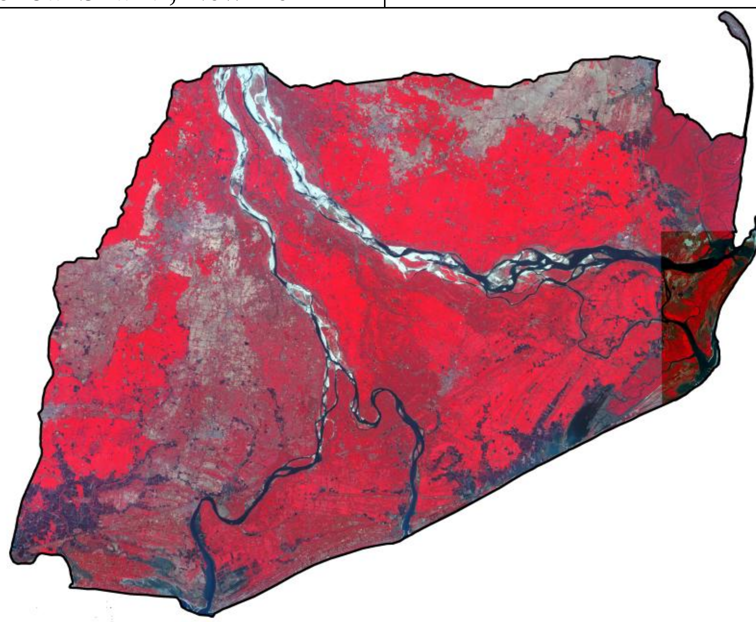
Groundwater salinity source identification in the Godavari delta, A.P.
(PDS No: SP-28/2017-18/PDS-13)

National Hydrology Project
Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, New Delhi

State Groundwater and Audit Department, Water Resource Department, Govt., of Andhra Pradesh



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PREFACE

Coastal aquifers are susceptible to regional and global phenomena, that includes sea-level rise, storm surges, changes in climatic conditions, shoreline erosion, and coastal flooding. Additionally, human activities are increasing the salinization process in coastal regions. The rivers and estuaries allow the natural inflow of seawater due to the backwater from the sea and make the surface water saline. The Godavari delta is a unique geomorphological unit with fertile soil and a dense network of irrigation canals. Unlike in other coastal regions, the recharge to the groundwater is from canal seepage than rainfall. Therefore, groundwater use is minimum in the Godavari delta, and all the mandals in the delta regions are under the safe category as per the Groundwater Estimation Committee norms. However, due to anthropogenic activities and climatic conditions, the groundwater salinity is slowly increasing over a period of time. The groundwater monitoring network in the delta was used for resource assessment and the network is mainly focused on the upland zone in the delta. After implementing the Hydrology Project, the monitoring network has been increased, and the coastal area is also being monitored in the delta. In this present work, the detailed analysis of the hydrochemistry and stable isotopes with a recent network of wells has been carried out, and the salinity zone maps have been prepared for shallow and piezometer well separately using water types and Cl/HCO_3 ratios. A total of five salinity zones have been identified in the Godavari deltaic region. The major salinity sources identified in these zones are evaporation and anthropogenic activities, especially the conversion of agricultural lands into aquaculture and other anthropogenic activities. This study is taken up as Purpose Driven Study (PDS) under Hydrology Project in collaboration with Andhra Pradesh State Groundwater and Audit department.

The study entitled ‘ Groundwater salinity source identification in the Godavari Delta, A.P is carried out by Dr.Y.R.Satyaji Rao, Dr. Sudhir Kumar, Sri. T. Vijay, Sri. R.Venkata Ramana of Deltaic Regional Centre, National Institute of Hydrology, Kakinada.

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Abstract

The groundwater quality in the Godavari delta, Andhra Pradesh has been evaluated in terms of salinity. It was found that the average salinity (EC) in shallow and piezometer wells has increased from 1664 to 2428 and 2515 µS/cm to 3606 µS/cm from the years 2005 to 2017 respectively. The surface water bodies mapping has been carried out using the Normalized Difference Water Index (NDWI) for the years 2005, 2009, 2014, and 2019 in the Godavari delta. The percentage of water bodies in the delta has increased from 13.6 to 21.17 from the year 2005 to 2019. These increased water bodies are compared with agriculture and aquaculture data and found that these changes are mainly due to aquaculture activities. A monitoring network of shallow wells (47) and piezometer wells (51) has been used to identify salinity zones in the Godavari Delta using water types and Cl/HCO_3 ratio (molar). The identified salinity zones are validated with the improved network of shallow wells (100) and piezometer wells (46) of the year 2020. Five salinity zones (Zone I to Zone V) have been identified in the Godavari delta. The stable isotope characteristics have helped to identify the salinity sources of each zone with the confirmation of hydrogeochemical evaluation. Zone I is classified as fresh water and recharge sources to the groundwater are canal seepage/precipitation. Zone II and Zone III are classified as slightly brackish and brackish respectively. The groundwater salinity in shallow wells is more when compared to piezometer wells in these two zones, this is mainly due to the impact of anthropogenic activities on shallow wells. Zone IV is identified as a saline zone, and the salinity source is the evaporation process for shallow and piezometer wells. Zone V is classified as high saline. Evaporation and marine clays are the dominant sources for the high salinity in the piezometer wells, however, there is not much evaporation in the shallow wells since rainfall is recharging shallow groundwater. The tritium data of shallow wells and piezometer wells further enhance the salinity sources in the Godavari delta.

Originating unit	Deltaic Regional Centre, National Institute of Hydrology, Kakinada, Andhra Pradesh
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1.0 INTRODUCTION

The need for freshwater from aquifers in coastal areas of India has increased manifold in recent decades. Many factors constrain groundwater quality in coastal aquifers, and a proper understanding of the quality aspects has a vital role in managing groundwater resources in coastal aquifers. Groundwater salinity is a significant challenge to the sustainable development of coastal regions, and it plays severe implications on water supply in rural areas and agricultural productivity. Groundwater salinity is one of the significant environmental challenges as the coastal areas are more susceptible to development due to the high density of the population and other anthropogenic activities (Barlow and Reichard 2010). Groundwater resources in semi-arid coastal areas are highly vulnerable to salinity problems from natural impacts such as rainfall variations, seawater intrusion, geogenic sources, evaporate dissolution, and by human influences such as the conversion of agricultural lands to brackish water fisheries, indiscriminate groundwater pumping leading serious consequences on environment of the region (Rina et al. 2013). The salinization processes of groundwater are the leading cause of the deterioration of groundwater quality, especially in the coastal areas of semi-arid/sub-humid regions where groundwater is the primary source for drinking and agricultural purposes (Srinivasamoorthy et al. 2014). The extent of salinization varies along the coast and in the deltaic areas. The main salinity processes for these variations are the uneven rainfall patterns, paleo-marine environment, geomorphological features, land use/cover changes, groundwater pumping, sea-level rise, reducing water bodies, backwater through creeks/drains/river mouths, downward seepage of saline water, polluted irrigation canal network, saline soils and hydro-geological conditions (Fakir et al. 2002; Fadili et al. 2015). In some coastal regions, the groundwater salinity is limited to a few specific zones or small parts of the shallow aquifer. While, the salinity is of a large to a regional extent in some other coastal areas, severely affecting the shallow and deeper aquifers. Due to these circumstances, the groundwater salinization processes in the coastal regions vary from location to location along the coast. The problem of increasing groundwater salinity in the Godavari delta, a coastal region of Andhra Pradesh state was first detected in the late eighties. The present investigations focused to find groundwater salinity zones (low and high) and to determine the actual causes for the salinity in the Godavari delta.

Over the years, the dynamic and inherent salinity in the shallow groundwater in the Godavari Delta has been a severe problem for managing potable water and agricultural productivity. In fact, in the Godavari delta region, utilization of groundwater for farming activities is very low as the delta has a dense network of irrigation canals and surface water bodies. The groundwater development is very low in the delta since shallow to deeper aquifers are brackish and saline in nature (CGWB 1999). According to Siddique et al. (2012), in the coastal regions, rice farms are the favored sites for conversion into aqua ponds because they pose several characteristics well suited for aquaculture. In this context, in the last two decades, paddy cultivation has been converted into fresh /brackish water aquaculture in the delta region. In recent years, there has been a significant increase in brackish water aquaculture in the Godavari Delta region, which may be a severe threat to the shallow groundwater for drinking needs and traditional agricultural practices (paddy/coconut cultivation) (Raju and Reddy 2013). Further, the surface water pathways such as river mouths, drains, and creeks are well connected with the sea which affects the shallow aquifer (backwater phenomena during high tides) at many coastal locations that render fertile agricultural land progressively saline. The sand mining and extreme hydrological events had further aggravated backwater into further inland.

Therefore the origin of salinity in the Godavari delta needs to be addressed systematically by studying many salinization processes which are mentioned above. Under these circumstances, an integrated approach was adopted to identify the salinity zones and the salinity sources in the Godavari Delta. Hence the Deltaic Regional Centre (DRC), National Institute of Hydrology (NIH), Kakinada has carried out a research project on ‘Groundwater Salinity Source Identification in Godavari Delta, Andhra Pradesh’, as a Purpose Driven Study (PDS) under National Hydrology Project (NHP) in collaboration with the Andhra Pradesh State Water Resources and Audit Department, Govt., of Andhra Pradesh. The project's main objectives are identifying groundwater salinity zones within the Godavari Delta, salinity source identification using an integrated approach, and possible remedial measures to control groundwater salinization in the Godavari delta.

2.0 REVIEW OF LITERATURE

The literature review within the Godavari delta region has been carried out to understand various hydrogeological, hydrogeochemical, and hydrological processes. Many researchers and government departments have studied multiple aspects related to the geology, soils, land use/land cover, agriculture, aquaculture, seawater intrusion, groundwater quality, hydrogeological processes, etc. of the Godavari delta. The published literature has been reviewed critically, and a few crucial findings are presented.

Nageswara Rao et al. (2017) studied the geochemical evolution of groundwater chemistry in the Godavari western delta region. The subsurface of the western Godavari delta region is covered by coarse sand with black clay (buried channels), black silty clay of recent origin (floodplain), and gray/white fine sand of modern beach sediment of marine source (coastal zone), including brown silty clay with fine sand (paleo-beach ridges). They highlighted that groundwater quality is controlled by rock weathering, mineral dissolution, evaporation, and ion exchange reactions. Anthropogenic and marine sources are also additional factors for brackish water quality. In the western delta region, they have also concluded that the initial quality of groundwater is of geogenic origin and has been subsequently modified by the influences of anthropogenic and marine sources.

Surinaidu et al. (2014) monitored groundwater levels at 42 locations in a part of the central Godavari delta (295 km^2) for a period of 2 years (2006–2007). They used groundwater flow modelling and calibrated hydraulic head for the year 2006 for steady-state and predicted the extent of subsurface seawater intrusion over the next 50 years. The estimated regional groundwater budget indicates a significant amount of groundwater outfall to the Bay of Bengal. The model predicted that seawater intrusion would not affect the study area at the present rate of groundwater exploitation near the coast.

Sreenivas and Reddy (2008) have established the Salinity-Sodicity relationships of the Kalipatnam drainage area in the western Godavari Delta. They confirmed that the soils of the Kalipatnam drainage area are saline-sodic. The linear regression equation between Sodium Absorption Ratio (SAR) and Electrical Conductivity (EC) indicates that sodium is the major cation contributing to salinity. Excess concentrations of sodium chloride present in the soil solution might contribute to lower pH values.

Karunya et al. (2016) analyzed 44 soil samples in the Kapileswarapuram mandal in the central Godavari Delta, which is about 50 km from the sea coast, to characterize waterlogging and salinity by using soil textural classification, soil chemical parameters, and groundwater table. They concluded that the soils in the study area are not having any salinity and do not require any remedy for soil salinization.

Surinaidu et al. (2012) investigated the salinity sources in a part of the central Godavari delta. The low resistivity values can be attributed to thick marine clays from the ground surface to 12–15 m below ground level near the coast. High resistivity values are due to coarse sand with freshwater away from the beach. The resistivity values are similar to saline water <0.01 Ω m and indicate the mixing of the saline water along surface water drains. In the Ravva Onshore Terminal, low resistivity values indicated up coning of saline water and mixing of saline water from the Pikaleru drain. The SO_4^{-2}/Cl^- and Na^{+2}/Cl^- ratios did not indicate saline water intrusion, and the salinity is due to marine paleo salinity, dilution of marine clays, and dissolution of evaporites.

Nageswara Rao et al. (2015) assessed the suitability of groundwater quality for drinking, irrigation, and industrial purposes in the western Godavari delta. The results of the chemical analysis of groundwater suggest that the quality of water is alkaline, low to high salinity, and hard to very hard. The trilinear diagram showed that groundwater is dominated by non-carbonate alkalis and mixed types. Because of the deterioration of groundwater quality, TH, Mg^{2+}, Na^+, Cl^- and SO_4^{2-} concentrations exceed their drinking water quality standards in most regions. The groundwater quality is not suitable concerning SAR, percent sodium (%Na^+), and Magnesium Hazard (MH), but they are safe concerning Residual Sodium Carbonate (RSC) and Permeability Index (PI) in some locations for irrigation.

Anand et al. (2017) studied groundwater quality in the central Godavari Delta. The study revealed that groundwater quality in the shallow aquifer is potable except in a small pocket around Katrenikona, Uppalaguptam, and Malikipuram, where the Electrical Conductivity (EC) is more than 3000 μS/cm at 25°C. The areas near the coast in Katrenikona, Malikipuram, Uppalaguptam, and I.Polavaram mandals have recorded chloride of more than 1000 mg/L during the post-monsoon season. Sakhinetipalli, Malikipuram, Razole, Katrenikona and Uppalaguptam, and I. Polavaram mandals show percent sodium above 60% during pre and post-monsoon seasons. The authors confirmed that the variation in electric conductivity also relates to the proximity to the sea. Hence, the suitability of the groundwater refers directly to the saline water mixing. They concluded that need to monitor a new fresh water-saline water interface by constructing purpose-built observation wells with predefined water quality monitoring parameters and depths.

According to the CGWB (2014) report, the EC values of shallow aquifer in the eastern Godavari delta are in the range of 650-5950 µS/cm, and western Godavari Delta is in the range of 926-15950 µS/cm. The maximum chloride value obtained in the shallow groundwater in the eastern Godavari Delta is 1631 mg/L with a mean value of 317 mg/L, and the maximum chloride value of western Godavari Delta is 4566 mg/L with a mean value of 934 mg/L. The EC value of deeper aquifers of the eastern Godavari Delta is as high as 19370 µS/cm, and the maximum EC value of deeper aquifers of the western Godavari delta is 6935 µS/cm. In the coastal plain of East Godavari district, some improvement in the groundwater quality has been observed, which may be due to the flushing of in-situ saline water with continuous irrigation by the Godavari canal for more than 100 years or by the river itself. These conclusions were made based on 18 groundwater samples in the eastern Godavari delta and seven in the western Godavari delta.

CGWB (2013a) has reported on the waterlogging conditions in the western delta region. He said that during the post-monsoon season, most of the canal command area in the western delta is under wet conditions. During the pre-monsoon, part of the area has water levels between 2.0 and 5.0 m bgl. It is evident in the region that the command area is either saturated or prone to waterlogging, and the site is also seasonally waterlogged. Excessive irrigation, flat topography, high rainfall, poor drainage, and soils are the factors that are responsible for the water logging in the delta. He has explained the groundwater salinity issues in the western delta. It is observed from groundwater exploration studies that the deeper aquifers of the delta region are brackish. Some western delta mandals such as Mogalturu, Narsapur, Kalla, Bhimavaram, and Elamanchali are affected by salinity and susceptible to tidal influence. Considering the prograding nature of the Godavari delta, it can be summarized that the poor quality water is mainly due to the depositional environment formation, waterlogging, intensive irrigation, tidal influence, and aquaculture practices also contribute to some extent.

CGWB (2013b) has reported that the shallow alluvial aquifers of the eastern delta exhibit a wide range of quality variations due to the deltaic nature of the deposits and drainage conditions. In alluvial aquifers in the east of the delta region, the deeper aquifers are invariably saline. The electrical conductivity varied from 372 to 7625 µS/cm at 25°C. Along the eastern delta coast i.e. at Kakinada, Jonnada and Vakalpudi, EC values are recorded at more than 3000 µS/cm at 25°C, whereas in the central part of the deltaic area, EC ranges are in between 1500 µS/cm and 3000 µS/cm at 25°C. It is also reported that waterlogging and salinity are the major problems in the eastern delta and coastal areas. Intensive irrigation, near-flat topography, low groundwater development, poor drainage, and clayey soils are responsible for waterlogging. The quality of groundwater varies widely from place to place, even within short distances, and the deeper aquifers are invariably saline. The salinity of groundwater is due to the geomorphic landform, waterlogging conditions, sluggish nature of groundwater movement and excess use of fertilizers, and unregulated growth of aquaculture in the coastal area.

Surinaidu et al. (2013) conducted Electrical Resistivity Tomography (ERT) surveys at several locations in the central deltaic region and delineated the aquifer geometry. The ERT results indicated that 12-15 m thick loamy sands exist from surface to subsurface, followed by 18-25 m thick clay layers. The thickness of clay increased towards the sea from inland. Low resistivity values indicate dense marine clays and freshwater resistivity. The elevated TDS, Na^+ and Cl^- are due to the dilution of clay minerals in the upstream areas, and the elevated values are due to seawater mixing along the drains in the downstream areas during the pre-monsoon. The quality is improving in the post-monsoon season. The molar ratios of Na^+/Cl^- (>0.86) and SO_4^{2-}/Cl^- (<0.05) in the pre-monsoon indicated a strong influence of seawater and in the post-monsoon increased Na^+/Cl^- and SO_4^{2-}/Cl^- (>0.05) indicated marine paleo salinity, dilution of marine clays and dissolution of evaporites. The high SO_4^{2-}/Cl^- in the post-monsoon was attributed to the dilution of groundwater salinity due to rainfall infiltration and irrigation return flows in the delta. The low Na^+/Cl^- ratios upstream of the delta are due to sand exposures and isolated freshwater lances in the perched aquifers.

Ramkumar (2003) has explained the progradation of the Godavari delta. The lower deltaic regime, and formation of barrier bar followed by lagoon and lagoon infilling lead to deltaic progradation over the sea. The growth rate has reached a standstill and is currently experiencing erosion. This erosion could be due to the combination of reducing river flow, rising sea levels, and subsidence (Ramkumar 1999). He highlighted that the sea level rise affects the coastal region whose degree varies geographically depending on wave and tidal climate, sediment supply, and geomorphic setting (Penland and Suter 1988). Since the Godavari delta has a primarily sandy coast, rising sea level triggers more significant erosion.

Surekha et al. (2015) evaluated groundwater quality in the East Godavari district using Water Quality Index. Moderate to high salinity was observed in nine mandals and partially in localized areas. Intensive irrigation, near-flat topography, groundwater development, poor drainage, and clayey soils are responsible for waterlogging. The brackish/ saline groundwater occurs in hydraulic contact with fresh groundwater in the deltaic and coastal areas. Groundwater quality varies widely from place to place, even within short distances, and in the deeper aquifers invariably saline.

Raju et al. (2013) have compared the irrigation canal waters of east and west Godavari deltas in Antarvedi and Kalavapudi areas that flourished with intensive aquaculture practices. Further, soil samples were collected from dried aqua pond regions and analyzed for various parameters to understand aquaculture's soil quality and impact on these areas. Aquaculture impact is more pronounced in the Kalavapudi area of West Godavari district than in the Antarvedi area of East Godavari district. All soil parameters like TDS, EC, nitrogen, potassium, sodium, sulfur, iron, manganese, zinc, and copper increased with the pond's age. Only pH is slightly less in the soils of the western Godavari delta than in the eastern Godavari delta. The possible reason is aquaculture in the study area of the western delta that was started much earlier, 25 to 30 years back, in comparison to the eastern delta, where it was started just 10-15 years back. So, the deposition of organic matter and other nutrients may be more in aqua ponds' bottom soils and leaching into groundwater.

Raju et al. (2014) have studied the alkalinity and hardness variation in groundwater samples of the East Godavari district due to aquaculture. It is observed that there is an increase in the concentration of sodium, and magnesium salts and a decrease in calcium and potassium salts from the summer to the rainy season in the study area. Large amounts of magnesium in the groundwater of the study area may be due to salinewater intrusion due to aquaculture, which may negatively impact the environment. They stated that the aquaculture ponds require mixing tube well water/creek water with fresh water for aquaculture activities. Due to this practice, the polluted water is discharged into the channels from the upstream aquaculture ponds, and the same water is used by downstream aquaculture ponds. This practice leads to increasing pollution to many folds in aquatic environments. The study also concluded that the groundwater quality is poor (very high Chlorides, TDS, EC, salinity, BOD, COD, ammonia, nitrates) and the quality is good in areas where the groundwater is free from salinity.

Satyaji Rao and Vijaya Kumar (2018) studied groundwater hydrochemistry in the central Godavari delta and found that the Electrical Conductivity of paleochannels is less than the groundwater. The paper presents the detailed hydrochemistry of canal water, drain water, and river water. The paleochannel water hydrochemistry indicated no significant seasonal change in paleo-channel water, and most of the samples are Ca-HCO_3 type. The recharge source to the significant paleo-channel was studied using stable isotopes ($\delta^{18}O$ and δD) in groundwater, rainwater, canal water, and river water. It is found that the recharge to the paleo-channel is mainly from river water and canal water than from rainwater. Optimum utilization planning of these limited fresh water resources in identified paleo-channel is of immense importance, and it is also necessary to protect its quality from anthropogenic activities.

Gurunadha Rao et al. (2013) studied the geochemical processes occurring in groundwater in the central Godavari delta and stated that rock-water interactions within the alluvial sediments influence the region. There is no groundwater pumping for irrigation elsewhere due to brackish water occurrence at shallow depths and salinity in the central Godavari deltaic region. The multiple salinization processes include the dilution of marine clays, return flow from irrigation water, and upcoming marine brines from the deeper parts of the aquifer. Ionic ratios using various combinations of chemical constituents have confirmed the salinity due to upcoming brines and dissolution of marine sediments.

A detailed hydrochemistry analysis has been carried out by Kumar and Rao (2018) in the rural and urban areas of Kakinada. The study indicated that high nitrate concentrations have been reported in many wells. It suggests that nitrate values are more elevated in the urban and agricultural regions. The physico-chemical parameters of water samples varied the permissible limits of standards in Kakinada rural areas. Potassium and magnesium are higher in all groundwater samples, and the wells which are nearer to the sea coast, salt creek, and drains have exceeded the desirable limits.

Nageswara Rao et al. (2017) have studied the geochemical evolution of groundwater in the western Godavari delta. The study concluded that groundwater quality is mostly brackish and very hard. The groundwater quality is controlled by rock weathering, mineral dissolution, evaporation, and ion exchange. The possible sources of groundwater ions are dolomite dissolution, calcium precipitation, plagioclase weathering, and other ferromagnesian minerals present in the sediments. The anthropogenic and marine origin are the supplementary factors for brackish water quality. The present study suggests that the original chemical composition has been affected by geogenic and subsequently modified by the impact of anthropogenic and marine sources.

Apart from the above literature review carried out within the Godavari delta, the following critical literature based on stable isotope characteristics and their techniques for interpreting the salinity variations of groundwater samples are also presented. Environmental tracers are useful for understanding groundwater recharge processes and source identification (Gonfiantini et al. 1998; Meredith et al. 2013). Tracers have been successfully used to understand the processes controlling solute transport in shallow aquifers (Runkel and Bencala 1995) and provide insights into catchment-scale solute cycling (Darracq et al. 2010). A robust linear relationship between $\delta^{18}O$ and δD around the world's precipitation is known as the Global Meteoric Water Line (GMWL), first defined by Craig (1961) and was later modified by Rozanski et al. (1993). Also from, the $\delta 18O$ and δD values of local or regional precipitation, a Local Meteoric Water Line (LMWL) or a Regional Meteoric Water Line (RMWL) can be established that might differ slightly from the GMWL due to local hydro-climatic conditions (Zhang and Yao 1998). Various LMWLs were developed by Kumar et al. (2020). The variations in isotopic compositions of water due to kinetic fractionation processes during evaporation result in heavy isotopic compositions in the residual waters (Hu et al. 2018; Sprenger et al. 2017). Dansgaard (1964) defined a relationship between δD and $\delta^{18}O$ (due to water evaporation), denoted by 'd', called deuterium excess (d or D-excess with the global average D-excess value being 10). D-excess value decreases due to evaporative processes and can be used to investigate the effect of evaporation (Huang and Pang, 2012) but unrelated to the isotopic composition of rainwater, waters with different δD and $\delta^{18}O$ values having the same D-excess value (Huang and Pang, 2012).

