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

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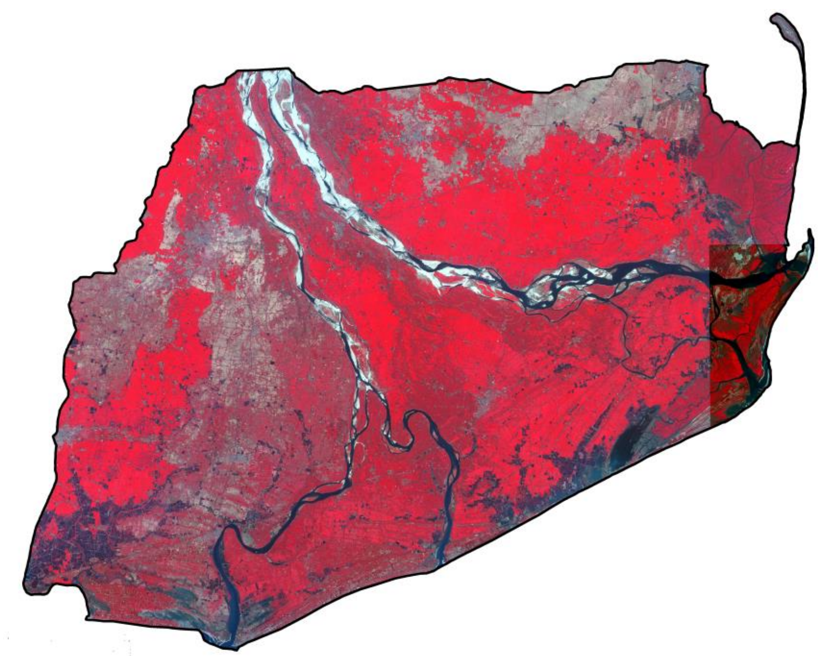
Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, New Delhi

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



Deltaic Regional Centre
National Institute of Hydrology
Sidhartha Nagar, Kakinada-533003
Andhra Pradesh

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Dr.Y.R. Satyaji Rao Scientist 'G'		Deltaic Regional Centre National Institute of Hydrology Sidhartha Nagar, Kakinada- 533003

PREFACE

Coastal aquifers are susceptible to regional and global phenomena, including sea-level rise, storm surges, change in climatic conditions, shoreline erosion, and coastal flooding. Additionally, human activities are enhancing 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 minium in the Godavari delta, and all the mandals in the delta regions are safe category as per the GEC norms. However, due to anthropogenic activities and climatic conditions, the groundwater salinity is increasing over a period of time. The groundwater monitoring network in the delta was used for resource assessment and mainly focused on the upland zones in the delta. After implementing Hydrology Project, the network has been increased, and the coastal area is also monitored in the delta. The detailed analysis of hydrochemistry and stable isotopes with a recent network of observations 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 classes has 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 Purposes 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.

Place: Kakinada
Date: 16.12.2021

Signature
(Name)

Project Team	
Lead organisation	Dr. Y.R Satyaji Rao, Scientist-G and PI Dr. Sudhir Kumar, Scientist G (Co-PI) Sri. T.Vijay, Scientist B (Co-PI) Sri. R.Venkata Ramana, Scientist D (Co-PI) Dr.S.V.Vijaykumar, Scientist G (Co-PI)
Partner organization	Director State Groundwater and Audit Department, Water Resources Department, Vijayawada, Andhra Pradesh

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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 2525 µS/cm to 3515 µS/cm, respectively, from the years 2005 to 2017. The surface water bodies mapping has been carried out using 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 been 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 identidied salinity zones are validated with the improved network of shallow wells (100) and piezometer wells (46) of the year 2020. There are five salinity zones (Zone I to Zone V) have been identified in the delta. The stable isotopes are 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 is 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 no 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.

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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 the 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. The groundwater salinity is one of the significant environmental challenges as the coastal areas are more susceptible to development due to the high density of population and other anthropogenic activities (Barlow and Reichard, 2010). The salinization processes of groundwater are the leading cause for 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 reasons for these variations are the rainfall patterns, paleo-marine environment, geomorphology, climatic conditions, land use/cover changes, groundwater pumping, sea-level rise, water bodies, backwater through creeks/drains/river mouths, irrigation canal network, 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. Therefore, the present investigations focus on groundwater salinity sources in the Godavari delta.

Over the years, the shallow groundwater salinization in the Godavari Delta has been a severe problem for managing potable water and agricultural productivity. In fact, in the 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 since shallow to deeper aquifers are brackish and saline in nature (CGWB, 2013). In the last two decades, paddy cultivation has 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). Further, the surface water pathways such as river mouths, drains, and creeks are well connected with the sea, affecting the shallow aquifer (backwater phenomena during high tides) at many locations that render fertile agricultural land progressively saline. The sand mining and extreme hydrological events had further aggravated backwater into further inland.

Therefore the salinization processes in the Godavari delta need to be addressed systematically by studying many processes. These processes are mainly dependent on natural/geogenic, the influence of the sea coast, sea/saltwater intrusion, anthropogenic factors (aquaculture practices and irrigation), rainfall patterns, groundwater levels, and its quality (both shallow and deep aquifers), water body mapping etc. Under these circumstances, an integrated approach was adopted to identify salinity zones and their sources within the Godavari Delta. 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 A.P. 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 was carried out in the Godavari delta region 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 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 western Delta region subsurface 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 the additional factors for brackish water quality. In the western Delta region, they have also concluded that the initial quality of groundwater is from geogenic origin has been subsequently modified by the influences of anthropogenic and marine sources.

Surinaidu et al. (2014) have monitored groundwater levels at 42 locations in a part of central Godavari delta (295 km^2) for a period of 2 years (2006–2007). They used flow modelling and calibrated hydraulic head for 2006 at a 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 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 Kalipatnam drainage area are saline-sodic. The linear regression equation between SAR and EC indicates that sodium is the major cation contributing to salinity. Excess concentration of sodium chloride present in the soil solution might contribute to lower pH values.

Karunya et al. (2016) analyzed the 44 soil samples in the Kapileswarapuram mandal in the Central Godavari Delta, which is about 50 km from the sea coast, to characterise waterlogging and salinity by using soil textural classification, soil chemical parameters, groundwater table and SEW_{30} index. They concluded that the soils in the study area are not having any salinity and does 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 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 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 Godavari western 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-dominated by non-carbonate alkali and mixed types. Because of the deterioration of groundwater quality, TH, Mg^{2+}, Na^{+}, Cl^{-} and SO_4 concentrations exceed their drinking water quality standards in most regions. The groundwater quality is not suitable concerning SAR, $\%Na^{+}$ and MH, but they are safe concerning RSC and 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, Malikipuram, where the Electrical conductivity 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 more than 1000 ppm 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 sea and the seawater mixing. They concluded a need to monitor the new 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 the eastern Godavari Delta shallow aquifer are in the range of 650-5950 µS/cm, and **w**estern Godavari Delta is in the range of 926-15950 µS/cm. The maximum Chloride value obtained in the shallow groundwater in Eastern Godavari Delta is 1631 mg/L with the mean value of 317 mg/L, and the maximum Chloride value of western delta Godavari Delta is 4566 mg/L with a mean value of 934 mg/L. The EC value of deeper aquifers of eastern Godavari Delta is as high as 19370 µS/cm, and the maximum EC value of deeper aquifers of 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 the 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 Delta and seven in the western Godavari Delta.

Rao (2013) has reported about the waterlogging conditions in the western Delta region. During the post-monsoon season, he said that 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 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, aquaculture practices also contribute to some extent.

Bhaskar Rao (2013) 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 was varied from 372 to 7625 µS/cm at 25°C. Along the coast i.e. at Kakinada, Jonnada and Vakalpudi EC values are recorded more than 3000 µS/cm at 25°C, whereas in the central part of the deltaic area, EC ranges in between 1500 and 3000 µS/cm at 25°C. He reported that waterlogging and salinity are the major problems in the district's Eastern Delta and coastal area. 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 in groundwater movement and excess use of fertilizers and unregulated growth of aquaculture in the coastal area.

Surinaidu et al. (2013) has conducted Electrical Resistivity Tomography surveys at several locations in the Central deltaic region and delineated the aquifer geometry. The results inferred from ERT indicate 12–15 m thick loamy sands exists 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 upstream and downstream seawater mixing along the drains in the pre-monsoon. The quality is increasing 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 attributed to dilution 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, 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 level, and subsidence (Ramkumar et al. 1999). 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 localised areas. Intensive irrigation, near-flat topography, groundwater development, poor drainage and clayey soils are responsible for the 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 in Antarvedi and Kalavapudi areas flourished with intensive aquaculture practices. Further, soil samples were collected from dried aqua ponds regions and analysed 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 the Antervedi area of East Godavari District. All soil parameters like TDS, EC, TOC, nitrogen, potassium, sodium, sulphur, iron, manganese, zinc and copper increased with the pond's age. Only pH is slightly less in W.G.Dt than E.G.Dt. The possible reason is aquaculture in the study area of West Godavari was started much earlier, 25 to 30 years back, in comparison to East Godavari, where it was started just 10-15 years back. So, 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 East Godavari due to aquaculture. It is observed that there is an increase in the concentration of sodium, 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 seawater intrusion due to aquaculture, which may negatively impact the environment.

Satyaji Rao and Vijaya Kumar (2018) studied groundwater's hydrochemistry in the central Godavari delta and found that paleochannels Electrical Conductivity (EC) is less than the groundwater. The paper presents the detailed hydrochemistry of canal water, drain water, and river water. The paleochannel water's 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 depth and salinity in the Central Godavari Deltaic region. The multiple salinisation processes include 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. The detailed hydrochemistry analysis has been carried out by Kumar and Rao (2018) in Kakinada rural and urban areas. The study indicated that high nitrate concentrations in excess have been in many wells. It suggests that more elevated in the urban and agricultural regions. The Physico-chemical parameters of water samples vary the permissible limits of standards in Kakinada rural areas. Potassium and Magnesium are higher in all groundwater samples, and the wells near the sea coast, salt creek, and drains exceed 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.

Raju et al. (2014) studied the impact of aquaculture on groundwater in a few coastal mandals of the East Godavari District. 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 that 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). The aquaculture practices more, and the quality is good in areas where the groundwater is free from salinity.

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 on 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 δ18O 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 LMWL was 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 (Huangand Pang, 2012).

The literature review indicated that the two coastal districts of Andhra Pradesh cover the entire Godavari delta. These two districts are East Godavari district and West Godavari district. The Godavari delta has been bifurcated into three parts, and they are Western Godavari Delta (West Godavari District), Central Godavari Delta (East Godavari District) and Eastern Godavari Delta (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, delta formations. Most of the studies conclude that there is no seawater intrusion in the delta, and most of the coastal regions are under saturated conditions. 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 its quality, water body mapping and isotope characterization in the Godavari delta. Therefore the proposed study (PDS) may fill the research gap on the salinization process 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 in the east coast of India, producing 35 km from 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 Holocene in age and the third-largest delta of India after 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 joins 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 joins into the Bay of Bengal smaller branches, i.e. Coringa, Gaderu rivers showing meandering and the strong influence of tides. Hence Godavari River opens through several mouths, and thus, 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 to a 10 km wide belt. This zone has lagoons, tidal flats and mangrove marsh affected by tides.

3.1 Location of Godavari Delta

The Godavari delta region is situated 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 Western side (Bhimavaram) and the Bay of Bengal on the Southern side. The delta region falls in 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. Deltaic width is 120 km, and the deltaic plain slope is 0.0004. Four historical strandlines are marked on the Godavari delta (Fig.1).

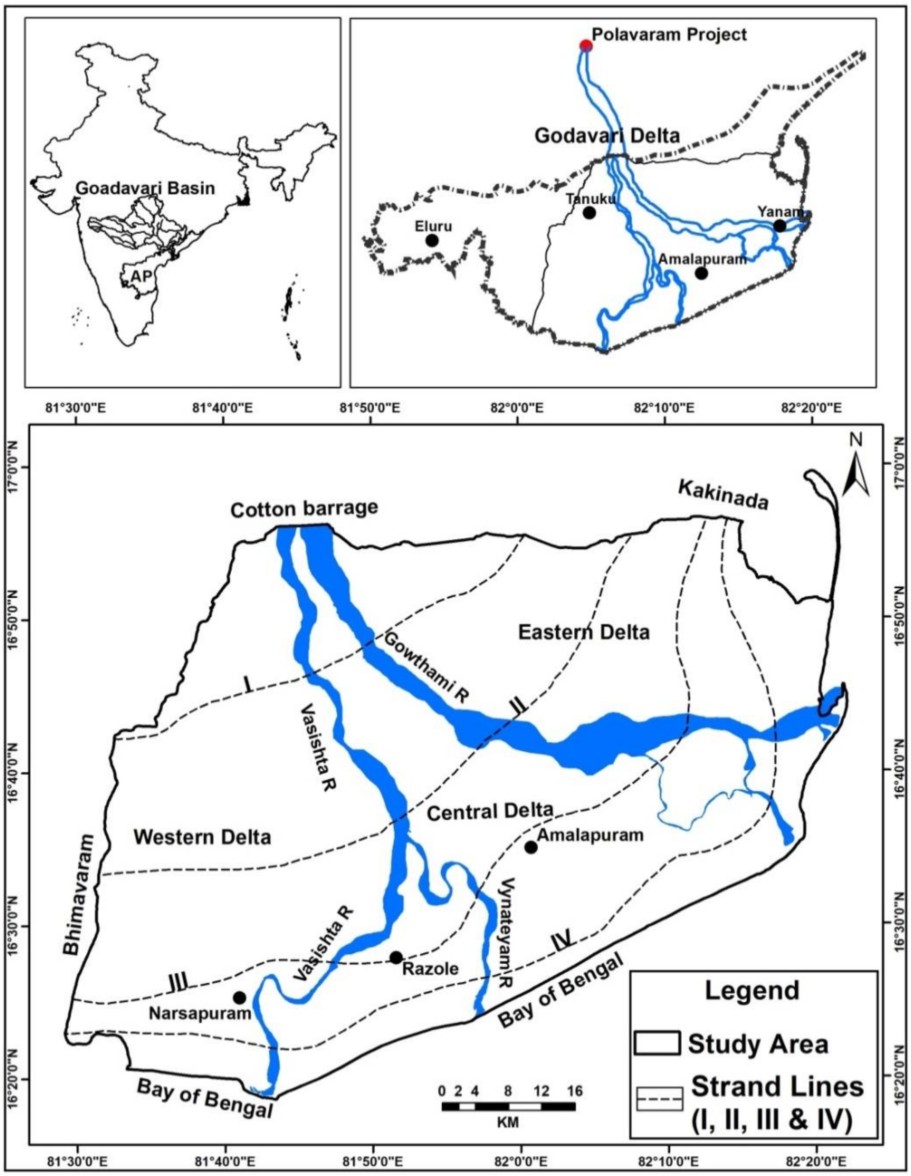


Fig.1 Location of the Godavari delta in Andhra Pradesh State, India

3.2 River and tidal influence

Significant discharges from the Godavari river commence from June and reach 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 discharging 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 upto Yanam; though during low river discharge, tidal influence is recorded up to Kapileswarapuram, 45 km upstream from 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 the 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 and shown in Figure 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 a plain land, sloping gently (<3^0) toward the southeast.

