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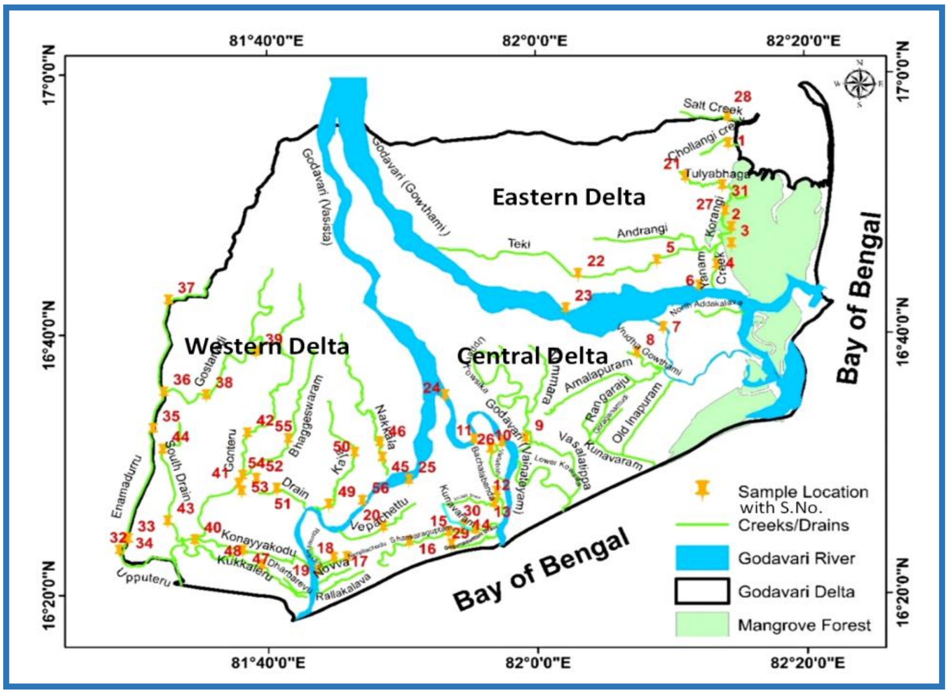
Interim Report / Final Report

Impact Assessment of Backwater through Drains, Creeks, and River Mouths on Groundwater Salinity in the Godavari Delta, Andhra Pradesh



National Institute of Hydrology
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Ministry of Jal Shakti, Govt. of India
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March, 2026

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PREFACE

In the Godavari delta, groundwater salinity is generally limited to specific zones within the inland delta, whereas in the coastal delta, salinity extends over a larger area. Surface water pathways, including river mouths, drains, and creeks, are well connected to the Bay of Bengal. These pathways significantly contribute to marine aquaculture development and progressively increase salinity in fertile agricultural lands. The present study aimed to assess the impact of backwater from drains, creeks, and river mouths on groundwater salinity using hydrochemical and stable isotope analyses. A total of 116 water samples were collected, comprising 11 creek water samples, 47 drain water samples, 29 shallow groundwater samples (near drains/creeks), 16 canal water samples, 7 backwater samples from Godavari river branches, 3 freshwater river samples, and 3 seawater samples. Among eleven high-salinity creeks, ten (average EC: 45,136 µS/cm) were identified in the Eastern and Central deltas, and one in the Western delta. Ionic ratios confirmed that all creeks are severely affected by seawater. Drain water (average EC: 3,764 µS/cm) represents a mixture of irrigation return flows and backwater. Low-salinity drains predominate in the Western delta, while backwater salinity is higher in the Eastern and Central deltas. Freshwater in the Godavari River is observed up to 50 km from the sea, whereas backwater extends approximately 35 km along the three major river branches. Stable isotope analysis revealed that creeks and river backwater (20 km from the seacoast) exhibit enriched isotopic signatures indicative of seawater influence. Shallow groundwater samples with enriched isotopes were located near six drains, Old Inapuram drain, Kummara drain, Kunavaram major drain, Rangaraju drain, Lower Kowsika drain, and Kaja drain, which influence the salinity of adjacent shallow aquifers through saline water seepage. Due to anthropogenic contamination from these six drains/creeks, shallow groundwater unsuitable for drinking purposes in nine villages namely N. Kottapalli, Katrenikona, Kodurupadu, Kunavaram, Kithana Cheruvu, Mogalamuru, Sannavelli, Navarasapuram, and Medapadu and hence, treated surface water supplied through canal systems should be considered as the primary source of drinking water in these villages. Groundwater with depleted isotopic signatures reflects freshwater mixing with marine clayey salts. Together, hydrochemical and stable isotope analyses effectively distinguished the sources and processes contributing to high shallow groundwater salinity in the Godavari delta.