The literature review indicated that the two coastal districts (East Godavari and West Godavari districts) of Andhra Pradesh State cover the entire Godavari delta. The Godavari delta has been further bifurcated into three parts, they are western Godavari delta (in the West Godavari District), central Godavari delta (in the East Godavari District), and eastern Godavari delta (in the East Godavari District). Different researchers have carried out in situ field studies in the central, eastern, and western portions of the Godavari delta. These studies focus on soils, groundwater, and delta formations in the respective individual delta regions. Most of the studies conclude that there is no direct seawater intrusion in the delta, and most of the coastal areas are under saturated conditions. In all the studies, it was mentioned that salinity is one of the significant groundwater contaminants in the Godavari Delta. Minimal studies have been carried out on the entire Godavari delta in terms of rainfall, groundwater levels, and quality. It is also observed from the literature review, there is no historical water body mapping in terms of aquaculture and isotope characterization studies in the Godavari delta. The earlier salinity studies are limited to a few parts of the Godavari delta and therefore the proposed PDS study may fill the research gap on the salinization processes and its source identification in the entire Godavari delta in an integrated manner.

3.0 STUDY AREA

The river Godavari has made an extensive arcuate type of delta on the east coast of India, producing 35 km from the adjoining coast into the Bay of Bengal (Ahamed 1972). Godavari deltaic area consists of four parallel beach ridges located far behind the present coastline. The present-day delta is the Holocene in age and the third-largest delta of India after the Ganges and Mahanadi. Much of the coastal plain comprises Holocene-Pleistocene sediments (Sambasiva Rao and Vaidyanadhan 1979). The Godavari delta shows an accurate shape. The deltaic plain starts near Rajahmundry, and the Godavari river had divided into two branches: Vasishta and Goutami rivers. Both of these rivers show low sinuosity and braided character. The Vasistha Godavari River branches off into another river (near Gannavaram) as Vainteyam Godavari and Vasista Godavari continue until both rivers join into the Bay of Bengal. The meandering characteristic of these channels is linked with the tidal influence up to the Gannavaram aqueduct.

Similarly, the Gautami Godavari River also branches off into another river as Nilarevu river, and Gautami Godavari continues until both rivers join into the Bay of Bengal with smaller branches, i.e. Coringa, and Gaderu rivers showing meandering and a strong influence of tides. Hence Godavari river opens through several mouths, and thus, the Godavari delta consists of a broad belt of river-borne alluvium. At the mouths of all river distributaries, spits have formed. A few islands have also been formed naturally adjacent to the mouth of the Godavari river. The upper delta plain of the Godavari river is very extensive, developed essentially as a flood plain. There are only a few localized ponds or swamps. The lower delta plain is formed essentially near the Gautami Godavari River mouth, making up a 10 km wide belt. This zone has lagoons, tidal flats, and mangrove marsh affected by tides.

3.1 Location of the Godavari Delta

The Godavari delta region is located in the East Godavari and West Godavari districts of Andhra Pradesh State, situated on the east coast of India (Fig.1). The location of the Godavari river and its branches in the delta is shown in Fig.1. The Godavari Delta is located between $16^{0}20^{1}$ N to $17^{0}00^{1}$ N latitude and $81^{0}30^{1}$ E to $82^{0}20^{1}$ E longitude with its hydrological boundaries as the Kakinada Canal on the Eastern side, Enamadurru drain on the Western side and the Bay of Bengal on the Southern side. The delta region falls in eighteen Survey of India toposheet Nos. 65H1, 65H2, 65H5, 65H6, 65H7, 65H9, 65H10, 65H11, 65H13, 65H14, 65H15, 65L1, 65L2, 65L3, 65L5, 65L6, 65K4 and 65K8. The study area covers about 4485 km^2 and has 48 mandals. The length of the deltaic coastline is 152 km. The deltaic width is 120 km, and the deltaic plain slope is 0.0004. Four historical strandlines are marked on the Godavari delta (Fig.1).

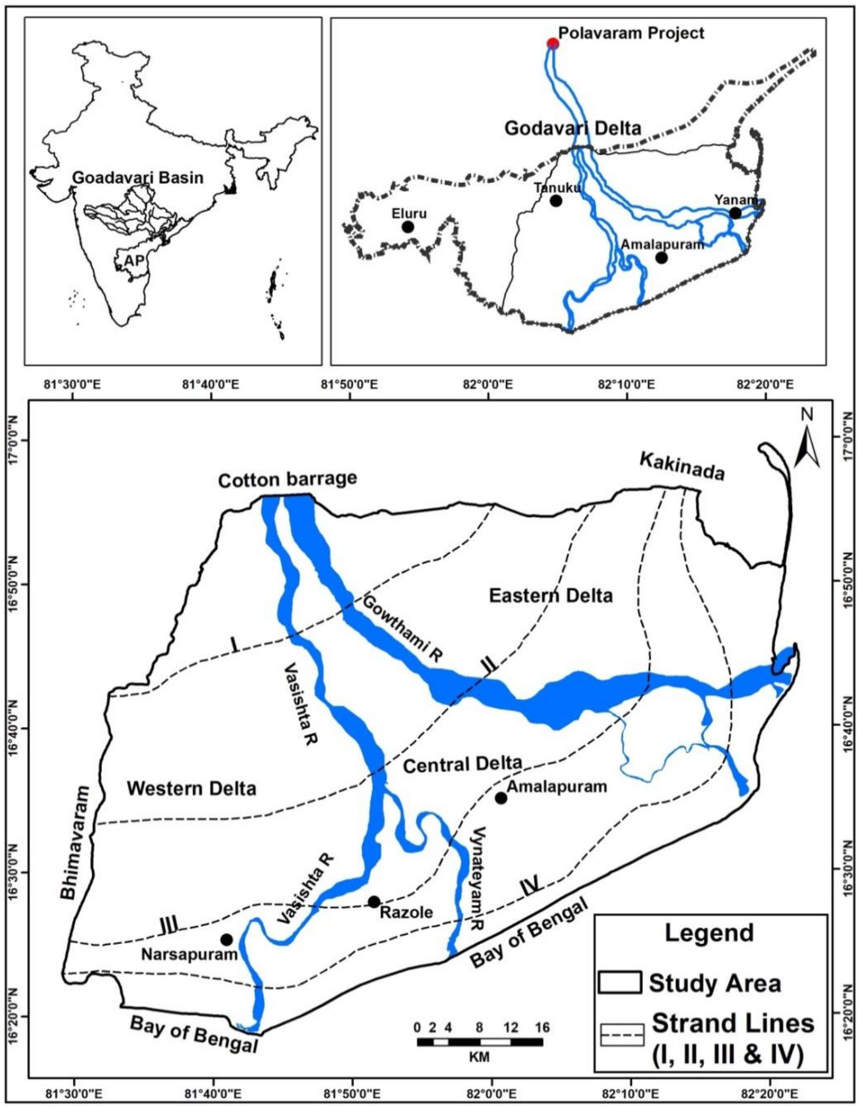


Fig.1 Location of the Godavari delta in Andhra Pradesh State, India

3.2 River and tidal influence

Significant discharges from the Godavari river commence in June and reach a maximum in August (Suryanayayana 1988). August and September are the months of peak discharge for the Godavari river (Sastry et al. 1971). Godavari river started discharges of significant sediments into the Bay of Bengal, thus initiating the delta-building processes during the quaternary. The study area experiences periodic flooding by the Godavari river (Gurunadha Rao et al. 2011). During periods of high river discharge, the influence of tides is recorded up to Yanam; though during low river discharge, tidal influence is recorded up to Kapileswarapuram, 45 km upstream from the Gautami river delta mouth. Thus, the deltaic distributary channels experience tidal influence up to about 45 km inland; while the plain area shows tidal influence up to 10 km inland from the coast. The river flow is regulated by a century-old Dowleswaram barrage near Rajahmundry town. Consequently, the Godavari estuarine system has negligible flow from the dam, due to which it acquires high salinity except during the high discharge period (Rengarajan and Sarma 2015).

3.3 Elevation of Godavari delta

The Digital Elevation Map (DEM) of the Godavari delta is prepared from satellite data (ALOS Pulsar data with 12.5 m resolution) and shown in Fig. 2. The general elevation of the Godavari delta varies from a few feet near the sea to a maximum of 18 m at the north portion. Regional topography varies from 2 to 7 m (amsl). It is flanked by upland crystalline terrain on the north. The study region has plain land, sloping gently (<3^0) toward the southeast.

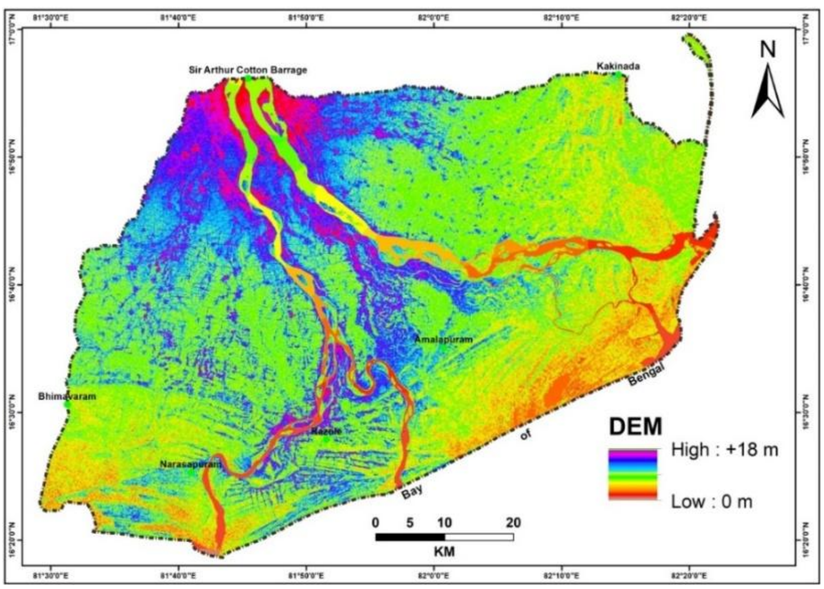


Fig.2 Digital elevation map of the Godavari delta

3.4 Drainage network

Irrigation drainage flows to the Bay of Bengal through different drains in the Godavari delta. The natural drains and creeks have been mapped from SOI topo sheets as well as satellite data and are shown in Fig. 3. The well-distributed Godavari irrigation canal network acts as a source of irrigation and drinking water throughout the year. These canals significantly help in reducing the native salinity of underlying marine clays due to the recession of the sea from inland to shore. The entire area is under the command of the Godavari Central Canal system, and the canal system remains operational for 11 months during the year with closure for one month for maintenance purposes. There are six major bridges across the various river branches to meet the local transport needs within the delta.

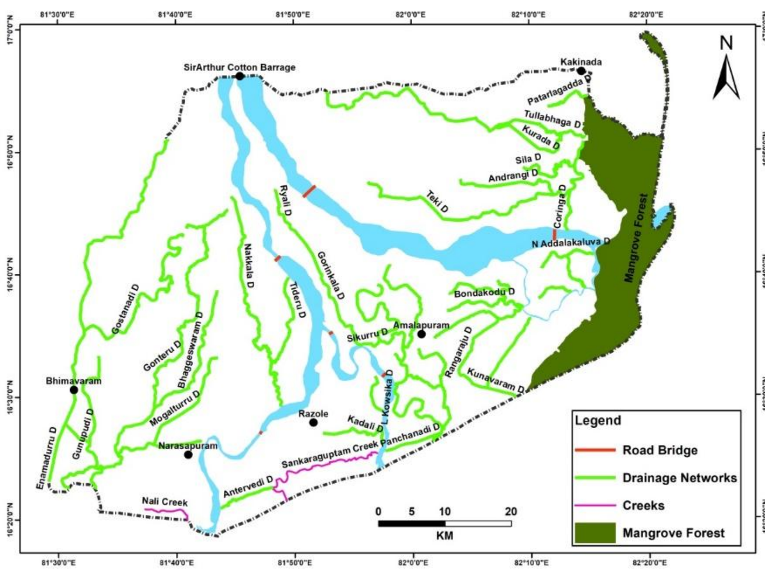


Fig. 3. Various drains and creeks in the Godavari delta

3.5 Climate and rainfall

The region experiences a humid tropical type. The temperature continuously increases from February to the hottest month (May) to between 33°C and over 45°C. Mean monthly humidity is 80% in the forenoon and 62% in the afternoon. The mean monthly wind speed ranges from 5.4 km/h in March to 12.7 km/h in July. The annual potential evapotranspiration is 1467 mm. The average yearly rainfall of the district is 1137 mm distributed unevenly over 57 rainy days annually. Most rain occurs during the southwest monsoon season (June–September), contributing about 72% of annual rainfall, while the rest occurs during the northeast monsoon (October–December). The area experiences seasonal floods every alternate year resulting in floods through the Godavari river (Surinaidu et al. 2013). The frequent cyclones have extreme weather conditions in the delta.

3.6 Agricultural activities

The principal crops are paddy, coconut, sugarcane, mango, and banana. Paddy is a major crop within the region and three crops are grown successively in a year. Fertilizers and pesticides are used very highly in this region. As ample surface water is made available to irrigate the delta, there has been little or not much use of groundwater in the deltaic area. The Godavari delta region provides an excellent opportunity for irrigated agriculture due to the availability of vast stretches of fertile arable land created by the river and coastal deltas (Surinaidu et al. 2012). Water is available in the canals throughout the year except between the last week of April and the second week of June. The use of fertilizers and pesticides is very high in this region.

3.7 Geomorphology of Godavari delta

The delta consists of two distinguished units as coastal alluvium and fluvial alluvium (Satapathy et al. 2007). The area has rich alluvial plains formed by the river Godavari and has a very gentle land slope of about 1 m/km (Bobba 2002). The quaternary sediments occupying the coastal track and inland river valleys include thick blankets of alluvium, gravel, and colluvial deposits, beach sand, kankar, and soils of various types. The fluvial deposits exist along the Godavari River. Geologically, the area is underlain by coarse sand with black clay (buried channels zone), black silty clay of recent origin (floodplain zone), and gray/white fine sand of modern beach sediment of paleo-beach ridges and active beach ridge of marine origin (coastal zone). Lithologs reveal that the top soil is followed by a sticky clay zone, fine sand zone, clayey zone, coarse to medium sand zone, and clay–silt zone (Nageswara Rao et al. 2017). The area has extensive tidal flats and inlets that receive seawater during high tides. The upper deltaic sediments are essentially fluvial, while those in the lower delta region are fluvio-marine sediments (GSI 2006). Silts and gravel beds are mixed with clay in varying proportions in the Godavari delta region. The thickness of alluvium varies from a few meters to more than 300 m, and it overlies Rajahmundry sandstones. The thickness of granular zones in the alluvium ranges from 18 to 258 m within the explored depths (CGWB 1999; Bobba 2000). Deltaic sediments of early Holocene age underlie the area with varying proportions of clay, silt, sand, and gravel with a gentle slope of 0.001 km/km toward the coast. The beach ridges are associated with delta progradation (Rengamannar and Pradhan 1961).

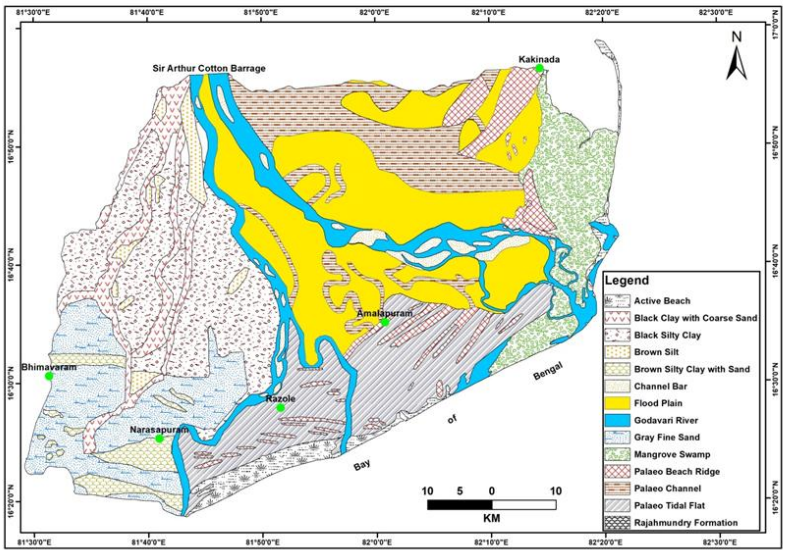


Fig. 4. Geomorphological features of Godavari delta (CGWB)

Significant landforms are valley fills, channels, levees, back swamps, channels, point bars of fluvial and active beaches, paleo-beach ridges, backwater and tidal flats, spits, mangrove swamps of marine origin (Rengamannar and Pradhan 1961; Nageswara Rao et al. 2005). The study area includes fluvial landforms such as channels, levees, back swamps, geologic floodplains, and landforms influenced by marine processes, such as tidal flats, beach ridge complexes, and mangrove swamps. The area is rich in Quaternary alluvial sediments derived from the Godavari river (Rao 1993; Bobba 2002). The geomorphological features of the Godavari delta are shown in Fig.4. A series of marine transgression and regression events have greatly influenced the depositional environments of the delta in the past. It was fluvial in the upper deltaic plain and the river courses. In the lower deltaic plain, towards the coast and other parts of the coastline, the fluvio-marine and fluvio-aeolian environments were dominant. Among the fluvial landforms, active channels (Gautami Godavari and Vasista Godavari) with associated braided/channel bars and levees form a part of the subaerial top-set beds of the delta. The concentrations of iron, manganese, sodium, and pH increase towards the delta, where they approach the marine environment. Calcium and magnesium distribution patterns are controlled mainly by shell fragments and clay minerals, particularly montmorillonite (Seetaramaswamy and Poornachandra Rao 1975). The coastal plain is of a prograding nature (advance towards the sea) and formed due to the shedding of sediment load by the Godavari river. The presence of sand bars and spits all along the shoreline of the coastal plain, lagoons, inland lakes, and tonal contrasts on satellite images due to the sedimentation process in the areas where river water enters the sea are clear indications of the prograding nature of the coast. Gaderu and Coringa rivers carry freshwater from the head of the bay in the south and from the west Kakinada canal. Salt-tolerant plants such as mangroves are distributed along abandoned distributaries and in areas near river mouths and adjacent lagoons. Thus, creeks and parts of the deltaic plain may contain an array of habitats in which mangrove colonies survived.

3.8 Soils of Godavari delta

There is primarily alluvial soil in the interior of the delta area and clayey soil at the tail portions of the Godavari river and red loamy soils in the upland delta. The central part of the area consists of sandy loams and sandy clay loams (GSI 2006). The delta region is occupied by loamy, sandy soils and underlined by thick clay beds of about 18–25 m, followed by coarse sands with saline water (Gurunadha Rao et al. 2011; Surinaidu et al. 2012). Kankar (concretion of $CaCO_3$) occurs in the soil zone. The soil map of the Godavari delta is shown in Fig.5.

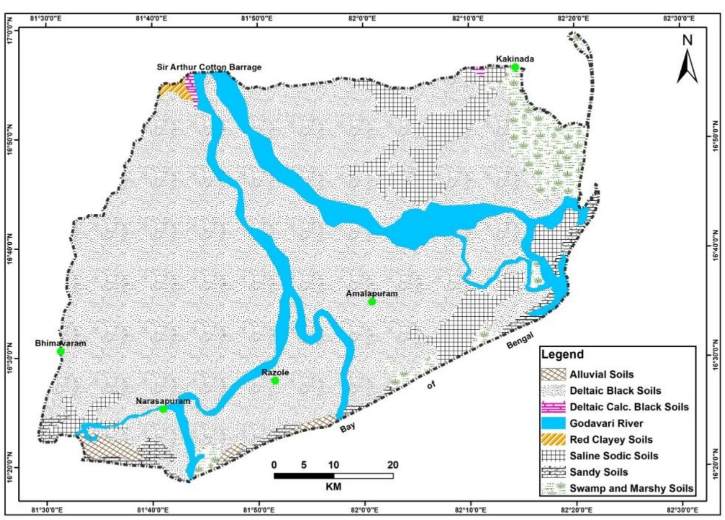


Fig.5 Soil map of Godavari delta

3.9 Occurrence of groundwater in the Godavari delta

Groundwater occurs under unconfined to semi-confined conditions (water table conditions) where impervious clay layers overlie the saturated granular zones. Extraction of groundwater is through open dug wells (10 m depth), filter point wells (10–30 m depth), and tube wells (30–60 m depth). Depth to water level varies from less than 1–22 m. Groundwater is tapped from shallow open wells with a depth range of 3–8 m and filter point wells penetrating up to 20 m depth. The depth to groundwater level (bgl) varies from 3 to 4 m. Near canals and drains, it was reported as <2 m. Permeability varies from 2 to 75 m/day with a specific yield of 0.05–0.2, and yield prospects are 100 m^3/h. The direction of groundwater flow is NW–SE, following the drainage. The shallow aquifer at 10–30 m and the deeper aquifer at 30–45 m. The 100-year-old canal network contributes significantly to groundwater recharge, thereby reducing the potential for saltwater intrusion into shallow aquifers (Chachadi and Teresa 2002; Gurunadha Rao et al. 2011; Surinaidu et al. 2013). The geophysical logs collected at Ravva On-shore terminal revealed that sandy clay is underlain by 45–55 m thick clay with fine sand followed by medium-to-coarse-grained sands up to a depth of 120 m below which clays saturated with saline water are found up to a depth of 143 m (Gurunadha Rao et al. 2011). The hydrogeology of the Central Godavari delta derived from borehole geophysical logs (at P.Gannavaram, Amalapuram, and Kandikuppa) is shown in Fig. 6.

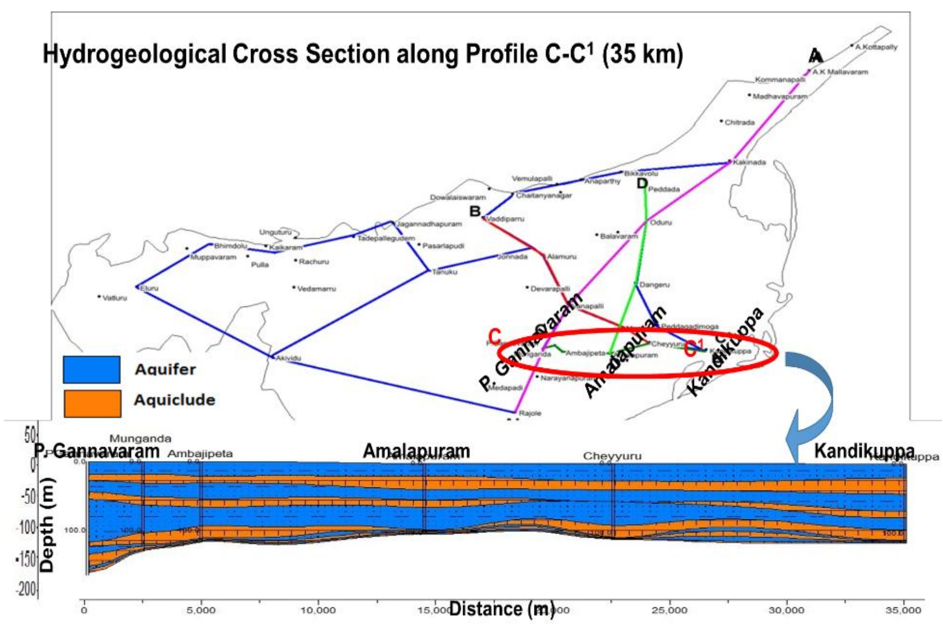


Fig. 6. The hydrogeology of the Central Godavari delta (CBWB, 2013)

4.0 METHODOLOGY

The groundwater salinization processes in the Godavari delta are studied systematically to identify the salinity zones and sources of groundwater salinity. The integrated methodology adopted in the present study is shown in the flow chart (Fig. 7).