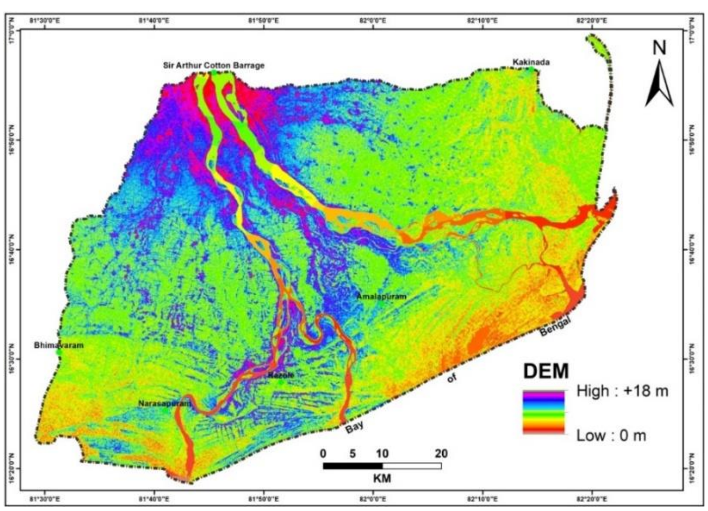


Fig.2 Digital elevation map of the Godavari delta

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 sheets, and satellite data is shown in Figure 3. The well-distributed Godavari irrigation canal network acts as a source for 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.

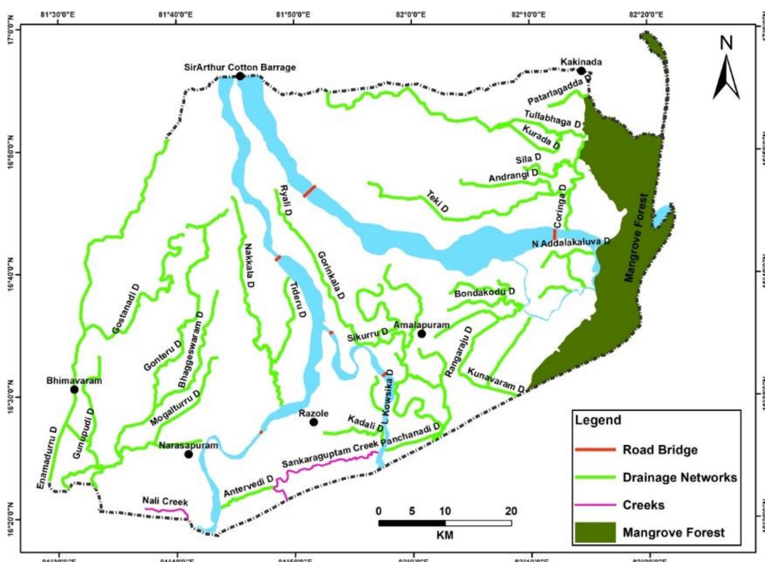


Fig. 3. Various drains and creeks in the Godavari delta

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. 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 1,137 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 occur during the northeast monsoon (October–December). The area experiences seasonal floods every alternate year resulted 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 the main land used within the region. Three crops are grown successively in a year, and fertilisers and pesticides are also very high in this region. As ample surface water is made available to irrigate the delta, there has been little or not much use 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 along the coastal track and inland river valleys include thick blankets of alluvium, gravel and colluvial deposits, beach sand, kankar, 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 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 the delta progradation (Rengamannar and Pradhan 1961).

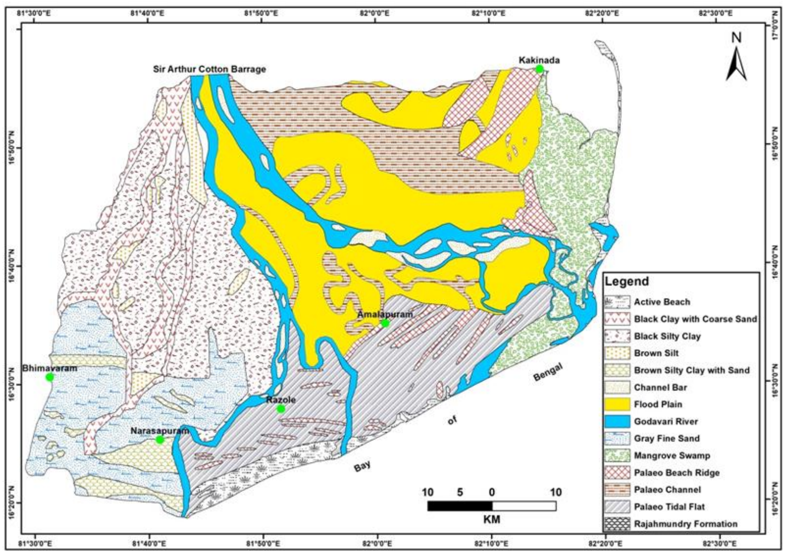


Fig. 4. Geomorphological features of Godavari delta (CGWB)

Significant landforms are valley fills, channels, levee, back swamp, channel, point bar of fluvial and active beach, 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.5. 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 prograding nature (advance towards the sea) and formed due to 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 mangroves colonies survived.

3.8 Soils of Godavari delta

There is primarily alluvial soil in the interior of delta area and clayey soil at the tail portions of 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.

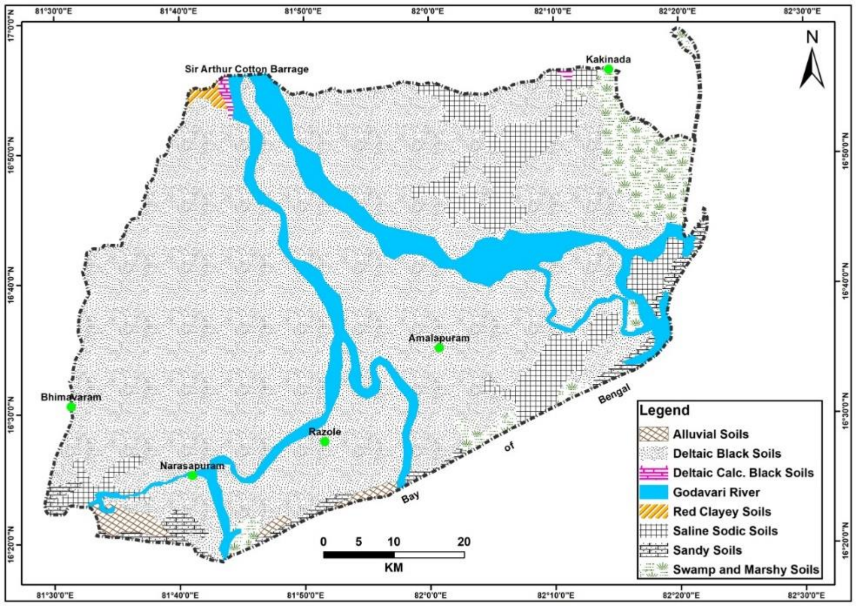


Fig.5 Soil map of Godavari delta

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 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 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) and are shown in Figure 6.

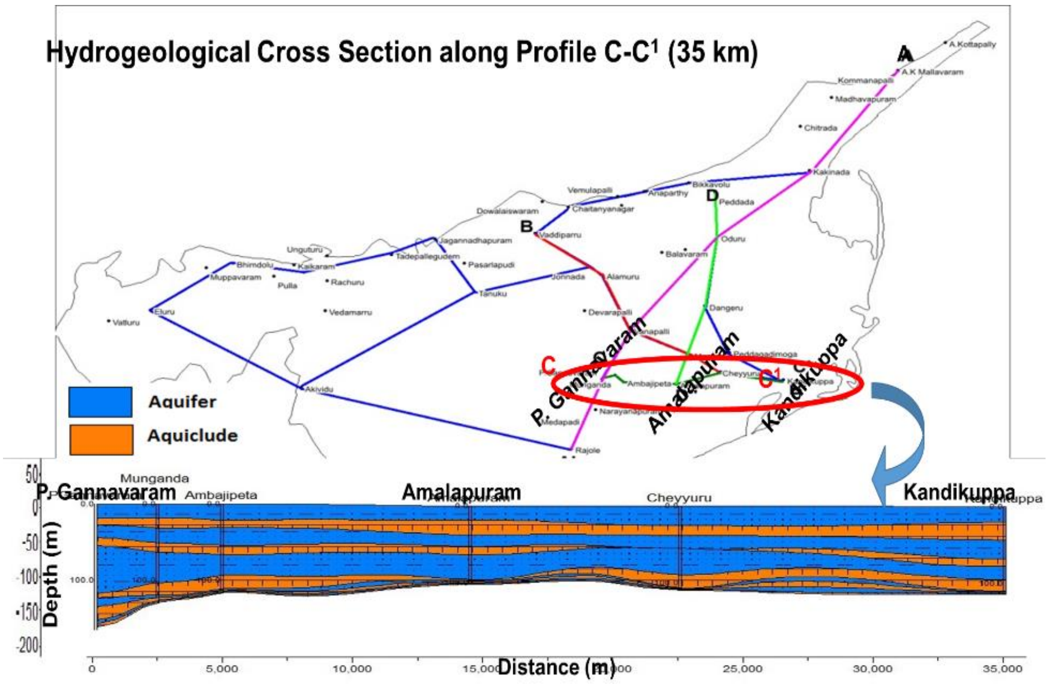


Fig. 6. The hydrogeology of the Central Godavari delta (CBWB, 2013)

4.0 METHODOLOGY

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

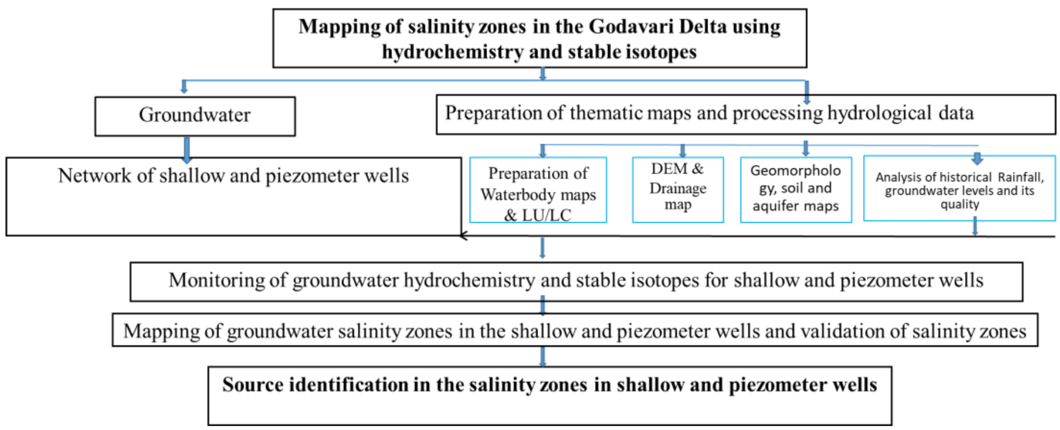


Fig. 7. Flow chart showing the methodology adopted for salinity source identification

4.1 Shallow and piezometer wells network of groundwater

The groundwater monitoring network covers shallow and piezometer wells in the Godavari delta. The depth of shallow wells ranges between 5 to 10 m, and in piezometer wells, the depth is between 10 to 30 m. The network of these wells was increased from 2005 to 2020, and due to some reasons, a few wells were excluded from the monitoring network. This monitoring network objective was to make groundwater resource estimates in each Mandal (As per GEC norms) 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 and seasonal changes in the

Godavari delta, the groundwater levels and quality data from 2005 to 2017 have been obtained from the State Groundwater Department (Andhra Pradesh).

4.2 Preparation of various thematic maps

To obtain the basic information of the Godavari Delta, the toposheets falling under the study area (18 No.) are georeferenced and mosaiced in 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 map has been prepared from IRS LISS IV satellite data (5.8 m resolution), geomorphology, soil, drainage, aquifer maps have been prepared from published maps from various sources in GIS framework. The Normalized Difference Water Index (NDWI) maps have been prepared for different years using LANDSAT satellite images to find waterbody changes. The NDWI mapping could be helpful for the identification of the areas where the most significant shift in water bodies occurred over some time. The water bodies maps for 2005, 2009, 2015 and 2019 has been prepared. The mandal boundaries (administrative boundary) has been prepared to identify field locations, ground truth, and other villages. Each mandal has been assigned an Identification Number (ID), and the study area has been divided into the upland zone (1 to 25) and coastal zone (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 A.P. State Water Resources and Audit Department were collected for the present analysis. The saline zones are identified using EC, Cl and Cl/HCO_3 ratio with the help of historical groundwater quality data. Several visits were made to A.P. State Ground Water Department district offices located in Rajahmundry, Kakinada in East Godavari district; Eluru in West Godavari district also State Ground Water Department Head Office located at Vijayawada and collected the seasonal and temporal groundwater levels and quality data. The historical monitoring network of shallow and deep wells available with APSGWD was collected. These historical data have been analysed to identify the salinity zones in the Godavari Delta. The historical average EC values for both shallow and deep groundwater is made, and the initial findings of groundwater quality are noted in the Godavari delta. The locations of increased water bodies are compared with the chloride and groundwater levels. The NDWI maps for the different years are further compared with the rainfall, groundwater levels, and Cl concentration in mg/L to understand the impact of water bodies on groundwater quality.

4.3.1 Impact of water bodies on groundwater salinity

The effect of 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 km2) on shallow groundwater salinity in different mandals of coastal delta 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 year period (2005-2019) are studied to find the sources of shallow groundwater salinity. Conversion of agricultural lands into aqua ponds are 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. Piper diagrams indicate that, based on the dominance of different cations and anions in the groundwater, major water types can be defined in the study area. The piper diagrams also suggest that the major processes and hydro-chemical facies. However, the factors that influence the change of chemical composition of groundwater can be investigated graphically with the help of Chadda's plots. From the Chadda's plots, four water types such as (i) Seawater mixing zone possibly represents NaCl mixed seawater, (ii) base-ion exchange water which represents Na-HCO_3 type of water, (iii) recharging water which indicates Ca-Mg-HCO_3 type of water and (iv) reverse ion-exchange water (Ca-Mg-Cl type) can be found. Thus, using both Piper and Chadda's diagrams, 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 also considered for the analysis of seawater mixing contamination into the fresh aquifer. 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 was 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 have the ratio Cl/HCO_3 ranging between 1.3–2.8 indicate moderate contamination, and 2-8-6.6 indicates high contamination with the 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 as well as deep aquifers 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 2017 year's quality data) of both shallow and deep aquifer are further compared with the water quality data of 2020 quality data (APSGWD data).