The study, titled *"Impact Assessment of Backwater through Drains, Creeks, and River Mouths on Groundwater Salinity in the Godavari Delta, Andhra Pradesh,"* is an internal research collaboration with the Andhra Pradesh State Groundwater and Audit Department, carried out by Dr. Y.R. Satyaji Rao, Dr. Y. Sivaprasad, Er. R.Venkata Ramana, and Dr. V.S. Jeyakanthan of the Deltaic Regional Centre, National Institute of Hydrology, Kakinada.

(Y. R. Satyaji Rao)
Director

EXECUTIVE SUMMARY

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Abstract

Salinity in shallow groundwater poses a significant challenge to sustainable development in delta regions, affecting both drinking water sources and agricultural productivity. In the Godavari delta, surface water pathways, including river mouths, drains, and creeks, are closely connected to the sea, supporting brackish water aquaculture. This study assessed the impact of backwater from drains and creeks on shallow groundwater salinity using hydrochemical and stable isotope analyses. Between June 2023 and June 2024, 11 creek water samples, 47 drain water samples, 29 shallow groundwater samples (near drains/creeks), and 16 canal water samples were collected, along with 7 backwater samples from Godavari river branches, 3 freshwater river samples, and 3 seawater samples. In-situ measurements indicated average Electrical Conductivity (EC) values of 45,136 µS/cm in creeks, 3,764 µS/cm in drains, 6,100 µS/cm in shallow wells, and 265 µS/cm in canals. The Central delta exhibited the highest number of saline creeks (7), compared to 3 in the Eastern delta and 1 in the Western delta. Lower salinity in drains was attributed to dilution of backwater with irrigation return flows. Hydrogeochemical ratios and seawater fraction analysis showed that five creeks/drains were significantly affected by seawater intrusion, while the remaining drains experienced minimal impact. Stable isotopes ($\delta^{18}O$, $\delta^{2}H$) analysis confirmed high evaporation in creeks due to prolonged backwater residence. Backwater samples collected 20 km from the coast displayed isotopic signatures similar to seawater, indicating direct seawater influence. Six creeks/drains namely Old Inapuram drain, Kummara drain, Kunavaram major drain, Rangaraju drain, Lower Kowsika drain, and Kaja drain, were identified as influencing nearby shallow groundwater salinity through saline seepage. Anthropogenic contamination resulting from these six drains/creeks has rendered the shallow groundwater unsuitable for drinking purposes in nine villages and hence, treated surface water supplied through canal systems may be adopted as the primary drinking water source for these villages. Groundwater samples with depleted isotopes suggested freshwater mixing with marine clayey salts. Overall, stable isotope and hydrochemical analyses effectively distinguished the anthropogenic and geogenic factors contributing to high shallow groundwater salinity in the Godavari Delta.

Originating unit	Deltaic Regional Centre, National Institute of Hydrology, Kakinada, Andhra Pradesh
Key words	Godavari Delta, Groundwater, Creeks; Salinity
Security classification	Unrestricted
Distribution	General

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1. INTRODUCTION

The demand for freshwater from coastal aquifers has increased substantially in recent decades. However, several factors constrain groundwater quality in these regions, making a clear understanding of quality aspects essential for sustainable management (Barlow and Reichard, 2010). Among these, groundwater salinity poses a major challenge to the sustainable development of coastal zones, with serious implications for rural water supply and agricultural productivity (Srinivasamoorthy et al., 2014). Given the high population density and rapid development, coastal areas are particularly vulnerable, making groundwater salinity one of the most pressing environmental concerns. Groundwater resources in semi-arid coastal regions are highly susceptible to salinity problems arising from both natural and anthropogenic factors. Natural drivers include rainfall variability, seawater intrusion, geogenic sources, and evaporite dissolution, while human influences such as indiscriminate groundwater extraction further exacerbate the problem, leading to serious environmental consequences (Agoubi and Gzam, 2016). Groundwater salinity plays a critical role in degrading soil structure and restricting plant water uptake, thereby threatening agricultural productivity (Mkilima, 2023). In recent decades, extensive conversion of fertile agricultural lands into freshwater and brackish-water aquaculture in coastal delta regions has further intensified salinity levels, particularly within shallow aquifers.

