainfall: 93.38 bcm; non-monsoon rainfall: 12.67 bcm). The rest 59.68 bcm is obtained from other sources including canal seepage, return flow from irrigation, recharge from tanks, ponds, water conservation structures, etc. Out of the total natural replenishable water, 13.48 bcm is discharged naturally per annum during the non-monsoon season, and 152.23 bcm is available for various usages. Further, it is estimated that the net annual groundwater draft including domestic, industrial, and agricultural usages is 82.27 bcm, which will leave 69.96 bcm of groundwater for future usages (Table 1). Based on the present population growth rate, Gupta and Deshpande (2004) have estimated that India will face severe water scarcity problem by 2050.

Central Ground Water Board (2017) in association with the state groundwater departments has assessed different administrative units of Indian coastal states and categorized them as safe, semi-critical, critical, over-exploited, and saline. It is found that out of 3307 administrative units, 495 units are over-exploited, 409 units are semi-critical, 146 units are critical, and 92 units are entirely saline (Table 2). The saline units are mainly found in the states of Gujarat, Tamil Nadu, Andhra Pradesh, and Odisha. Further, the number of semi-critical, critical, and over-exploited units is significantly higher in the states of Tamil Nadu, Andhra Pradesh, Karnataka, and West Bengal. However, all the coastal states are under stress in terms of semi-critical, critical, over-exploited, and saline groundwater conditions, except Goa, where all units are found to be safe. Mukherjee et al. (2015) have reported that intensive irrigation is the main factor in stressing the groundwater resources in India.

5.2. Status of seawater intrusion

On the basis of geomorphic setup, the Indian coast can be divided into two types: (a) East coast and (b) West coast. The east coast comprises vast coastal plains and sedimentary depositions with the development of well-defined deltaic plains at the river mouths. In contrast, the west coast is mostly rocky with a number of islands, inundated river channels, tidal creeks, rock-cut surfaces, etc. (Central Water Commission, 2017). The east coastal plains extend from the Sundarban delta in West Bengal to Coromandal coast in Tamil Nadu, while the west coastal plains stretch from Rann of Kutch in Gujarat to Malabar coast in Kerala. The status of seawater intrusion in the coastal states of India is explained in detail in the following paragraphs.

5.2.1. West Bengal

The state of West Bengal includes three coastal districts on its southern side. Goswami (1968) has conducted a hydrological survey in the coastal regions by sinking an Auger borehole and groundwater quality analysis. The study identified the presence of a freshwater wedge that is separated by two 7–9 m thick saline units in the aquifer. It is also found that the movement of the interface is controlled combined by tides, natural recharge, and groundwater pumping. Several studies have confirmed extensive groundwater withdrawal as the main cause of seawater intrusion in the coastal regions (Das et al., 2018; Maity et al., 2017). VES method has been integrated with the geochemical

Table 2
Groundwater condition in different administrative units in the coastal states of India.
Source: Central Ground Water Board (2017).

States	Length of coastline (km)[a]	Total no. of assessed units	Safe	Semi-critical	Critical	Over-exploited	Saline
Gujarat	1214.7	223	175	9	6	23	10
Maharashtra	652.6	353	324	19	1	9	0
Karnataka	280.0	176	98	21	14	43	0
Goa	151.0	12	12	0	0	0	0
Kerala	569.7	152	131	18	2	1	0
Tamil Nadu	906.9	1139	429	212	105	358	35
Andhra Pradesh	973.7	670	497	54	17	61	41
Odisha	476.4	314	308	0	0	0	6
West Bengal	157.5	268	191	76	1	0	0
Total	5382.5	3307	2165	409	146	495	92

Blocks: Kerala, Odisha, West Bengal; Taluks: Karnataka, Goa, Gujarat, Maharashtra; Mandal: Andhra Pradesh; Firka: Tamil Nadu.
[a] Mukhopadhyay and Karisiddaiah (2014).

method to identify different subsurface layers (Majumdar et al., 2016, 2014; Majumdar and Das, 2011). It is found that the deeper aquifers are mostly safe for various usages, while the seawater contaminates the shallow aquifer. By integration of VES with shallow seismic refraction method, Choudhury et al. (2001) have identified clay patches in the subsurface up to a depth of 60 m, which prevents large-scale seawater intrusion at depth. In a few places, Adyalkar et al. (1981) have reported paleo-seawater as the source of salinity. It has been observed that groundwater over-extraction is the main cause of groundwater salinization in the state. However, the saline units in the state have irregular distribution patterns, and there exits limited literature. Thus, extensive hydrological studies are needed for a better understanding of seawater intrusion in the state.

5.2.2. Odisha

In the neighbouring state of Odisha, around 8500 sq. km area spreading in six coastal districts is under the influence of seawater. Central Ground Water Board (2014) has reported that the saline groundwater zones have a width of around 15 km in the northeast, 1.5–5 km in the north, and 2–3 km in the southeast of Odisha. Over-exploitation of groundwater has been reported to cause a reduction in groundwater levels and closure of several tube wells in the coastal regions of the state (Panda and Kumar, 2011; Rejani et al., 2009; Vijay and Mohapatra, 2016). Hydrochemical studies have shown that mixing of seawater with the fresh groundwater has increased the major ion concentrations in the coastal groundwater (Mohanty and Rao, 2019; Mohapatra et al., 2011; Prusty et al., 2020, 2018). The deteriorating groundwater condition due to the mixing of seawater with freshwater in the central deltaic region is well-demonstrated by self-potential and resistivity surveys (Radhakrishna, 2001; Singh et al., 2011). These studies have identified different hydrological zones such as freshwater, freshwater underlain by saline water, freshwater overlain by saline water, and alternate fresh-saline zones in the coastal areas. However, the salinity of the soils is mainly associated with the inundation of land by the seawater during high tides and seawater ingression through estuaries, creeks, drains, rivers, etc. (Farooqui et al., 2009). The state shows a high degree of variation in salinity and lack of uniformity in terms of lateral and vertical distribution of water types in the coastal regions. The problem of seawater intrusion is emerging in the state and needs urgent attention.

5.2.3. Andhra Pradesh

Andhra Pradesh has the 2nd largest coastline in India. An area of around 1760 sq. km in the state has been estimated to have higher salinity in the groundwater (Farooqui et al., 2009). Sea-level rise plays a significant role in deteriorating groundwater quality and agricultural land degradation (Kantamaneni et al., 2019). Using remote sensing and GIS techniques, Rao et al. (2008) have assessed the coastal vulnerability of the state by calculation of coastal vulnerability index from geomorphology, tide, coastal slope, shoreline change, and wave heights. It has been calculated that with a sea-level rise of 0.6 m, around 43% of the coast will be under very high risk and 35% under high risk. In another study, a huge loss of land has been predicted with 1 m rise in sea-level, especially in the low-lying deltaic regions (Rao et al., 2011a). Numerical simulations by Bobba (2002) have also predicted a significant risk of seawater intrusion in the deltaic regions due to sea-level rise during non-irrigation periods. Based on hydrochemical analysis, Surinaidu et al. (2015) have identified up-coning of brines and paleo-seawater in contributing to groundwater salinity at some places. However, the presence of thick clay layers and steep hydraulic gradients prevents the seawater to further intrude into the aquifer. The presence of thick clay layers has also been confirmed by the ERT method (Naidu et al., 2013; Rao et al., 2011b; Surinaidu et al., 2013). Raju et al. (2013) have traced seawater intrusion up to 11.6 km in the state. However, it has been traced up to 40 km away from the coastline through the lake water (Karanam et al., 2019). Such studies highlight that the deltaic regions in the state are highly vulnerable to seawater intrusion due to sea-level rise.

5.2.4. Tamil Nadu

In the state of Tamil Nadu, the problem of seawater intrusion is more prevalent, and highly saline groundwater extends to far inland areas. Nair et al. (2016, 2015, 2013) have conducted extensive hydrochemical studies in the coastal regions of Chennai. From the ratios of seawater tracers (Cl/Br) and isotopic signature, they have traced seawater intrusion up to 13–15 km from the coastline and identified over-pumping as the main cause of seawater intrusion. Similar observations have also been made in other parts of the state (Gopinath et al., 2019, 2016). However, at a few places, higher salt content in soils is found to be associated with over-pumping related to agriculture activities (Farooqui et al., 2009). Senthilkumar et al. (2019) have pointed out the existence of various subsurface saline water zones occurring at different depths. In a few studies, the existence of saltpans along with the anthropogenic activities has also been reported as the main cause of groundwater salinity at a local scale (Chandrasekar et al., 2014; Kanagaraj et al., 2018; Singaraja et al., 2015, 2014; Srinivas et al., 2017). The existence of saltpans with groundwater over-pumping has been identified as the main cause of groundwater salinity in the state.