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 made in the field. The chemical analysis of all major ions, including Bicarbonate (HCO_3), Carbonates (CO_3), Chloride (Cl), Sodium, Potassium, Sulphates, 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 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 sq.km and having the coastal length is about 200 km. However, the Godavari delta, which is considered for the present investigations, is approximately 4485 sq.km having a coastal distance of about 152 km. The study area is bounded by Enamadurru drain on one side, Kakinada canal on the other side, and the Bay of Bengal as coastline (Figure 1). Various thematic layers like DEM, soil, geomorphology, groundwater observation well network 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 Figure 8. One is the upland zone with mandals (1 to 25), and the other is the coastal zone with mandals (26 to 48). The Land Use/Land Cover (LU/LC) map for the post-monsoon season of 2019 (November) has been prepared for the Godavari delta using the IRS LISS IV satellite image (5.8 m resolution) and the same is shown in Figure 9. The details about LU/LC are given in Table 1. According to the LU/LC map, the highest area of 42% is occupied by the agriculture, followed by plantation (29.94%) and water bodies (11.78%).

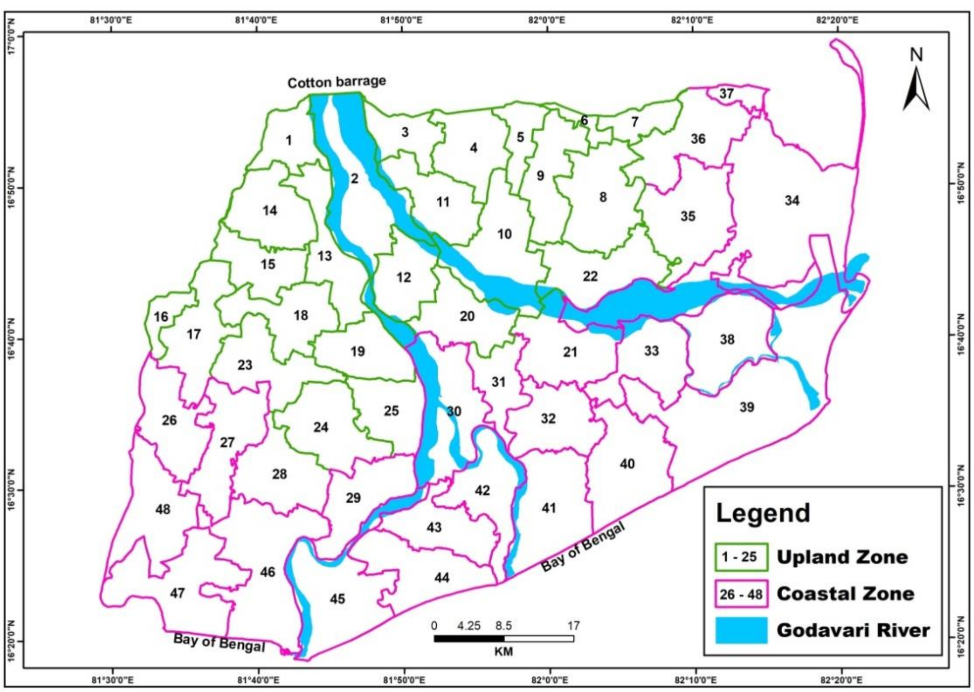


Fig. 8 Upland and coastal zones and their mandal IDs of the Godavari delta

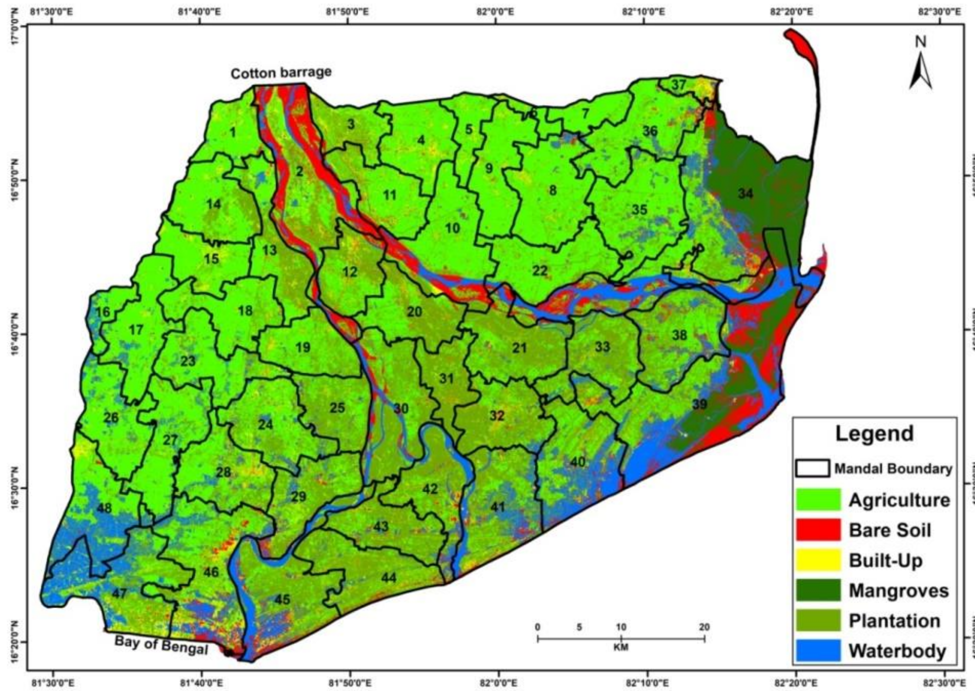


Fig 9. Land Use/Land Cover map of the Godavari delta (November 2019)

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

Class Name	**Area in km²**	**Percentage of the total area**
Agriculture	1883.93	42.00
Bare Soil	330.84	7.38
Built-Up	211.88	4.72
Mangroves	187.21	4.17
Plantation	1342.90	29.94
Water bodies	528.58	11.78
Total Area	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 A.P. State Groundwater Department (APSGWD) has a monitoring network of shallow and piezometer wells. The average depth of shallow wells is 5 m and piezometer wells 23 m. This network of observation wells varied with respect to time, and few wells were discontinued due to various reasons. Therefore an attempt has been made to analyze the groundwater table and water 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 varied during the last 12 years (2005-2017). 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 been 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.

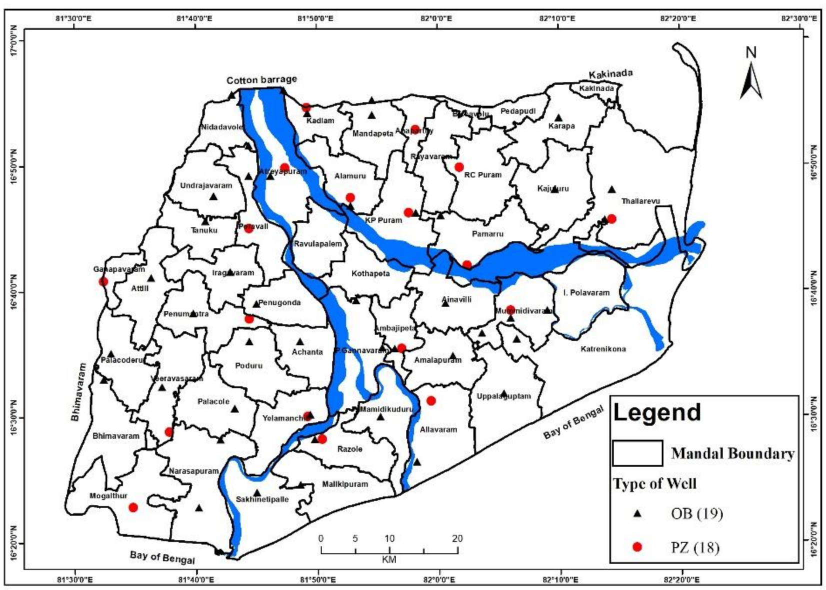


Fig. 10 Shallow and piezometer wells network in the year 2005 in the Godavari delta

The depth of observation wells and piezometer wells is less than 8 m and is between 10 and 30 m below ground level (bgl), respectively. Fixed network of observation wells (19) and piezometer wells (18) are considered and compared with the groundwater quality data for temporal analysis from 2005 to 2017. 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. Hence, it has indicated that the quality in shallow and piezometer wells significantly changed from 2005 to 2017.

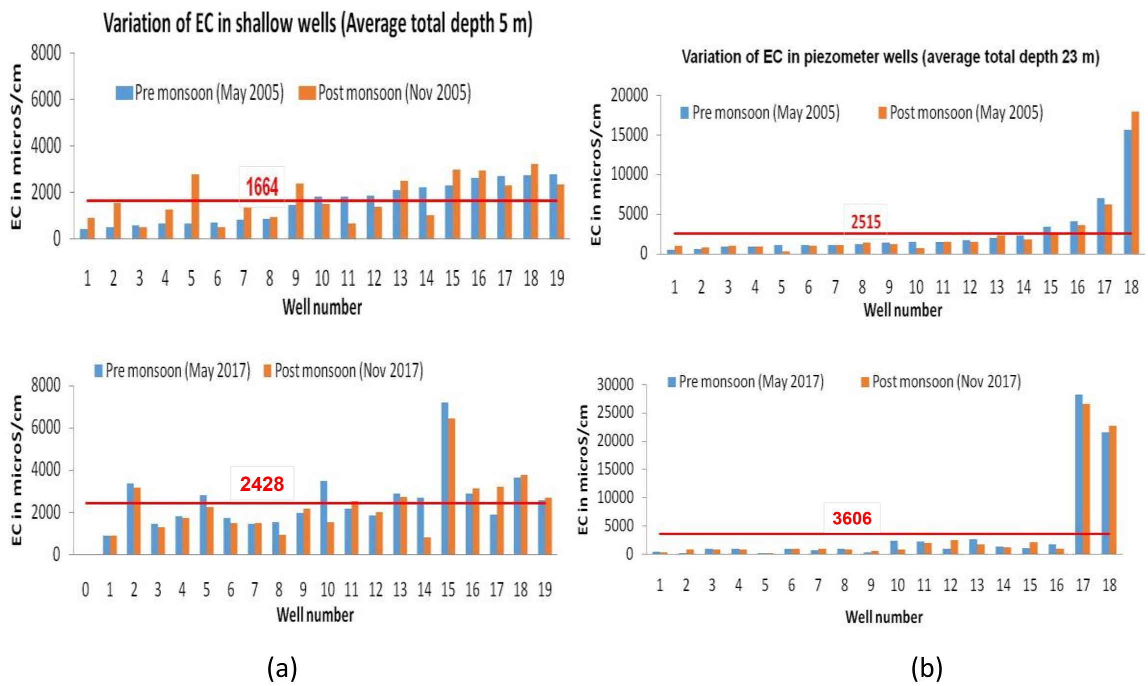


Fig.11 Comparison of average EC (2005 and 2017) in (a) shallow wells and (b) piezometer wells in the Godavari delta

5.1.2 Analysis of rainfall data (1971–2013)

The rainfall data is available only at two locations in the Godavari delta for a period of 1971-2013 (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 Figure 12. 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 behaviours 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 1971-2013.

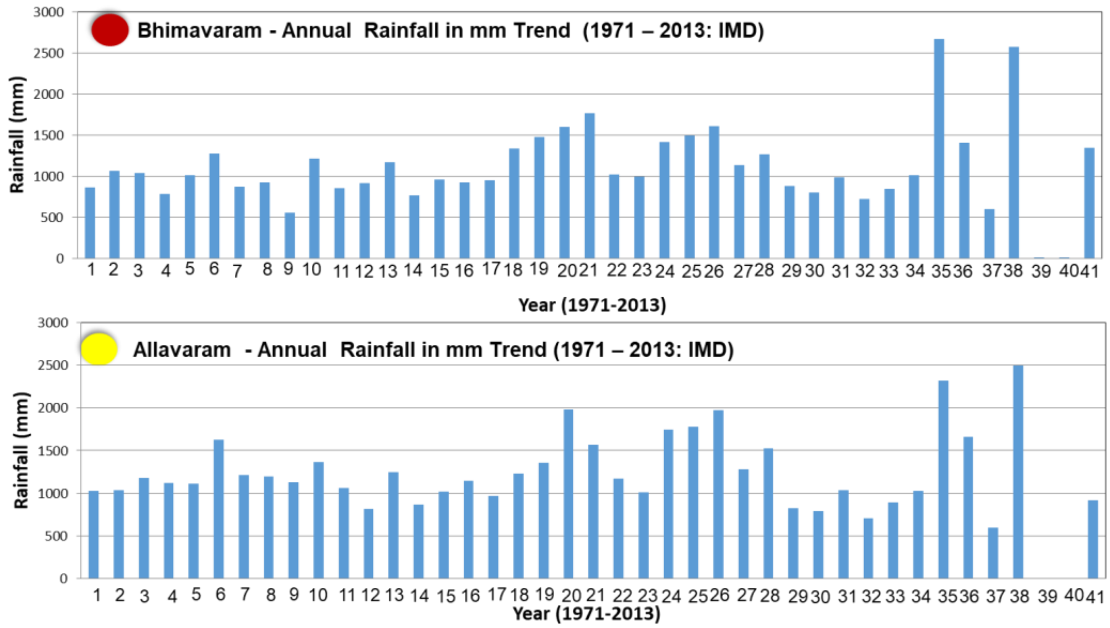


Fig. 12 Annual rainfall at Bhimavaram (Western delta) and Allavaram (Central delta) during the period 1971-2013

Table 2: Mann Kandle 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 Godavari Delta

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

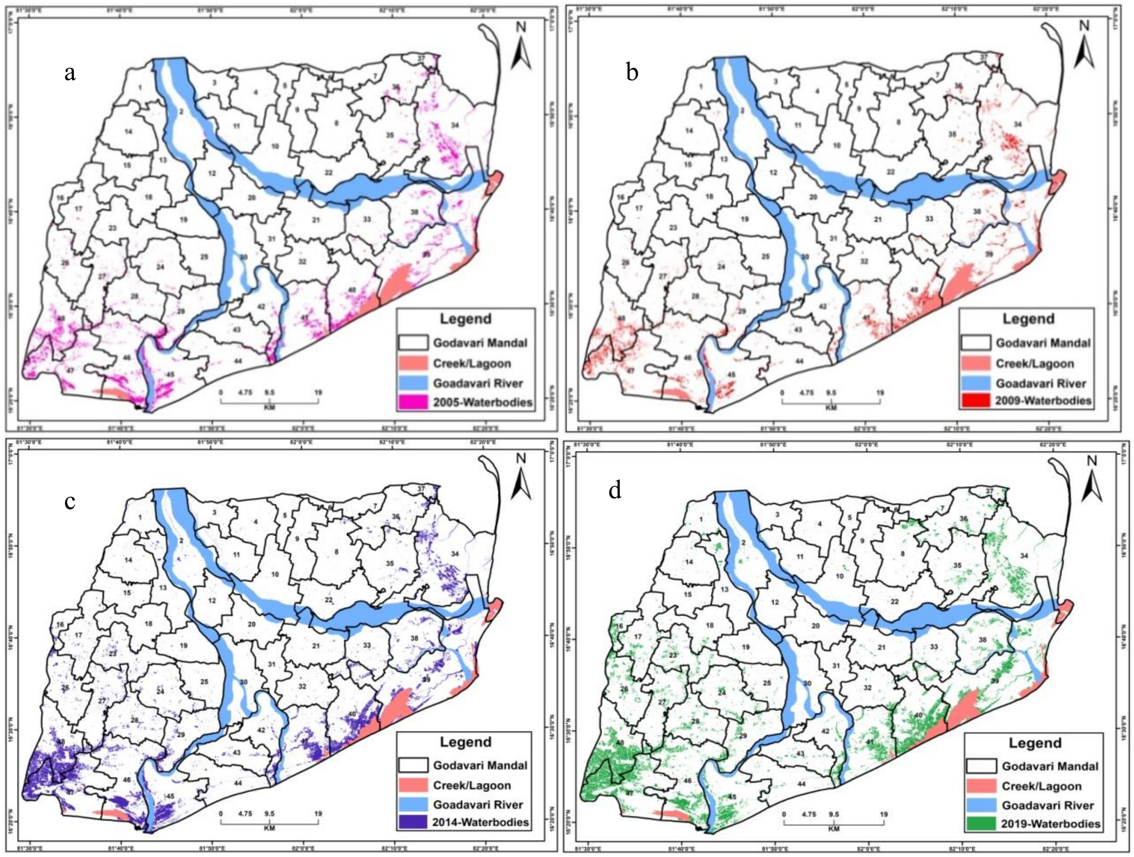


Fig 13. NDWI maps of Godavari delta for the years (a) 2005 (b) 2009 (c) 2014 (d) 2019

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 the fifteen years (2005-2019) is 1.60% and in the coastal zone (26 to 48 mandals) is 5.97%. The details of the waterbody area along with 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 and in Percentage			
		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	249.46/9.50	428.03/16.30	462.06/17.60

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 upland zone and the coastal zone is shown in Figure 14 and Figure 15, respectively. It is clearly 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 by 11.39%, Narasapuram by 10.43% and Mogalthuru by 8.07%), followed by Central delta (Uppalaguptham by 8.38% and Sakhinetipally by 7.1%).