In the Godavari delta, groundwater salinity is confined to specific zones or localized portions of the shallow aquifers in the inland areas, whereas in the coastal regions it is much more widespread, severely affecting both shallow and deeper aquifers. The issue of rising groundwater salinity in this coastal region of Andhra Pradesh was first reported in the late 1980s, and since then it has intensified due to a combination of natural processes and human activities. Sand mining and extreme hydrological events have intensified the inland movement of backwater through river branches. In the Godavari delta, surface water pathways, including river mouths, drains, and creeks, are directly connected to the Bay of Bengal. These pathways not only facilitate the expansion of marine aquaculture practices in the region but also contribute to the progressive salinization of fertile agricultural lands in the delta. In response to the rising salinity in shallow aquifers, driven by both natural and anthropogenic factors, a detailed internal study was undertaken under the title *"Impact Assessment of Backwater through Drains, Creeks, and River Mouths on Groundwater Salinity in the Godavari Delta, Andhra Pradesh."* The study aimed to monitor and delineate salinity levels, assess water flow in major outfalls into the Bay of Bengal, and map surface water pathways to improve understanding of groundwater salinity dynamics. To achieve this, hydrochemical analyses and stable isotope techniques were applied to evaluate the extent and influence of backwater intrusion from drains, creeks, and river mouths on groundwater salinity.

2. LITERATURE REVIEW

The literature review of national and international studies of geochemical processes controlling groundwater salinity, and research gaps have been presented below.

2.1. National Studies

A literature survey on groundwater salinity issues in the Godavari delta was conducted to synthesize existing research findings. Nageswara Rao et al. (2017) investigated the geochemical evolution of groundwater in the western delta region of the Godavari. Raju et al. (2013) compared irrigation canal waters in the east and west Godavari deltas, areas characterized by intensive aquaculture, and examined the resulting variations in alkalinity and hardness in groundwater samples from the East Godavari district. Satyaji Rao and Vijaya Kumar (2018) analysed groundwater hydrochemistry in the central Godavari delta and reported that the electrical conductivity of paleo channels is lower than that of surrounding groundwater. Gurunadha Rao et al. (2013) investigated the geochemical processes controlling groundwater in the central Godavari delta and highlighted the significant influence of rock–water interactions within the alluvial sediments. Nageswara Rao et al. (2017) examined the geochemical evolution of groundwater in the western Godavari delta, concluding that groundwater in this region is predominantly brackish and very hard. In addition to these studies within the Godavari delta, relevant literature on stable isotope techniques and their application in interpreting groundwater salinity variations is also reviewed to provide insights into salinity sources and processes. Environmental tracers are valuable tools for understanding groundwater recharge processes and identifying water sources (Gonfiantini et al., 1998; Meredith et al., 2013).

2.2. International Studies

Estuarine rivers act as important conduits for seawater movement upstream from the coast, thereby contributing to the salinization of adjacent aquifers. Yet, this process, hereafter referred to as riparian saltwater intrusion, has received comparatively less attention in the literature than the more widely studied coastal saltwater intrusion. While saltwater intrusion is most commonly associated with coastal boundaries, surface water bodies connected to the sea, such as rivers, creeks, canals, and ditches, also serve as critical pathways for seawater to migrate inland and salinize adjacent groundwater systems (Renken et al., 2005; Bhattachan et al., 2018; Tully et al., 2019). An estuarine river or creek can be identified as a potential source of salinity when shallow groundwater exhibits increasing salinity levels closer to the river and progressively lower salinity with distance away from it (Setiawan et al., 2022). Saltwater intrusion from estuarine rivers and creeks occurs through two distinct processes: (i) the upstream movement of seawater within the river channel, commonly referred to as *seawater encroachment*, and (ii) the subsurface migration of saline water from estuarine channels into adjacent aquifers (Mikhailova, 2013; Werner et al., 2013).

The interaction between fresh groundwater and estuarine rivers—characterized by fluctuating salinity and hydraulic head, creates complex mixing dynamics that further influence groundwater quality (Trefry et al., 2007; Westbrook et al., 2005). Density contrasts between fresh groundwater and brackish to saline river water generate a saltwater wedge beneath estuarine channels, within which a mixed convection cell develops. In this zone, river water infiltrates the adjacent aquifer, mixes with ambient groundwater, and the resulting saline mixture may subsequently recirculate back into the river (Fig. 2.1) (Linderfelt and Turner, 2001; Smith and Turner, 2001). The degree of this recirculation is strongly controlled by river salinity: the higher the salinity, the greater the buoyancy forces, and consequently, the larger the recirculation zone beneath the river (Lenkopane et al., 2009). Similar to coastal saltwater intrusion, tidal forcing at river boundaries induces groundwater level fluctuations synchronized with tidal cycles. This process enhances groundwater–river water mixing, broadens the freshwater–saltwater transition zone through hydrodynamic dispersion, and establishes an upper convective recirculation cell along the riverbank (Fig. 2.1) (Robinson et al., 2007; Setiawan et al., 2023). Wave lines shown in Fig.2.1 indicate tidal influence.