5.2.5. Kerala

Limited attempts have been made to determine the status of seawater intrusion in the state of Kerala, which is located at the southern tip of India. Sindhu et al. (2012), through groundwater simulation models, have demonstrated that a 1% increase in pumping activity may develop a landward hydraulic gradient sufficient to accelerate the seawater intrusion in the coastal regions. Interestingly, there are areas in the state, where the groundwater level is below the sea-level. In these areas, the negative hydraulic gradient causes seawater intrusion. With the help of hydrochemical and statistical analysis, Shaji et al. (2009) found that tidal activity and marine aerosols are degrading the coastal groundwater and may form shallow patches of saline groundwater. However, the groundwater along a major part of the coastal stretch is safe from the seawater intrusion (Jacks and Thambi, 2018; Kumar et al., 2015, 2020; Prasanth et al., 2012). The widespread application of the rooftop rainwater harvesting method in the state helps in quick replenishment of groundwater resources. Further, direct utilization of the harvested rainwater minimizes the groundwater pumping activity in the area and limits the seawater intrusion.

5.2.6. Karnataka

The vulnerability of the state to seawater intrusion has been assessed by GALDIT index involving six parameters such as groundwater occurrence (G), aquifer hydraulic conductivity (A), groundwater level above the sea (L), distance from the shoreline (D), impact of existing seawater intrusion (I), and thickness of the aquifer (T) (Lathashri and Mahesha, 2008). Based on the GALDIT index, the areas with low, moderate, and high vulnerability to seawater intrusion were identified. Hydrochemical and isotopic studies conducted in various river basins of the state do not show a significant effect of seawater on coastal groundwater (Ravikumar and Somashekar, 2017, 2011; Sylus and Ramesh, 2018). Further, saturated-unsaturated transport model (SUTRA) has related groundwater salinization with over-exploitation during dry periods (Vyshali et al., 2008). The study has also identified tidal activity as the main cause of seawater intrusion in some cases. It is further observed that the effect of seawater is limited up to 200 m throughout the year, which may extend up to 5 km during dry periods. Studies have indicated that the coastal regions in the state have adequate water sources, which are suitable for various usages. However, continued industrialization in the coastal belt may lead to salinization of coastal aquifer in near future. Thus, regular monitoring of water resources and pumping activity are essential to safeguard the aquifer from seawater intrusion.

5.2.7. Goa

The state of Goa has the least coastline among the Indian states. Chachadi (2005) has applied the GALDIT index to assess the vulnerability of the coastal aquifer to the seawater intrusion in the state. It has been found that the low-lying alluvial areas close to the rivers have a higher susceptibility to the seawater intrusion due to tidal activity. Based on finite element model, the extent of seawater intrusion has been predicted up to 300 m away from the coastline (Kumar et al., 2007). Besides tidal activity, marine depositional environments also contribute to groundwater salinity in the state (Central Water Commission, 2017). Using the GPR technique, Loveson et al. (2014) have observed extension and widening of beach in the state due to marine depositions. The depositions are enhanced by high sediment influx by the rivers due to mining activities in upstream. The withdrawal of groundwater is increasing over time, with a rapid increase in the infrastructure development for tourism, which may cause serious groundwater problems in the state.

5.2.8. Maharashtra

In the state of Maharashtra, the VES-geophysical method has been adopted to delineate the effects of seawater intrusion along the coastal zones (Gupta et al., 2010). It is found that the movement of seawater from the Arabian Sea towards the inland areas is facilitated by deep-seated faults/lineaments. The study, along with other studies, also indicated that the southwestern parts of the state are under higher seawater influence (Maiti et al., 2013, 2012). A hydrochemical study conducted in one of the districts shows that the low-lying areas are affected by the seawater intrusion due to the backwater of the sea through the rivers (Omprakash and Gadikar, 2018). Another study by Naik et al. (2007) has indicated seawater intrusion through the creeks in the coastal regions. With the help of radioactive isotope (^{82}Br), seawater intrusion has been traced even in the deeper aquifer, which is a serious cause of concern in the state (Keesari et al., 2014). The coastal regions in the state are mostly covered by the Deccan traps, composed of basalts. The volcanic rock comprises numerous vesicles and lava flows, which allows the inflow of seawater in several places along the coast during high tide periods.

5.2.9. Gujarat

The state of Gujarat has the longest coastline among the Indian states and is well-known for its coastal communities. Hydrochemical and isotopic studies have shown that intense groundwater pumping for irrigation reverses the hydraulic gradient at many places near the coast that results in seawater intrusion (Maurya et al., 2019; Pujari and Soni, 2009; Rina et al., 2013; Soni and Pujari, 2010). From the ERT images of the subsurface, Pujari and Soni (2009) concluded that the seawater intrusion occurs at a depth range of 4–13 m. According to Kumar et al. (2019), changes in land-use patterns have significantly enhanced the water demand in the coastal regions resulting in seawater intrusion. Kale et al. (2012) have predicted the seawater movement up to 20 km from the coastline in the highly industrialized areas of the state. It has been suggested that an increase of 6.3 m in the water table at a groundwater recharge rate of 2.175×10^{-3} m^3/s/m will cause ≈50% reduction in seawater intrusion. Thus, extensive groundwater usage for domestic, agricultural, and industrial purposes has been the main cause of seawater intrusion in the state.

5.3. Management strategies adopted in India

India has a vast coastline with a good percentage of the population residing along with it. Seawater intrusion has degraded the coastal aquifers due to large-scale groundwater developments along the shores. In order to save the coastal groundwater resources from the seawater contamination, several measures have been taken by the central and state governments. The National Water Policy-2002 formulated that the "over-exploitation of groundwater should be avoided, especially near the coast to prevent the ingress of seawater into sweet water aquifers". The Water Prevention and Control of Pollution Act enacted in 1974 to maintain or restore the wholesomeness of water across the country. Central Ground Water Board (CGWB) has been constituted by the government of India to monitor and implement national policies for the sustainable development and management of groundwater resources. CGWB has developed a monitoring network across the country for continuous monitoring of groundwater quality. It also conducts several Mass Awareness Programmes (MAP) and Water Management Training Programmes (WMTP) for the development of awareness among the people to save the coastal groundwater resources (Central Ground Water Board, 2013b). It regularly publishes the status of seawater intrusion and groundwater quality through various reports. Additionally, the state governments have formulated various water quality monitoring boards for the preservation of groundwater resources. Individual researchers, working in various educational institutions or organizations are also monitoring the coastal groundwater quality and status of seawater intrusion from time to time.

In many parts of India, rainwater harvesting techniques have been widely utilized to address various groundwater problems. Some ancient rainwater harvesting methods followed in India include havelis, bandh, bandhulia, virda, eri, dhora, khadins, madakas, ahar-pynes, surangas, taankas, etc. (Rivera-Ferre et al., 2013). Adaptation and implementation of rainwater harvesting have been made mandatory in more or less all states of India through various legislative decisions. The Central Ministry for Drinking Water and Sanitation, in association with the CGWB, has set up multiple projects with an intention to mitigate the groundwater problems in the rural and urban areas of India through the construction of various rainwater harvesting structures.

As a part of the groundwater recharge drive, CGWB has constructed various recharge structures in several parts of the country. Several recharge projects have been undertaken in coastal areas that are affected by seawater intrusion, and special efforts have been made in the over-exploited and critical regions. Several steps have been undertaken to maintain the existing structures with the construction of many new additional recharge structures for groundwater recharge (Central Ground Water Board, 2013a). Construction of a series of check dams across the rivers in the coastal areas has been proved to be quite successful in preventing seawater intrusion (Nair et al., 2013; Sakthivadivel, 2007). To deal with the problem of soil salinity in coastal areas, provisions for storing surface runoff and its usage for irrigation purposes has also been tested.