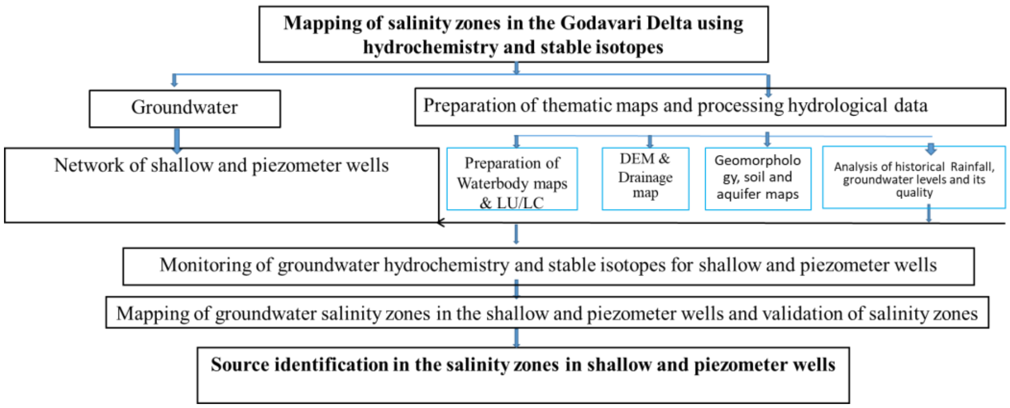


Fig. 7. Flow chart showing the methodology adopted for salinity source identification

4.1 Shallow and piezometer wells network of groundwater

The groundwater monitoring network of the Andhra Pradesh State Groundwater Department (APSGWD) covers shallow and piezometer wells in the Godavari delta. The depth of shallow wells ranges between 5 to 10 m, and the depth is between 10 to 30 m in piezometer wells. The network of these wells was increased during the period 2005–2020, and the objective of this monitoring network was to make groundwater resource estimates in each mandal and find contaminants in the groundwater. However, the importance of this monitoring network has increased exponentially to understand the impact of various anthropogenic activities and changes in land use/cover, seawater intrusion, climate change, and sustainable development. Recently the network of shallow wells has been increased to assess the impact of aquaculture in shallow wells in the Godavari delta. To determine the historical salinity changes in the Godavari delta, the groundwater levels and quality data from the year 2005 to 2020 have been obtained from the APSGWD.

4.2 Preparation of various thematic maps

To obtain the basic information about the Godavari delta, the toposheets falling under the study area are georeferenced and mosaiced in the GIS framework. The hydrological boundaries of the Godavari delta have been delineated with the help of topo sheets, satellite maps, and Google Earth Imagery. Digital Elevation Model (DEM) has been prepared using ALOS Pulsar data (12.5 m resolution). Land use/land cover maps have been prepared from LANDSAT 5 (30 m resolution) and IRS-LISS IV satellite data (5.8 m resolution). Geomorphology, soil, and drainage maps have been prepared from published maps from various sources in the GIS framework. Normalized Difference Water Index (NDWI) maps have been prepared for different years (2005, 2009, 2015, and 2019) using LANDSAT satellite images to find waterbody changes. The NDWI mapping helpful for the identification of the areas where the most significant shift in water bodies occurred over some time (Frazier and Kenneth 2000). The mandal boundary maps have been prepared to identify the field locations in the villages and ground truth verification. Each mandal has been assigned an Identification Number (ID), and the study area has been divided into the upland zone (ID: 1 to 25) and coastal zone (ID: 26 to 48).

4.3 Data collection and analysis of historical hydrological data

The collection of historical hydrological data is of utmost importance and essential to understand the groundwater salinity over the years in the Godavari delta. The recorded rainfall data from IMD, groundwater level, and quality data from APSGWD were collected for the historical data analysis. The saline zones are identified using EC, chloride and Cl/HCO_3 ratio with the help of historical groundwater quality data. Several visits were made to APSGWD district offices located in Rajahmundry, Kakinada in East Godavari district; Eluru in West Godavari district also its Head Office located at Vijayawada and collected the seasonal and temporal groundwater levels and groundwater quality data. These historical data have been analyzed to identify the salinity zones in the Godavari Delta. The historical EC values (average) for both shallow and piezometer wells are observed, and the initial findings of groundwater quality in the Godavari delta are noted. The locations of increased water bodies are identified. The NDWI maps for the different years are further compared with the rainfall, groundwater levels, and chloride concentration to understand the impact of water bodies on groundwater quality.

4.3.1 Impact of water bodies on groundwater salinity

The effect of change in waterbodies on groundwater salinity is studied with help of historical NDWI maps. After verification of the water bodies with associated features, ground truth, and other statistical information, these changes are mainly attributed to aquaculture. The effect of aqua ponds (in terms of their area in km^2) on shallow groundwater salinity in different mandals is identified. In addition to this, the impact of the recent aquaculture boom on the reduction of agriculture as well as on groundwater salinity is studied by considering the historical rainfall data, groundwater level, and groundwater quality data. The increased water bodies, the groundwater levels, the rainfall trends, and groundwater salinity during the 15 years (2005-2019) are studied to find the sources of shallow groundwater salinity. Conversion of agricultural lands into aqua ponds is studied in both upland and coastal mandals.

4.4 Criteria adopted for salinity zones

The geochemical evolution of the shallow and piezometer wells and its relationship with different dissolved ions can be understood by plotting the geochemical data on a Piper trilinear diagram (Chidambaram et al. 2011). Piper diagrams indicated the dominance of different cations and anions in the groundwater and major water types. The piper diagrams also suggest the major processes and hydro-chemical facies. However, a detailed recognition of facies evolution sequence during recharge and encroachment events is not possible with the Piper trilinear diagram (Ghiglieri et al. 2012). Therefore, the factors that influence the change in the chemical composition of groundwater are investigated graphically with the help of Chadda's plots. From Chadda's plots, four water types such as (i) Seawater mixing zone possibly represents the NaCl mixed seawater, (ii) base-ion exchange water which represents the Na-HCO_3 type of water, (iii) recharging water which indicates the Ca-Mg-HCO_3 type of water and (iv) reverse ion-exchange water (Ca-Mg-Cl type) is found. Thus, using both Piper and Chadda's diagrams, the major water types of each groundwater sample (shallow and deep) in the Godavari delta are found based on the dominance of different cations and anions.

The Simpson's ratio (molar ratio of Cl/HCO_3) is considered for the analysis of seawater mixing contamination into the fresh aquifer (El Moujabber et al. 2006). The ratio of $Cl/HCO_3 < 0.5$ indicates the sample is not mixing with seawater. The ratio $Cl/HCO_3 > 0.5$ indicates that the water sample is contaminated with seawater (slight to severe). The ratio Cl/HCO_3 ranges between 0.5-1.3, which indicates that groundwater is slightly affected by seawater. Samples having the ratio Cl/HCO_3 ranging between 1.3–2.8 indicate moderate contamination, and 2-8-6.6 indicates high contamination with seawater. The Cl/HCO_3 greater than 6.6 indicates that the groundwater is severely affected by seawater. The high and low saline zones of shallow wells as well as piezometer wells in the Godavari delta are identified using Piper trilinear diagram, Chadda's plot, and Cl/HCO_3 ratio (molar). Due to this, five types of salinity classifications are achieved by considering the water types and Cl/HCO_3 ratio. Finally, based on these classifications, the shallow and deep aquifer salinity zone maps for 2017 (post-monsoon) have been prepared. For the validation of these salinity maps, the salinity zones (obtained from the quality data of the year 2017) of both shallow and piezometer wells are further compared with the water quality data of the year 2020.

4.5 Salinity source identification using stable isotopes

The stable isotope data of $\delta^{18}O$ and $\delta^{2}H$ for shallow wells (104), piezometer wells (41), rainfall (3), seawater (2) have been collected. In-situ measurements for Temperature, pH, EC, and salinity were made in the field. The chemical analysis of all major ions, including bicarbonate (HCO_3^-), carbonates (CO_3^-), chloride (Cl^-), sodium, potassium, sulfates, and nitrates, have been carried out in the water quality laboratory of DRC, NIH, Kakinada. Further, samples were collected in acid-washed LDPE (Low-Density Polyethylene) Tarson bottles. These samples were transported to the National Institute of Hydrology laboratory, Roorkee. The ratios of heavy stable isotopes ($\delta^{18}O$ and δD) were measured at the Nuclear Hydrology Laboratory of the National Institute of Hydrology, Roorkee using a Dual Inlet Isotope Ratio Mass Spectrometer-DI IRMS (Isoprime GV instruments, UK) together with the use of automatic sample preparation units. For δD analysis, 400 µl of the water sample was equilibrated with ^{2}H and Pt catalyst at 40 °C for 3 h with gas induction into the mass spectrometer. The $\delta^{18}O$ of the sample was measured by equilibrating 400 µl of water with CO_2 gas at 40 °C for 7 h with induction of equilibrated gas into the mass spectrometer. The measured values are reported as delta (δ) values relative to VSMOW. The Gibbs diagrams representing the ratio of (Na+K)/(Na+K+Ca) and Cl/(Cl+HCO_3) as a function of TDS is used to understand the sources of dissolved chemical constituents, such as precipitation/rock/evaporation dominance in the study area.

5.0 RESULTS AND DISCUSSION

The total Godavari delta is around 6950 km^2 and has a coastal length of about 200 km. However, the Godavari delta, which is considered for the present investigations, is approximately 4485 km^2 having a coastal distance of about 152 km. The study area is bounded by Enamadurru drain on one side (right), the Kakinada canal on the other side (left), and the Bay of Bengal as the coastline (Fig. 1). Various thematic layers like DEM, soil, geomorphology, drainage, groundwater shallow and piezometer well network, etc. have been prepared for the study area. The mandal/block boundaries are superimposed on the delta, and then the delta has been classified into two zones, and the same is shown in Fig. 8.

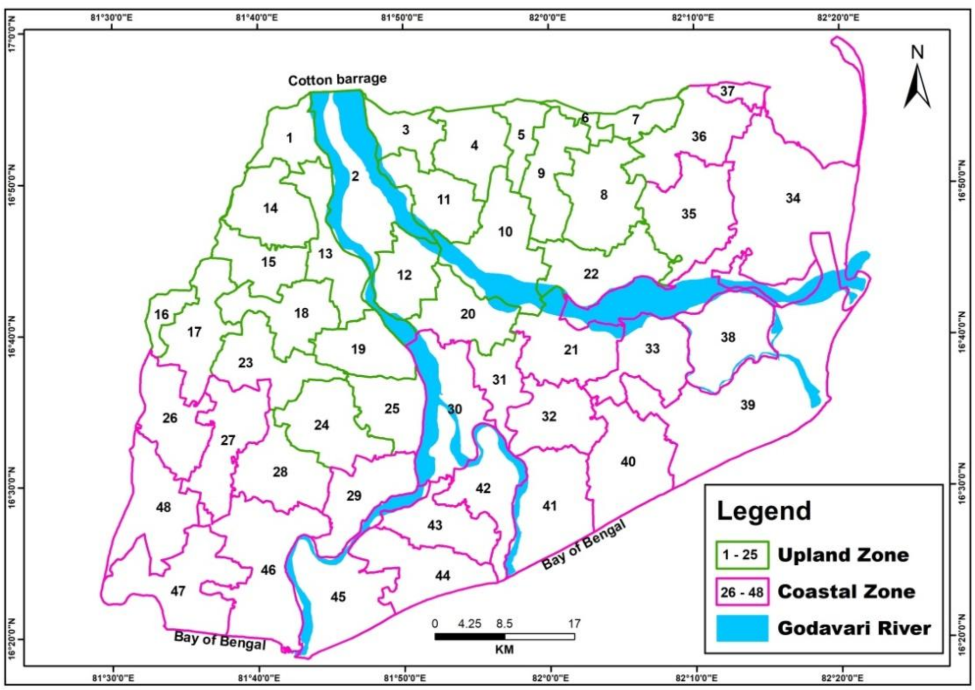


Fig. 8 Upland and coastal zones and their mandal IDs of the Godavari delta

One is the upland zone with 25 mandals (ID: 1 to 25), and the other is the coastal zone with 23 mandals (ID: 26 to 48). The coastal zone is having two set of mandals i.e., (i) the coastal mandals located adjacent to the sea coast (ii) the inland mandals which are adjacent to the coastal mandals. The criteria adopted for this coastal zone are due to the availability of the creeks, drains, the impact of the backwater, etc. These mandals have relatively low topographic slope (0-2 m) with thick marine clays. The rest of the inland mandals are treated as upland zone. The criteria adopted for this upland zone are due to the dense network of canals and agriculture practices (mostly paddy). The regional topographic slope is varying from 2-7 m with alluvium deposits in this zone.

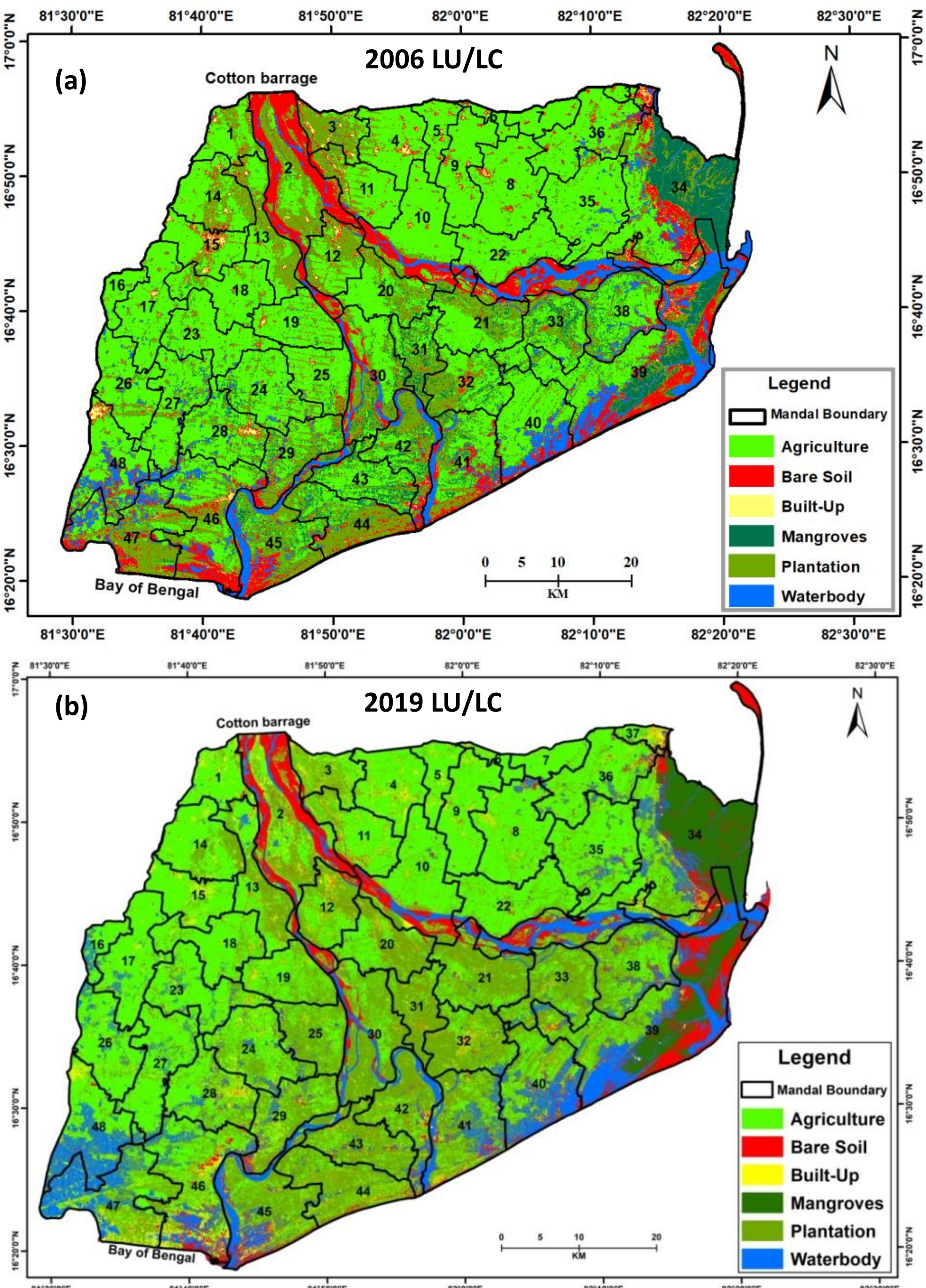


Fig 9. Land Use/Land Cover map of the year (a) 2006 and (b) 2019 in the post-monsoon season (November)

The land use/land cover (LU/LC) maps for the post-monsoon season of 2012 and 2019 (November) have been prepared for the Godavari delta using the LANDSAT 5 and IRS LISS IV satellite images respectively and the same is shown in Fig. 9. The area of each class (in km^2) and its percentage of the total geographic area are given in Table 1. The highest area of 48% and 42% is occupied by agriculture in the years 2006 and 2019 respectively with a decrease of 6%. This decrease is shown in the increase of water bodies (from 7.95 to11.78%) during the 15 years.

Table 1: The area covered in different LU/LC features of the Godavari delta in the years 2006 and 2019

Class Name	**2006**		**2019**	
	Area in km^2	**Percentage of the total area**	**Area in km^2**	**Percentage of the total area**
Agriculture	2166.53	48.30	1883.93	42.00
Bare Soil	485.58	10.83	330.84	7.38
Built-Up	38.36	0.86	211.88	4.72
Mangroves	339.38	7.57	187.21	4.17
Plantation	1098.89	24.50	1342.90	29.94
Water bodies	356.61	7.95	528.58	11.78
Total Area	4485.34	100	4485.34	100

5.1 Analysis of historical hydrological data

The collection of historical hydrological data is of utmost importance to understand the groundwater salinity over the years in the Godavari Delta. The hydrological data is mainly related to rainfall, groundwater levels, and hydrochemistry. The APSGWD has a monitoring network of shallow and piezometer wells separately in the Godavari delta with the average depth is 5 m and 23 m respectively. This network of observation wells (shallow and piezometer wells) varied over the years, and a few wells were discontinued due to various reasons. Therefore an attempt has been made initially to analyze the groundwater table and groundwater quality by fixing the same network of observation wells for the years 2005 and 2017 to find the temporal changes in the Godavari delta.

5.1.1 Decadal changes in groundwater Electrical Conductivity (EC) in the Godavari delta

The historical monitoring network of shallow and piezometer wells available with APSGWD has significantly increased during the 12 years (2005-2017) period. In the year 2005, a significantly lower number of shallow wells network (19) and piezometer wells network (18) is available with APSGWD (Fig.10). After implementing the Hydrology Project, this network has increased to 100 (shallow wells) and 17 (piezometer well) in 2020. It is observed that a very less number of wells (shallow and piezometer) are available near the sea coast in the year 2005.

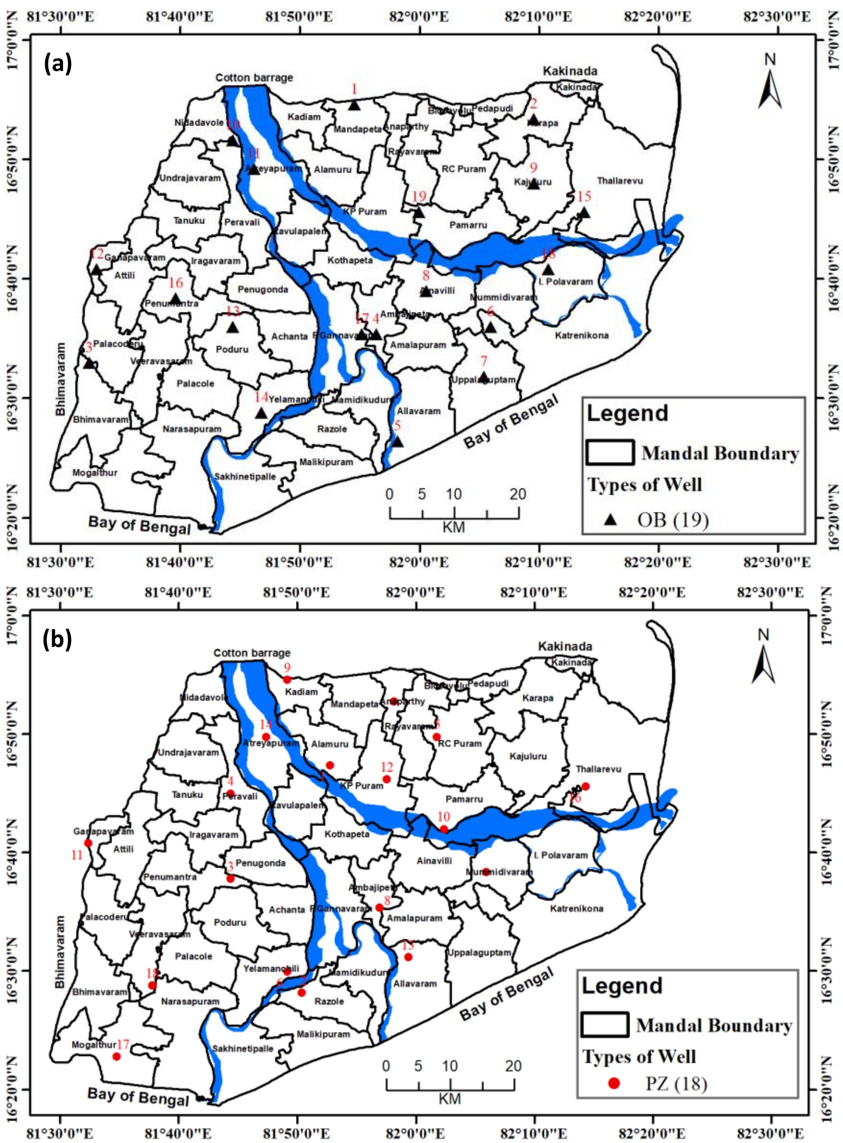


Fig. 10 Network of (a) Shallow and (b) piezometer wells in the year 2005

The depth of shallow wells is less than 8 m and that of piezometer wells is between 10 and 30 m below ground level (bgl), respectively. Fixed network of shallow wells (19) and piezometer wells (18) are considered and compared with the groundwater quality data for temporal analysis from the years 2005 to 2017. The locations of these wells are shown in Fig. 10. The comparison of average EC values for 2005 and 2017 is shown in Fig.11. It is observed from Fig.11 that, over the years, the average EC of shallow wells has increased from 1664 to 2428 µS/cm, and for piezometer wells, the average EC has increased from 2515 to 3606 µS/cm. It is observed from Fig.11 that on an average, the EC values of most of the shallow and piezometer wells are increased. Hence, it is indicated that the quality in both shallow and piezometer wells significantly changed from 2005 to 2017.

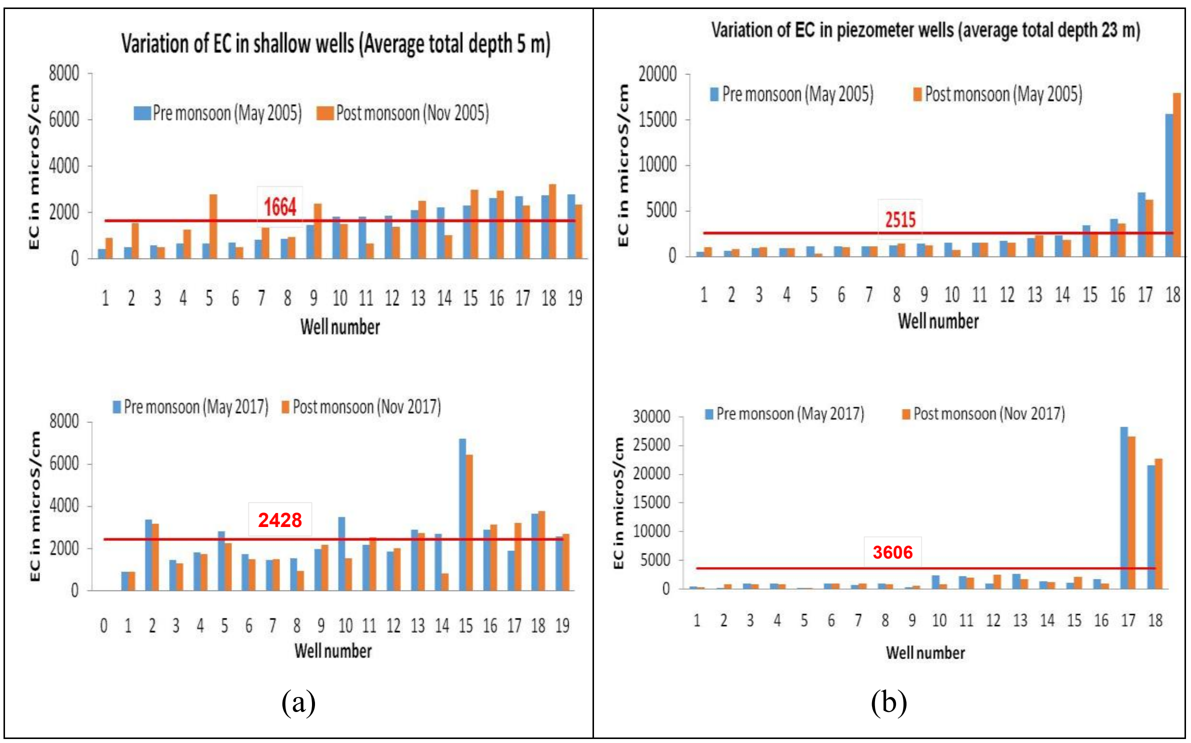


Fig.11 Comparison of average EC (2005 and 2017) in (a) shallow wells and (b) piezometer wells in the Godavari delta

5.1.2 Analysis of rainfall data (1973–2013)

The rainfall data is available only at two locations in the Godavari delta from 1973 to 2013 (IMD data). Mann Kendall (MK) test has been used for monthly and annual rainfall trend analysis. The yearly rainfall patterns of two locations (Bhimavaram (ID: 48) and Allavaram (ID: 41)) are shown in Fig. 12. These two locations are shown in Fig. 10. The MK test is performed on monthly and annual rainfall at two representative locations in the Godavari delta, and trends are given in Table 2. The monthly rainfall trend indicated that the onset and receding of monsoon are delayed in June and November, respectively. Unlike other months, these two peculiar behaviors of rainfall patterns are observed in these two months. These rainfall patterns are essential to understand the groundwater salinity issues in the Godavari delta. There is no significant change in the average annual rainfall patterns in the Delta. The lowest annual rainfall was observed in the year 2009 as 600 mm during the period 1973-2013.