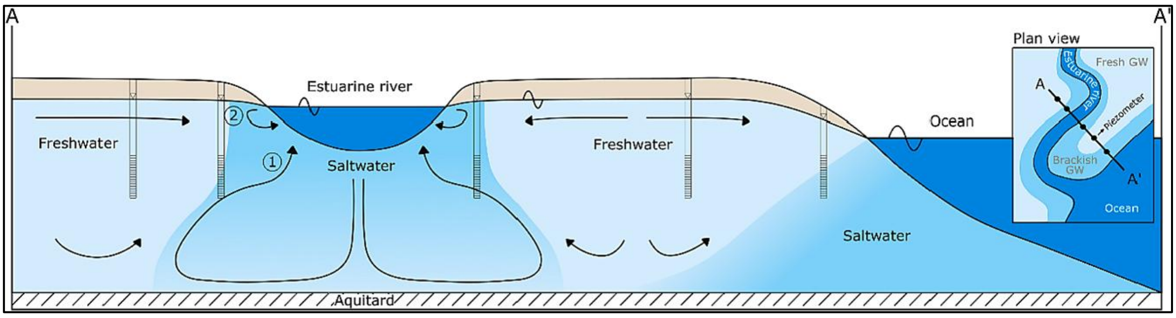

Fig. 2.1. Cross-section map of conceptual saltwater intrusion from the coast and estuarine river at transect AA'.

2.3. Research Gaps

In the Godavari Delta, groundwater salinity in the inland delta is confined to a few localized zones. In contrast, salinity in the coastal stretches is severe, affecting both shallow and deeper aquifer systems. The surface water pathways, comprising river mouths, drains, and tidal creeks, is well connected to the Bay of Bengal. These pathways not only facilitate backwater but also significantly contribute to the expansion of marine aquaculture practices in the delta. Over time, this has accelerated the salinization of fertile agricultural lands and adjoining groundwater systems. Although numerous creeks and drains exist across the Godavari delta, systematic salinity data for these surface water bodies are presently unavailable. No comprehensive study has been undertaken earlier to measure salinity levels in these creeks and drains or to evaluate their influence on shallow groundwater salinity. Therefore, the present study focuses on assessing salinity levels in drains, creeks, and river mouths, and evaluating their impact on groundwater salinity in the Godavari delta region.

3. OBJECTIVES AND SCOPE OF THE STUDY

In response to these critical research gaps, this study is envisaged with the following key objectives:

1. To understand the salinity levels in drains, creeks, and river mouths on groundwater salinity using historical water quality and rainfall data
2. Identification of high saline creeks and drains in the Godavari delta
3. Analysis of hydrochemistry of creeks and drains and nearby shallow wells to identify the salinity sources
4. Identification of backwater impact through drains, creeks, and river mouths on groundwater salinity using stable isotopes.

4. STUDY AREA AND DATA USED

4.1. Location of Godavari Delta

Downstream of the Cotton Barrage at Dhawaleswaram near Rajahmundry City, Andhra Pradesh, the Godavari River bifurcates into two branches: the Gautami Godavari and the Vasista Godavari. Further downstream, the Vasista branch again divides into the Vainateya and Vasista branches. The Gautami Godavari meets the Bay of Bengal at Yanam, the Vainateya at Antarvedi in East Godavari district, and the Vasista at Narasapuram in West Godavari district. Consequently, the Godavari River forms the Eastern, Central, and Western delta regions. The Godavari delta is situated between latitudes 16°20′ N to 17°00′ N and longitudes 81°30′ E to 82°20′ E. The region experiences two distinct monsoon seasons: the Southwest Monsoon from June to September and the Northeast Monsoon from September to November, with the Southwest Monsoon contributing the majority of rainfall. The average annual rainfall in the study area is approximately 1,150 mm. The study area, the Godavari Delta, is situated in the coastal region encompassing East Godavari (Central and Eastern deltas) and West Godavari (Western delta) districts of Andhra Pradesh, India (Fig. 4.1). Hydrologically, the delta is bounded by the Kakinada Canal to the east, the Enamadurru drain to the west, and the Bay of Bengal to the south. The region spans eighteen Survey of India toposheets: 65H1, 65H2, 65H5, 65H6, 65H7, 65H9, 65H10, 65H11, 65H13, 65H14, 65H15, 65L1, 65L2, 65L3, 65L5, 65L6, 65K4, and 65K8. Covering an area of approximately 4,485 km^2 and comprising 48 mandals, the delta has a coastline length of 152 km, a maximum width of 120 km, and a gentle plain slope of 0.0004. Four historical strandlines have been identified across the Godavari delta (Fig. 4.1). The Godavari River has formed an extensive arcuate delta along the east coast of India, projecting approximately 35 km from the adjacent coast into the Bay of Bengal (Ahamed, 1972). The deltaic region is characterized by four parallel beach ridges located well inland from the present coastline. The modern delta is of Holocene age and is the third-largest delta in India, after the Ganges and Mahanadi. Much of the coastal plain consists of Holocene–Pleistocene sediments (Sambasiva Rao and Vaidyanadhan, 1979).