5.4. Summary

The studies have demonstrated that the seawater intrusion is more prominent on the east coast than the west coast of India. The east coast not only has a more extensive coastline but also comprises thicker alluvial sediments as compared to the narrow and crystalline west coast. Such geological settings facilitate a smoother inflow of seawater into the east coast aquifers. Further, huge sediment loads brought by the east-flowing rivers and their subsequent deposition into the Bay of Bengal results in a lower hydraulic gradient. This allows the seawater from the Bay of Bengal to easily intrude into the coastal aquifers. The east coast also experiences frequent cyclonic disturbances originating from the Bay of Bengal. These cyclonic disturbances result in higher tidal activities along with severe flooding and salinization in the coastal areas. The non-existence of such conditions along the west coast minimizes the seawater intrusion from the Arabian Sea. Further, it has been observed that the seawater intrusion along the west coast is mainly controlled by the structural features existing in the area. On account of the wide variation in geological, structural, climatic, and coastal geomorphic set-up along the Indian coast, it is advisable to adopt the best mitigation strategies based on the local conditions. Several measures have been taken by the government on the national level. However, it is felt that involvement and active participation of the individuals at the local level are necessary for more effective management of seawater intrusion. The awareness among the coastal community is of foremost importance in the safekeeping of coastal water resources for future usages.

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References

Abdalla, F., 2016. Ionic ratios as tracers to assess seawater intrusion and to identify salinity sources in Jazan coastal aquifer, Saudi Arabia. Arab. J. Geosci. 9, 40. https://doi.org/10.1007/s12517-015-2065-3.

Adyalkar, P.G., Ghosh, P.C., Mehta, B.C., 1981. On the salinity of groundwater in South 24-Parganas District, West Bengal, India. Studies in Environmental Science. Elsevier B.V., pp. 63–67 https://doi.org/10.1016/S0166-1116(08)71883-1.

Alcalá, F.J., Custodio, E., 2008. Using the Cl/Br ratio as a tracer to identify the origin of salinity in aquifers in Spain and Portugal. J. Hydrol. 359, 189–207. https://doi.org/10.1016/j.jhydrol.2008.06.028.

Alfarrah, N., Walraevens, K., 2018. Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. Water 10, 143. https://doi.org/10.3390/w10020143.

Allow, K.A., 2011. Seawater intrusion in Syrian coastal aquifers, past, present and future, case study. Arab. J. Geosci. 4, 645–653. https://doi.org/10.1007/s12517-010-0261-8.

Ammar, S. Ben, Taupin, J.-D., Zouari, K., Khouatmia, M., 2016. Identifying recharge and salinization sources of groundwater in the Oussja Ghar el Melah plain (northeast Tunisia) using geochemical tools and environmental isotopes. Environ. Earth Sci. 75, 606. https://doi.org/10.1007/s12665-016-5431-x.

Anbazhagan, S., Nair, A.M., 2004. Geographic information system and groundwater quality mapping in Panvel Basin, Maharashtra. India. Environ. Geol. 45, 753–761. https://doi.org/10.1007/s00254-003-0932-9.

Astaras, T., Oikonomidis, D., 2006. Remote sensing techniques to monitoring coastal plain areas suffering from salt water intrusion and detection of fresh water discharge in coastal, karstic areas: case studies from Greece, in: Groundwater and Ecosystems. Kluwer Academic Publishers, Dordrecht, pp. 1–13 https://doi.org/10.1007/1-4020-4738-X_1.

Ataie-Ashtiani, B., Volker, R.E., Lockington, D.A., 1999. Tidal effects on sea water intrusion in unconfined aquifers. J. Hydrol. 216, 17–31. https://doi.org/10.1016/S0022-1694(98)00275-3.

Ataie-Ashtiani, B., Volker, R.E., Lockington, D.A., 2001. Tidal effects on groundwater dynamics in unconfined aquifers. Hydrol. Process. 15, 655–669. https://doi.org/10.1002/hyp.183.

Ataie-Ashtiani, B., Werner, A.D., Simmons, C.T., Morgan, L.K., Lu, C., 2013. How important is the impact of land-surface inundation on seawater intrusion caused by sea-level rise? Hydrogeol. J. 21, 1673–1677. https://doi.org/10.1007/s10040-013-1021-0.

Ayolabi, E.A., Folorunso, A.F., Odukoya, A.M., Adeniran, A.E., 2013. Mapping saline water intrusion into the coastal aquifer with geophysical and geochemical techniques: the University of Lagos campus case (Nigeria). Springerplus 2, 433. https://doi.org/10.1186/2193-1801-2-433.

Barlow, P.M., 2003. Ground Water in Freshwater-saltwater Environments of the Atlantic Coast. US Department of the Interior. US Geological Survey, Reston, Virginia.

Barlow, P.M., Reichard, E.G., 2010. Saltwater intrusion in coastal regions of North America. Hydrogeol. J. 18, 247–260. https://doi.org/10.1007/s10040-009-0514-3.

Barrett, B., Heinson, G., Hatch, M., Telfer, A., 2002. Geophysical methods in saline groundwater studies: locating perched water tables and fresh-water lenses. Explor. Geophys. 33, 115–121. https://doi.org/10.1071/EG02115.

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier Pubishing Company, New York.

Bear, J., Cheng, A.H.D., Sorek, S., Ouazar, D., Herrera, I. (Eds.), 1999. Seawater Intrusion in Coastal Aquifers: Concepts, Methods and Practices (Springer Science & Business Media).

Bobba, A.G., 2002. Numerical modelling of salt-water intrusion due to human activities and sea-level change in the Godavari Delta. India. Hydrol. Sci. J. 47, S67–S80. https://doi.org/10.1080/02626660209493023.

Carr, P.A., van der Kamp, G.S., 1969. Determining aquifer characteristics by the tidal method. Water Resour. Res. 5, 1023–1031. https://doi.org/10.1029/WR005i005p01023.

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., Lasseur, E., Picot, G., Guerrot, C., Fléhoc, C., Labasque, T., Santos, J.G., Paiva, A., Braibant, G., Pierre, D., 2015. Origins and processes of groundwater salinization in the urban coastal aquifers of Recife (Pernambuco, Brazil): a multi-isotope approach. Sci. Total Environ. 530–531, 411–429. https://doi.org/10.1016/j.scitotenv.2015.05.015.

Central Ground Water Board, 2013a. Master Plan for Artificial Recharge to Ground Water in India (New Delhi).

Central Ground Water Board, 2013b. Groundwater Information Booklet, Puri District, Orissa. Ministry of Water Resources. India, South Eastern Region, Bhubaneswar, Govt. of.

Central Ground Water Board, 2014. Report on status of ground water quality in coastal aquifers of India. Ministry of Water Resources. India, Faridabad, Govt. of.

Central Ground Water Board, 2017. Dynamic Ground Water Resources of India. Ministry of Water Resources, River Development & Ganga Rejuvenation, Faridabad, Govt. of India.

Central Water Commission, 2017. Problems of Salination of Land in Coastal Areas of India and Suitable Protection Measures. Ministry of Water Resources, River Development & Ganga Rejuvenation. India, New Delhi, Govt. of.

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

Chandrasekar, N., Selvakumar, S., Srinivas, Y., John Wilson, J.S., Simon Peter, T., Magesh, N.S., 2014. Hydrogeochemical assessment of groundwater quality along the coastal aquifers of southern Tamil Nadu. India. Environ. Earth Sci. 71, 4739–4750. https://doi.org/10.1007/s12665-013-2864-3.

Chang, S.W., Clement, T.P., Simpson, M.J., Lee, K.-K., 2011. Does sea-level rise have an impact on saltwater intrusion? Adv. Water Resour. 34, 1283–1291. https://doi.org/10.1016/j.advwatres.2011.06.006.

Chen, W.-B., Liu, W.-C., Hsu, M.-H., 2015. Modeling assessment of a saltwater intrusion and a transport time scale response to sea-level rise in a tidal estuary. Environ. Fluid Mech. 15, 491–514. https://doi.org/10.1007/s10652-014-9367-y.

Choudhury, K., Saha, D., Chakraborty, P., 2001. Geophysical study for saline water intrusion in a coastal alluvial terrain. J. Appl. Geophys. 46, 189–200. https://doi.org/10.1016/S0926-9851(01)00038-6.

Custodio, E., 1997. Seawater Intrusion in Coastal Aquifers: Guidelines for Study, Monitoring and Control, Water Report 11. Food and Agriculture Organization of the United Nation. Rome, Italy.

Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P., Ritsema, C.J., 2016. The threat of soil salinity: a European scale review. Sci. Total Environ. 573, 727–739. https://doi.org/10.1016/j.scitotenv.2016.08.177.

Dams, J., Salvadore, E., Van Daele, T., Ntegeka, V., Willems, P., Batelaan, O., 2012. Spatio-temporal impact of climate change on the groundwater system. Hydrol. Earth Syst. Sci. 16, 1517–1531. https://doi.org/10.5194/hess-16-1517-2012.

Daniel III, C.C., Miller, R.D., Wrege, B.M., 1996. Application of Geophysical Methods to the Delineation of Paleochannels and Missing Confining Units Above the Castle Hayne Aquifer at US Marine Corps Air Station, Cherry Point, North Carolina, Water-Resources Investigations Report 95-4252. Raleigh, North Carolina.

Das, S., Maity, P.K., Das, R., 2018. Remedial measures for saline water ingression in coastal aquifers of South West Bengal in India. MOJ Ecol. Environ. Sci. 3. https://doi.org/10.15406/mojes.2018.03.00061.

Datta, P.S., 2019. Water Harvesting for Groundwater Management: Issues, Perspectives, Scope, and Challenges. John Wiley & Sons.

Davis, S.N., Whittemore, D.O., Fabryka-Martin, J., 1998. Uses of chloride/bromide ratios in studies of potable water. Ground Water 36, 338–350. https://doi.org/10.1111/j.1745-6584.1998.tb01099.x.

Demirel, Z., 2004. The history and evaluation of saltwater intrusion into a coastal aquifer in Mersin. Turkey. J. Environ. Manage. 70, 275–282. https://doi.org/10.1016/j.jenvman.2003.12.007.

Dey, S., Prakash, O., 2020. Management of saltwater intrusion in coastal aquifers: an overview of recent advances. In: Singh, R., Shukla, P., Singh, P. (Eds.), Environmental Processes and Management. Water Science and Technology Library. Springer, Cham, pp. 321–344.

Dhakate, R., Sankaran, S., Kumar, V.S., Amarender, B., Harikumar, P., Subramanian, S.K., 2016. Demarcating saline water intrusion pathways using remote sensing, GIS and geophysical techniques in structurally controlled coastal aquifers in Southern India. Environ. Earth Sci. 75, 363. https://doi.org/10.1007/s12665-015-4940-3.

Einsiedl, F., 2012. Sea-water/groundwater interactions along a small catchment of the European Atlantic coast. Appl. Geochem. 27, 73–80. https://doi.org/10.1016/j.apgeochem.2011.09.004.

Elbeih, S.F., 2015. An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. Ain Shams Eng. J. 6, 1–15. https://doi.org/10.1016/j.asej.2014.08.008.

Falls, W.F., Ransom, C., Landmeyer, J.E., Reuber, E.J., Edwards, L.E., 2005. Hydrogeology, water quality, and saltwater intrusion in the Upper Floridan Aquifer in the offshore area near Hilton Head Island, South Carolina, and Tybee Island, Georgia. Scientific Investigations Report 1999–2002, 2005–5134.

Fang, L., Chen, S., Wang, H., Qian, J., Zhang, L., 2010. Detecting marine intrusion into rivers using EO-1 ALI satellite imagery: Modaomen Waterway, Pearl River Estuary. China. Int. J. Remote Sens. 31, 4125–4146. https://doi.org/10.1080/01431160903229218.

Farooqui, A., Srivastava, J., Hussain, S.M., 2009. Comparative leaf epidermal morphology and foliar Na: K accumulation in Suaeda species: a case study from coastal ecosystem, India. Phytomorphology 59, 102–111.

Felisa, G., Ciriello, V., Di Federico, V., 2013. Saltwater intrusion in coastal aquifers: a primary case study along the Adriatic Coast investigated within a probabilistic framework. Water 5, 1830–1847. https://doi.org/10.3390/w5041830.

Feng, Q., Liu, G., Meng, L., Fu, E., Zhang, H., Zhang, K., 2008. Land subsidence induced by groundwater extraction and building damage level assessment—a case study of Datun. China. J. China Univ. Min. Technol. 18, 556–560. https://doi.org/10.1016/S1006-1266(08)60293-X.

Fuchs, R.J., 2010. Cities at Risk: Asia's Coastal Cities in an Age of Climate Change Analysis From the East-West Center, AsiaPacific Issues. East-West Center, Honolulu, HI.

Gallardo, A.H., Marui, A., 2007. Modeling the dynamics of the freshwater-saltwater interface in response to construction activities at a coastal site. Int. J. Environ. Sci. Technol. 4, 285–294. https://doi.org/10.1007/BF03326286.

Gambolati, G., Teatini, P., 2015. Geomechanics of subsurface water withdrawal and injection. Water Resour. Res. 51, 3922–3955. https://doi.org/10.1002/2014WR016841.