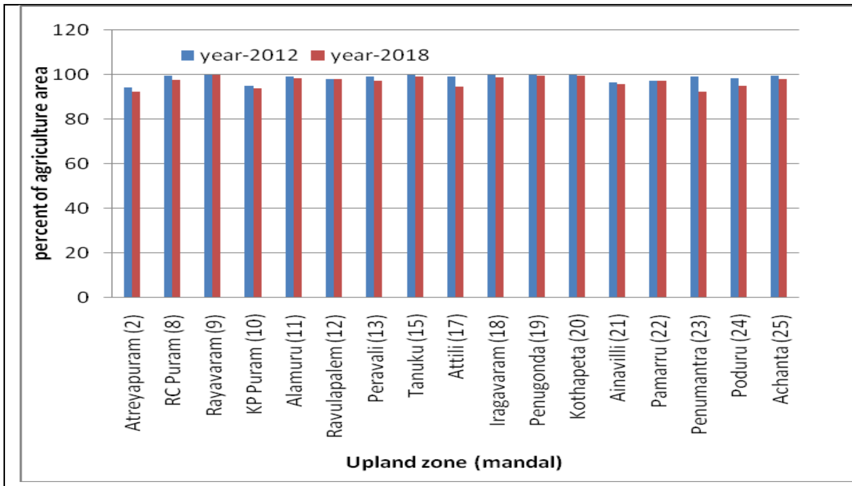


Fig.14 The reduction of agriculture area in each mandal (upland zone)

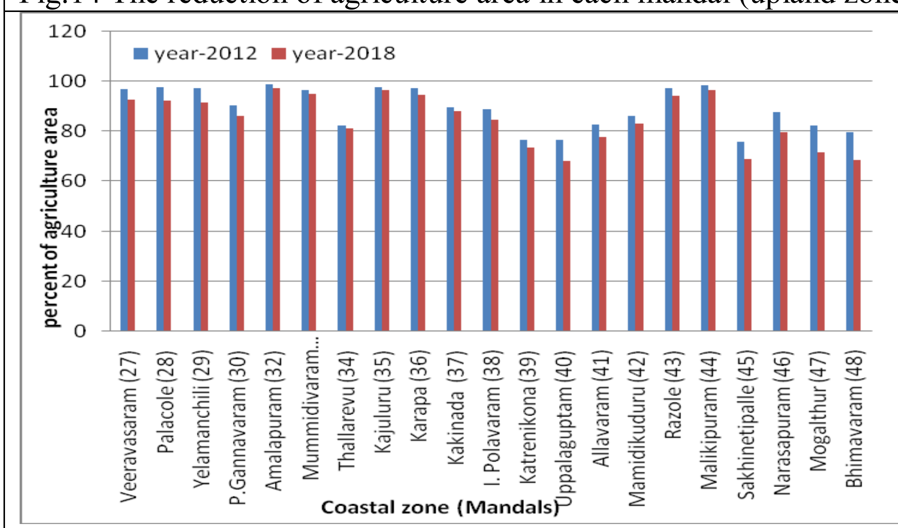


Fig.15 The reduction of agriculture area in each mandal (coastal zone)

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: The area of water bodies (km^2) with highest change mandals in Godavari delta

Mandal	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 Andhra Pradesh Space Application Centre (APSAC). It is identified that the increase in water bodies is mainly due to the increased aquaculture practices during the 15 years period. It was 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). Thus, it can be identified that the change in water bodies during the period 2005-2019 is mainly due to the increased aquaculture practices in the delta. The mandals of increased water bodies in the coastal delta region are compared with the salinity (Cl), groundwater levels and rainfall. The variation of historical groundwater levels of shallow aquifer, rainfall, and its 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 the aquaculture. However, the groundwater levels are declined 17(a) and groundwater salinity (chloride) increased 17(c) in the Sakhinetipally mandal (ID 45). The aquaculture ponds using groundwater pumping may be the cause for the increased salinity in this mandal. A similar phenomenon was 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 (Figure 18c), and the groundwater table is raised (Fig 18a). It is mainly due to the fresh water fish culture (canal water).

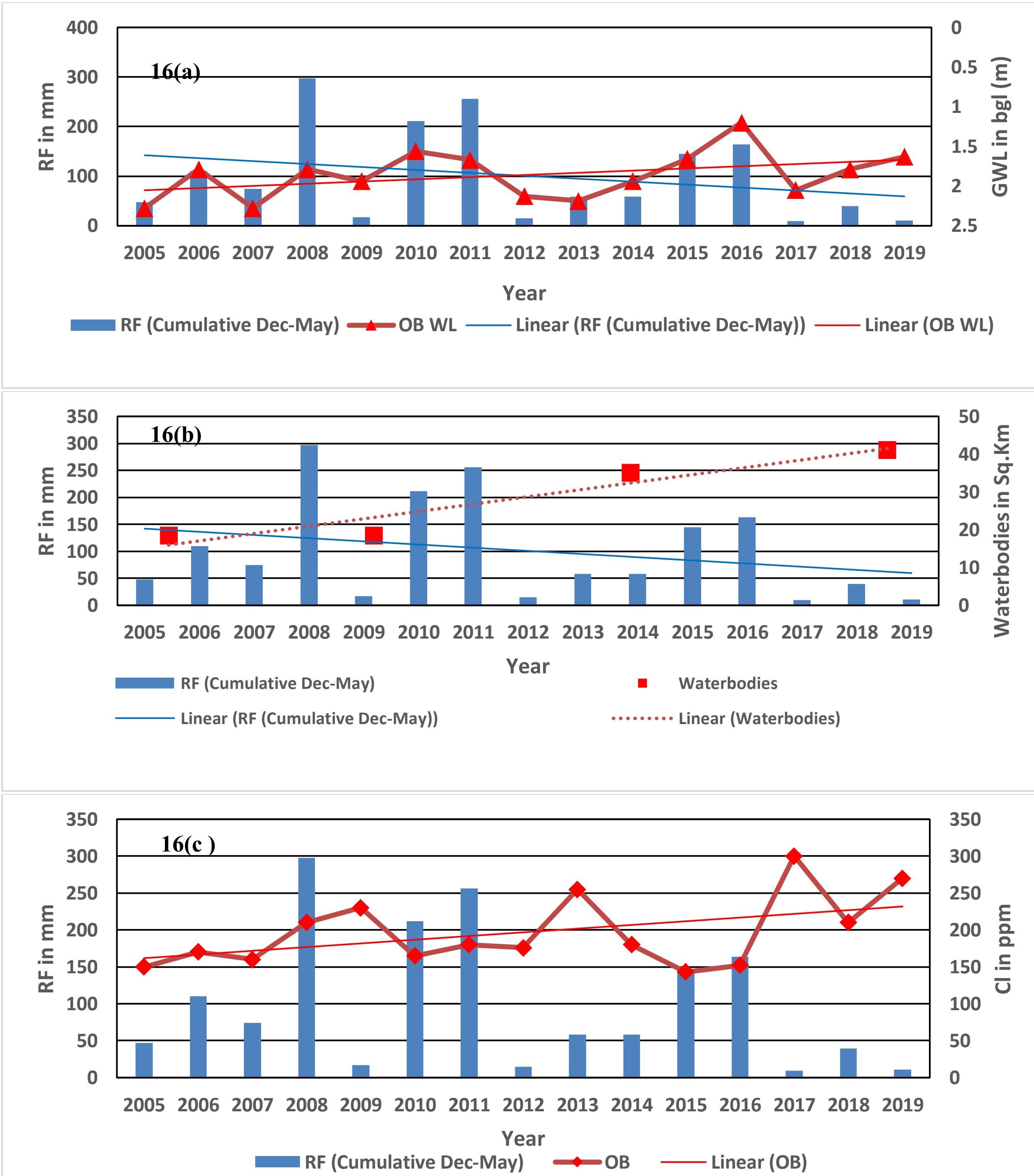


Fig.16 (a) The variation of groundwater levels (shallow wells), 16(b) water bodies, 16(c) salinity (Cl) with rainfall during the period 2005-2019 in the Uppalaguptham mandal (ID:44)

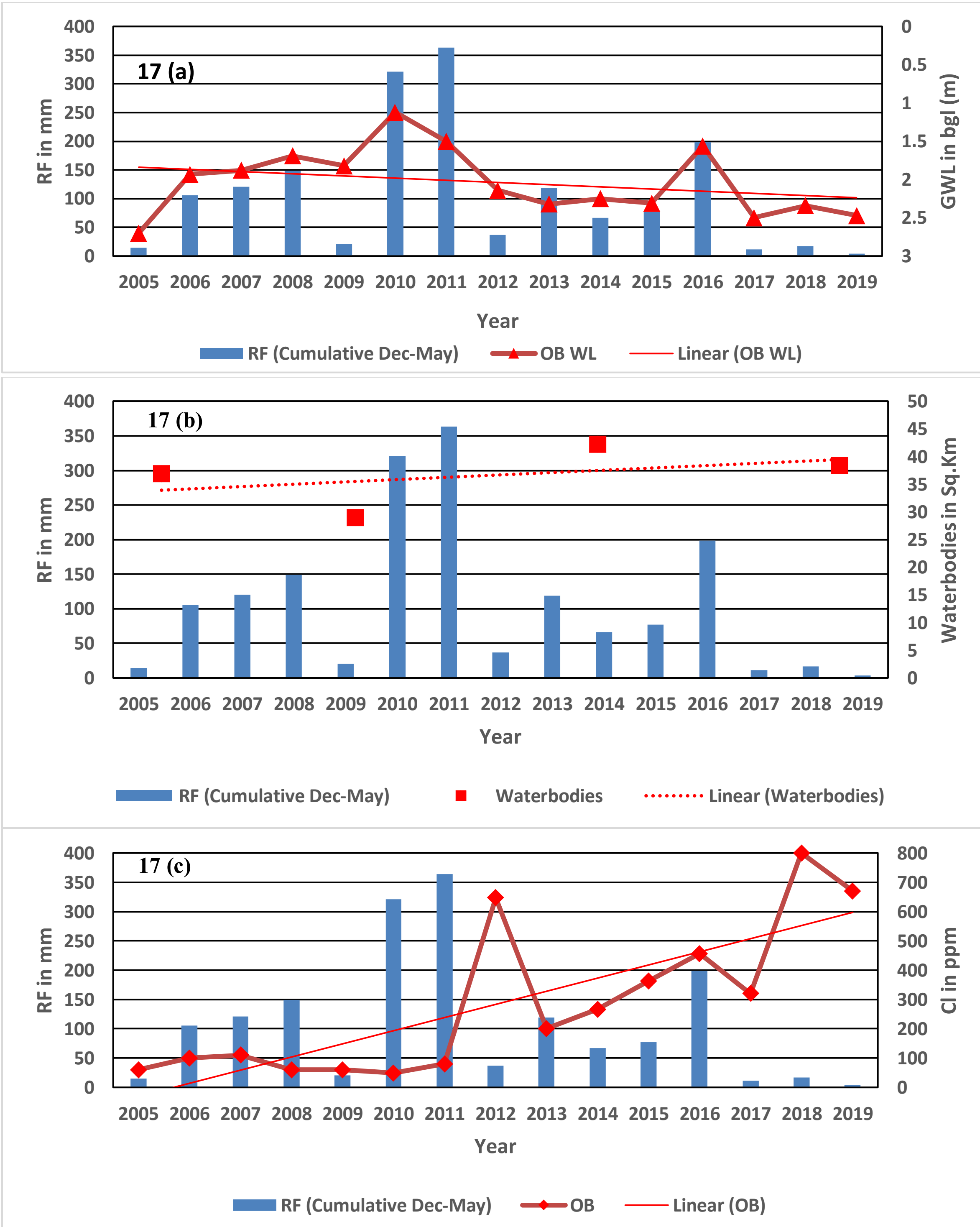


Fig.17 (a) The variation of groundwater levels (shallow wells), 17 (b) water bodies, 17 (c) salinity (Cl) with rainfall during the period 2005-2019 in the Sakhinetipally mandal (ID: 45)