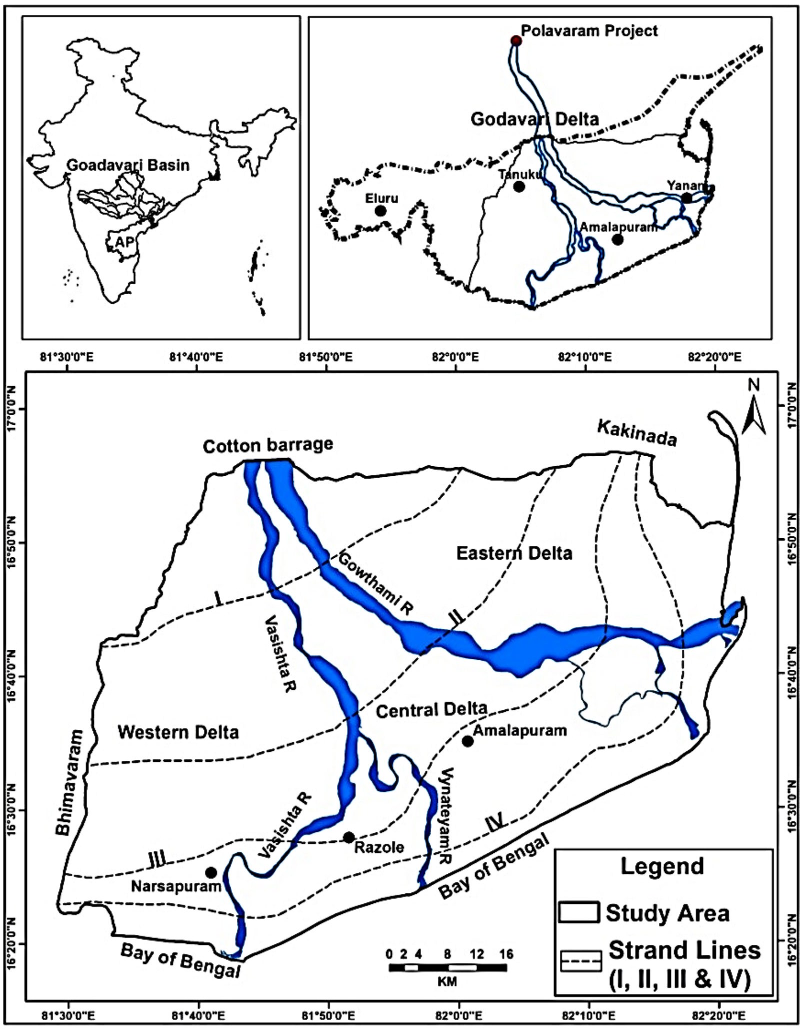

Fig. 4.1. Location of the Godavari delta in Andhra Pradesh State, India

The Godavari delta exhibits a well-defined, arcuate shape. The deltaic plain begins near Rajahmundry, where the Godavari River divides into two main branches: the Vasishta and Gautami rivers. Both branches display low sinuosity and a braided character. The Vasishta Godavari further bifurcates near Gannavaram into the Vainateyam Godavari, while the main Vasishta branch continues toward the Bay of Bengal. The meandering patterns of these channels are influenced by tidal forces up to the Gannavaram aqueduct. Similarly, the Gautami Godavari branches into the Nilarevu River, with both rivers eventually reaching the Bay of Bengal. Smaller distributaries, such as the Coringa and Gaderu rivers, exhibit pronounced meandering and strong tidal influences. As a result, the Godavari River opens through multiple mouths, forming a broad belt of river-borne alluvium. Spits have developed at the mouths of the distributaries, and several islands have formed naturally near the river outlets. The upper delta plain is extensive and primarily functions as a floodplain, with only a few localized ponds or swamps. In contrast, the lower delta plain, especially near the Gautami Godavari mouth, forms a 10 km-wide zone characterized by lagoons, tidal flats, and mangrove marshes strongly influenced by tidal activity.

4.2. River and Tidal Influence

Significant discharges from the Godavari River commence in June and reach a maximum in August (Suryanarayana, 1988). August and September are the months of peak discharge for the Godavari River (Sastry et al. 1971). The 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 up to Yanam; though during low river discharge, tidal influence is recorded up to Kapileswarapuram, 45 km upstream from the Gautami river delta mouth. Thus, the deltaic distributary channels experience tidal influence up to about 45 km inland, while the plain area shows tidal influence up to 10 km inland from the coast. The river flow is regulated by a century-old Dowleswaram Barrage near Rajahmundry town. Consequently, the Godavari estuarine system has negligible flow from the dam, due to which it acquires high salinity except during the high discharge period (Rengarajan and Sarma 2015).