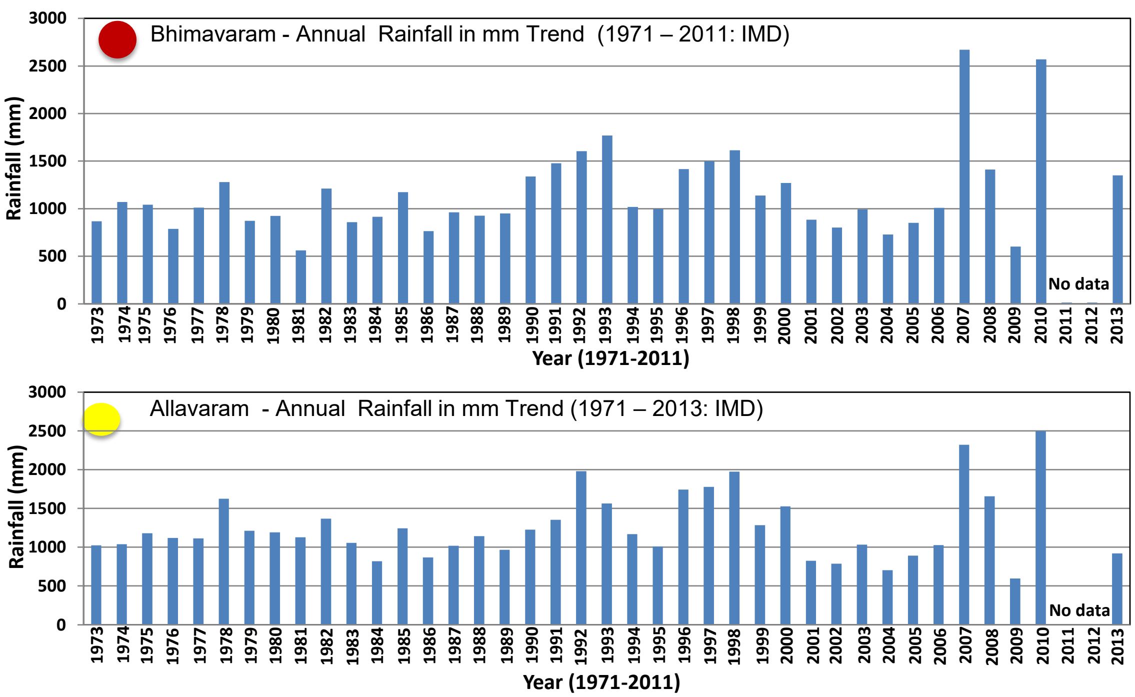


Fig. 12 Annual rainfall at Bhimavaram (Western delta) and Allavaram (Central delta) during the period 1973-2013

Table 2: Mann Kendall test of monthly and annual rainfall for the Bhimavaram and Allavaram locations

Location	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Bhimavaram	I	I	I	D	I	**D**	I	I	I	I	**D**	I	I
Allavaram	NC	NC	I	D	I	**D**	I	D	D	D	**D**	I	D
I – Increasing trend, D – Decreasing trend and NC – No Change													

5.1.3 Decadal changes in water bodies in the Godavari delta

The Normalized Difference Water Index (NDWI) maps have been prepared for the pre-monsoon (May) in the years 2005, 2009, 2014, and 2019 using LANDSAT satellite images. These maps are shown in Fig.13 (a,b,c,d) along with mandal IDs.

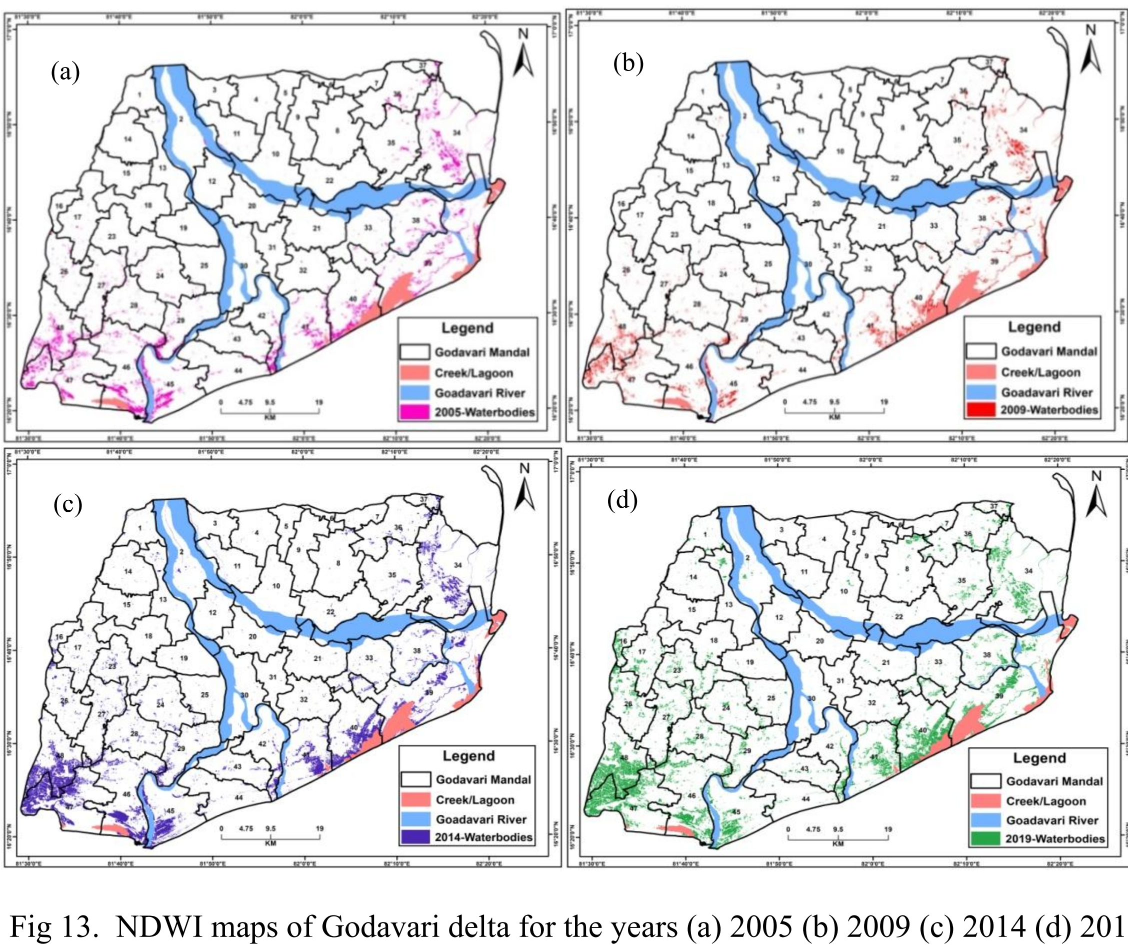


Fig 13. NDWI maps of Godavari delta for the years (a) 2005 (b) 2009 (c) 2014 (d) 2019

The water bodies in the entire Godavari delta have increased from 13.6% in the year 2005 to 21.17% in the year 2019. Hence it is observed that the water bodies of the Godavari delta are increasing, unlike in other watersheds/urban areas in the country. It is further noted that the percentage of water bodies increased in the upland zone (1 to 25 mandals) during fifteen years period (2005-2019) is 1.60% while in the coastal zone (26 to 48 mandals) is 5.97%. The details of the waterbody area along with the percentage in the coastal zone and upland delta zone are given in Table 3.

Table 3: Water body area and its percentage in the Upland and Coastal delta zones

Delta Zones	Zone area (km^2)	Waterbody Area in sq.km			
		2005	2009	2014	2019
Upland Zone	1860.00	36.60 (1.97%)	22.61 (1.21%)	53.03 (2.85%)	66.45 (3.57%)
Coastal Zone	2625.18	305.19 (11.63%)	249.46 (9.5%)	428.03 (16.3%)	462.06 (17.6%)

The mandal wise agriculture area was collected from A.P. agricultural department for the years 2012 and 2018. The reduction of the agricultural area in each mandal in the upland zone and the coastal zone is shown in Fig. 14 and Fig. 15, respectively. It is observed from Fig.15 that the highest conversion of paddy fields into aquaculture is taking place in the coastal zone of the western delta (Bhimavaram: 11.39%, Narasapuram: 10.43%, and Mogalthuru: 8.07%), followed by central delta (Uppalaguptham: 8.38% and Sakhinetipally: 7.1%).

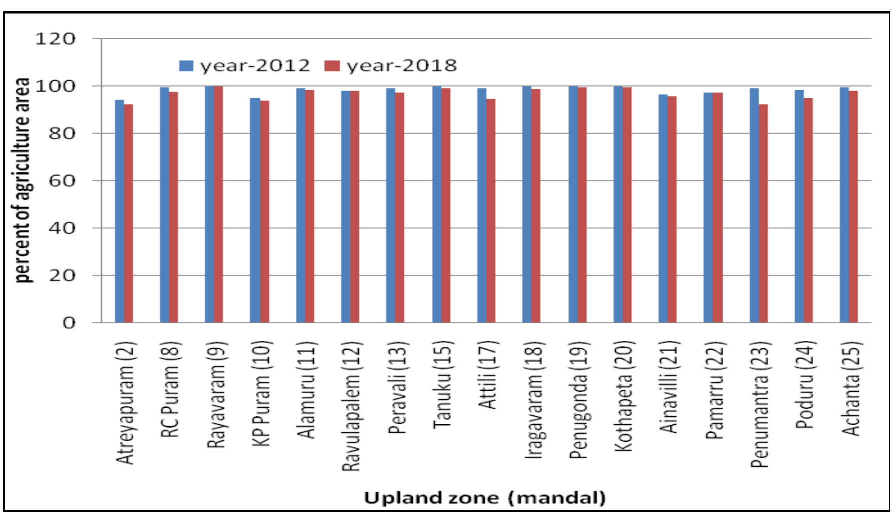


Fig.14 The reduction of agriculture area in each mandal (upland zone)

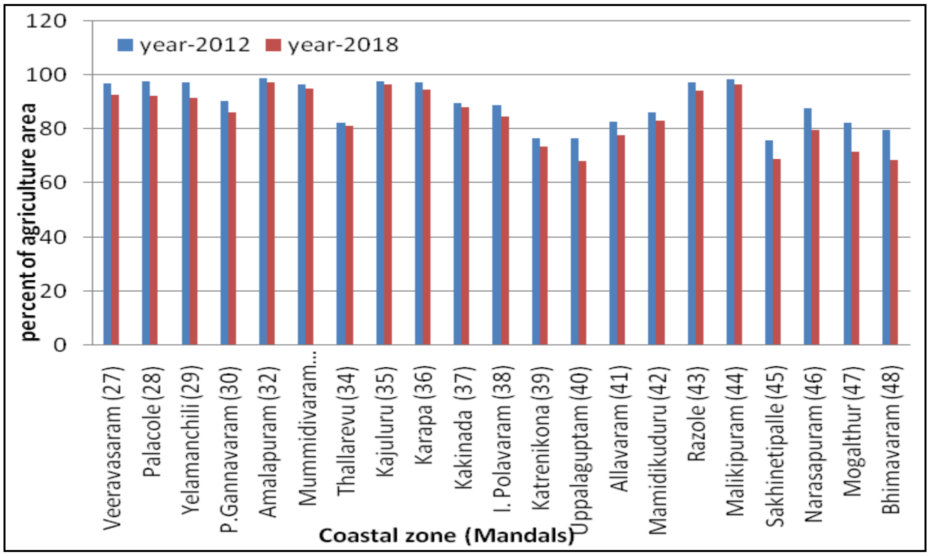


Fig.15 The reduction of agriculture area in each mandal (coastal zone)

However, the increase of water bodies during 2005-2019 is comparatively high in these 5 coastal mandals. The details of water bodies for these five mandals are listed in Table 4.

Table 4: Area of water bodies (km^2) with highest change mandals in the Godavari delta

Mandal (ID)	2005	2009	2014	2019
Bhimavaram (48)	13.44	9.71	32.54	36.77
Mogalthur (47)	16.03	11.68	38.64	39.39
Narasapuram (46)	23.38	10.56	34.19	34.61
Sakhinetipalle (45)	36.94	28.96	38.33	42.22
Uppalaguptam (44)	18.42	18.45	35.13	41.18

The increased water bodies in these mandals are compared with the aqua zonation maps of the Andhra Pradesh Space Application Centre (APSAC). It is identified that the increase in water bodies is mainly due to the increased aquaculture practices during these 15 years. It is also observed that the area of water bodies has decreased in the year 2009 throughout the Godavari delta as compared to the year 2005. This is due to the lowest annual rainfall in the year 2009 (600 mm). The mandals of increased water bodies during these 15 years in the coastal delta region are compared with the chloride (as salinity parameter), shallow groundwater levels, and annual rainfall. The variation of historical groundwater levels of shallow aquifer, rainfall, and groundwater salinity changes in three mandals (IDs 44, 45, 46) among the above-mentioned 5 mandals are analyzed and shown in Figs. 16 (a, b, c), 17 (a,b,c) and 18 (a,b,c), respectively to understand the impact of water bodies (fresh or brackish water aqua ponds) on groundwater quality. The decreased trend in the rainfall is observed in these three mandals and hence there is no impact of rainfall on water bodies. In Uppalaguptam mandal (ID: 44), the groundwater salinity (Cl) has increased and the groundwater table has raised (Fig.16a and 16c). This may be due to the creek water/ backwater utility in aquaculture. However, the groundwater levels have declined [17(a)] and groundwater salinity (chloride) has increased [17(c)] in the Sakhinetipally mandal (ID 45). The pumping of deep groundwater for the aqua ponds may be the cause for the increased salinity in this mandal. A similar phenomenon is also observed at Bhimavaram (ID: 48) and Mogalthur (ID: 47) mandals. In the case of Narasapuram mandal (ID: 46), the groundwater salinity (Cl) is decreased (Fig. 18c), and the groundwater table is raised (Fig 18a). It is mainly due to the fresh water fish culture by using canal water.

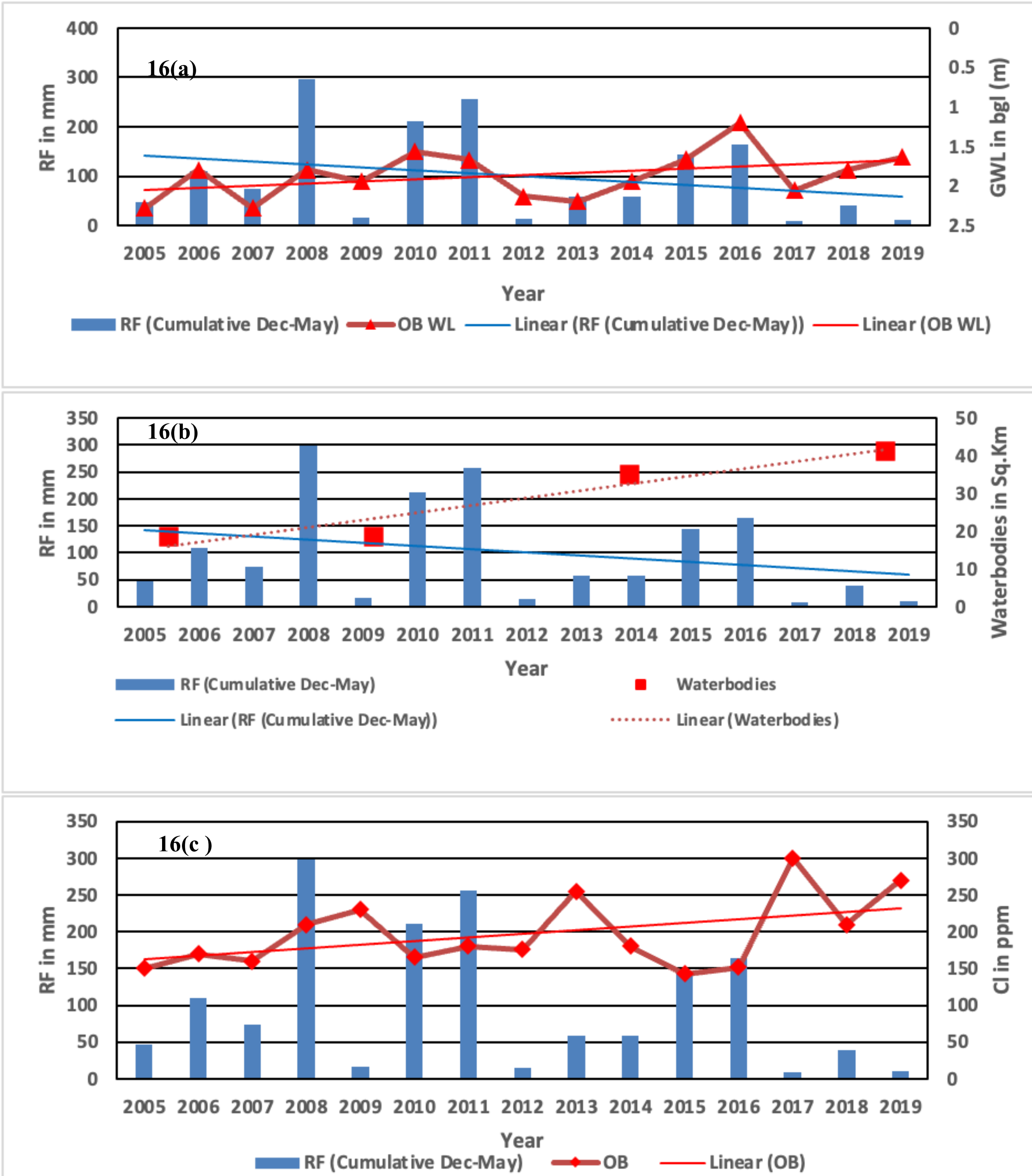


Fig.16 (a) The variation of groundwater levels (shallow wells), 16(b) water bodies, 16(c) salinity (Cl) with rainfall during the period 2005-2019 in the Uppalaguptham mandal (ID:44)

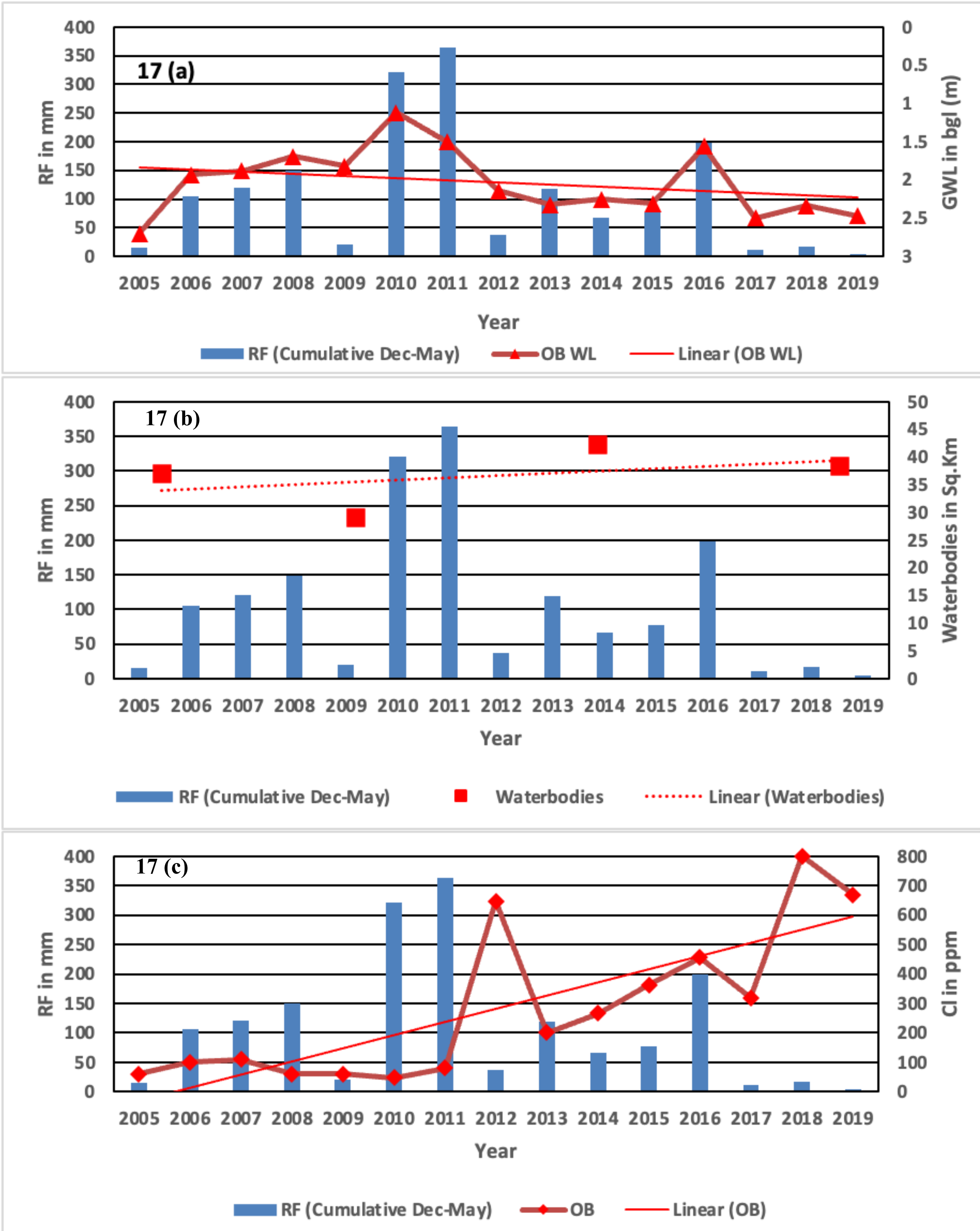
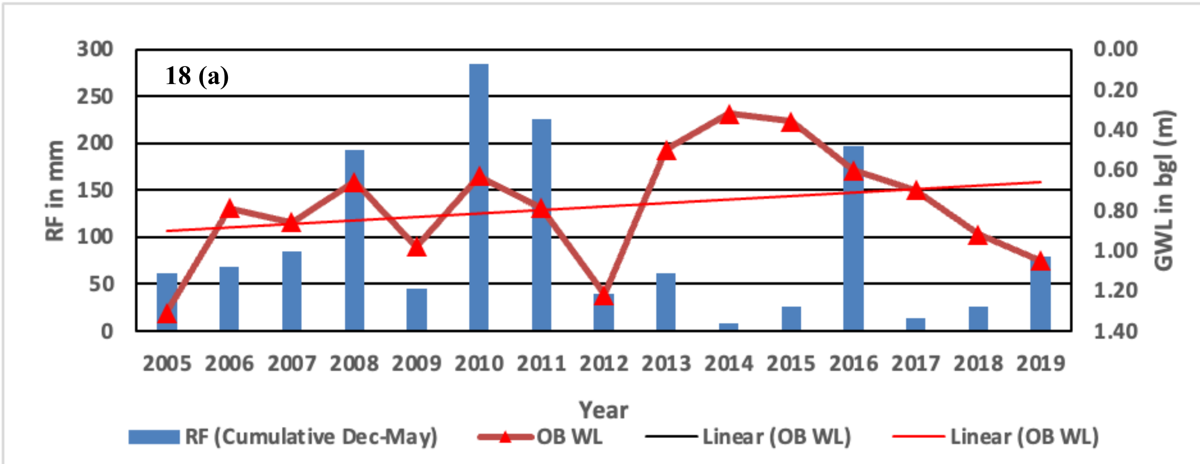
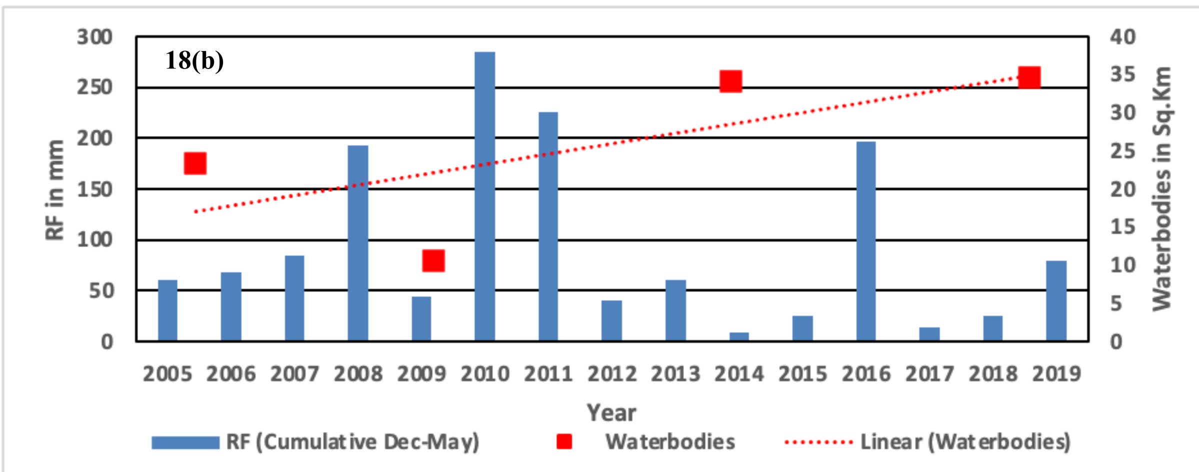