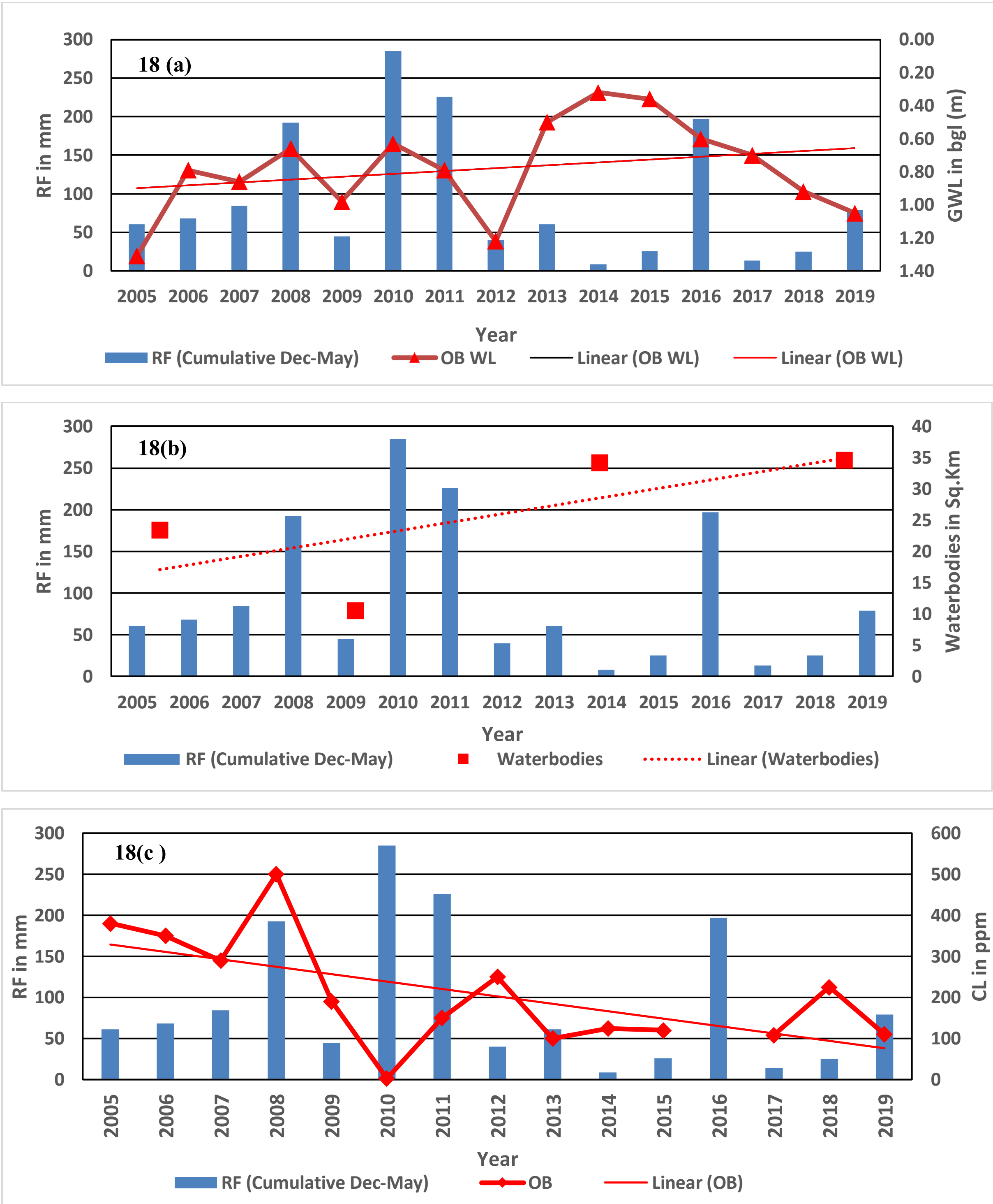


Fig.18 (a) The variation of groundwater levels (shallow wells), 18 (b) water bodies, 18 (c) salinity (Cl) with rainfall during the period 2005-2019 in the Narasapuram mandal (ID:46)

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 Figure 19. The average depth of each shallow and piezometer wells is 5 m and 23 m, respectively are shown in Figure 20.

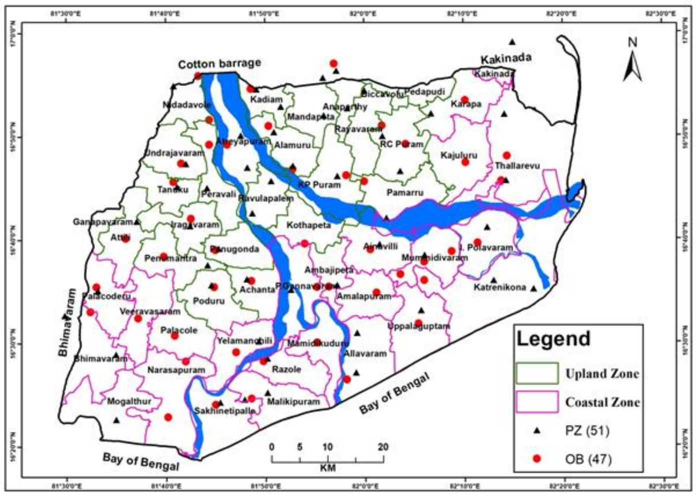
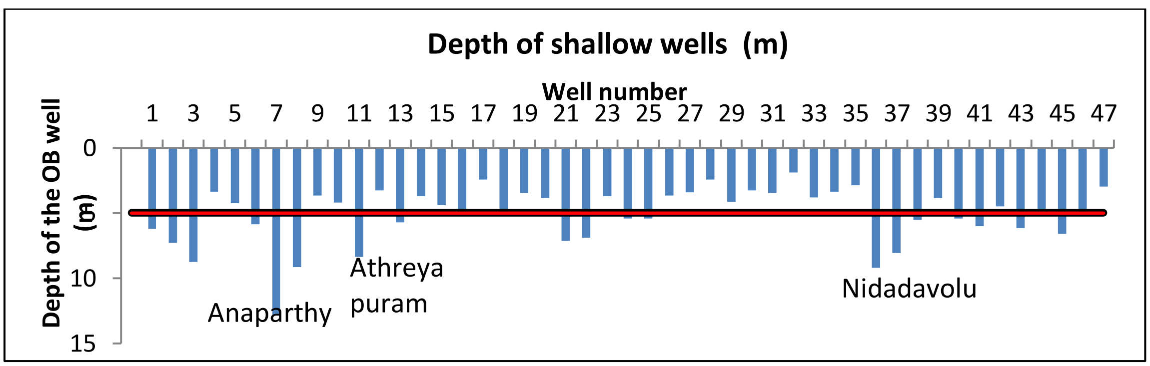


Figure 19 Locations of observation and piezometer wells in the year 2017



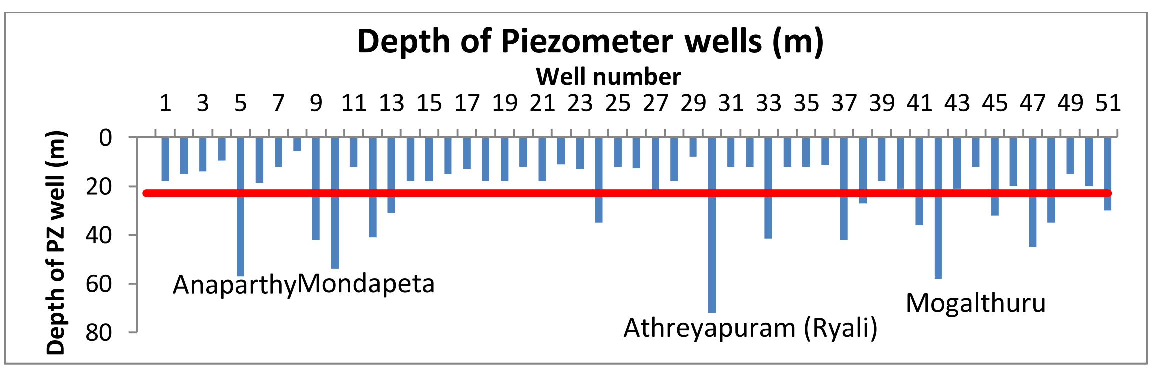
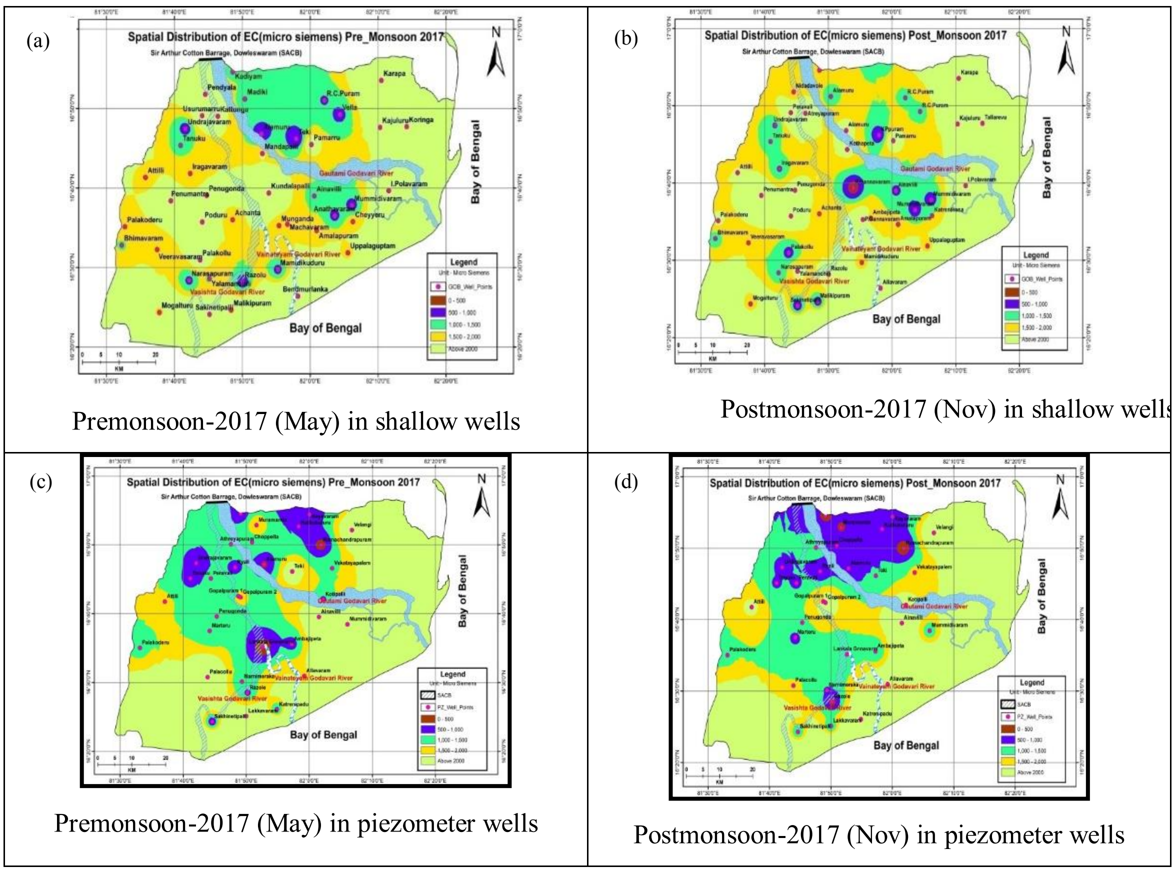


Fig.20 Depths of each shallow and piezometer wells in the Godavari delta

For the initial understanding of salinity, the Electrical Conductivity (EC) contour maps have been prepared for shallow [Figure 21 (a), (b)] and deep aquifers [Figure 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 (Figure 21). Groundwater table contour maps of shallow and piezometer wells are also plotted for 2017 (pre and post-monsoon) and are shown in Figure 22. The spatial analysis maps of EC and groundwater levels indicated significant seasonal changes in shallow and piezometer wells. It is observed that, on an average, 1 m increase (0-3 m contour) of the water table has been observed from the pre to post-monsoon period in shallow and piezometer wells.



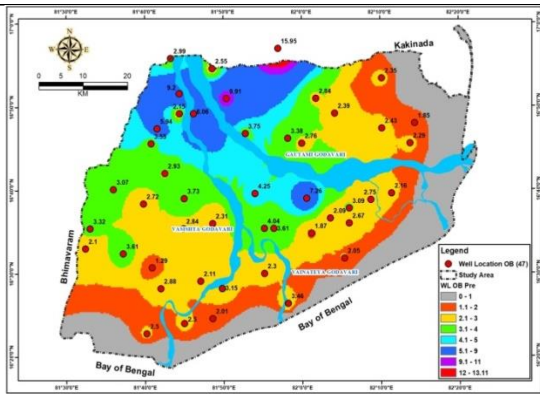
Premonsoon-2017 (May) in shallow wells

Postmonsoon-2017 (Nov) in shallow wells

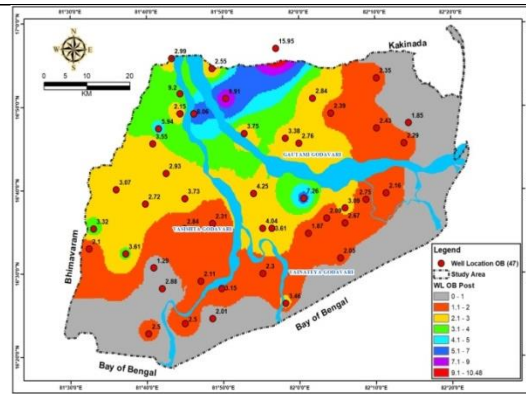
Premonsoon-2017 (May) in piezometer wells

Postmonsoon-2017 (Nov) in piezometer wells

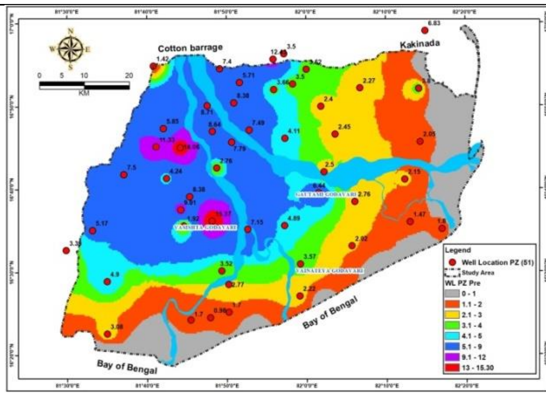
Fig. 21 Spatial distribution of Electrical Conductivity in shallow and piezometer wells



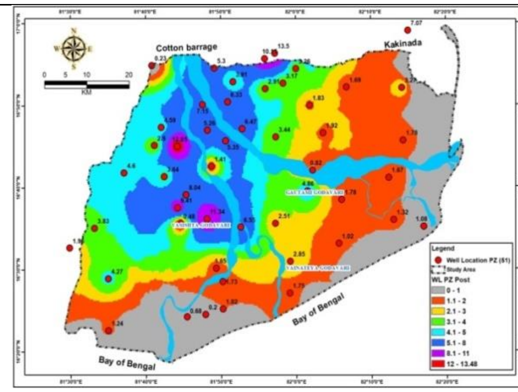
(a) Shallow groundwater table contours (bgl, m) during May 2017 (Pre-monsoon)



(b) Shallow groundwater table contours (bgl, m) during Nov 2017 (Post-monsoon)



(c) Piezometer groundwater table contours (bgl, m) during May 2017 (Pre-monsoon)



(d) Piezometer groundwater table contours (bgl, m) during Nov 2017 (Post-monsoon)

Fig.22 Groundwater table contours of shallow and piezometer aquifer during the year 2017 (pre and post-monsoon)

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 showed the pH values ranged 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 nature. 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 the seasons is as $HCO_3^->$

Cl^{-}> SO_4^{2-}. The highest HCO_3^{-} and Na^{+} ions concentration revealed that the study area might be influenced by silicate mineral dissolution.