4.3. Elevation of Godavari Delta

A Digital Elevation Model (DEM) of the Godavari delta was generated using ALOS PALSAR satellite data with a 12.5 m resolution (Fig. 4.2). The general elevation of the delta ranges from a few feet near the coastline to a maximum of 18 m in the northern region, with the regional topography typically varying between 2 and 7 m above mean sea level. The delta is bordered to the north by upland crystalline terrain. The study area consists predominantly of gently sloping plains (<3°) trending southeast toward the Bay of Bengal.

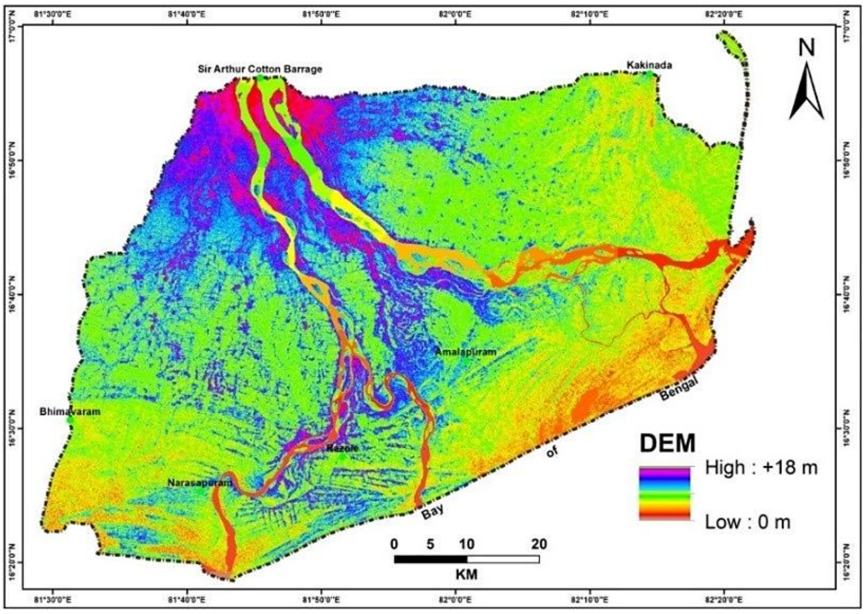

Fig.4.2 Digital elevation map of the Godavari delta

4.4. Drainage Network

Irrigation drainage in the Godavari delta flows into the Bay of Bengal through a network of natural drains and creeks, which have been mapped using Survey of India topographic sheets and satellite imagery (Fig. 4.3). The well-distributed Godavari irrigation canal system provides both irrigation and drinking water throughout the year and plays a key role in mitigating native salinity in underlying marine clay soils, facilitated by the gradual recession of the sea from inland to the shoreline. The study area falls entirely under the command of the Godavari Central Canal system, which remains operational for 11 months annually, closing for one month for maintenance. Additionally, six major bridges span the various river branches to support local transportation within the delta.