Fig.17 (a) The variation of groundwater levels (shallow wells), 17 (b) water bodies, 17 (c) salinity (Cl) with rainfall during the period 2005-2019 in the Sakhinetipally mandal (ID: 45)





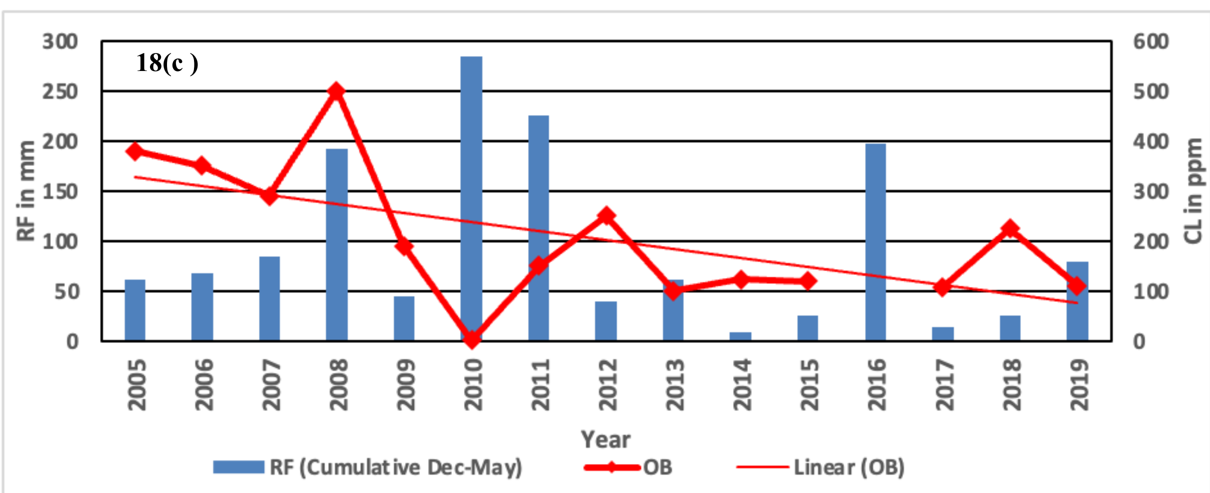


Fig.18 (a) The variation of groundwater levels (shallow wells), 18 (b) water bodies, 18 (c) salinity (Cl) with rainfall during the period 2005-2019 in the Narasapuram mandal (ID:46)

5.2 Assessment of seasonal changes in groundwater levels and quality

In the year 2017, a total of 47 shallow wells and 51 piezometer wells were available with the APSGWD and are shown in Fig. 19. The average depth of shallow and piezometer wells is 5 m and 23 m respectively (Fig. 20).

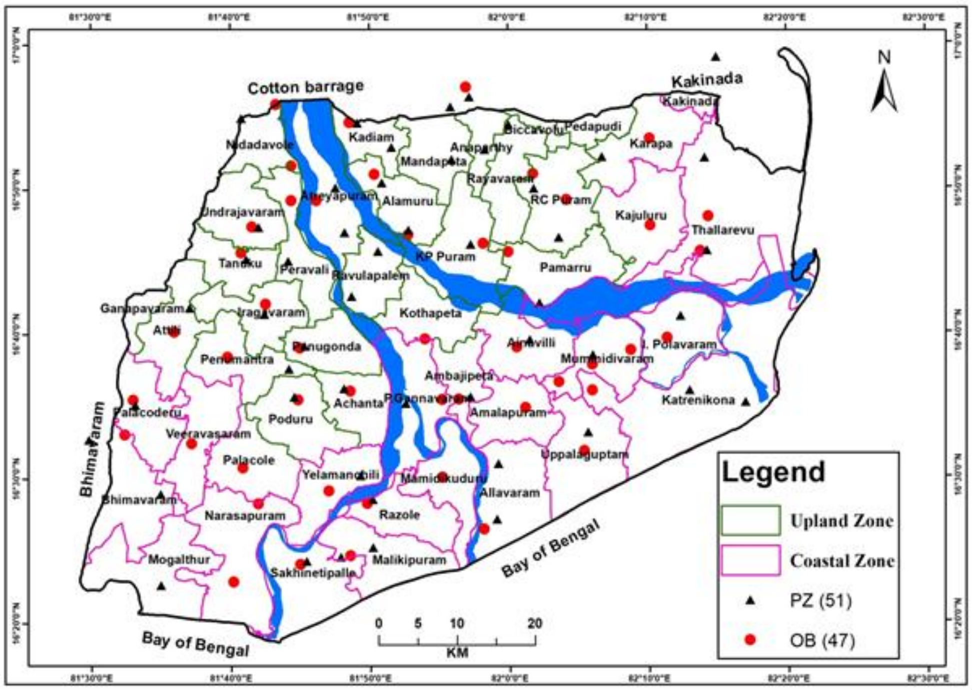


Fig. 19 Locations of shallow and piezometer wells in the year 2017

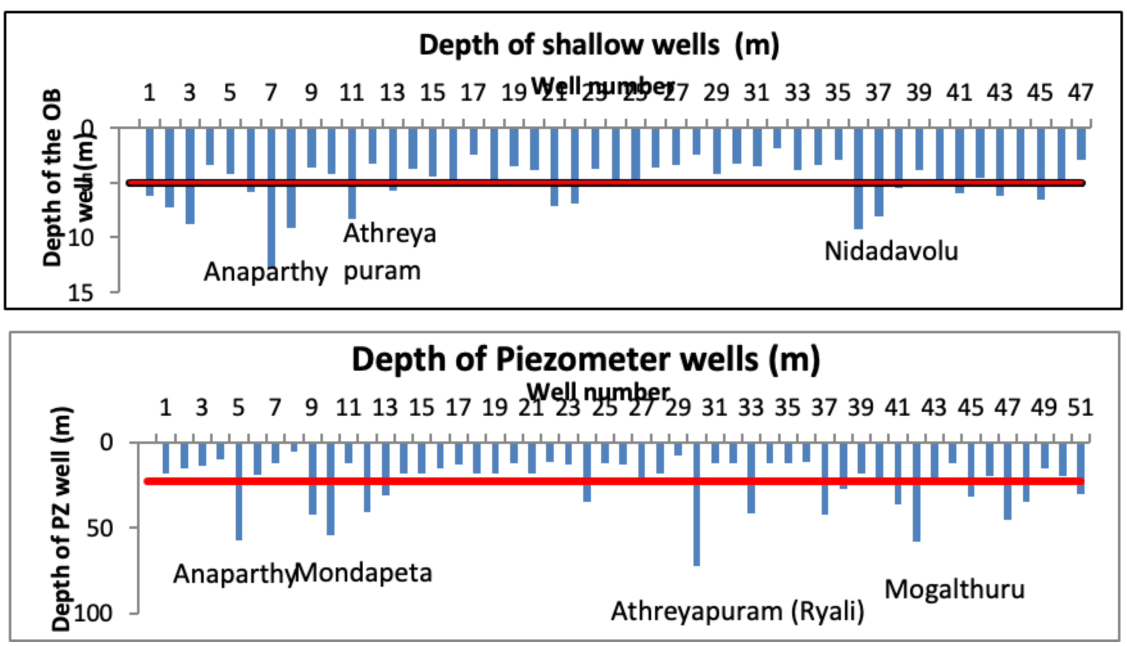
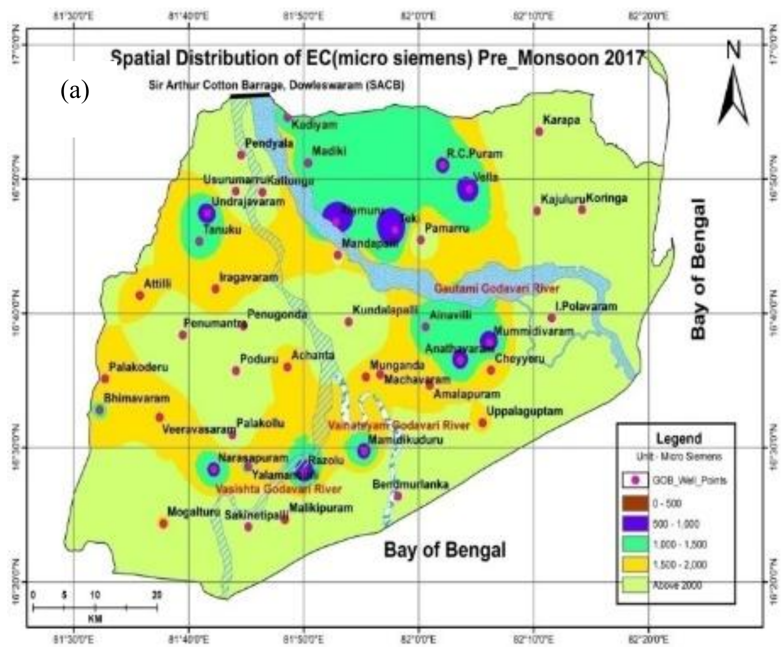
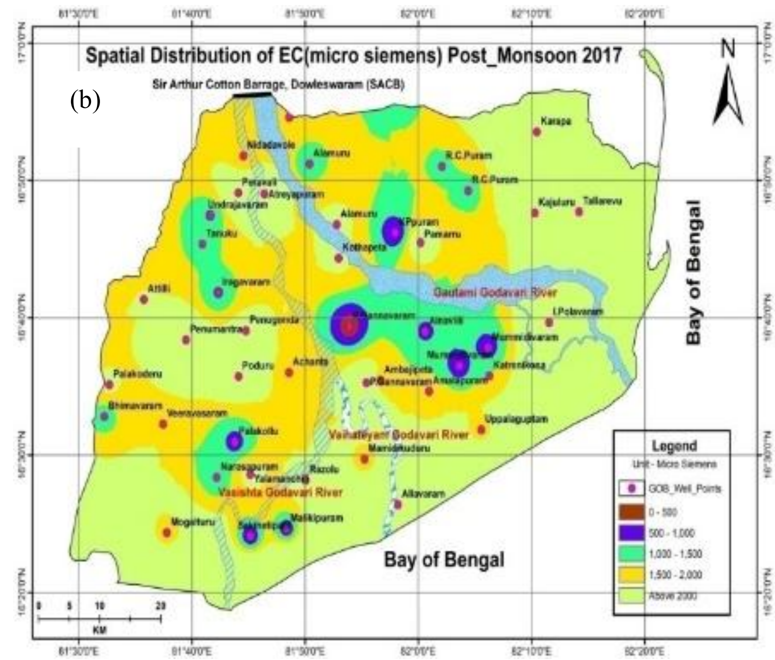
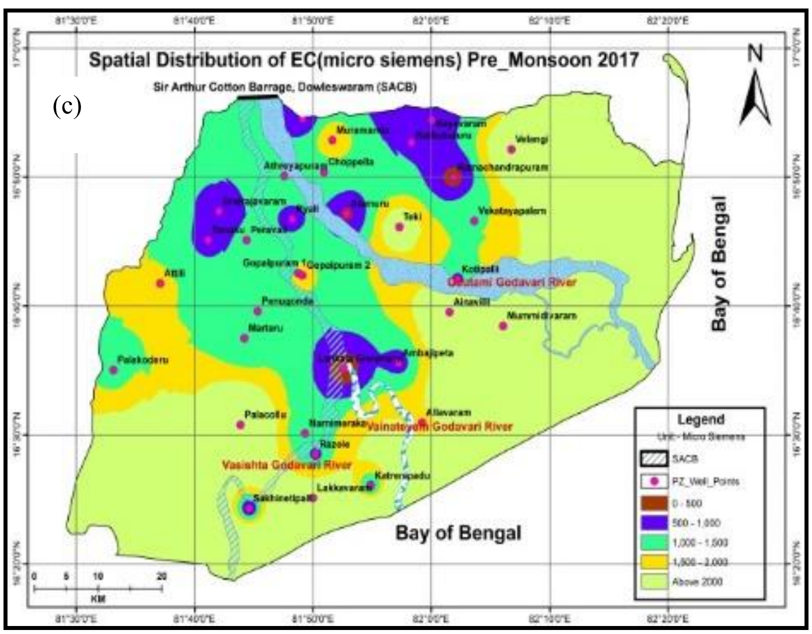


Fig.20 Depths of each shallow and piezometer well in the Godavari delta

For the initial understanding of salinity, the EC contour maps of pre and post-monsoon seasons have been prepared for shallow [Fig. 21 (a), (b)] and piezometer wells [Fig. 21 (c), (d)] in the Godavari delta. Primarily it is understood that all along the coast and in a few pockets of the upper and middle delta, EC values of more than 2000 µS/cm are observed in both shallow and piezometer wells (Fig. 21). Groundwater table contour maps of shallow and piezometer wells are also plotted for the year 2017 (pre and post-monsoon) and are shown in Fig. 22. The spatial analysis maps of EC and groundwater levels indicated significant seasonal changes in shallow and piezometer wells. It is observed that, on average, a 1 m rise (0-3 m contour) of the water table has been observed from the pre to post-monsoon period in shallow and piezometer wells.




Spatial Distribution of EC(micro siemens) Post_Monsoon 2017
Sir Arthur Cotton Barrage, Dowleswaram (SACB)
(b)
N
Gautami Godavari River
Vainateyam Godavari River
Vasishta Godavari River
Bay of Bengal
Bay of Bengal
Legend
GOB_Well_Points
0 - 500
500 - 1,000
1,000 - 1,500
1,500 - 2,000
Above 2000
KM


Spatial Distribution of EC(micro siemens) Pre_Monsoon 2017
Sir Arthur Cotton Barrage, Dowleswaram (SACB)
(c)
N
Gautami Godavari River
Vainateyam Godavari River
Vasishta Godavari River
Bay of Bengal
Bay of Bengal
Legend
SACB
PZ_Well_Points
0 - 500
500 - 1,000
1,000 - 1,500
1,500 - 2,000
Above 2000
KM

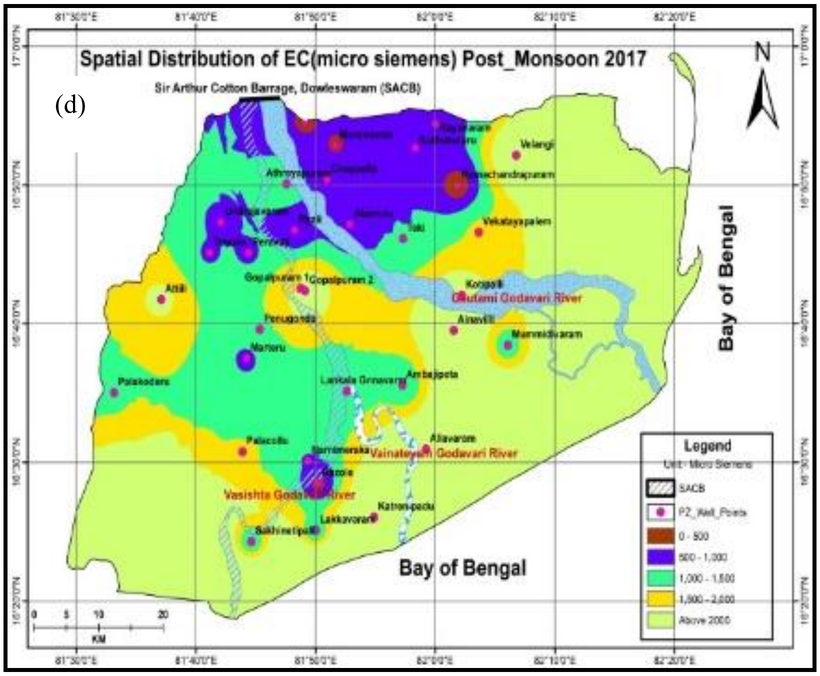
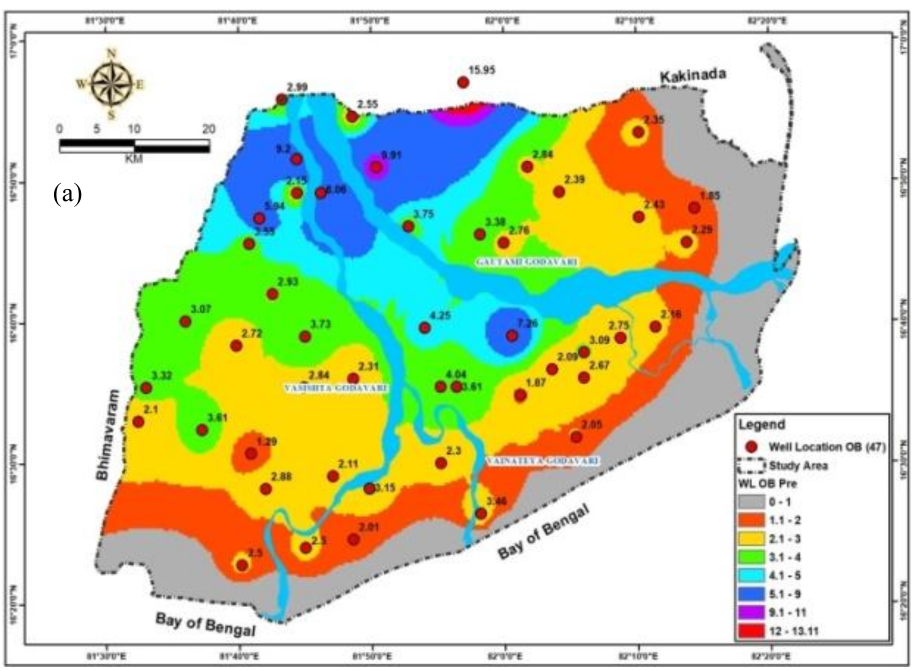
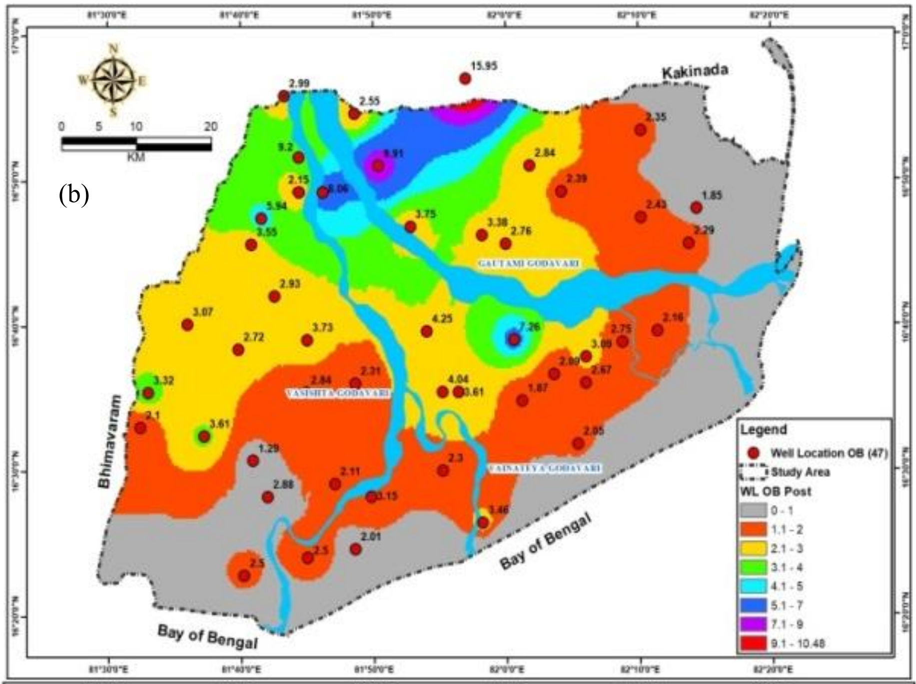
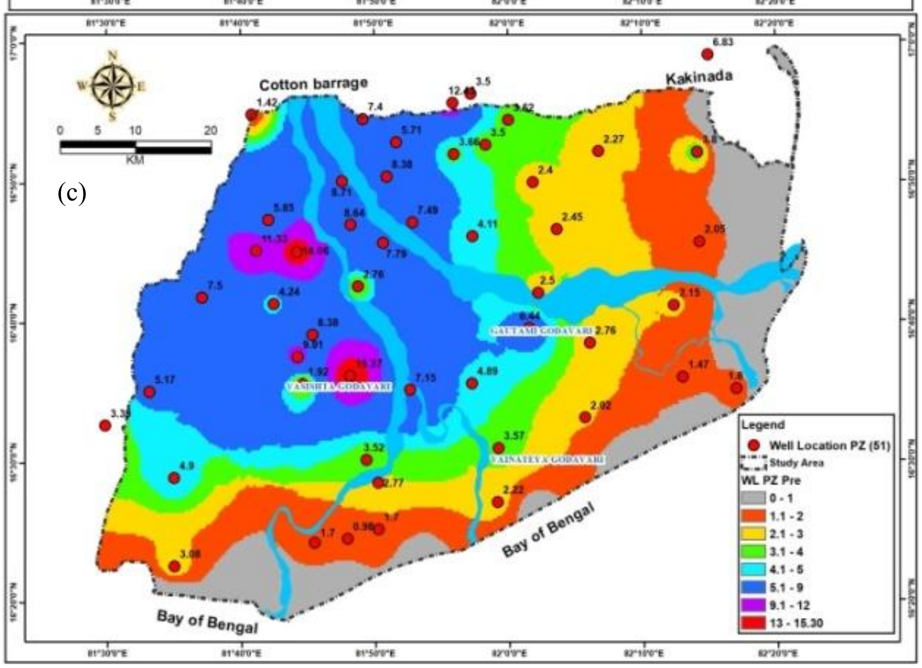


Fig. 21 Spatial distribution of Electrical Conductivity in shallow wells in (a) pre (b) post and piezometer wells in (c) pre (d) post monsoon seasons




(b)
Kakinada
0 5 10 20
KM
GAUTAMI GODAVARI
VASISHTA GODAVARI
VAINATEYA GODAVARI
Bhimavaram
Bay of Bengal
Bay of Bengal
Legend
Well Location OB (47)
Study Area
WL OB Post
0 - 1
1.1 - 2
2.1 - 3
3.1 - 4
4.1 - 5
5.1 - 7
7.1 - 9
9.1 - 10.48


(c)
Cotton barrage
Kakinada
0 5 10 20
KM
GAUTAMI GODAVARI
VASISHTA GODAVARI
VAINATEYA GODAVARI
Bay of Bengal
Bay of Bengal
Legend
Well Location PZ (51)
Study Area
WL PZ Pre
0 - 1
1.1 - 2
2.1 - 3
3.1 - 4
4.1 - 5
5.1 - 9
9.1 - 12
13 - 15.30

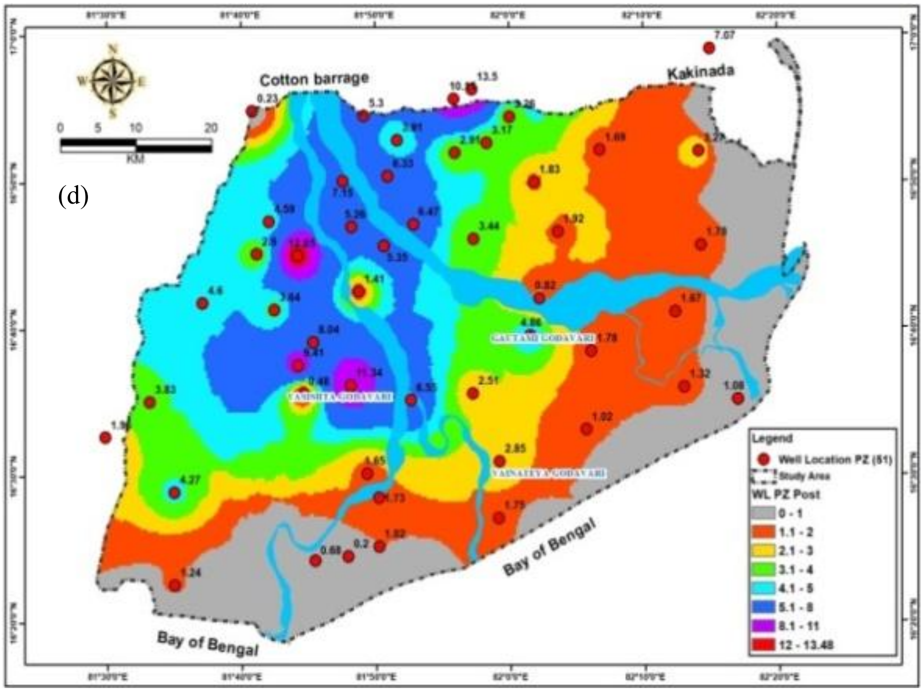


Fig.22 Groundwater table contours of shallow wells of (a) pre (b) post-monsoon and piezometer wells of (c) pre (d) post-monsoon during the year 2017

Physicochemical statistics (minimum, maximum, mean, and standard deviation) of shallow groundwater wells (47) in pre and post-monsoon seasons are summarized in Table 5. Shallow groundwater samples have shown pH values ranging from a minimum of 7.7 and a maximum of 9.45, with a mean value of 8.4, indicating the shallow aquifer is alkaline. In the pre-monsoon season, the EC value of shallow aquifer in the Godavari delta varied from 461 to 7199 µS/cm with a mean value of 1868 µS/cm. The mean value of EC is slightly higher in post-monsoon than pre-monsoon, and this may be due to the dissolution of salts accumulated in the soils due to evaporation. The chronological order of essential cations of the groundwater samples in the pre-monsoon season is $Na^+>K^+>Mg^{2+}>Ca^{2+}$ however, this order is changed in the post-monsoon season as $Na^+>K^+>Ca^{2+}>Mg^{2+}$. The order of significant anions in both seasons is as $HCO_3^-> Cl^-> SO_4^{2-}$. The highest HCO_3^- and Na^+ ions concentrations revealed that the study area might be influenced by silicate mineral dissolution.