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

	Shallow wells (Pre-monsoon)				Shallow wells (Post-monsoon)			
	Min	Max	Average	Std	Min	Max	Average	Std
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
T.D.S.	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	8.0	184.0	43.1	35.7	16.0	216.0	52.6	42.7
Mg	14.6	215.0	55.8	41.0	9.7	159.0	47.5	28.8

All units are in mg/L

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 the that pH values are in the range of 7.0–9.0 with a mean value of 8.4, which indicates the deep aquifer is alkaline. The average EC value of the piezometer with a mean value of 4252 (pre) and 4301(post) µS/cm indicates that the deep aquifer is affected with high/very salinity. The higher EC in the deep groundwater may be due to the mixing of saline water into the deep soils due to paleo-marine environment. Cation concentrations 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 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) in the deep aquifer. 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 deep groundwater is 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 the HCO_3 concentration, which infers that the dissolution of minerals has taken place in the deep aquifer.

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

	Piezometer wells (Pre-monsoon)				Piezometer wells (Post-monsoon)			
	Min	Max	Average	Std	Min	Max	Average	Std
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
T.D.S.	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
SO4	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	8.0	400.0	78.4	110.1	8.0	400.0	83.5	117.2
Mg	9.7	632.1	91.5	128.9	0.0	600.0	117.1	170.4

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 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 vs other major anions and cations during the year 2017 (pre and post-monsoon periods) in shallow wells/observation wells (102) and piezometer wells (94) are shown in Figure 23 (a), 23(b) and 23 (c) respectively. The piezometer wells Cl, HCO_3 and Ca are highly correlated with other anions and cations than shallow wells. Therefore, it may be indicated that the shallow wells are vulnerable to various anthropogenic and climatic conditions.

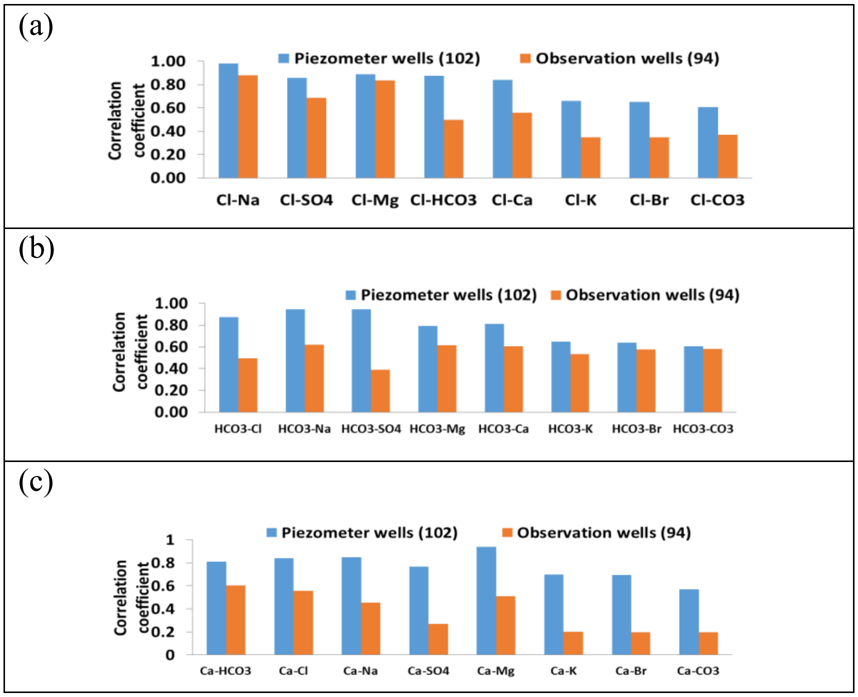


Fig.23 The correlation coefficient of (a) Cl, (b) HCO_3 and (c) Ca with major ions in piezometer and observation wells

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 a Piper trilinear diagram (Piper 1944). The various hydrogeochemical facies using Piper Trilinear diagram is shown in Fig.24. The ionic concentration of major cations and anions found in shallow and piezometer wells of 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.

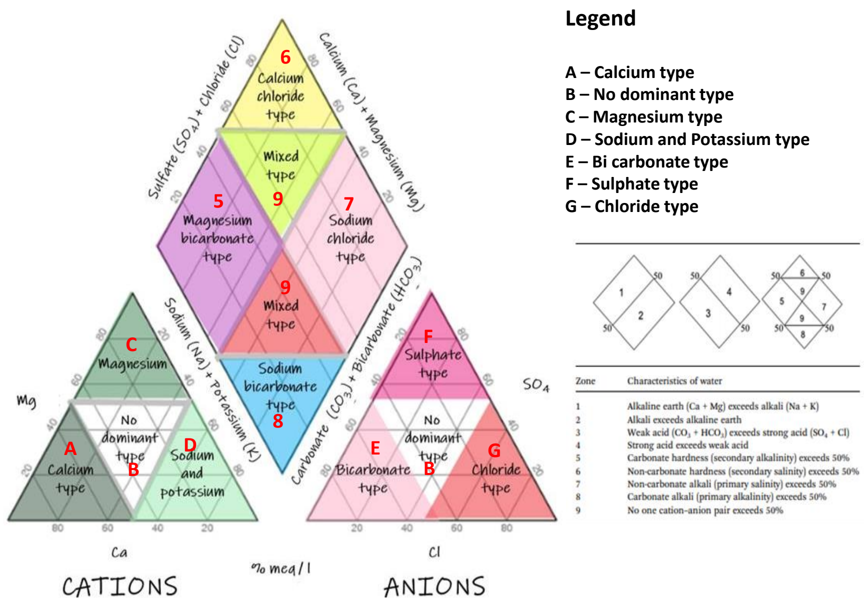


Fig.24 Various hydrogeochemical facies using Piper Classification

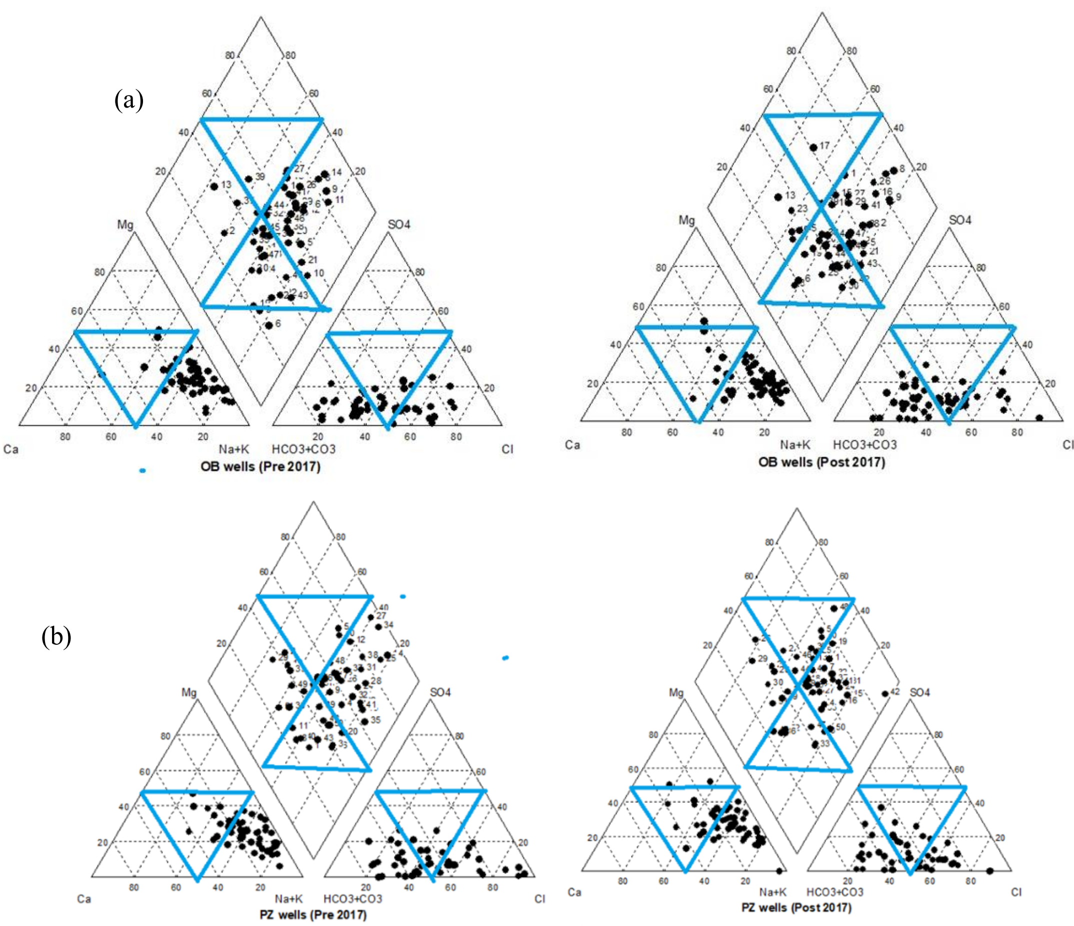


Fig.25 Piper trilinear diagrams for hydrochemical facies in the (a) shallow (pre and post-monsoon seasons) and (b) piezometer wells (pre and post-monsoon seasons)

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%) fall into Na+K type (D). Very few samples are in no dominance type, 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 exceeds 50%. Most of the samples has fell into zone 7, suggesting Na-Cl type of water, which means non-carbonate alkali (primary salinity) exceeds 50%. No groundwater sample fallen into zone 6 (Ca-Mg-SO_4 type), which represents non-carbonate hardness (secondary salinity) exceeds 50%. The samples that fall in zone 5 indicate Ca-Mg-HCO_3 type, which represents carbonate hardness (secondary alkalinity) exceeds 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^{2+}–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 dominance of Ca-Mg-Cl type and Na-HCO_3-Cl type. These two types represent no one cation–anion pair exceeds 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 deep aquifer, 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, a major water type can be defined as Na^{2+}– HCO_3^-–Cl type. Piper diagram reveals that nearly 65% of the analyzed groundwater samples of deep aquifer fall in the field of Na-Cl water type. These water samples are influenced by saline water, and the deep aquifer of this water type has no source to recharge. The hydro-chemical facies of deep aquifer suggests from Piper diagram that alkalis (Na) exceed alkaline earth (Ca+Mg), and strong acids (Cl) surpasses 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 well samples collected during pre and post-monsoon periods (2017) in the Godavari delta are plotted in Chadda's diagram and shown in Figure 26. The majority of the shallow groundwater samples (80%) falling in the sea water mixing zone represents Na–Cl type of water (or Na–Cl mixed sea water). Shallow water samples fell in Na-HCO3 type of water in pre and post-monsoon periods indicates base-ion exchange water. Very few samples fall 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).

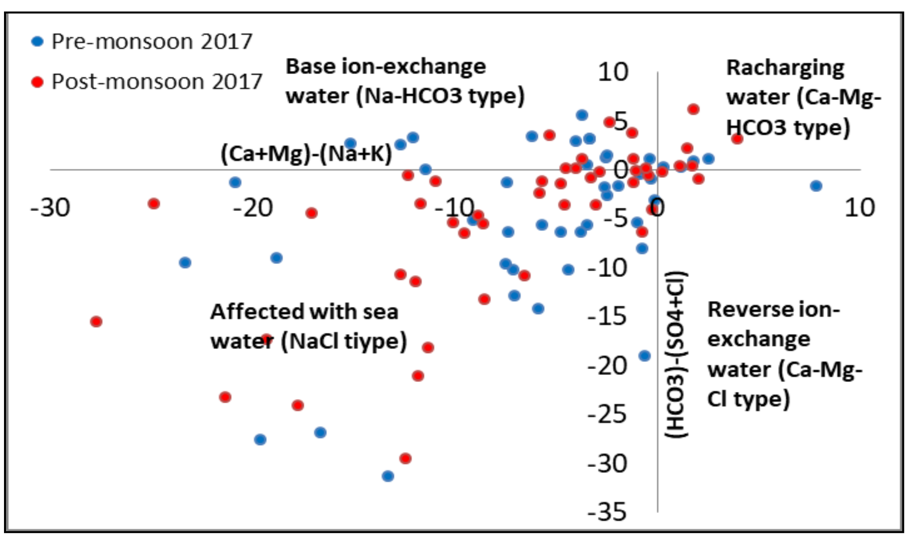


Fig.26 Chadda's plot of pre and post monsoon groundwater samples for shallow aquifer

Piezometer well samples collected during pre and post-monsoon periods (2017) in the Godavari delta are plotted in Chadda's diagram and shown in Figure 27. According to Chadda's plot (Fig.27), the majority of the deep groundwater samples (90%) have fallen in the sea water 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.

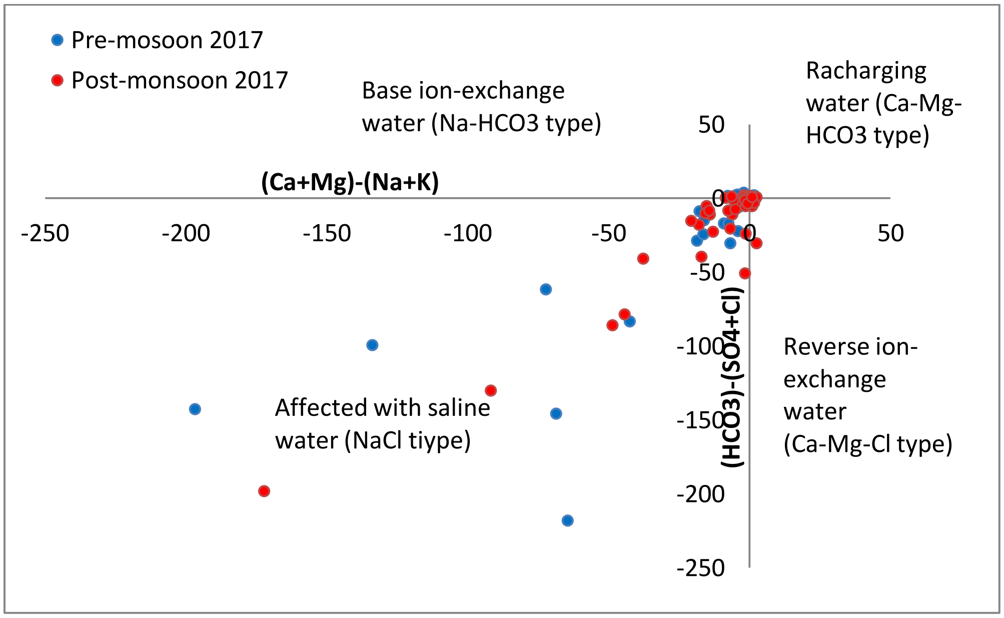


Fig.27 Chadda's plot for deep groundwater samples in pre and post-monsoon seasons

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

On the basis of Cl/HCO_3, in both seasons, more than 50% of the shallow groundwater samples (30 samples) are considered to be slight to moderately influenced by the saline water. Fig.28 (a) and (b) shows the seawater contamination based on the scatter plot of Cl/HCO_3 versus Cl in the shallow and piezometer samples, respectively. In the shallow aquifer, most of the samples are either not affected 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 are fallen in the injuriously to severely contaminated with saline water [Fig.28(b)].