Garing, C., Luquot, L., Pezard, P.A., Gouze, P., 2013. Geochemical investigations of saltwater intrusion into the coastal carbonate aquifer of Mallorca. Spain. Appl. Geochemistry 39, 1–10. https://doi.org/10.1016/j.apgeochem.2013.09.011.
Gopinath, S., Srinivasamoorthy, K., Saravanan, K., Suma, C.S., Prakash, R., Senthilnathan, D., Chandrasekaran, N., Srinivas, Y., Sarma, V.S., 2016. Modeling saline water intrusion in Nagapattinam coastal aquifers, Tamilnadu. India. Model. Earth Syst. Environ. 2, 2. https://doi.org/10.1007/s40808-015-0058-6.
Gopinath, S., Srinivasamoorthy, K., Saravanan, K., Prakash, R., 2019. Tracing groundwater salinization using geochemical and isotopic signature in southeastern coastal Tamilnadu, India. Chemosphere 236, 124305. https://doi.org/10.1016/j.chemosphere.2019.07.036.
Goswami, A.B., 1968. A study of salt water encroachment in the coastal aquifer at Digha, Midnapore district, West Bengal, India. Hydrol. Sci. J. 13, 77–87. doi:https://doi.org/10.1080/02626666809493609.
Gupta, S.K., Deshpande, R.D., 2004. Water for India in 2050: first-order assessment of available options. Curr. Sci. 86, 1216–1224.
Gupta, G., Erram, V.C., Maiti, S., Kachate, N.R., Patil, S.N., 2010. Geoelectrical studies for delineating seawater intrusion in parts of Konkan coast. Western Maharashtra. Int. J. Environ. Earth Sci. 1, 62–79.
Hamed, Y., Hadji, R., Redhaounia, B., Zighmi, K., Bâali, F., El Gayar, A., 2018. Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. Euro-Mediterranean J. Environ. Integr. 3, 25. https://doi.org/10.1007/s41207-018-0067-8.
Han, D., Song, X., Currell, M.J., Cao, G., Zhang, Y., Kang, Y., 2011. A survey of groundwater levels and hydrogeochemistry in irrigated fields in the Karamay Agricultural Development Area, northwest China: implications for soil and groundwater salinity resulting from surface water transfer for irrigation. J. Hydrol. 405, 217–234. https://doi.org/10.1016/j.jhydrol.2011.03.052.
Han, D., Post, V.E.A., Song, X., 2015. Groundwater salinization processes and reversibility of seawater intrusion in coastal carbonate aquifers. J. Hydrol. 531, 1067–1080. https://doi.org/10.1016/j.jhydrol.2015.11.013.
Hossain, M.S., Uddin, M.J., Fakhruddin, A.N.M., 2013. Impacts of shrimp farming on the coastal environment of Bangladesh and approach for management. Rev. Environ. Sci. Bio/Technology 12, 313–332. https://doi.org/10.1007/s11157-013-9311-5.
Hussain, M.S., Javadi, A.A., 2016. Assessing impacts of sea level rise on seawater intrusion in a coastal aquifer with sloped shoreline boundary. J. Hydro-environment Res. 11, 29–41. https://doi.org/10.1016/j.jher.2016.01.003.
Hussain, M.S., Abd-Elhamid, H.F., Javadi, A.A., Sherif, M.M., 2019. Management of seawater intrusion in coastal aquifers: a review. Water 11, 2467. https://doi.org/10.3390/w11122467.
Jacks, G., Thambi, D.S.C., 2018. Hydrochemistry and turnover of the Kerala Tertiary aquifers, India. In: Mukherjee, A. (Ed.), Groundwater of South Asia. Springer, Singapore, pp. 335–347 https://doi.org/10.1007/978-981-10-3889-1_21.
Kale, G.D., Samtani, B.K., Patel, S.B., Patel, H., Anajwala, N.J., Shah, B.H., Chaudhary, P., Patel, R.A., 2012. Modelling of sea water intrusion with Hele–Shaw model: a case study around Surat City. Gujarat. ISH J. Hydraul. Eng. 18, 215–223. https://doi.org/10.1080/09715010.2012.721658.
Kanagaraj, G., Elango, L., Sridhar, S.G.D., Gowrisankar, G., 2018. Hydrogeochemical processes and influence of seawater intrusion in coastal aquifers south of Chennai, Tamil Nadu. India. Environ. Sci. Pollut. Res. 25, 8989–9011. https://doi.org/10.1007/s11356-017-0910-5.
Kantamaneni, K., Du, X., Aher, S., Singh, R.M., 2017. Building blocks: a quantitative approach for evaluating coastal vulnerability. Water 9, 905. https://doi.org/10.3390/w9120905.
Kantamaneni, K., Rani, N.N.V.S., Rice, L., Sur, K., Thayaparan, M., Kulatunga, U., Rege, R., Yenneti, K., Campos, L., 2019. A systematic review of coastal vulnerability assessment studies along Andhra Pradesh, India: a critical evaluation of data gathering, risk levels and mitigation strategies. Water 11, 393. https://doi.org/10.3390/w11020393.
Karanam, H., Gummapu, J., Rao, V.V., 2019. Integrated Methodology for Delineation of Salt-water and Fresh Water Interface Between Kolleru Lake and Bay of Bengal Coast, Andhra Pradesh, India. Springer Series in Geomechanics and Geoengineering. Springer Verlag, pp. 503–513 https://doi.org/10.1007/978-3-319-77276-9_45.
Keesari, T., Kulkarni, U.P., Jaryal, A., Mendhekar, G.N., Deshmukh, K.N., Hegde, A.G., Kamble, S.N., 2014. Groundwater dynamics of a saline impacted coastal aquifer of western Maharashtra, India: insights from a radiotracer study. J. Radioanal. Nucl. Chem. 300, 1–6. https://doi.org/10.1007/s10967-014-2940-5.
Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., Simmons, C.T., 2016. Sea-level rise impacts on seawater intrusion in coastal aquifers: review and integration. J. Hydrol. 535, 235–255. https://doi.org/10.1016/j.jhydrol.2016.01.083.
Kim, J.-H., Lee, J., Cheong, T.-J., Kim, R.-H., Koh, D.-C., Ryu, J.-S., Chang, H.-W., 2005. Use of time series analysis for the identification of tidal effect on groundwater in the coastal area of Kimje. Korea. J. Hydrol. 300, 188–198. https://doi.org/10.1016/j.jhydrol.2004.06.004.
Kim, K.-Y., Seong, H., Kim, T., Park, K.-H., Woo, N.-C., Park, Y.-S., Koh, G.-W., Park, W.-B., 2006. Tidal effects on variations of fresh–saltwater interface and groundwater flow in a multilayered coastal aquifer on a volcanic island (Jeju Island, Korea). J. Hydrol. 330, 525–542. https://doi.org/10.1016/j.jhydrol.2006.04.022.
Kuan, W.K., Jin, G., Xin, P., Robinson, C., Gibbes, B., Li, L., 2012. Tidal influence on seawater intrusion in unconfined coastal aquifers. Water Resour. Res. 48, 2502. https://doi.org/10.1029/2011WR010678.
Kumar, C.P., 2006. Management of groundwater in salt water ingress coastal aquifers. Groundw. Model. Manag. 540–560.
Kumar, R., Singh, R.D., Sharma, K.D., 2005. Water resources of India. Curr. Sci. 89, 794–811.
Kumar, C.P., Chachadi, A.G., Purandara, B.K., Kumar, S., Juyal, R., 2007. Modelling of seawater intrusion in coastal area of North Goa. Water Dig. 2, 80–83.
Kumar, P.J.S., Elango, L., James, E.J., 2014. Assessment of hydrochemistry and groundwater quality in the coastal area of South Chennai. India. Arab. J. Geosci. 7, 2641–2653. https://doi.org/10.1007/s12517-013-0940-3.
Kumar, K.S.A., Priju, C.P., Prasad, N.B.N., 2015. Study on saline water intrusion into the shallow coastal aquifers of Periyar river basin. Kerala using hydrochemical and electrical resistivity methods. Aquat. Procedia 4, 32–40. https://doi.org/10.1016/j.aqpro.2015.02.006.
Kumar, V.S., Dhakate, R., Amarender, B., Sankaran, S., 2016. Application of ERT and GPR for demarcating the saline water intrusion in coastal aquifers of Southern India. Environ. Earth Sci. 75, 393. https://doi.org/10.1007/s12665-015-5207-8.
Kumar, P., Dasgupta, R., Johnson, B., Saraswat, C., Basu, M., Kefi, M., Mishra, B., 2019. Effect of land use changes on water quality in an ephemeral coastal plain: Khambhat City, Gujarat, India. Water 11, 724. https://doi.org/10.3390/w11040724.
Kumar, P.J.S., Kokkat, A., Kurian, P.K., James, E.J., 2020. Nutrient chemistry and seasonal variation in the groundwater quality of a Riverine Island on the west coast of Kerala. India. Sustain. Water Resour. Manag. 6, 3. https://doi.org/10.1007/s40899-020-00358-y.
Lathashri, U.A., Mahesha, A., 2008. Assessment of aquifer vulnerability to saltwater intrusion in the D.K. District. Karnataka. J. Appl. Hydrol. 21, 113–123.
Lee, C.-H., Cheng, R.T.-S., 1974. On seawater encroachment in coastal aquifers. Water Resour. Res. 10, 1039–1043. https://doi.org/10.1029/WR010i005p01039.
Li, L., Dong, P., Barry, D.A., 2002. Tide-induced water table fluctuations in coastal aquifers bounded by rhythmic shorelines. J. Hydraul. Eng. 128, 925–933. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:10(925).
Liu, Q., Liu, G., Zhao, J., 2008. The indication function of soil type and soil texture and land type to soil salinization levels. Chinese Agric. Sci. Bull. 24, 297–300.
Loáiciga, H.A., Pingel, T.J., Garcia, E.S., 2012. Sea water intrusion by sea-level rise: scenarios for the 21st century. Ground Water 50, 37–47. https://doi.org/10.1111/j.1745-6584.2011.00800.x.
Loveson, V.J., Gujar, A.R., Iyer, S.D., Udayaganesan, P., Luis, R.A.A., Gaonkar, S.S., Chithrabhanu, P., Tirodkar, G.M., Singhvi, A.K., 2014. Beach dynamics and oscillations of shoreline position in recent years at Miramar Beach, Goa. India: a study from a GPR survey. Nat. Hazards 73, 2089–2106. https://doi.org/10.1007/s11069-014-1175-7.
Mahmuduzzaman, M., Ahmed, Z.U., Nuruzzaman, A.K.M., Ahmed, F.R.S., 2014. Causes of salinity intrusion in coastal belt of Bangladesh. Int. J. Plant Res. 2014, 8–13. https://doi.org/10.5923/s.plant.201401.02.
Maiti, S., Erram, V.C., Gupta, G., Tiwari, R.K., 2012. ANN based inversion of DC resistivity data for groundwater exploration in hard rock terrain of western Maharashtra (India). J. Hydrol. 464–465, 294–308. https://doi.org/10.1016/j.jhydrol.2012.07.020.
Maiti, S., Gupta, G., Erram, V.C., Tiwari, R.K., 2013. Delineation of shallow resistivity structure around Malvan, Konkan region. Maharashtra by neural network inversion using vertical electrical sounding measurements. Environ. Earth Sci. 68, 779–794. https://doi.org/10.1007/s12665-012-1779-8.
Maity, P.K., Das, S., Das, R., 2017. Methodology for groundwater extraction in the coastal aquifers of Purba Midnapur District of West Bengal in India under the constraint of saline water intrusion. Asian J. Water. Environ. Pollut. 14, 1–12. https://doi.org/10.3233/AJW-170011.
Majumdar, R.K., Das, D., 2011. Hydrological characterization and estimation of aquifer properties from electrical sounding data in Sagar Island Region, South 24 Parganas, West Bengal. India. Asian J. Earth Sci. 4, 60–74. https://doi.org/10.3923/ajes.2011.60.74.
Majumdar, R.K., Kar, S., Talukdar, D., Duttagupta, T., 2014. Geoelectric and geochemical studies for hydrological characterization of canning and adjoining areas of South 24 Parganas district. West Bengal. J. Geol. Soc. India 83, 21–30. https://doi.org/10.1007/s12594-014-0003-8.
Majumdar, R.K., Kar, S., Panda, A., Samanta, S.K., 2016. Hydrological characterization of Budge Budge and Dum Dum areas of south and north 24 Parganas districts. West Bengal using geoelectric and geochemical methods. J. Geol. Soc. India 88, 330–338. https://doi.org/10.1007/s12594-016-0495-5.
Manivannan, V., Elango, L., 2018. Management of coastal groundwater resources. Coastal Management. Elsevier Inc., pp. 383–397 https://doi.org/10.1016/b978-0-12-810473-6.00018-2.
Manivannan, V., Elango, L., 2019. Seawater intrusion and submarine groundwater discharge along the Indian coast. Environ. Sci. Pollut. Res. 26, 31592–31608. https://doi.org/10.1007/s11356-019-06103-z.
Maurya, P., Kumari, R., Mukherjee, S., 2019. Hydrochemistry in integration with stable isotopes (δ18O and δD) to assess seawater intrusion in coastal aquifers of Kachchh district, Gujarat. India. J. Geochemical Explor. 196, 42–56. https://doi.org/10.1016/j.gexplo.2018.09.013.
Melloul, A.J., Goldenberg, L.C., 1997. Monitoring of seawater intrusion in coastal aquifers: basics and local concerns. J. Environ. Manag. 51, 73–86. https://doi.org/10.1006/jema.1997.0136.
Michael, H.A., Russoniello, C.J., Byron, L.A., 2013. Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. Water Resour. Res. 49, 2228–2240. https://doi.org/10.1002/wrcr.20213.
Minderhoud, P.S.J., Erkens, G., Pham, V.H., Bui, V.T., Erban, L., Kooi, H., Stouthamer, E., 2017. Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta. Vietnam. Environ. Res. Lett. 12. https://doi.org/10.1088/1748-9326/aa7146.
Mishra, N., Khare, D., Gupta, K.K., Shukla, R., 2014. Impact of land use change on groundwater—a review. Adv. Water Resour. Prot. 2, 28–41.
Misut, P.E., Voss, C.I., 2007. Freshwater–saltwater transition zone movement during aquifer storage and recovery cycles in Brooklyn and Queens, New York City. USA. J. Hydrol. 337, 87–103. https://doi.org/10.1016/j.jhydrol.2007.01.035.
MoEF & CC, 2016. Coastal districts of India [WWW document]. Cent. Coast. Zo. Manag. Coast. Shelter Belt. URL http://iomenvis.nic.in/index2.aspx?slid=3680&sublinkid=259&langid=1&mid=1 (accessed 1.21.17).