Table 5: Descriptive statistics of physicochemical parameters for shallow wells (47) during pre and post-monsoon seasons in the Godavari delta

Parameter	Shallow wells (Pre-monsoon)				Shallow wells (Post-monsoon)			
	Min	Max	Average	SD	Min	Max	Average	SD
pH	7.7	9.5	8.4	0.4	7.1	9.0	8.5	0.4
EC	461	7199	1868	1213	571	6433	2007	1219
TDS	295	4607	1195	776	365	4117	1284	780
CO_3^-	0.0	240.0	52.3	68.3	0.0	360.0	75.3	75.6
HCO_3^-	80.0	1431.0	373.6	255.4	100.0	1435.0	364.9	228.6
Cl^-	20.0	1539.0	304.4	294.0	40.0	1146.0	302.2	273.9
SO_4^-	10.0	360.0	93.0	82.5	5.2	350.0	108.1	94.7
Na^+	22.0	877.0	231.4	173.3	10.0	948.0	251.3	192.3
K^+	1.0	599.4	92.6	118.0	2.5	412.0	95.5	90.0
Br^-	0.2	97.9	15.1	19.3	0.4	67.3	15.6	14.7
Ca^{2+}	8.0	184.0	43.1	35.7	16.0	216.0	52.6	42.7
Mg^{2+}	14.6	215.0	55.8	41.0	9.7	159.0	47.5	28.8

All units are in mg/L except pH and EC

The physicochemical parameters (minimum, maximum, mean, and standard deviation) of piezometer wells during pre and post-monsoon seasons are presented in Table 6. In both pre and post-monsoon seasons, groundwater samples have shown that pH values are in the range of 7.0–9.0 with a mean value of 8.4, which indicates that the deep aquifer is alkaline. The average EC value of the piezometer with a mean value of 4252 µS/cm (pre-monsoon) and 4301 µS/cm (post-monsoon) indicates that the piezometer wells are affected by high/very salinity. The higher EC in the piezometer wells may be due to the mixing of saline water into the deep soils due to the paleo-marine environment. Cation concentrations are follow the order of Na^+>Mg^{2+}>Ca^{2+}>K^+, with contributions of 55%, 25%, 15% and 5%, respectively. Minimum and maximum values of sodium content are 22 mg/L and 5804 mg/L with an average value of 580 mg/L, indicating very high sodium values due to rock weathering, dissolution of halite, and the marine water contribution (Freeze and Cherry 1979). The concentration of Mg^{2+} varied from 10 to 632 mg/L with an average of 91 mg/L. The high concentration of Mg^{2+} indicates that the salinity in groundwater is derived from the marine source. The higher Mg^{2+} values over Ca^{2+} values also indicate that the piezometer wells are affected by saline water due to the evaporation process or paleo marine environment. The anions that decreased concentration were Cl^->HCO_3^->SO_4^-, with contributions of 51%, 39%, and 10%. High bicarbonates have resulted from the dissolution of carbonates and silicates. The chloride concentration was found to be higher than HCO_3^- concentration, which infers that the dissolution of minerals has taken place in the piezometer wells.

Table 6: Descriptive statistics of physicochemical parameters for piezometer wells (51) during pre and post-monsoon seasons in the Godavari delta

Parameter	Piezometer wells (Pre-monsoon)				Piezometer wells (Post-monsoon)			
	Min	Max	Average	SD	Min	Max	Average	SD
pH	7.2	9.0	8.4	0.4	7.0	9.0	8.4	0.5
EC	442	40170	4252	7831	227	40170	4301	7658
TDS	282	25708	2721	5011	145	25708	2752	4901
CO_3^-	0.0	200.0	43.9	50.6	0.0	220.0	73.3	71.8
HCO_3^-	60.0	8796.0	719.1	1527.8	70.0	7615.0	793.4	1451.1
Cl^-	20.0	8963.0	970.7	1996.8	10.0	10223.0	933.2	1884.0
SO_4^-	0.0	1458.0	134.8	255.6	1.8	1471.0	150.1	263.8
Na^+	22.0	5804.0	579.9	1102.1	7.0	5356.0	547.8	991.5
K^+	1.0	260.0	53.4	68.9	2.0	260.0	59.3	77.5
Br^-	0.2	42.5	8.7	11.3	0.3	42.5	9.7	12.7
Ca^{2+}	8.0	400.0	78.4	110.1	8.0	400.0	83.5	117.2
Mg^{2+}	9.7	632.1	91.5	128.9	0.0	600.0	117.1	170.4

All units are in mg/L except pH and EC

5.2.1 Correlation between major ions in shallow and piezometer wells

Correlation is the mutual relationship between two variables. The correlation coefficient has a value between +1 and –1. The correlation between the two parameters is characterized as strong when it is in the range of +0.8 to +1.0, moderate in the range of +0.5 to +0.8 weak when in the range of 0.0 to +0.5. The correlation coefficient between Cl^- vs other major anions and cations; HCO_3^- vs other major anions and cations; and Ca^{2+} vs other major anions and cations for the year 2017 (pre and post-monsoon periods) in shallow wells (102) and piezometer wells (94) are shown in Fig. 23 (a), 23(b) and 23 (c) respectively. The ions Cl^-, HCO_3^- and Ca^{2+} of piezometer wells are highly correlated with other anions and cations than shallow wells. Therefore, it may be indicated that shallow wells are vulnerable to various anthropogenic and climatic conditions.

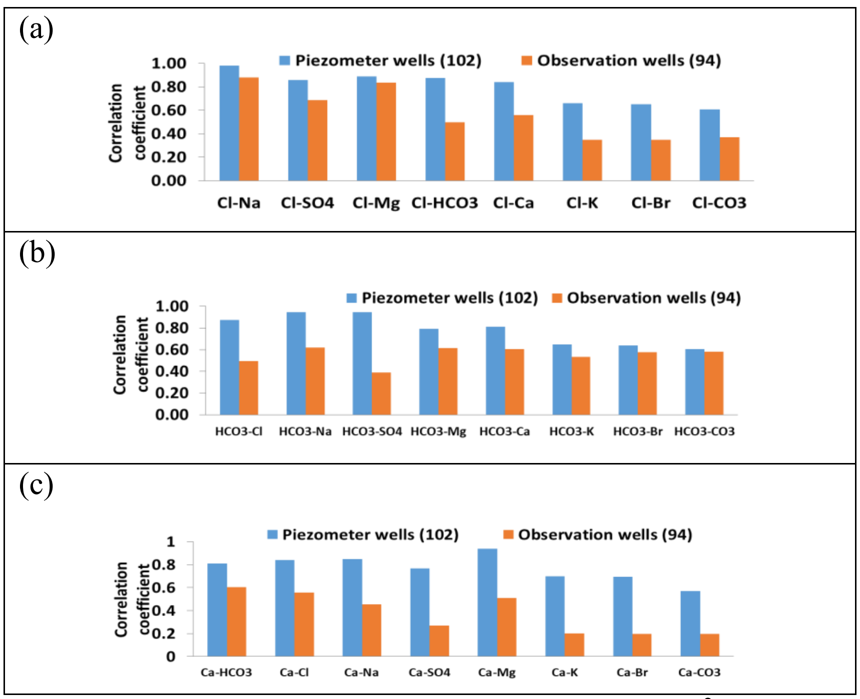


Fig.23 Correlation coefficient of (a) Cl^-, (b) HCO_3^- and (c) Ca^{2+} with major ions in piezometer and shallow wells

5.3 Salinity zone identification for the shallow and piezometer wells

5.3.1 Piper's hydrogeochemical process evaluation

Hydrogeochemical facies can be defined as zones within a groundwater system with unique combinations of cation and anion concentrations which is useful to explain the distribution of principal groundwater types. The geochemical evolution of the groundwater and its relationship with different dissolved ions can be understood by plotting the geochemical data on Piper's trilinear diagram (Piper 1944). The various hydrogeochemical facies using Piper's Trilinear diagram is shown in Fig.24. The ionic concentration of major cations and anions in shallow and piezometer wells during pre and post-monsoon seasons is plotted in Piper's trilinear diagram using AquaChem software and is shown in Fig.25(a) and 25(b), respectively.

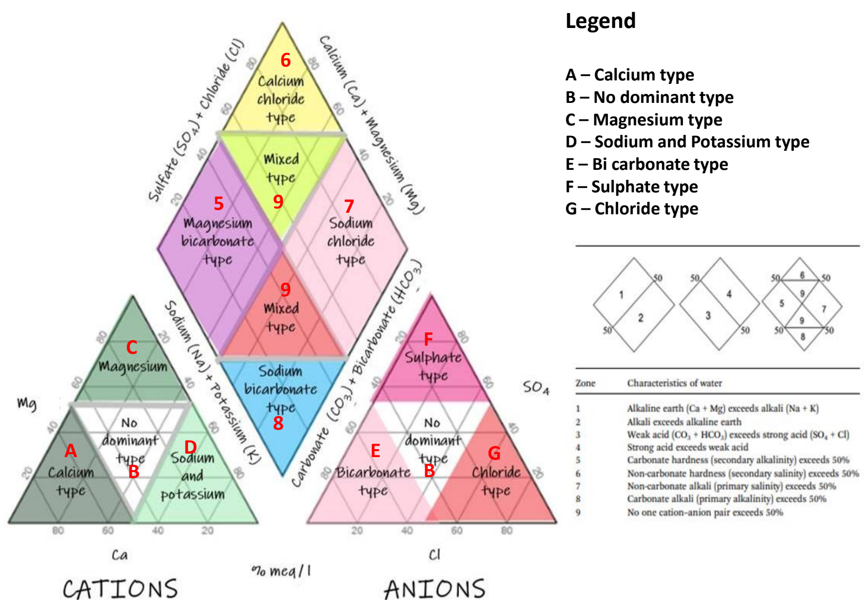


Fig.24 Various hydrogeochemical facies using Piper Classification

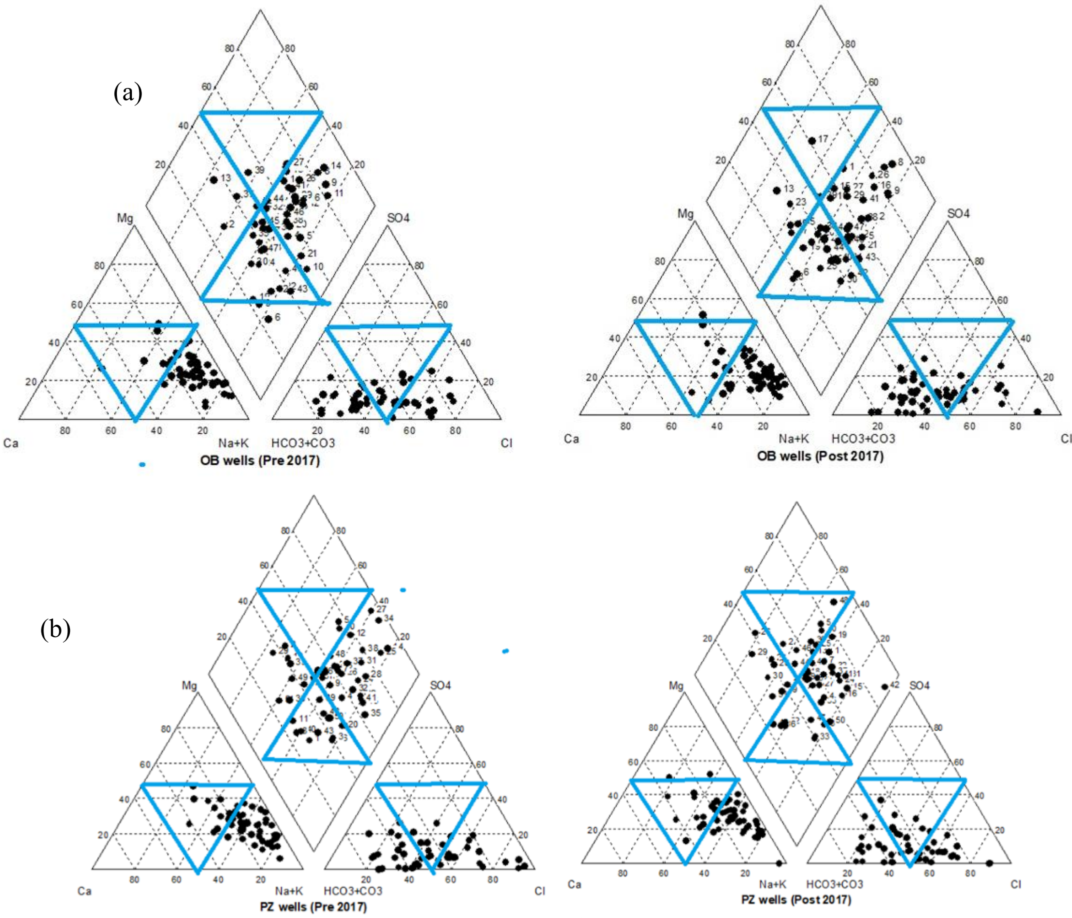


Fig.25 Piper trilinear diagrams for hydrochemical facies in the (a) shallow wells (pre and post-monsoon seasons) and (b) piezometer wells (pre and post-monsoon seasons)

The characteristics of shallow wells during the pre and post-monsoon periods in each hydrochemical facies are shown in Fig.25(a). The triangular cationic zone of the Piper diagram revealed that most of the groundwater samples (more than 90%) fell into Na+K type (D). Very few samples are in no dominance type, and no sample was classified as a Ca^{2+} and Mg^{2+} zones, whereas in the anionic triangle, most of the samples fell into HCO_3^- (E) and Cl^- (G) dominant zone. Moreover, the groundwater samples fell in zone 9, indicating the mixed chemical character of the groundwater, with Ca-Mg-Cl type and Na-HCO_3-Cl type being dominant in the chemical composition. These two water types represent no one cation–anion pair exceeding 50%. Most of the samples have fallen into zone 7, suggesting Na-Cl type of water, which means non-carbonate alkali (primary salinity) exceeds 50%. No groundwater sample fell into zone 6 (Ca-Mg^{2+}-SO_4^- type), which represents non-carbonate hardness (secondary salinity) exceeding 50%. The samples that fall in zone 5 indicate Ca-Mg-HCO_3 type, which represents carbonate hardness (secondary alkalinity) exceeding 50%. Based on the dominance of different cations and anions in the shallow wells, a major water type in the study area was found to be Na–HCO_3–Cl.

The characteristics of piezometer wells during the pre and post-monsoon periods in each hydrochemical facies are shown in Fig.25(b). In the cationic triangle, most of the piezometer samples have fallen into Na and K type (D). Few piezometer samples are in no dominance type (B). In the anionic triangle, most of the samples fell into HCO_3^- (E) and Cl^- (G) dominant types. Few piezometer samples fell in zone 9, indicating a mixed chemical character of the groundwater, with the dominance of Ca-Mg-Cl type and Na–HCO_3–Cl type. These two types represent no one cation–anion pair exceeding 50%. Few piezometer samples have carbonate hardness (zone 5). Most of the deep groundwater samples fell into zone 7, suggesting Na-Cl type of water, which means non-carbonate alkali (primary salinity) exceeds 50%. The Na-Cl type indicated the presence of high chloride concentrations in the piezometer wells, which may originate from the dissolution of halite/influx of saline water near the sea coast. No groundwater sample fell into zone 6 (Ca-Mg-SO_4 type) and zone 8. Based on the dominance of different cations and anions in the deep groundwater samples, the major water type can be defined as Na–HCO_3–Cl type. Piper diagram reveals that nearly 65% of the analyzed piezometer samples fell in the field of Na-Cl water type. These water samples are influenced by saline water, and the aquifer of this water type has no source to recharge. The hydro-chemical facies of deep aquifer suggests from the Piper diagram that alkalis (Na) exceed alkaline earth (Ca-Mg), and strong acids (Cl^-) surpass weak acids (HCO_3^-), which may be due to the influence of paleo saline water and dissolution of the minerals from ion exchange reactions are the major processes occurring in the Godavari delta.

5.3.2 Chadda's hydrogeochemical process evaluation

The factors that influence the change of chemical composition of groundwater can be investigated graphically by plotting between (Ca-Mg)–(Na+K) and (HCO_3^-)–(SO_4+Cl) in milli-equivalent concentrations (Chaddha 1999). Shallow water samples collected during pre and post-monsoon periods of the year 2017) in the Godavari delta are plotted in Chadda's diagram and are shown in Fig.26. The majority of the shallow groundwater samples (80%) falling in the seawater mixing zone represents Na-Cl type of water (or Na-Cl mixed sea water). Shallow water samples fell in Na-HCO_3 type of water in pre and post-monsoon periods indicating base-ion exchange water. Very few samples fell in Ca-Mg-HCO_3 type of water, which indicates recharging water. Only one sample of both seasons has fallen in the reverse ion-exchange water (Ca-Mg-Cl type).

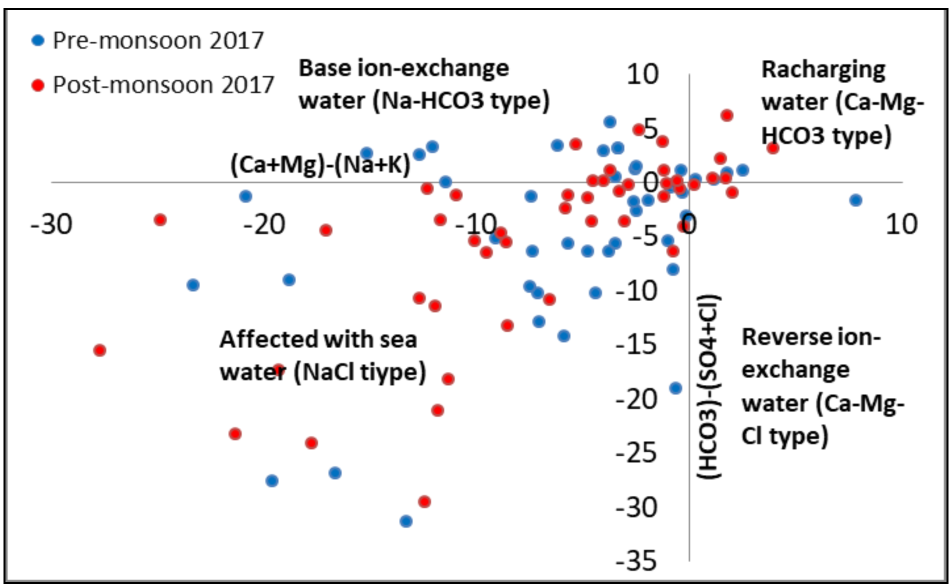


Fig.26 Chadda's plot of pre and post-monsoon groundwater samples for shallow aquifer

Piezometer water samples collected during pre and post-monsoon periods in the Godavari delta are plotted in Chadda's diagram and shown in Fig. 27. According to Chadda's plot (Fig.27), the majority of the piezometer water samples (90%) have fallen in the seawater mixing zone, which represents Na-Cl type of water (or Na-Cl mixed sea water). Other than Na-Cl water type, the other three water types (Na-HCO_3, Ca-Mg-HCO_3 and Ca-Mg-Cl water types) are obtained at a few inland delta locations.

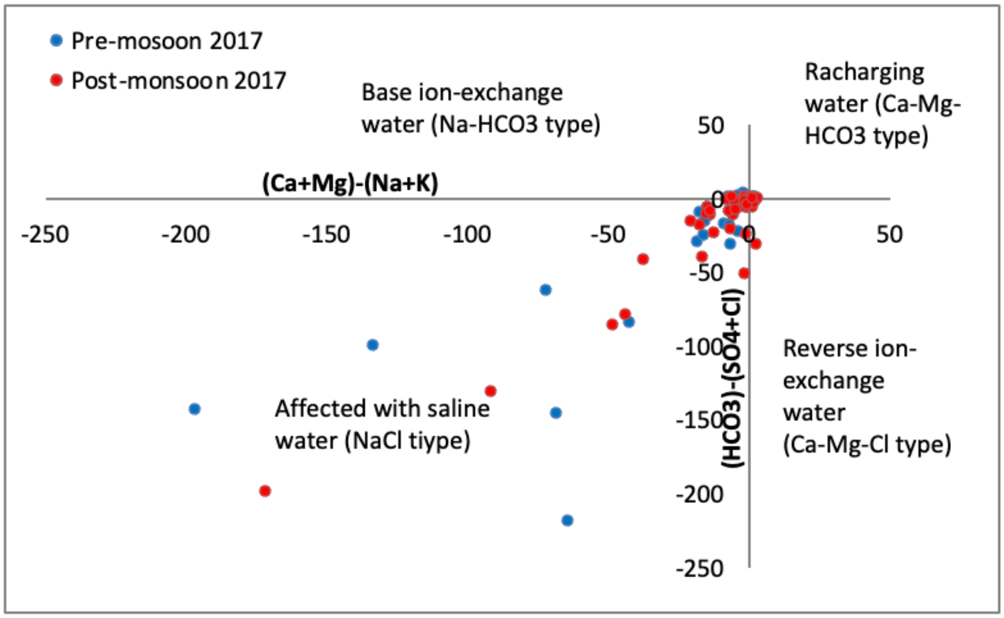


Fig.27 Chadda's plot for deep groundwater samples in pre and post-monsoon seasons

5.3.3 Cl/HCO$_3$ ratio (molar)

The Simpson's ratio (Cl/HCO$_3$) is considered for the analysis of saline water mixing contamination into the fresh aquifer (Todd 1959). The water samples are classified into five classes using the molar ratio of Cl/HCO$_3$ (Table 7).