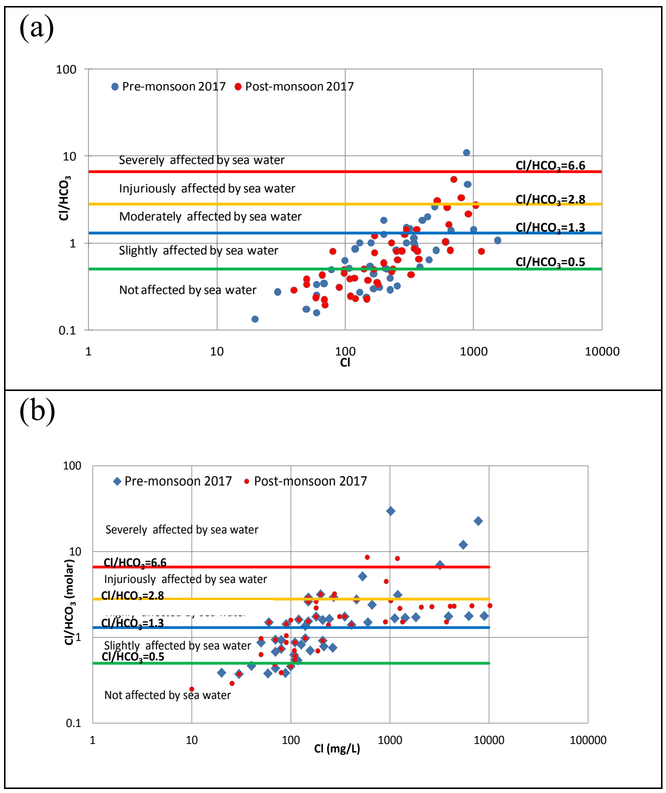


Fig.28(a) Salinity contamination based on the scatter plot of Cl/HCO_3 versus Cl for the shallow wells and 28(b) for piezometer wells during pre and post monsoon periods

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 from as well as the Chadha classification and the Cl/HCO3 (molar) ratio. The criteria used for the development of salinity zone maps is 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	$Na-HCO_3/Ca-Mg-HCO_3$	<0.5	Fresh water
II	$Ca-Mg-HCO_3/Na-Cl/Ca-Mg-Cl$	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 has been prepared using the chemical 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 6 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 uplands 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 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.

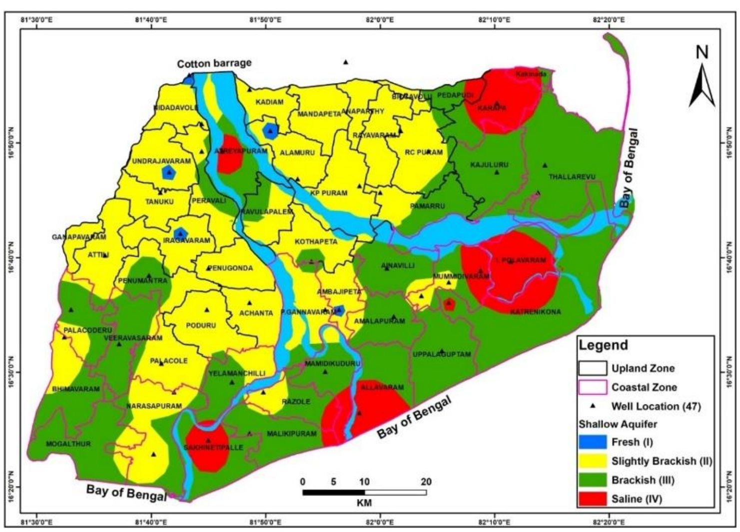


Fig 29. Salinity map of shallow aquifer of the Godavari delta (Nov. 2017)

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 localities namely Malikipuram, Rajolu, P.Gannavaram, Mamidikuru and Mummidivaram, is identified as brackish/lightly brackish water. It is interesting to note that the saline (IV) and high saline (V) zones occurred in the deep aquifer of coastal and upland region (nearer to coastal mandals) in the Western coastal delta. There is no fresh water in the Western Delta uplands and slightly brackish or brackish waters occupy it. The Na-Cl water type is the only type of water obtained in the Godavari Delta's saline/high salinity areas.

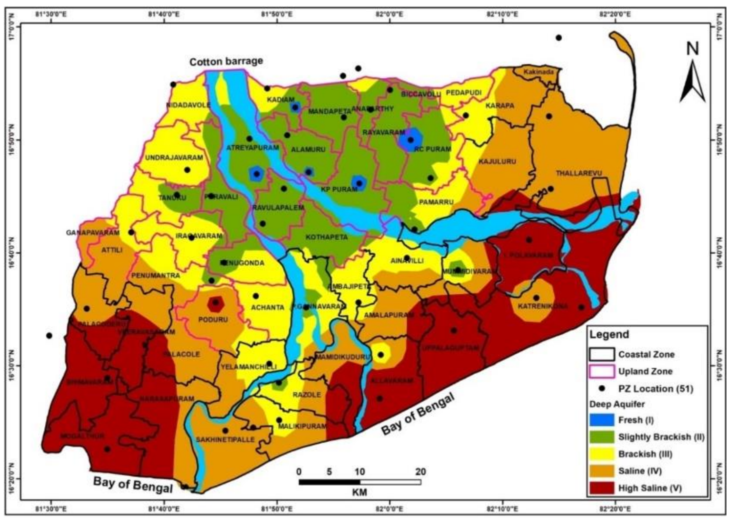


Fig 30. Salinity map of piezometer wells of the Godavari delta (Nov. 2017)

5.5 Validation of salinity maps in the Godavari delta for 2020

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

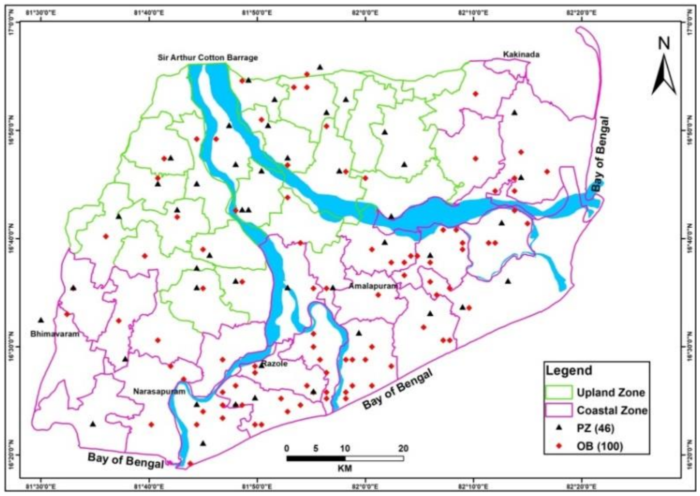


Fig.31 Location of shallow wells (100 No.) and piezometer wells (46 No.) in the year 2020

Salinity zones 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 years 2017, the average values of all major ion concentrations of shallow and piezometer wells has increased again from Zone I to Zone V (Table 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 the 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	SO4	Na	K	Ca	Mg
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	SO4	Na	K	Ca	Mg
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 Figure 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.

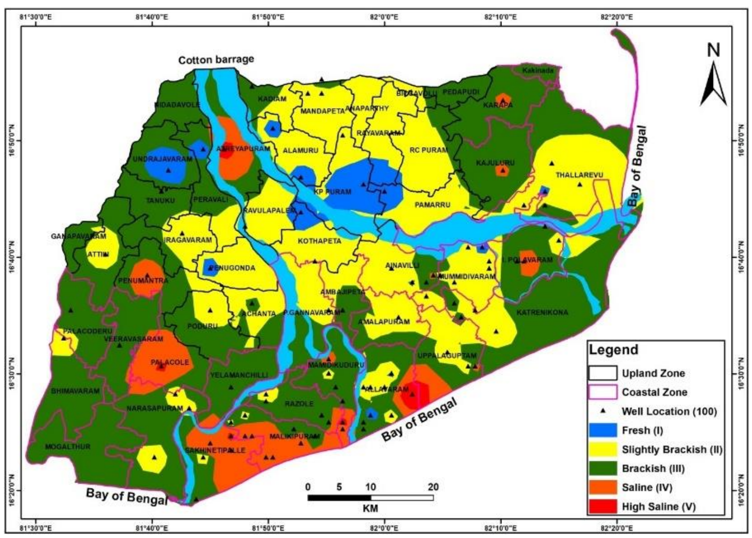


Fig.32. Salinity map of shallow wells from the extended network of observation wells (100 No.) for the year 2020 in the Godavari delta

The salinity map of the piezometer wells with the current monitoring network 46 wells in the year 2020 is prepared and shown in Figure 33. This salinity map (Fig. 33) is almost identical to the 2017 piezometer wells salinity map with a 51-well system (Fig. 30). This indicates that the groundwater salinity is not altered by any anthropogenic and natural sources in the deep aquifer of the Godavari Delta.

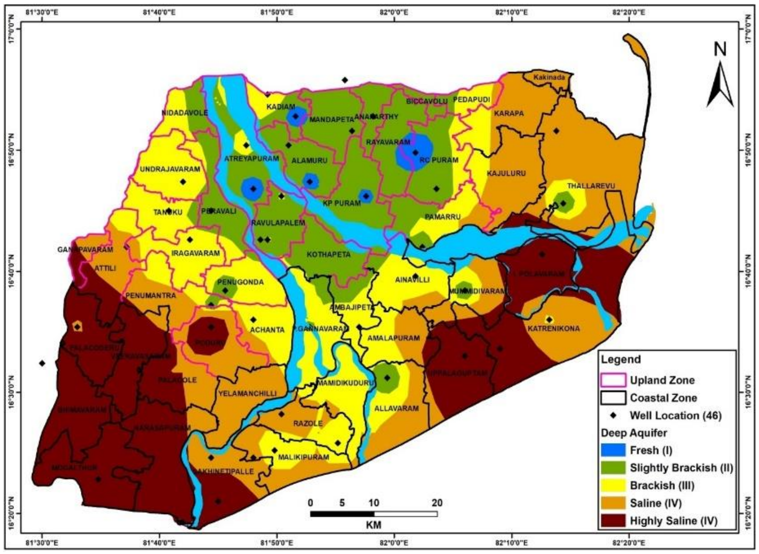
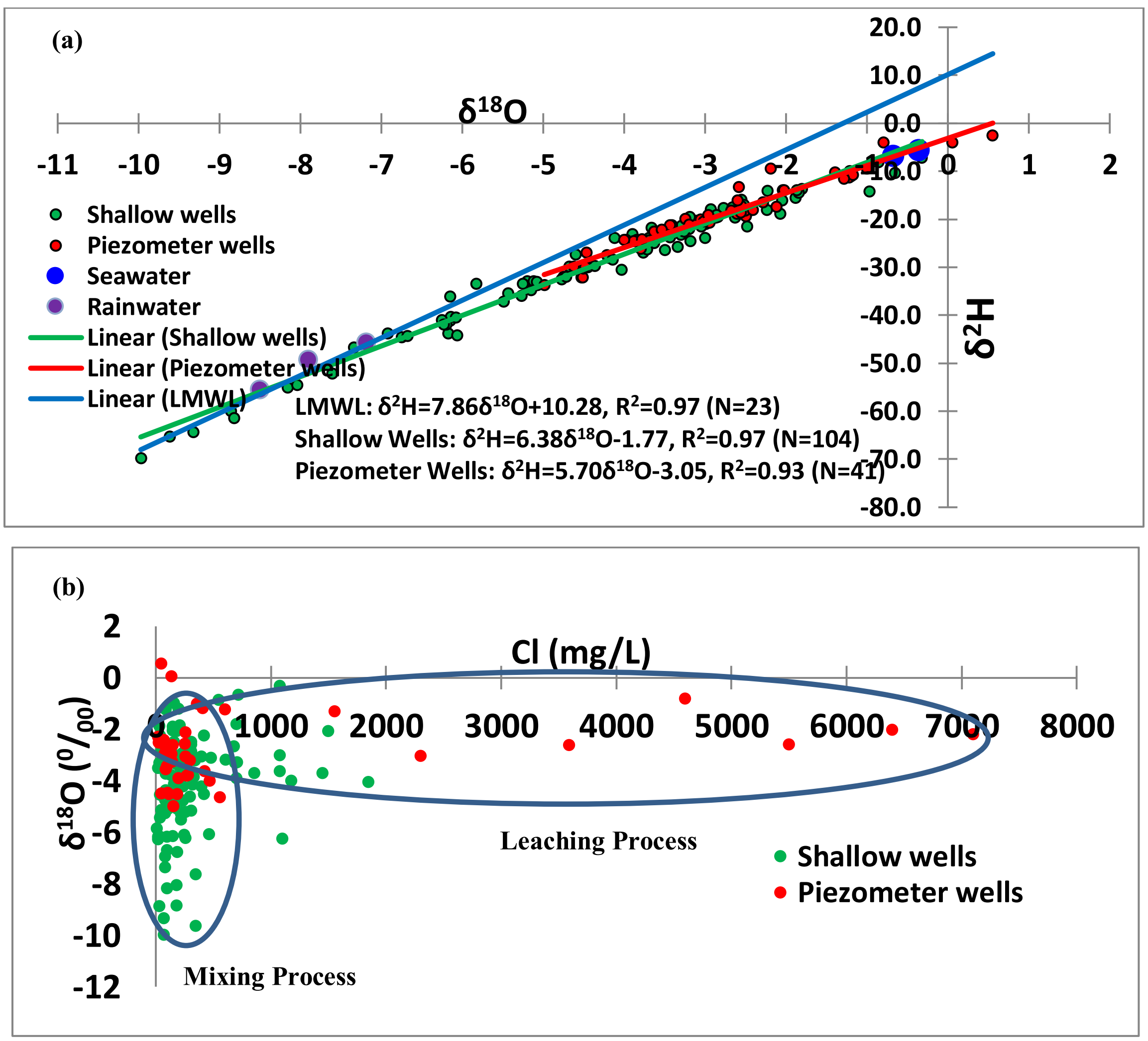


Fig.33. Salinity map of piezometer wells (46 No.) for the year 2020 in the Godavari delta

5.6 Salinity source identification using stable isotopes

The stable isotopes ^2H 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, or changes occur due to different land-use practices (Darling W 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 δ^2H for shallow wells (104), piezometer wells (41), rainfall (3), seawater (2) are shown in Figure 34 (a). The isotopic trend line for groundwater data of shallow wells (slope: 6.38) and piezometer wells (slope: 5.7) shows a variation. The comparison of these slopes with 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 are shown in Figure 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 are shown in Figure 34(c). The relation provided the origin of salinity, and three combinations of samples were clearly observed. The first group is rainfall and shallow wells, and the second is shallow wells, piezometer wells, and the third is a shallow well, 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 Figures 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.