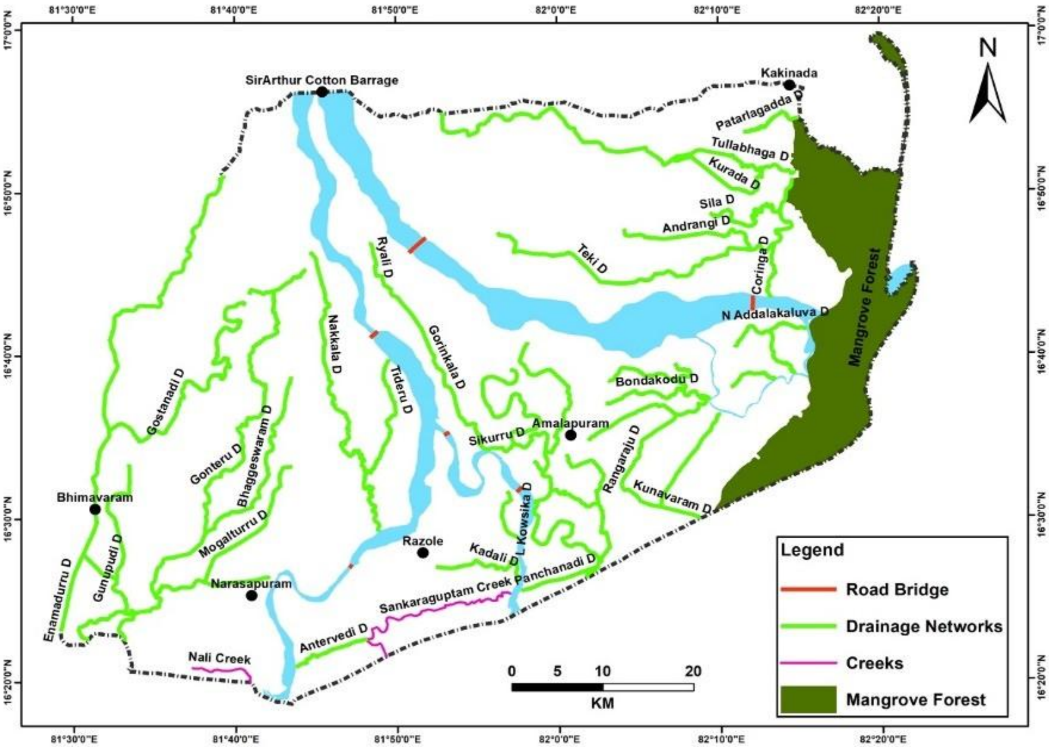

Fig. 4.3 various drains and creeks in the Godavari delta

4.5. Climate and Rainfall

The region exhibits a humid tropical climate. Temperatures rise steadily from February, reaching a peak between 33°C and over 45°C in May. Mean monthly relative humidity averages around 80% in the forenoon and 62% in the afternoon. Monthly mean wind speeds range from 5.4 km/h in March to 12.7 km/h in July, and the annual potential evapotranspiration is approximately 1,467 mm. The district receives an average annual rainfall of 1,137 mm, unevenly distributed over roughly 57 rainy days. The majority of precipitation occurs during the Southwest Monsoon (June–September), contributing about 72% of the annual total, while the Northeast

Monsoon (October–December) accounts for the remainder. The area experiences seasonal flooding almost every alternate year due to overflow from the Godavari River (Surinaidu et al., 2013), and frequent cyclones contribute to extreme weather conditions across the delta.

4.6 Agricultural Activities

The principal crops in the Godavari delta include paddy, coconut, sugarcane, mango, and banana, with paddy being the dominant crop. Three successive cropping cycles are practiced annually. Fertilizer and pesticide use are intensive throughout the region. Given the ample availability of surface water for irrigation, reliance on groundwater is minimal in most parts of the delta. The region offers excellent potential for irrigated agriculture due to extensive fertile lands formed by riverine and coastal depositional processes (Surinaidu et al., 2013). Canal water is generally available year-round, except during a short period between the last week of April and the second week of June.

4.7 Geomorphology of Godavari Delta

The Godavari delta comprises two distinct geomorphic units: coastal alluvium and fluvial alluvium (Satapathy et al., 2007). The region is characterized by rich alluvial plains formed by the Godavari River, with a very gentle slope of approximately 1 m/km (Bobba, 2002). Quaternary sediments occupy both the coastal tract and inland river valleys and include thick layers of alluvium, gravel, colluvial deposits, beach sand, kankar, and diverse soil types. Fluvial deposits are predominantly found along the Godavari River. Geologically, the area is underlain by coarse sand with black clay in buried channel zones, black silty clay of recent origin in the floodplain, and gray to white fine sands representing modern beach sediments, paleo-beach ridges, and active beach ridges of marine origin in the coastal zone. Lithological logs indicate a stratigraphic sequence consisting of topsoil, followed by sticky clay, fine sand, clayey layers, coarse to medium sand, and clay–silt zones (Nageswara Rao et al., 2017).

The Godavari delta features extensive tidal flats and inlets that are inundated by seawater during high tides. Sediments in the upper deltaic region are predominantly fluvial, whereas those in the lower delta consist of fluvio-marine deposits (GSI, 2006). Silts and gravel beds are interbedded with clay in varying proportions throughout the delta. The alluvium ranges in thickness from a few meters to over 300 m, overlying the Rajahmundry sandstones, with granular zones within the alluvium varying from 18 to 258 m in explored depths (CGWB, 1999). Early Holocene deltaic sediments underlie the region, consisting of varying proportions of clay, silt, sand, and gravel, and the delta exhibits a gentle slope of approximately 0.001 km/km toward the coast. The formation of beach ridges is closely associated with deltaic progradation (Rengamannar and Pradhan, 1961). The Godavari delta exhibits a variety of significant landforms, including valley fills, channels, levees, backswamps, point bars, active beaches, paleo-beach ridges, backwater and tidal flats, spits, and mangrove swamps of marine origin (Rengamannar and Pradhan, 1961; Nageswara Rao et al., 2015). The study area encompasses fluvial landforms such as channels, levees, backswamps, and geologic floodplains, alongside landforms shaped by marine processes, including tidal flats, beach ridge complexes, and mangrove swamps. The region is underlain by extensive Quaternary alluvial sediments derived from the Godavari River (Bobba, 2002). The geomorphological features of the delta are illustrated in Fig. 4.4.