Table 7: Contamination by salinity into the fresh aquifer based on Cl/HCO$_3$ ratio

Cl/HCO$_3$	Water class
<0.5	good water (not affected by salinity)
0.5-1.3	Slightly contaminated
1.3-2.8	Moderately contaminated
2.8-6.6	Injuriously contaminated
>6.6	Severely contaminated

Based on Cl/HCO$_3$, in both seasons, more than 50% of the shallow groundwater samples (30 samples) are considered to be slightly to moderately influenced by the saline water. Fig.28 (a) and (b) show the seawater contamination based on the scatter plot of Cl/HCO$_3$ versus Cl in the shallow and piezometer samples, respectively. In the shallow wells, most of the samples are either unaffected or slightly affected by saline water in both seasons. Very few samples are moderately contaminated with saline water [Fig.28(a)]. In the piezometer wells, most of the samples are either slightly contaminated or moderately contaminated with saline water. Few samples have fallen injuriously to severely contaminated with saline water [Fig.28(b)].

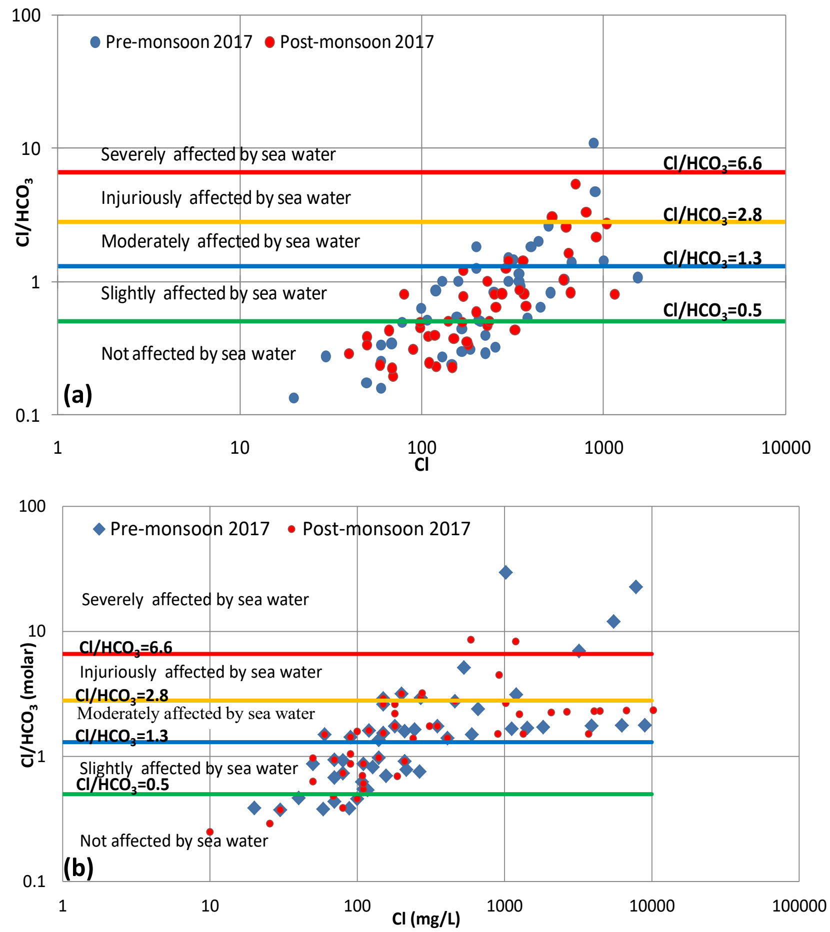


Fig.28 (a) Salinity contamination based on the scatter plot of Cl/HCO_3 versus Cl for the shallow wells and (b) for piezometer wells during pre and post monsoon periods

5.4 Preparation of salinity maps for shallow and piezometer wells

The Godavari delta salinity zone maps for shallow and piezometer wells are prepared from the Piper classification as well as the Chadha classification and the Cl/HCO_3 (molar) ratio. The criteria used for the development of salinity zone maps are presented below in Table 8.

Table 8: Salinity classification according to water types (using the Piper and Chadda plots) and Cl/HCO_3 ratio.

Zone	Water type	Cl/HCO_3 (molar)	Salinity classification
I	$Na\text{-}HCO_3/Ca\text{-}Mg\text{-}HCO_3$	<0.5	Freshwater
II	$Ca\text{-}Mg\text{-}HCO_3/Na\text{-}Cl/Ca\text{-}Mg\text{-}Cl$	0.5-1.3	Slightly brackish
III	Na-Cl	1.3-2.8	Brackish
IV	Na-Cl	2.8-6.6	Saline
V	Na-Cl	>6.6	High Saline

Based on the above classification, the salinity maps for the year 2017 have been prepared using the quality data of 47 shallow wells and 51 piezometer wells network, respectively. The salinity map of the shallow aquifer in the Godavari Delta is presented in Fig. 29. From Fig.29, it is observed that six locations in the upland zone [Nidadavolu (1,1a), Kapileswarapuram (10), Alamuru (11a), Undrajavaram (14), Iragavaram (18), Ambajipeta (31)] and one location in the coastal zone [Mummidivaram (33a)] are identified as freshwater zones (I). The remaining upland and coastal delta areas are contaminated with groundwater salinity, with salinity zones ranging from slightly brackish (II) to saline (IV). In the coastal zone of the Godavari delta, the shallow aquifer is saline (IV) at Karapa (36), I.Polavaram (38), Allavaram (41), and Sakhinetipalli (45). It is interesting to note that the shallow aquifer at Athreyapuram, in the upland delta area, is also identified as the saline zone.

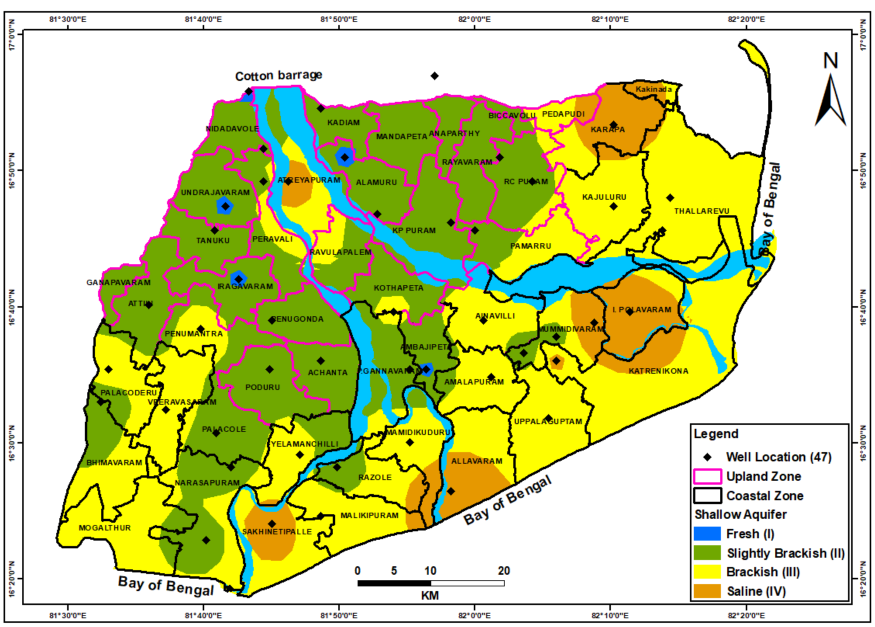


Fig 29. Salinity map of shallow aquifer of the Godavari delta (Nov. 2017)

The salinity map of the piezometer wells in the Godavari Delta is shown in Fig. 30. As shown in Fig. 30, the coastal zone is either saline or highly saline in the piezometer wells. In the coastal zone, five locations namely Malikipuram, Rajolu, P.Gannavaram, Mamidikuru, and Mummidivaram, are identified as brackish/slightly brackish water. It is interesting to note that the saline (IV) and high saline (V) zones occurred in the deep aquifer of the coastal and upland region (nearer to coastal mandals) in the western coastal delta. There is no fresh water in the western delta upland region and slightly brackish or brackish water is obtained in this region. The Na-Cl water type is the only type of water obtained in the Godavari delta's saline/high salinity areas.

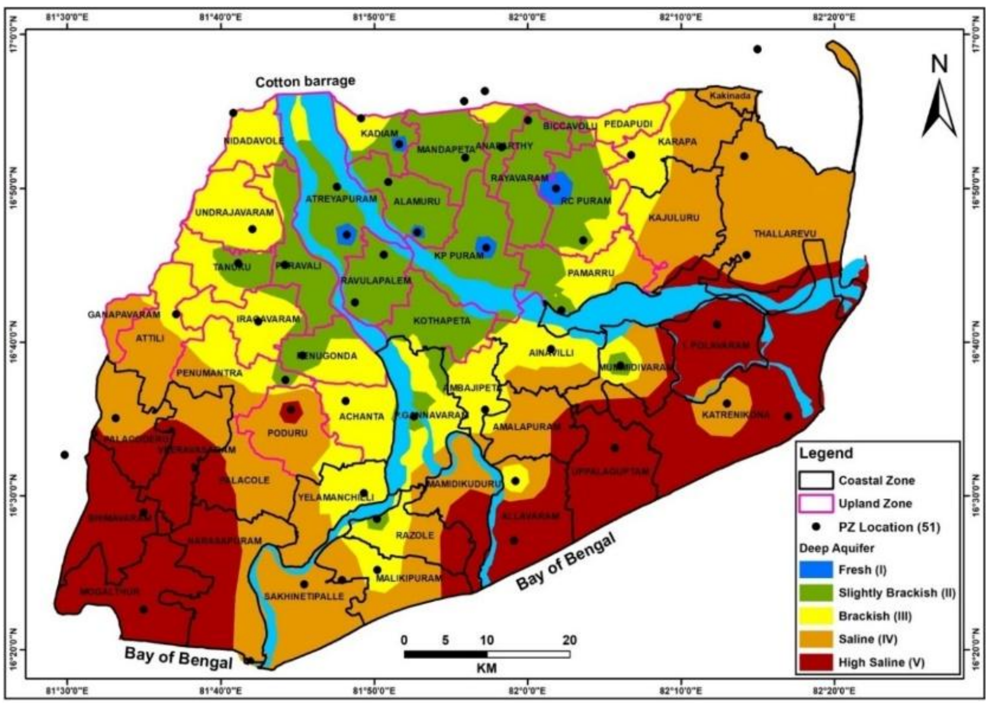


Fig 30. Salinity map of piezometer wells of the Godavari delta (Nov. 2017)

5.5 Validation of salinity maps in the Godavari delta for 2020

The APSGWD monitoring well network has been increased to 100 shallow wells in the year 2020 as compared to the previous network of 47 wells in the year 2017 and the piezometer well monitoring network is reduced to 46 wells in the year 2020 compared to the previous network (51 in 2017). The locations of shallow and piezometer wells in the Godavari delta of the year 2020 are shown in Fig.31. Coastal and upland mandals in the Godavari Delta are shown in Fig.31 and it is clear that a greater number of shallow wells were included in the coastal delta zone in 2020.

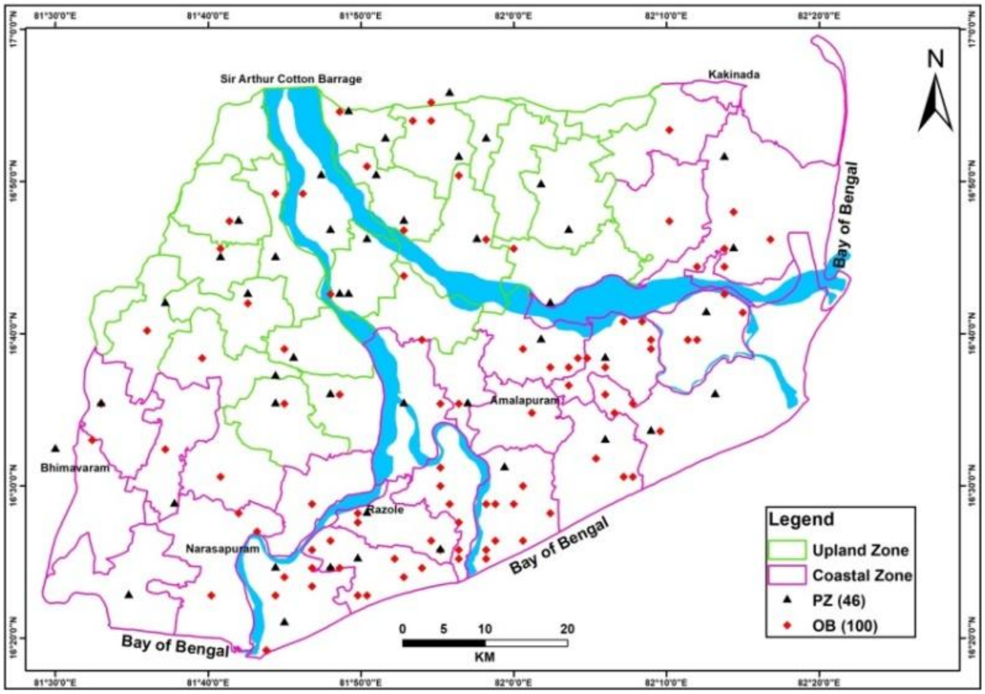


Fig.31 Location of shallow wells (100 No.) and piezometer wells (46 No.) in the year 2020

Salinity zone criteria adopted for shallow and piezometer wells for the year 2017 are validated with the new shallow and piezometer well monitoring network for the year 2020. Similar to the results of the year 2017, the average values of all major ion concentrations of shallow and piezometer wells increased again from Zone I to Zone V (Tables 9 and 10) in the year 2020. Findings from an extensive network of shallow wells (100 No.) in the year 2020 are well correlated to the previous network (47 No.) during the year 2017. Also, in 2020, the mean values for all major constituents in Zone I and II are higher in shallow aquifers than in deep aquifers. Hence it is identified that these two zones are more sensitive to groundwater salinization by the present agriculture and aquaculture practices in the Godavari delta. The above analysis indicates the validity of salinity maps of shallow and piezometer wells for the Godavari delta.

Table 9: Average values of the major chemical constituents in each zone of the shallow wells in the year 2020 (post-monsoon)

Zone	No of Samples	TDS	HCO_3^-	Cl^-	SO_4^-	Na^+	K^+	Ca^{2+}	Mg^{2+}
I	16	539	297	60	29	83	44	48	25
II	41	938	372	176	76	168	64	62	42
III	23	1139	291	310	78	217	79	50	43
IV	14	2008	351	733	146	418	89	112	91
V	6	2016	168	885	92	411	72	61	98

All units are in mg/L

Table 10: Average values of the major chemical constituents in each zone of the piezometer wells in the year 2020 (post-monsoon)

Zone	No of Samples	TDS	HCO_3^-	Cl^-	SO_4^-	Na^+	K^+	Ca^{2+}	Mg^{2+}
I	6	391	174	43	32	67	8	22	28
II	17	786	288	156	73	193	44	33	51
III	13	1191	296	328	96	304	41	72	82
IV	7	2198	328	798	134	429	84	80	125
V	8	11875	402	4708	558	2381	150	288	407

All units are in mg/L

The salinity map of the shallow wells with the monitoring network of 100 wells for the year 2020 is prepared and is shown in Fig. 32. It is identified that the salinity map for the year 2020 (Fig.32) is more or less similar to the salinity map of the shallow aquifer for the year 2017 (Fig.29) except in a few locations in the coastal delta zone. The reasons are studied and verified from the isotopic characteristics.

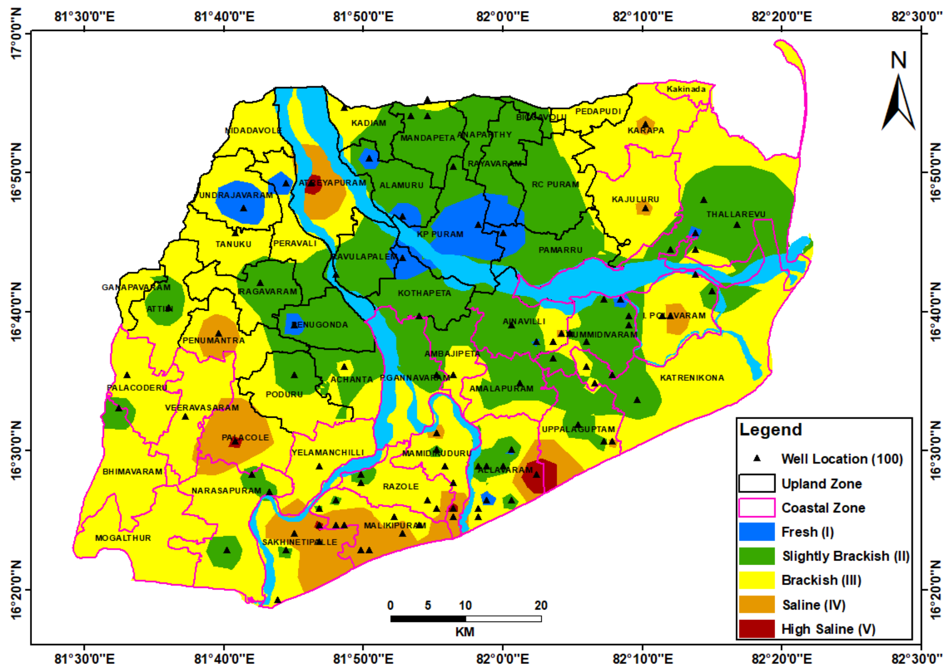


Fig.32. Salinity map of shallow wells from the extended network (100 No.) for the year 2020 in the Godavari delta

The salinity map of the piezometer wells with the current monitoring network of 46 wells in the year 2020 is prepared and shown in Fig. 33. This salinity map (Fig. 33) is almost similar to the 2017 piezometer wells salinity map of the piezometer wells network (51) for the year 2017 (Fig. 30). This indicates that the groundwater salinity is not altered by any anthropogenic and natural sources in the piezometer wells of the Godavari delta.

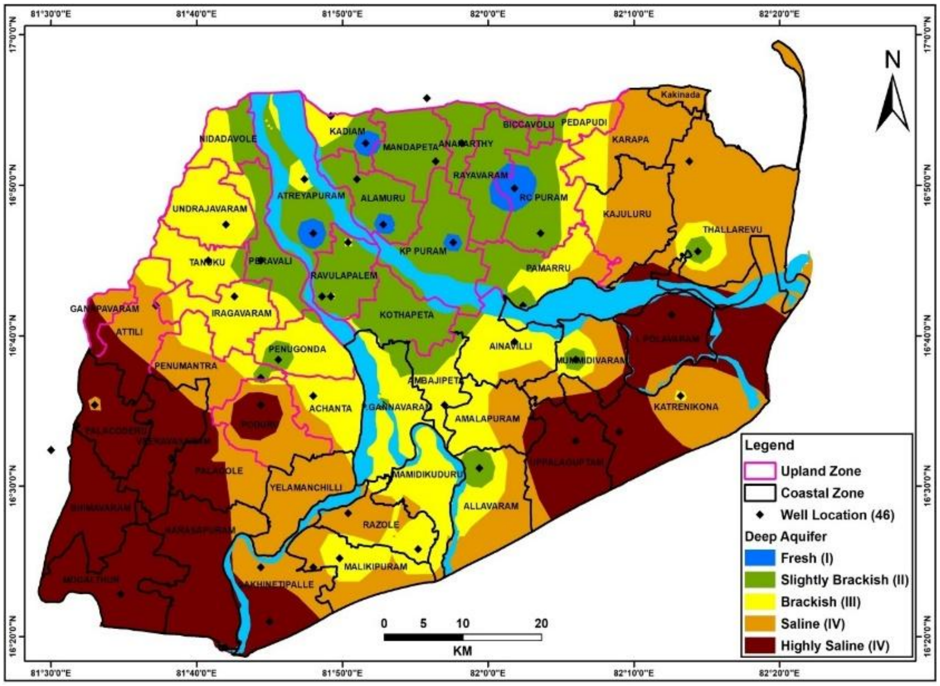
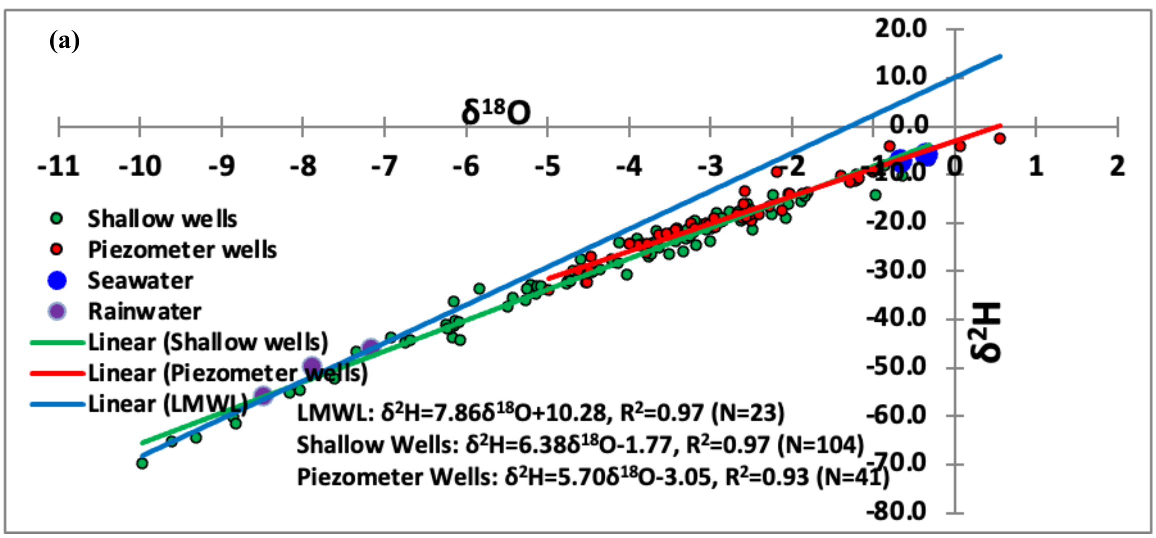
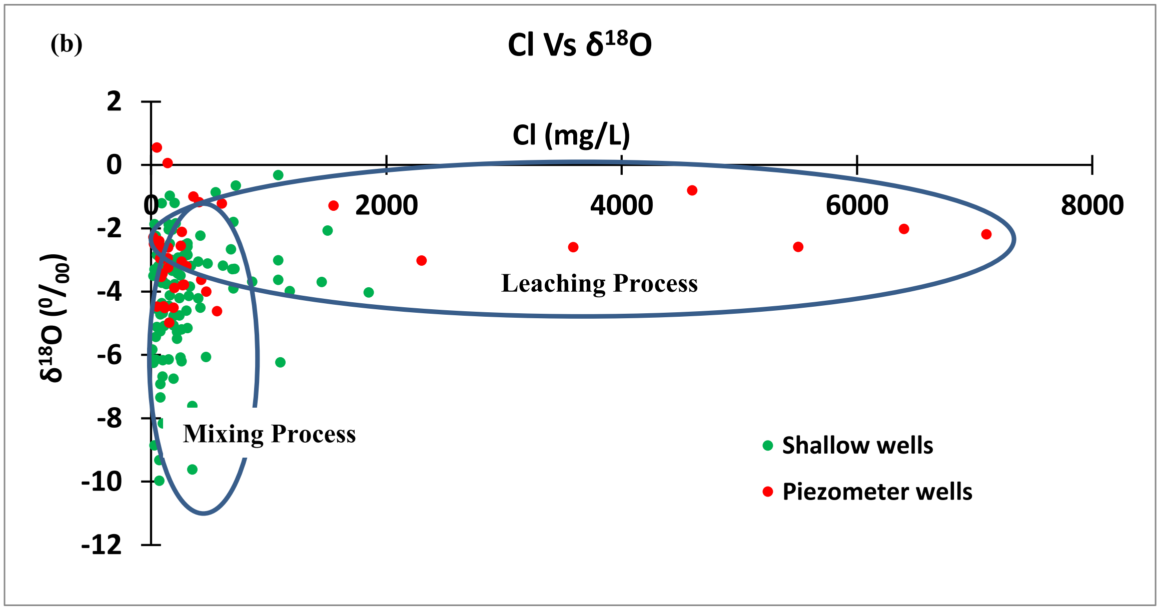


Fig.33. Salinity map of piezometer wells (46 No.) for the year 2020 in the Godavari delta

5.6 Salinity source identification using stable isotopes

The stable isotopes ^{2}H and ^{18}O of groundwater provide very useful information about the origin and source of recharge, including vital information about salinity (Krishan et al. 2021). At the recharge area, the stable isotope values of groundwater are considered close to the annual weighted average isotopic value of the recharging water. Minor deviation, if any occurs, accounts for the evaporative enrichment of recharging water during the process of its infiltration, changes that occur due to different land-use practices (Darling and Bath 1988), or climate change. If mixing with any other sources of water does not occur within the aquifer, the isotope value of groundwater remains almost unchanged all along the flow path up to the discharge zone. This principle is used in the present study to identify the recharge sources of groundwater and salinity processes in the Godavari delta. The stable isotope data of precipitation in Godavari delta (Kakinada) is taken as Local Meteoric Waterline (LMWL: slope 7.86). The stable isotope data of $\delta^{18}O$ and $\delta^{2}H$ for shallow wells (104), piezometer wells (41), rainfall (3), and seawater (2) are shown in Fig. 34 (a). The isotopic trend line for groundwater data of shallow wells (slope: 6.38) and piezometer wells (slope: 5.7) shows variation in their isotopic characteristics. The comparison of these slopes with the LMWL slope indicated that the stable isotopes are enriched in piezometer wells than in shallow wells. The relation between $\delta^{18}O$ and Cl in shallow and piezometer wells is shown in Fig. 34(b). This relation indicates leaching process is more in piezometer wells, and the mixing process is more in shallow wells. The relation between $\delta^{18}O$ and d-excess in shallow and piezometer wells is shown in Fig. 34(c). The relation provided the origin of salinity, and three combinations of samples were observed. The first group is rainwater and shallow wells, the second is shallow wells and piezometer wells, and the third is shallow wells, piezometer wells, and seawater. To resolve the multiplicity, the data was divided into five zones based on Cl/HCO_3 ratio and water types (Zone I: <0.5, Zone II: 0.5 to 1.3, Zone III: 1.3 to 2.8, Zone IV: 2.8 to 6.6 and Zone V: >6.6) to identify the salinity source. The Cl/HCO_3 Vs $\delta^{18}O$ and Cl/HCO_3 vs d-excess relations were plotted and shown in Fig. 35 (a) and 35 (b), respectively. Among all salinity zones, the d-excess and $\delta^{18}O$ values are closer to each other in salinity zone V, which indicates that anthropogenic activities impact is less in salinity Zone V.