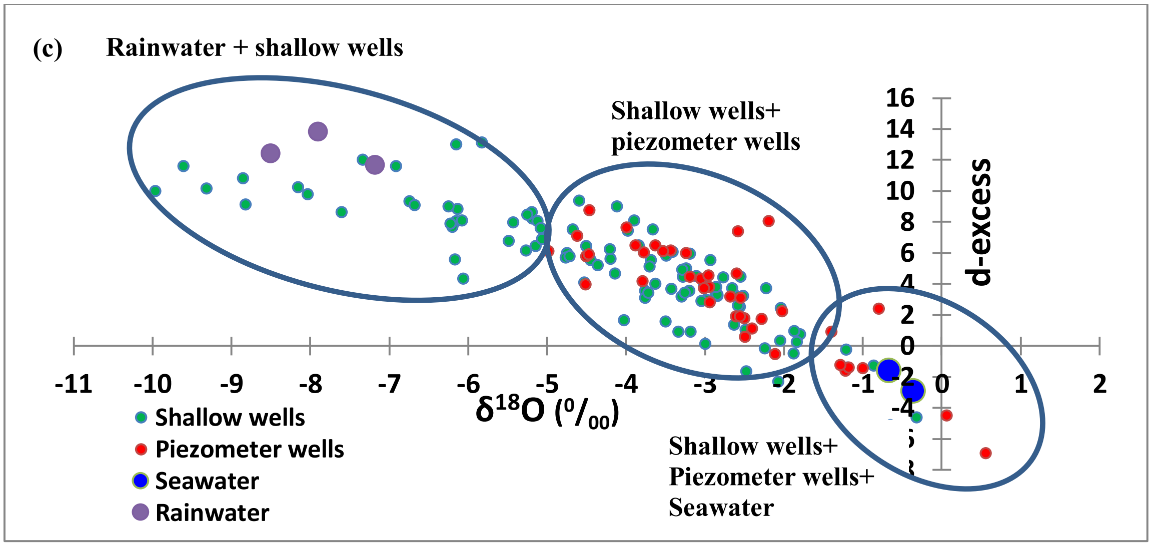


Fig.34 (a) Relation between $\delta^{18}O$ and δ^2H, 34(b) Relation between $\delta^{18}O$ and Cl and 34(c) Relation between $\delta^{18}O$ Vs d-excess in the Godavari delta.

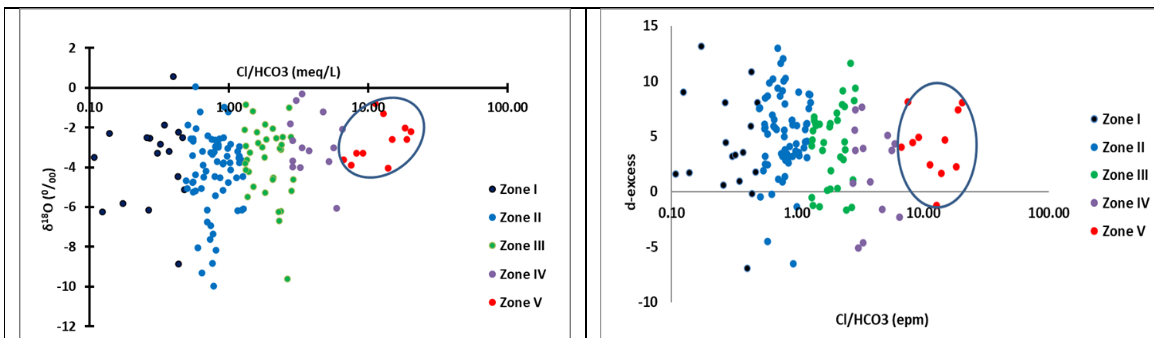


Fig. 35(a) Relation between Cl/HCO_3 Vs $\delta^{18}O$ and 35 (b) Relation between Cl/HCO_3 vs d-excess in each salinity zone in the Godavari delta

Further, the relation between $\delta^{18}O$ and δ^2H in each salinity zone for shallow wells have 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 have 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

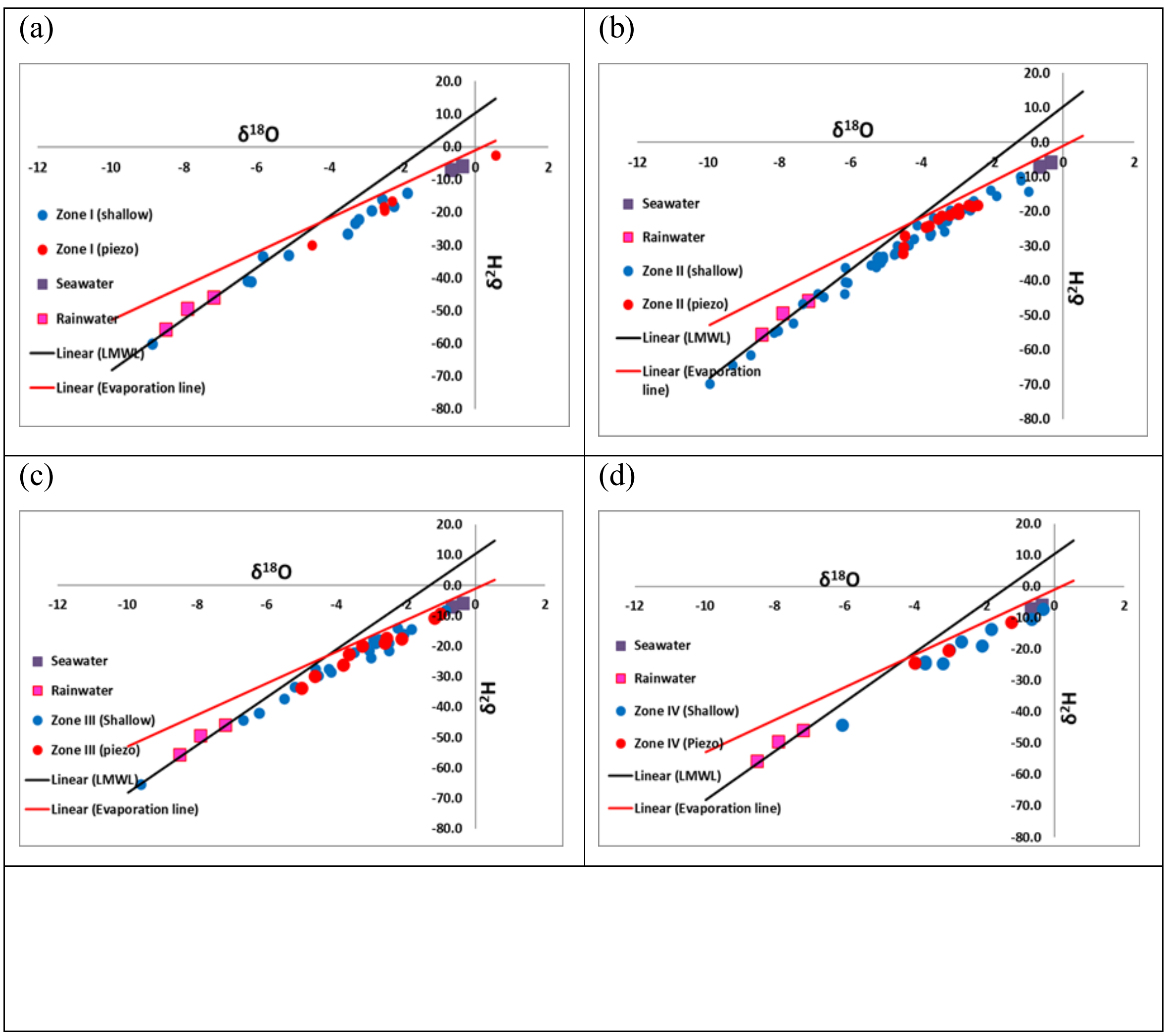
Zone II: $\delta D=5.5\delta^{18}O–1.1$, $R^2=0.95$ (N=16) and average Cl=144 mg/L

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 Figures 36 (a, b, c, d, e)



(e)

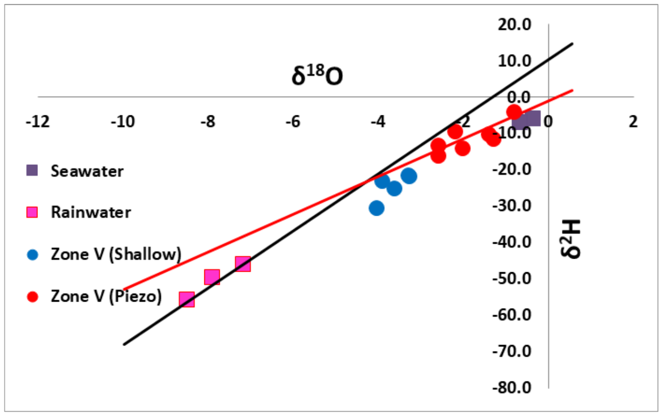


Fig. 36 (a, b, c, d, e) Relation between $\delta^{18}O$ and δD in each salinity zone along with LMWL, evaporation line and shallow wells, piezometer wells, rainwater and seawater

In order 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 shown in Fig.37. The detailed analysis of salinity sources in each zone is given below.

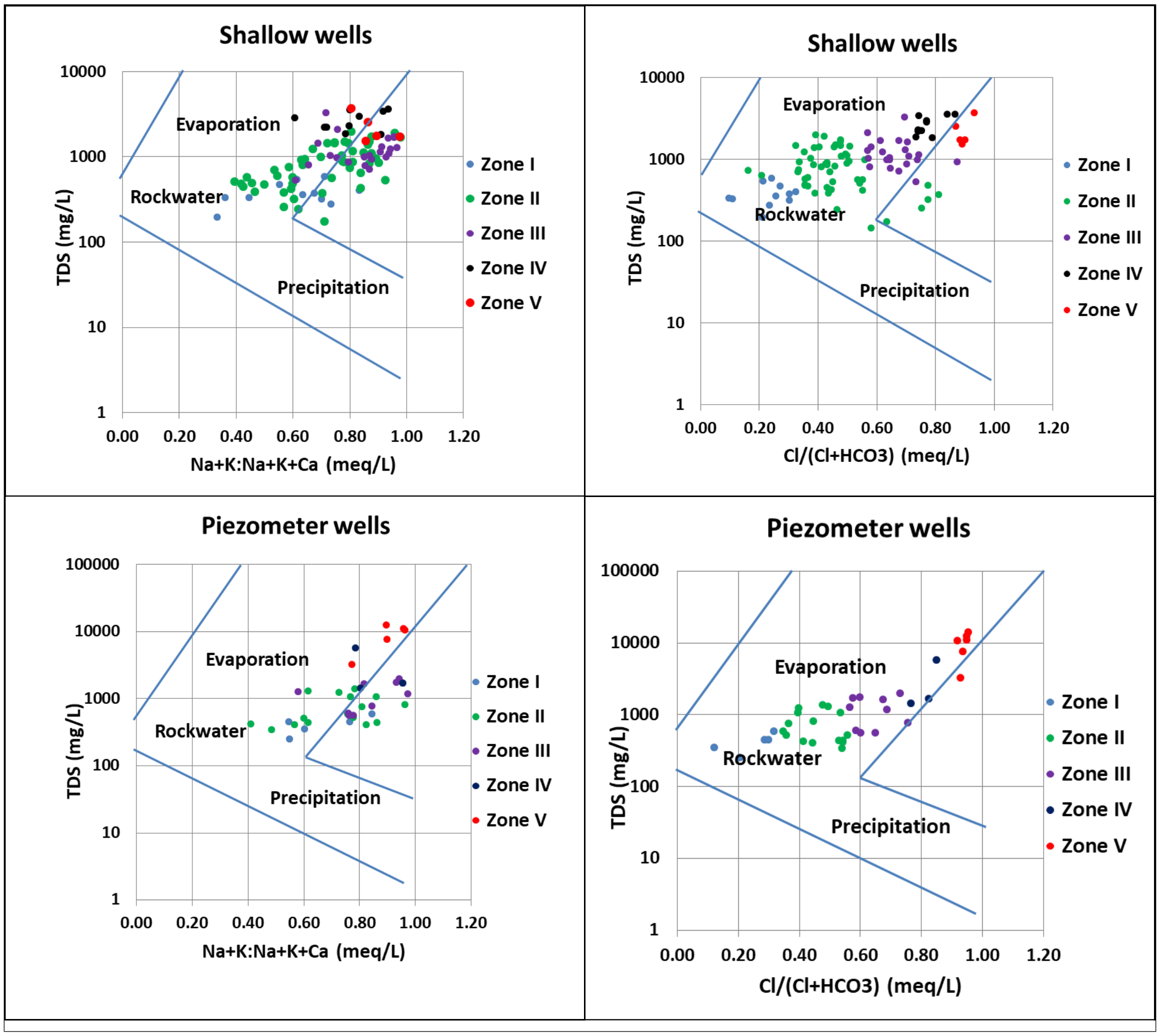


Fig.37 Gibbs diagrams for shallow and piezometer wells

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 to LMWL (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 of 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.

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 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 (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 piezometer wells (144 mg/L) in this zone. This indicates even the rainwater is the primary recharge source for groundwater (shallow and piezometer wells), the shallow wells are influenced by anthropogenic activities (agriculture). Therefore, this zone is considered slightly brackish.

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 precipitation-evaporation region and more samples have fallen on 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 (36c). Stable isotopes of shallow wells have fallen on LMWL line and on the evaporation line (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 piezometer wells (298 mg/L) in this zone. This indicates the shallow wells are influenced by anthropogenic activities (aquaculture activities). Further, the highest increase of water bodies was found to be in this region from 2005 to 2019 (Sakhinetipally, Uppalagutam, Mogalthuru, Bhimavaram). Therefore, this zone is considered as brackish water.

Zone IV: The major water typically found in this zone are Na-Cl, but the zone is considered saline water. From Gibbs diagrams, the shallow and piezometer wells samples are fallen on direct evaporation regions in both cations and anions plots. The stable isotopes of all Zone IV samples are close to the evaporation line (36d). This indicates 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 backwater. This zone is located in the coastal region of the Godavari delta.

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 on precipitation–evaporation region; however, the piezometer wells are found to be on evaporation region. The stable isotopes of shallow wells are towards the precipitation line, and piezometer wells are fallen on the evaporation line (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 initiations 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.

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 observation wells network from the year 2005 to 2020. In the year 2005, the shallow and piezometer well network were 19 and 18, respectively. The same network is used for the year 2017 to find the changes in groundwater salinity. It was found that the average salinity (EC) in shallow and piezometer wells has increased from 1664 to 2428 µS/cm and 2525 to 3515 µS/cm, respectively, from the years 2005-2017. The long term monthly and annual rainfall data trend analysis at Bhimavaram and Allavaram using Mann Kendall test for a period of 41 years (1971-2013) indicated that there is no significant change in average annual rainfall data and there is a change in the onset of monsoon and receding on 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 of 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/HCO3 (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.

An improved network of shallow wells (100) and piezometer wells (46) have been used for the validation of salinity classification zones. There are five salinity zones identified with this network. Further, the salinity sources in these zones have been determined using stable isotopes data and Gibbs diagrams. Zone I is classified as fresh water and recharge sources to the groundwater is 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 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 piezometer wells in this zone. This indicates the shallow wells are influenced by aquaculture activities. Zone IV is identified as saline zone, and the salinity source is the evaporation process which is indicated by both 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. A detailed hydrogeochemical modelling in the vicinity of aquaculture and column test would provide a better understanding of solute transport in the shallow aquifer.

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