Mohanty, A.K., Rao, V.V.S.G., 2019. Hydrogeochemical, seawater intrusion and oxygen isotope studies on a coastal region in the Puri District of Odisha, India. CATENA 172, 558–571. https://doi.org/10.1016/j.catena.2018.09.010.

Mohapatra, P.K., Vijay, R., Pujari, P.R., Sundaray, S.K., Mohanty, B.P., 2011. Determination of processes affecting groundwater quality in the coastal aquifer beneath Puri city. India: a multivariate statistical approach. Water Sci. Technol. 64, 809–817. https://doi.org/10.2166/wst.2011.605.

Mukherjee, A., Saha, D., Harvey, C.F., Taylor, R.G., Ahmed, K.M., Bhanja, S.N., 2015. Groundwater systems of the Indian Sub-Continent. J. Hydrol. Reg. Stud. 4, 1–14. https://doi.org/10.1016/j.ejrh.2015.03.005.

Mukherjee, S., Bebermeier, W., Schütt, B., 2018. An overview of the impacts of land use land cover changes (1980–2014) on urban water security of Kolkata. Land 7, 91. https://doi.org/10.3390/land7030091.

Mukhopadhyay, R., Karisiddaiah, S.M., 2014. The Indian coastline: processes and landforms. In: Kale, V.S. (Ed.), Landscapes and Landforms of India. World Geomorphological Landscapes. Springer, Dordrecht, pp. 91–101 https://doi.org/10.1007/978-94-017-8029-2.

Mulligan, A.E., Evans, R.L., Lizarralde, D., 2007. The role of paleochannels in groundwater/seawater exchange. J. Hydrol. 335, 313–329. https://doi.org/10.1016/j.jhydrol.2006.11.025.

Naidu, L.S., Rao, V.V.S.G., Rao, G.T., Mahesh, J., Padalu, G., Sarma, V.S., Prasad, P.R., Rao, S.M., Rao, B.M.R., 2013. An integrated approach to investigate saline water intrusion and to identify the salinity sources in the Central Godavari delta, Andhra Pradesh. India. Arab. J. Geosci. 6, 3709–3724. https://doi.org/10.1007/s12517-012-0634-2.

Naik, P.K., Dehury, B.N., Tiwari, A.N., 2007. Groundwater pollution around an industrial area in the coastal stretch of Maharashtra State. India. Environ. Monit. Assess. 132, 207–233. https://doi.org/10.1007/s10661-006-9529-6.

Nair, I.S., Renganayaki, S.P., Elango, L., 2013. Identification of seawater intrusion by Cl/Br ratio and mitigation through managed aquifer recharge in aquifers North of Chennai. India. J. Groundw. Res. 2, 155–162.

Nair, I.S., Rajaveni, S.P., Schneider, M., Elango, L., 2015. Geochemical and isotopic signatures for the identification of seawater intrusion in an alluvial aquifer. J. Earth Syst. Sci. 124, 1281–1291. https://doi.org/10.1007/s12040-015-0600-y.

Nair, I.S., Brindha, K., Elango, L., 2016. Identification of salinization by bromide and fluoride concentration in coastal aquifers near Chennai, southern India. Water Sci. 30, 41–50. https://doi.org/10.1016/j.wsj.2016.07.001.

Narayan, K.A., Schleeberger, C., Bristow, K.L., 2007. Modelling seawater intrusion in the Burdekin Delta Irrigation Area, North Queensland. Australia. Agric. Water Manag. 89, 217–228. https://doi.org/10.1016/j.agwat.2007.01.008.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - a global assessment. PLoS One 10, e0118571. https://doi.org/10.1371/journal.pone.0118571.

Ngo, M.T., Lee, J.M., Lee, H.A., Woo, N.C., 2015. The sustainability risk of Ho Chi Minh City, Vietnam, due to saltwater intrusion. Geosci. J. 19, 547–560. https://doi.org/10.1007/s12303-014-0052-4.

Nguyen, P.T., Koedsin, W., McNeil, D., Van, T.P., 2018. Remote sensing techniques to predict salinity intrusion: application for a data-poor area of the coastal Mekong Delta. Vietnam. Int. J. Remote Sens. 39, 6676–6691. https://doi.org/10.1080/01431161.2018.1466071.

Nguyen, T.T.N., Tran, H.C., Ho, T.M.H., Burny, P., Lebailly, P., 2019. Dynamics of farming systems under the context of coastal zone development: the case of Xuan Thuy National Park, Vietnam. Agriculture 9, 138. https://doi.org/10.3390/agriculture9070138.

Nguyen, K.-A., Liou, Y.-A., Tran, H.-P., Hoang, P.-P., Nguyen, T.-H., 2020. Soil salinity assessment by using near-infrared channel and Vegetation Soil Salinity Index derived from Landsat 8 OLI data: a case study in the Tra Vinh Province, Mekong Delta. Vietnam. Prog. Earth Planet. Sci. 7, 1. https://doi.org/10.1186/s40645-019-0311-0.

Nielsen, P., 1990. Tidal dynamics of the water table in beaches. Water Resour. Res. 26, 2127–2134. https://doi.org/10.1029/WR026i009p02127.

Omprakash, M.D., Gadikar, N., 2018. Salt Water Intrusion and Water Security Issues of Coastal Community: Case of Thane District (Maharashtra), in: Water Resources Management. Springer, Singapore, pp. 167–177 https://doi.org/10.1007/978-981-10-5711-3_12.