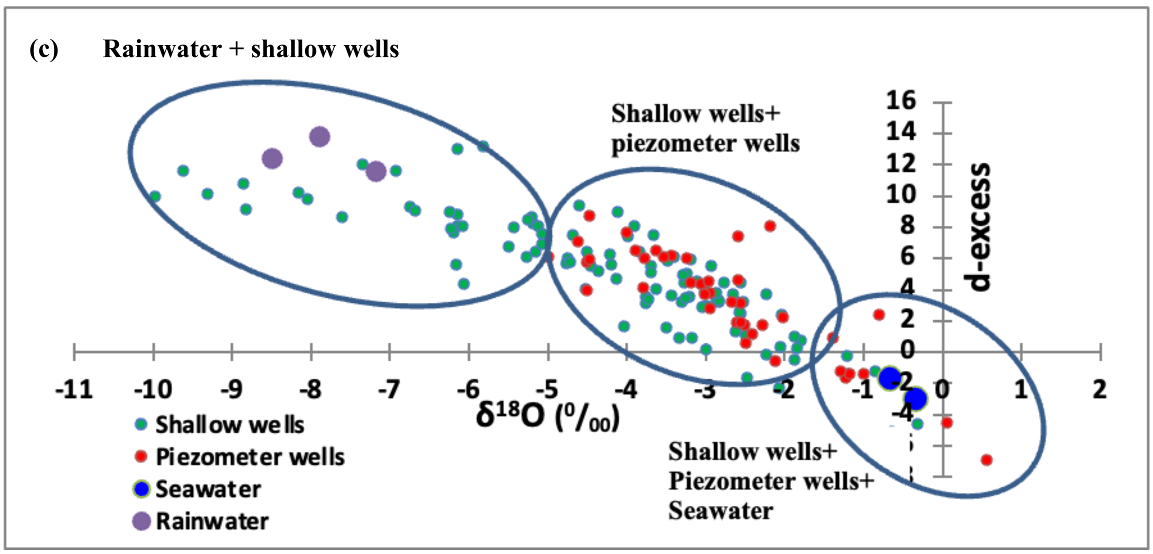


Fig.34 (a) Relation between $\delta^{18}O$ and $\delta^{2}H$, (b) Relation between $\delta^{18}O$ and Cl and (c) Relation between $\delta^{18}O$ Vs d-excess in the Godavari delta.

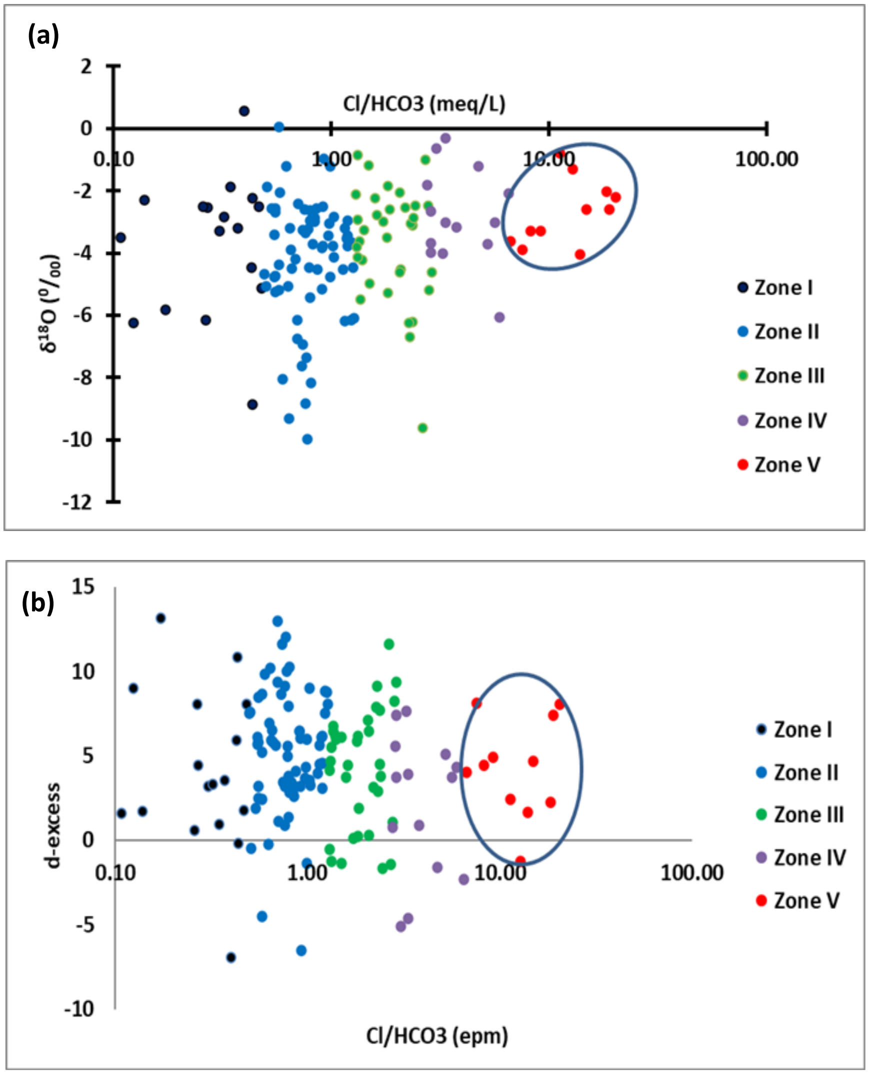


Fig. 35(a) Relation between Cl/HCO_3 Vs $\delta^{18}O$ and (b) Relation between Cl/HCO_3 vs d-excess in each salinity zone in the Godavari delta

Further, the relation between $\delta^{18}O$ and δ^2H in each salinity zone for shallow wells has been developed. The details of each trend line equation along with the average Cl concentration for shallow wells are given below.

Shallow Wells (104)

Zone I: $\delta D=6.2\delta^{18}O-1.9$, $R^2=0.97$ (N=12) and average Cl=34 mg/L

Zone II: $\delta D=6.51\delta^{18}O-1.1$, $R^2=0.97$ (N=53) and average Cl=161 mg/L

Zone III: $\delta D=6.4\delta^{18}O-1.5$, $R^2=0.98$ (N=23) and average Cl=335 mg/L

Zone IV: $\delta D=5.8\delta^{18}O-4.2$, $R^2=0.93$ (N=11) and average Cl=938 mg/L

Zone V: $\delta D=8.63\delta^{18}O+6.9$, $R^2=0.62$ (N=5) and average Cl=1006 mg/L

Similarly, the relation between $\delta^{18}O$ and $\delta^{2}H$ in each salinity zone for piezometer wells has been developed. The details of each trend line equation along with the average Cl concentration for piezometer wells are given below.

Piezometer wells (41)

Zone I: $\delta D=5.4\delta^{18}O–5.1$, $R^2=0.99$ (N=5) and average Cl=42 mg/L

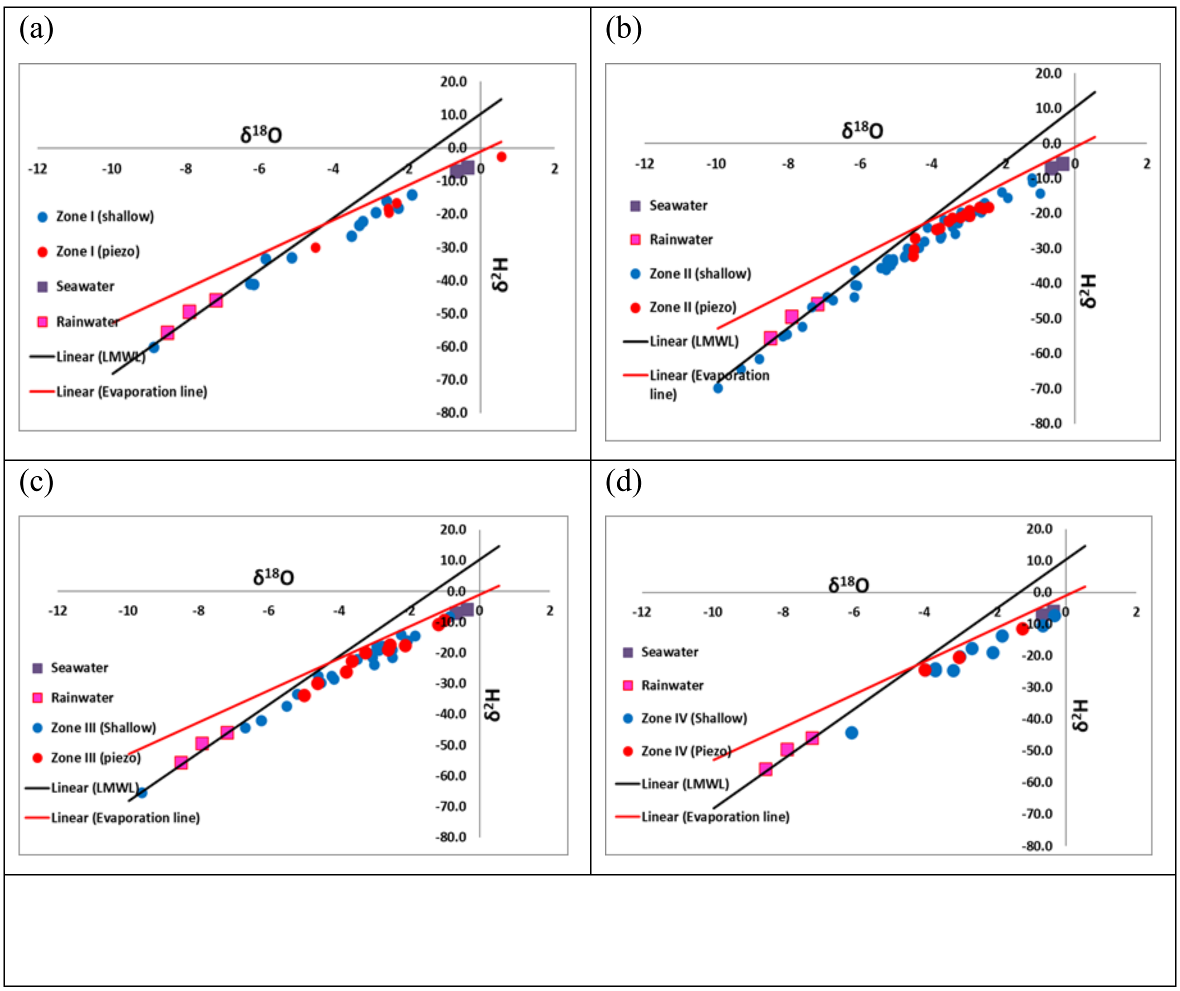
Zone II: $\delta D=5.5\delta^{18}O–1.1$, $R^2=0.95$ (N=16) and average Cl=144 mg/L

Zone III: $\delta D=5.7\delta^{18}O–3.6$, $R^2=0.97$ (N=10) and average Cl=298 mg/L

Zone IV: $\delta D=4.7\delta^{18}O–5.7$, $R^2=0.99$ (N=3) and average Cl=1123 mg/L

Zone V: $\delta D=4.5\delta^{18}O–2.9$, $R^2=0.63$ (N=7) and average Cl=4790 mg/L

The relation between $\delta^{18}O$ and δD along with LMWL, evaporation line ($\delta D = 5.2\ \delta^{18}O-1$), and shallow wells, piezometer wells, rainwater, and seawater have been plotted for each salinity zone are shown in Fig. 36 (a, b, c, d, e)



(e)

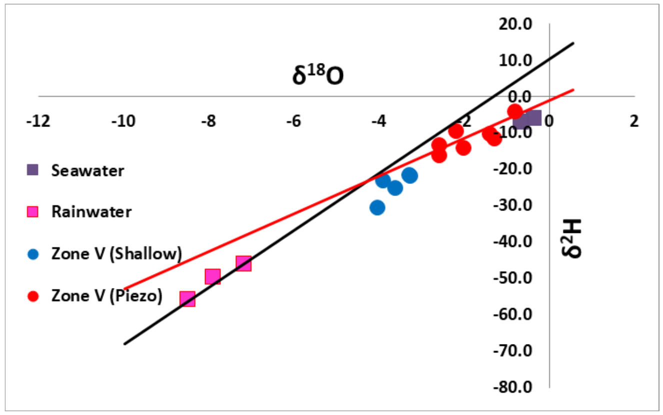


Fig. 36 (a, b, c, d, e) Relation between $\delta^{18}O$ and δD in each salinity zone along with LMWL, evaporation line and shallow wells, piezometer wells, rainwater and seawater

To interpret the salinity source in each zone, the stable isotopes and Gibb's diagrams are used. Accordingly, the Gibbs diagrams for shallow wells (anions and cations) and piezometer wells (anions and cations) have been prepared and are shown in Fig.37. The detailed analysis of salinity sources in each zone is given below.

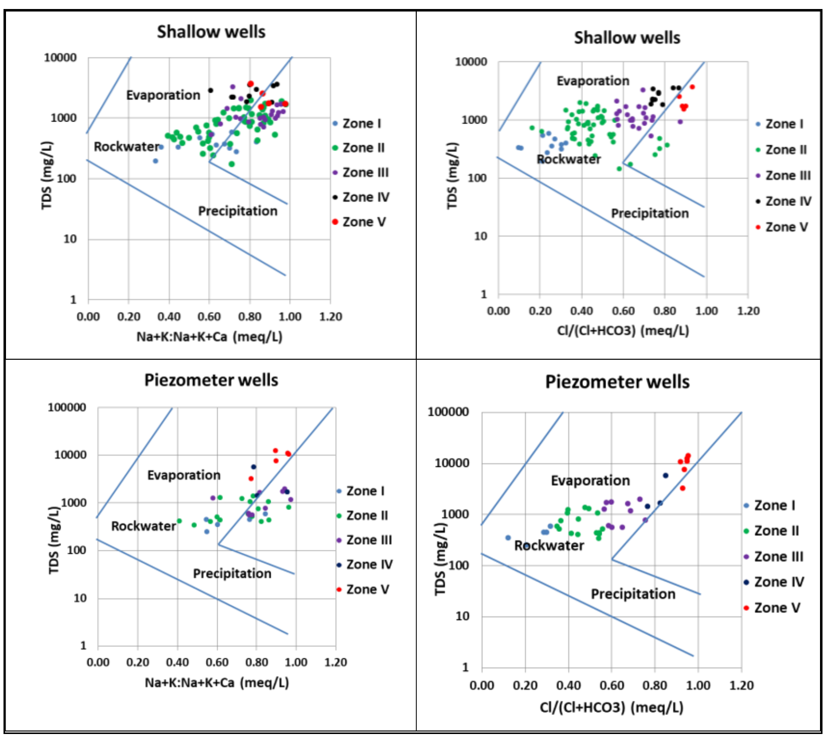


Fig.37 Gibbs diagrams for shallow and piezometer wells

Salinity Zone I: The major water types found in this zone are Na-HCO_3 and Ca-Mg-HCO_3. From Gibbs diagrams, the cations and anions in both shallow and piezometer wells are fallen under rock-water dominance. It is also confirmed that the shallow and piezometer wells are found to be away from the evaporation line and near LMWL (Fig.36a). However, the slope between $\delta^{18}O$ and δD for shallow and piezometer wells was found to be 6.2 and 5.4, respectively. Therefore, the source for shallow and piezometer wells is rainfall without much evaporation. The average Cl ion concentration is below 42 mg/L in this zone. Therefore, this zone is considered relatively fresh water.

Salinity Zone II: The major water types found in this zone are Ca-Mg-HCO_3 and Ca-Mg-Cl. From Gibbs diagrams, the cations and anions in both shallow and piezometer wells are dominated by the precipitation-evaporation process (rainfall influenced), and the direct evaporation process is low. It is also confirmed that the shallow and piezometer wells are found to be on LMWL and away from the evaporation line (Fig.36b). However, the slope between $\delta^{18}O$ and δD for shallow and piezometer wells was found to be 6.5 and 5.5, respectively. Therefore, zone II has less evaporation. The average Cl ion concentration in shallow wells (161 mg/L) is more than in piezometer wells (144 mg/L) in this zone. This indicates that even rain water is a primary recharge source for groundwater (shallow and piezometer wells), the shallow wells are influenced by anthropogenic activities (agriculture). Therefore, this zone is considered as slightly brackish.

Salinity Zone III: The major water typically found in this zone are Na-Cl, but the zone is considered as brackish water. From Gibbs diagrams, fewer samples have fallen on the precipitation-evaporation region and more samples have fallen on the evaporation region in both cations and anions plots of shallow wells. All cations and anions of piezometer wells have fallen on the evaporation region in the Gibbs diagram. It is also confirmed that the piezometer wells are observed to be near to evaporation line (Fig.36c). Stable isotopes of shallow wells have fallen on the LMWL line and the evaporation line (Fig.36c). The slope between $\delta^{18}O$ and δD for shallow and piezometer wells is found to be 6.4 and 5.7, respectively. The piezometer wells slope (5.7) also supports the evaporation process obtained from Gibbs diagrams. The average Cl ion concentration in shallow wells (335 mg/L) is more than in piezometer wells (298 mg/L) in this zone. This indicates that shallow wells are influenced by anthropogenic activities (aquaculture activities). Further, the highest increase of water bodies was found to be in this region from the year 2005 to year 2019 (Sakhinetipally, Uppalagutam, Mogalthuru, Bhimavaram). Therefore, this zone is considered as brackish water.

Salinity Zone IV: The major water typically found in this zone is Na-Cl, but the zone is considered saline water. From Gibbs diagrams, the shallow and piezometer wells samples fall on direct evaporation process in both cations and anions plots. The stable isotopes of all Zone IV samples are close to the evaporation line (Fig.36d). This indicates that all the samples of Zone IV are dominated by the evaporation process. The slope between $\delta^{18}O$ and δD for shallow and piezometer wells is found to be 5.8 and 4.7, respectively. The average Cl concentration in shallow and piezometer wells are 938 mg/L and 1123 mg/L, respectively. The major source of salinity in this zone is evaporation and the proximity of the backwater. This zone is located in the coastal region of the Godavari delta.

Salinity Zone V: The major water typically found in this zone are Na-Cl, and this zone is considered high saline water. From Gibbs diagrams, the shallow wells are fallen in precipitation–evaporation region; however, the piezometer wells are found to be in the evaporation region. The stable isotopes of shallow wells are towards the precipitation line, and piezometer wells are fallen on the evaporation line (Fig.36e). The slope between $\delta^{18}O$ and δD for shallow and piezometer wells is 8.63 and 4.5, respectively. The average Cl concentration in shallow and piezometer wells are 1006 mg/L and 4790 mg/L, respectively. There is not much evaporation in the shallow wells, and rainfall is directly joining into the shallow groundwater without evaporation since the groundwater table is very shallow. The significant salinity sources in piezometer wells are high evaporation, marine clays (black silty clay), saline soils, the proximity of seacoast, and natural disasters of storm surges and cyclones.

The remedial measures for controlling salinity leaching into the shallow aquifer are possible with guidelines provided by the Central Institute of Brackish Water Aquaculture (CIBA) and awareness among people converting agriculture fields into aquaculture activities. The strict implementation of initiatives taken by the A.P State

Fisheries department on aqua zones would help the region's sustainable development and decrease further degradation of groundwater salinity in the Godavari delta.

6.0 CONCLUSIONS AND SCOPE OF FUTURE WORK

The groundwater quality in the Godavari delta has been evaluated in terms of salinity with the help of existing shallow and piezometer wells network from the year 2005 to 2020. The same network of shallow (19) and piezometer wells (18) is used for the years 2005 and 2017 to find the changes in groundwater salinity and it is found that the average salinity (EC) in shallow and piezometer wells has increased from 1664 to 2428 μS/cm in shallow wells and 2515 to 3606 μS/cm in piezometer wells. The long-term monthly and annual rainfall data trend analysis at Bhimavaram and Allavaram using Mann Kendall test for a period of 41 years (1973-2013) indicated that there is no significant change in average annual rainfall values and there is a change in the onset and receding of the monsoon. The surface water bodies mapping has been carried out using NDWI for the years 2005, 2009, 2014, and 2019 for the Godavari delta. The percentage of water bodies in the delta has increased from 13.6 to 21.17 % from the year 2005 to 2019. It is further classified that the upland and coastal regions of the Godavari delta have an increase in the water bodies from 1.97 to 3.57% and 11.63 to 17.63%, respectively. These increases are compared with agriculture and aquaculture data and found that these changes are mainly due to aquaculture activities. In the coastal zone of the Godavari delta, five mandals (Uppalaguptam, Sakhinetipally, Mogaluthuru, Bhimavaram, and Narasapuram) have shown a significant increase in the water bodies from the year 2005 to 2019. The impact of these increased water bodies on shallow groundwater salinity is more in all the mandals due to brackish water aquaculture except Narasapuram. The groundwater salinity in the Narasapuram mandal is decreased due to predominant freshwater aquaculture and the increasing trend of the groundwater table. Detailed analysis of groundwater quality data for the year 2017 using an improved network of shallow wells (47) and piezometer wells (51) has been carried out, and salinity zone maps for shallow and piezometer wells have been prepared using Cl/HCO_3 (molar) ratio and water types. There are four salinity zones in shallow wells and five salinity zones in piezometer wells found in the Godavari delta. The average salinity in shallow wells

(Zone II and Zone III) is higher than in piezometer wells. This may be due to the increase in aquaculture activities.

A further improved network of shallow wells (100) and piezometer wells (46) of the year 2020 have been used for the validation of salinity classification zones. There are five salinity zones identified with this network. The average values of all major ion concentrations of shallow and piezometer wells have increased from Zone I to Zone V and the results are well correlated for both the years 2017 and 2020. Further, the salinity sources in these salinity zones have been determined using stable isotope data and Gibbs diagrams. Zone I is classified as fresh water and recharge sources to the groundwater are precipitation without evaporation and rock-water interaction. The major water types found in this Zone I are Na-HCO_3 and Ca-Mg-HCO_3. Zone II is classified as slightly brackish, and Gibbs diagrams and stable isotopes indicated that both shallow and piezometer wells are influenced by rainfall with less evaporation process. The major water types found in this zone are Ca-Mg-HCO_3 and Ca-Mg-Cl. Zone III is classified as brackish, and the Gibbs diagram and stable isotope analysis indicated that shallow wells are influenced by less evaporation than piezometer wells. The salinity in shallow wells is more than in piezometer wells in this zone. This indicates that shallow wells are influenced by aquaculture activities. Zone IV is identified as a saline zone, and the salinity source is the evaporation process which is indicated by both the Gibbs diagram and stable isotope data. Zone V is classified as high saline and evaporation, and marine clays are the main dominant sources for the high salinity in the piezometer wells, and there is not much evaporation in the shallow wells since rainfall is directly joining into the shallow groundwater without evaporation. The tritium data of shallow wells and piezometer wells further enhance the salinity sources in the Godavari delta. Detailed hydrogeochemical modelling in the vicinity of aquaculture and column tests would provide a better understanding of solute transport in the shallow aquifer.

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