Oude Essink, G.H., 2001. Improving fresh groundwater supply—problems and solutions. Ocean Coast. Manag. 44, 429–449. https://doi.org/10.1016/S0964-5691(01)00057-6.

Panda, D.K., Kumar, A., 2011. Evaluation of an over-used coastal aquifer (Orissa, India) using statistical approaches. Hydrol. Sci. J. 56, 486–497. https://doi.org/10.1080/02626667.2011.563741.

Patra, S., Sahoo, S., Mishra, P., Mahapatra, S.C., 2018. Impacts of urbanization on land use/cover changes and its probable implications on local climate and groundwater level. J. Urban Manag. 7, 70–84. https://doi.org/10.1016/j.jum.2018.04.006.

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

Prusty, P., Farooq, S.H., Zimik, H.V., Barik, S.S., 2018. Assessment of the factors controlling groundwater quality in a coastal aquifer adjacent to the Bay of Bengal. India. Environ. Earth Sci. 77, 762. https://doi.org/10.1007/s12665-018-7943-z.

Prusty, P., Farooq, S.H., Swain, D., Chandrasekharam, D., 2020. Association of geomorphic features with groundwater quality and freshwater availability in coastal regions. Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-020-02706-z.

Pujari, P.R., Soni, A.K., 2009. Sea water intrusion studies near Kovaya limestone mine, Saurashtra coast. India. Environ. Monit. Assess. 154, 93–109. https://doi.org/10.1007/s10661-008-0380-9.

Radhakrishna, I., 2001. Saline fresh water interface structure in Mahanadi delta region, Orissa. India. Environ. Geol. 40, 369–380. https://doi.org/10.1007/s002540000182.

Rajaveni, S.P., Nair, I.S., Elango, L., 2016. Evaluation of impact of climate change on seawater intrusion in a coastal aquifer by finite element modelling. J. Clim. Chang. 2, 111–118. https://doi.org/10.3233/JCC-160022.

Raju, N.J., Reddy, T.V.K., Muniratnam, P., Gossel, W., Wycisk, P., 2013. Managed aquifer recharge (MAR) by the construction of subsurface dams in the semi-arid regions: a case study of the Kalangi river basin. Andhra Pradesh. J. Geol. Soc. India 82, 657–665. https://doi.org/10.1007/s12594-013-0204-6.

Rao, K.N., Subraelu, P., Rao, T.V., Malini, B.H., Ratheesh, R., Bhattacharya, S., Rajawat, A.S., Ajai, 2008. Sea-level rise and coastal vulnerability: an assessment of Andhra Pradesh coast, India through remote sensing and GIS. J. Coast. Conserv. 12, 195–207. https://doi.org/10.1007/s11852-009-0042-2.

Rao, K.N., Subraelu, P., Kumar, K.C.V.N., Demudu, G., Malini, B.H., Ratheesh, R., Rajawat, A.S., Ajai, 2011a. Climate change and sea-level rise: impact on agriculture along Andhra Pradesh coast—a geomatics analysis. J. Indian Soc. Remote Sens. 39, 415–422. https://doi.org/10.1007/s12524-011-0120-4.

Rao, V.V.S.G., Rao, G.T., Surinaidu, L., Rajesh, R., Mahesh, J., 2011b. Geophysical and geochemical approach for seawater intrusion assessment in the Godavari Delta Basin, A.P., India. Water Air Soil Pollut. 217, 503–514. https://doi.org/10.1007/s11270-010-0604-9.

Rapti-Caputo, D., 2010. Influence of climatic changes and human activities on the salinization process of coastal aquifer systems. Ital. J. Agron. 5, 67. https://doi.org/10.4081/ija.2010.s3.67.

Ravikumar, P., Somashekar, R.K., 2011. Environmental tritium (3H) and hydrochemical investigations to evaluate groundwater in Varahi and Markandeya river basins, Karnataka. India. J. Environ. Radioact. 102, 153–162. https://doi.org/10.1016/j.jenvrad.2010.11.006.

Ravikumar, P., Somashekar, R.K., 2017. Principal component analysis and hydrochemical facies characterization to evaluate groundwater quality in Varahi river basin, Karnataka state. India. Appl. Water Sci. 7, 745–755. https://doi.org/10.1007/s13201-015-0287-x.

Rejani, R., Jha, M.K., Panda, S.N., 2009. Simulation-optimization modelling for sustainable groundwater management in a coastal basin of Orissa. India. Water Resour. Manag. 23, 235–263. https://doi.org/10.1007/s11269-008-9273-5.

Rekha, J., 2002. Rainwater harvesting in India. Artha - J. Soc. Sci. 1, 49–56. https://doi.org/10.12724/ajss.1.4.

Rezaie, A.M., Ferreira, C.M., Rahman, M.R., 2019. Storm surge and sea level rise: threat to the coastal areas of Bangladesh. Extreme Hydroclimatic Events and Multivariate Hazards in a Changing Environment. Elsevier, pp. 317–342 https://doi.org/10.1016/B978-0-12-814899-0.00013-4.

Rina, K., Datta, P.S., Singh, C.K., Mukherjee, S., 2013. Isotopes and ion chemistry to identify salinization of coastal aquifers of Sabarmati River Basin. Curr. Sci. 104, 335–344.

Rivera-Ferre, M.G., Di Masso, M., Mailhost, M., López-i-Gelats, F., Gallar, D., Vara, I., Cuellar, M., 2013. Understanding the Role of Local and Traditional Agricultural Knowledge in a Changing World Climate: The Case of the Indo-Gangetic Plains. CGIAR-CCAFS Program, Nepal.

Robinson, M.A., Gallagher, D.L., 1999. A model of ground water discharge from an unconfined coastal aquifer. Ground Water 37, 80–87. https://doi.org/10.1111/j.1745-6584.1999.tb00960.x.

Sakthivadivel, R., 2007. The groundwater recharge movement in India. In: Giordano, M., Villholth, K.G. (Eds.), The Agricultural Groundwater Revolution: Opportunities and Threats to Development. CABI Publishing Series, pp. 195–210.

Samadder, R.K., Kumar, S., Gupta, R.P., 2011. Paleochannels and their potential for artificial groundwater recharge in the western Ganga plains. J. Hydrol. 400, 154–164. https://doi.org/10.1016/j.jhydrol.2011.01.039.

Sathish, S., Elango, L., Rajesh, R., Sarma, V.S., 2011. Assessment of seawater mixing in a coastal aquifer by high resolution electrical resistivity tomography. Int. J. Environ. Sci. Technol. 8, 483–492. https://doi.org/10.1007/BF03326234.

Senthilkumar, S., Vinodh, K., Babu, G.J., Gowtham, B., Arulprakasam, V., 2019. Integrated seawater intrusion study of coastal region of Thiruvallur district, Tamil Nadu. South India. Appl. Water Sci. 9, 124. https://doi.org/10.1007/s13201-019-1005-x.

Shaji, E., Vinayachandran, N., Thambi, D.S., 2009. Hydrogeochemical characteristics of groundwater in coastal phreatic aquifers of Alleppey district. Kerala. J. Geol. Soc. India 74, 585–590. https://doi.org/10.1007/s12594-009-0172-z.

Shalev, E., Lazar, A., Wollman, S., Kington, S., Yechieli, Y., Gvirtzman, H., 2009. Biased monitoring of fresh water-salt water mixing zone in coastal aquifers. Ground Water 47, 49–56. https://doi.org/10.1111/j.1745-6584.2008.00502.x.

Shammas, M.I., Jacks, G., 2007. Seawater intrusion in the Salalah plain aquifer. Oman. Environ. Geol. 53, 575–587. https://doi.org/10.1007/s00254-007-0673-2.

Sharma, K.L., Rao, C.S., Chandrika, D.S., Nandini, N., Munnalal, Reddy, K.S., Indoria, A.K., Kumar, T.S., 2016. Assessment of GMean biological soil quality indices under conservation agriculture practices in rainfed Alfisol soils. Curr. Sci. 111, 1383. https://doi.org/10.18520/cs/v111/i8/1383-1387.

Sherif, M.M., Singh, V.P., 1999. Effect of climate change on sea water intrusion in coastal aquifers. Hydrol. Process. 13, 1277–1287. https://doi.org/10.1002/(SICI)1099-1085(19990615)13:8<1277::AID-HYP765>3.0.CO;2-W.

Shi, L., Jiao, J.J., 2014. Seawater intrusion and coastal aquifer management in China: a review. Environ. Earth Sci. 72, 2811–2819. https://doi.org/10.1007/s12665-014-3186-9.

Shirke, J.M., Krishnaiah, C., Panvalkar, G.A., 2005. Mapping of a palaeo-channel course of the Wainganaga River, Maharashtra. India. Bull. Eng. Geol. Environ. 64, 307–314. https://doi.org/10.1007/s10064-004-0263-4.

Shrivastava, G.S., 1998. Impact of sea level rise on seawater intrusion into coastal aquifer. J. Hydrol. Eng. 3, 74–78. https://doi.org/10.1061/(ASCE)1084-0699(1998)3:1(74).

Sindhu, G., Ashith, M., Jairaj, P.G., Raghunath, R., 2012. Modelling of coastal aquifers of Trivandrum. Procedia Eng. 38, 3434–3448. https://doi.org/10.1016/j.proeng.2012.06.397.

Singaraja, C., Chidambaram, S., Anandhan, P., Prasanna, M.V., Thivya, C., Thilagavathi, R., Sarathidasan, J., 2014. Hydrochemistry of groundwater in a coastal region and its repercussion on quality, a case study—Thoothukudi district, Tamil Nadu. India. Arab. J. Geosci. 7, 939–950. https://doi.org/10.1007/s12517-012-0794-0.

Singaraja, C., Chidambaram, S., Anandhan, P., Prasanna, M.V., Thivya, C., Thilagavathi, R., 2015. A study on the status of saltwater intrusion in the coastal hard rock aquifer of South India. Environ. Dev. Sustain. 17, 443–475. https://doi.org/10.1007/s10668-014-9554-5.

Singh, S.B., Veeraiah, B., Dhar, R.L., Prakash, B.A., Tulasi Rani, M., 2011. Deep resistivity sounding studies for probing deep fresh aquifers in the coastal area of Orissa. India. Hydrogeol. J. 19, 355–366. https://doi.org/10.1007/s10040-010-0697-7.

Soni, A.K., Pujari, P.R., 2010. Ground water vis-a-vis sea water intrusion analysis for a part of limestone tract of Gujarat Coast. India. J. Water Resour. Prot. 02, 462–468. https://doi.org/10.4236/jwarp.2010.25053.

Srinivas, Y., Aghil, T.B., Oliver, D.H., Nair, C.N., Chandrasekar, N., 2017. Hydrochemical characteristics and quality assessment of groundwater along the Manavalakurichi coast, Tamil Nadu. India. Appl. Water Sci. 7, 1429–1438. https://doi.org/10.1007/s13201-015-0325-8.

Strack, O.D.L., 1976. A single-potential solution for regional interface problems in coastal aquifers. Water Resour. Res. 12, 1165–1174. https://doi.org/10.1029/WR012i006p01165.

Sugio, S., Nakada, K., Urish, D.W., 1987. Subsurface seawater intrusion barrier analysis. J. Hydraul. Eng. 113, 767–779. https://doi.org/10.1061/(ASCE)0733-9429(1987)113:6(767).

Suhartono, E., Purwanto, P., Suripin, S., 2015. Seawater intrusion modeling on groundwater confined aquifer in Semarang. Procedia Environ. Sci. 23, 110–115. https://doi.org/10.1016/j.proenv.2015.01.017.

Surinaidu, L., Rao, V.V.S.G., Prasad, P.R., Sarma, V.S., 2013. Use of geophysical and hydrochemical tools to investigate seawater intrusion in coastal alluvial aquifer, Andhra Pradesh, India. Coastal Research Library. Springer, pp. 49–65 https://doi.org/10.1007/978-94-007-5648-9_4.

Surinaidu, L., Rao, V.V.S.G., Mahesh, J., Prasad, P.R., Rao, G.T., Sarma, V.S., 2015. Assessment of possibility of saltwater intrusion in the central Godavari delta region, Southern India. Reg. Environ. Chang. 15, 907–918. https://doi.org/10.1007/s10113-014-0678-9.

Sylus, K.J., Ramesh, H., 2015. The study of sea water intrusion in coastal aquifer by electrical conductivity and total dissolved solid method in Gurpur and Netravathi River basin. Aquat. Procedia 4, 57–64. https://doi.org/10.1016/j.aqpro.2015.02.009.

Sylus, K.J., Ramesh, H., 2018. Geo-statistical analysis of groundwater quality in an unconfined aquifer of Nethravathi and Gurpur river confluence. India. Model. Earth Syst. Environ. 4, 1555–1575. https://doi.org/10.1007/s40808-018-0488-z.

Terry, J.P., Falkland, A.C., 2010. Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands. Hydrogeol. J. 18, 749–759. https://doi.org/10.1007/s10040-009-0544-x.

Tomaszkiewicz, M., Abou Najm, M., El-Fadel, M., 2014. Development of a groundwater quality index for seawater intrusion in coastal aquifers. Environ. Model. Softw. 57, 13–26. https://doi.org/10.1016/j.envsoft.2014.03.010.

Uchiyama, Y., Nadaoka, K., Rölke, P., Adachi, K., Yagi, H., 2000. Submarine groundwater discharge into the sea and associated nutrient transport in a Sandy Beach. Water Resour. Res. 36, 1467–1479. https://doi.org/10.1029/2000WR900029.

Underwood, M.R., Peterson, F.L., Voss, C.I., 1992. Groundwater lens dynamics of Atoll Islands. Water Resour. Res. 28, 2889–2902. https://doi.org/10.1029/92WR01723.

Urish, D.W., McKenna, T.E., 2004. Tidal effects on ground water discharge through a sandy marine beach. Ground Water 42, 971–982. https://doi.org/10.1111/j.1745-6584.2004.tb02636.x.

van Camp, M., Mtoni, Y., Mjemah, I.C., Bakundukize, C., Walraevens, K., 2014. Investigating seawater intrusion due to groundwater pumping with schematic model simulations: the example of the Dar es Salaam coastal aquifer in Tanzania. J. African Earth Sci. 96, 71–78. https://doi.org/10.1016/j.jafrearsci.2014.02.012.

Vijay, R., Mohapatra, P.K., 2016. Hydrodynamic assessment of coastal aquifer against saltwater intrusion for city water supply of Puri. India. Environ. Earth Sci. 75, 588. https://doi.org/10.1007/s12665-016-5357-3.

Vijay, R., Khobragade, P., Mohapatra, P.K., 2011. Assessment of groundwater quality in Puri City, India: an impact of anthropogenic activities. Environ. Monit. Assess. 177, 409–418. https://doi.org/10.1007/s10661-010-1643-9.

Vyshali, Palchaudhury, M., Mahesha, A., 2008. Simulation of saltwater intrusion in the Pavanje-Gurpur basins of Karnataka. ISH J. Hydraul. Eng. 14, 49–60. https://doi.org/10.1080/09715010.2008.10514904.

Wang, J., Tsay, T., 2001. Tidal effects on groundwater motions. Transp. Porous Media 43, 159–178. https://doi.org/10.1023/A:1010634114160.

Werner, A.D., Gallagher, M.R., 2006. Characterisation of sea-water intrusion in the Pioneer Valley, Australia using hydrochemistry and three-dimensional numerical modelling. Hydrogeol. J. 14, 1452–1469. https://doi.org/10.1007/s10040-006-0059-7.

Werner, A.D., Bakker, M., Post, V.E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv. Water Resour. 51, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.

Yousif, M., Bubenzer, O., 2012. Perched groundwater at the northwestern coast of Egypt: a case study of the Fuka Basin. Appl Water Sci 2, 15–28. https://doi.org/10.1007/s13201-011-0023-0.

Yu, J., Li, Y., Han, G., Zhou, D., Fu, Y., Guan, B., Wang, G., Ning, K., Wu, H., Wang, J., 2014. The spatial distribution characteristics of soil salinity in coastal zone of the Yellow River Delta. Environ. Earth Sci. 72, 589–599. https://doi.org/10.1007/s12665-013-2980-0.

Zghibi, A., Tarhouni, J., Zouhri, L., 2013. Assessment of seawater intrusion and nitrate contamination on the groundwater quality in the Korba coastal plain of Cap-Bon (North-east of Tunisia). J. African Earth Sci. 87, 1–12. https://doi.org/10.1016/j.jafrearsci.2013.07.009.