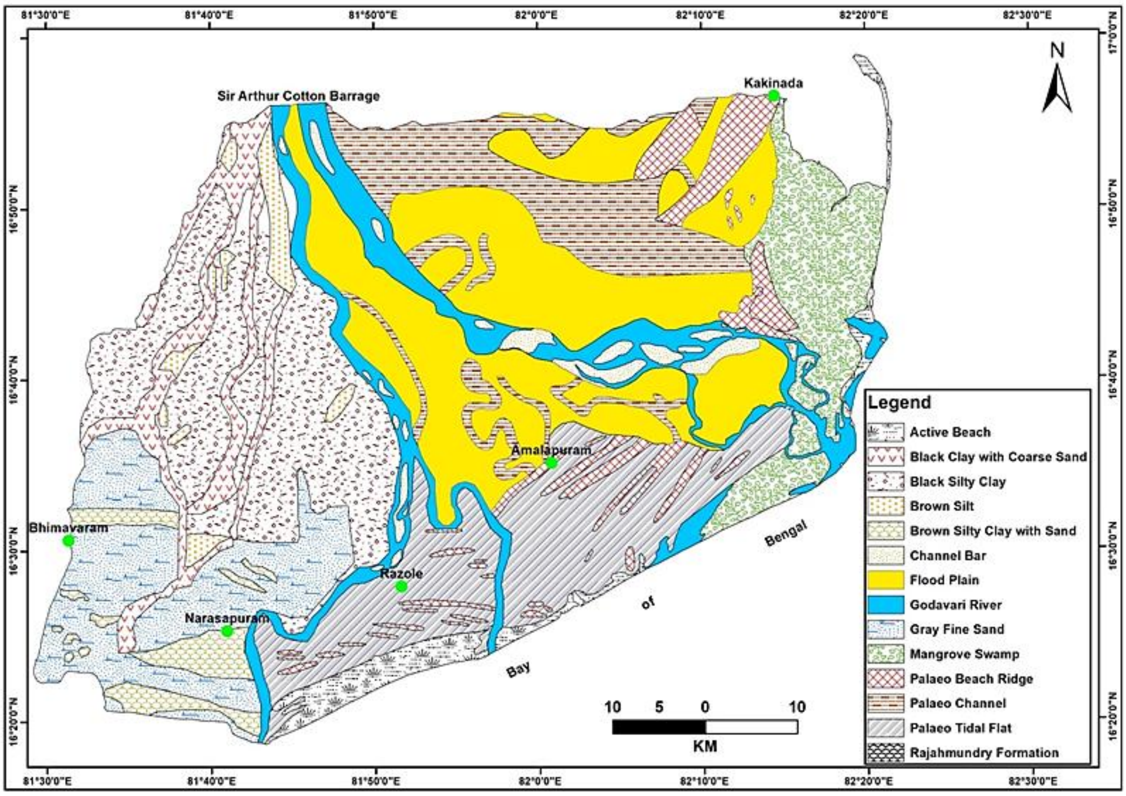

Fig. 4.4. Geomorphological features of Godavari delta

A series of marine transgression and regression events has strongly influenced the depositional environments of the Godavari delta over time. The upper deltaic plain and river courses are predominantly fluvial, whereas the lower deltaic plain, near the coast, is dominated by fluvio-marine and fluvio-aeolian environments. Among the fluvial landforms, active channels such as the Gautami Godavari and Vasista Godavari, along with associated braided/channel bars and levees, constitute the subaerial top-set beds of the delta (Sambasivarao and Vaidyanadhan, 1979). The concentrations of iron, manganese, sodium, and pH increase toward the coastal regions, approaching marine values, while calcium and magnesium distributions are largely controlled by shell fragments and clay minerals, particularly montmorillonite. The coastal plain exhibits a prograding nature, advancing seaward due to sediment deposition from the Godavari River. Features such as sand bars, spits along the shoreline, lagoons, inland lakes, and tonal contrasts in satellite imagery at river mouths reflect this progradation. Freshwater inflow from the Gaderu and Coringa rivers, as well as the western Kakinada canal, influences hydrology in the region. Salt-tolerant vegetation, particularly mangroves, is distributed along abandoned distributaries, near river mouths, and adjacent lagoons, forming diverse habitats across creeks and portions of the deltaic plain.

4.8. Soils of Godavari Delta

The interior regions of the Godavari delta are primarily covered by alluvial soils, while clayey soils are dominant in the tail portions of the river, and red loamy soils occur in the upland delta. The central deltaic area is characterized by sandy loams and sandy clay loams (GSI, 2006). Overall, the delta exhibits loamy and sandy soils underlain by thick clay beds, approximately 18–25 m thick, followed by coarse sands containing saline groundwater (Gurunadha Rao et al., 2011). Kankar, a calcareous concretion of $CaCO_3$, is also present within the soil profile. The soil distribution of the Godavari delta is illustrated in Fig. 4.5.

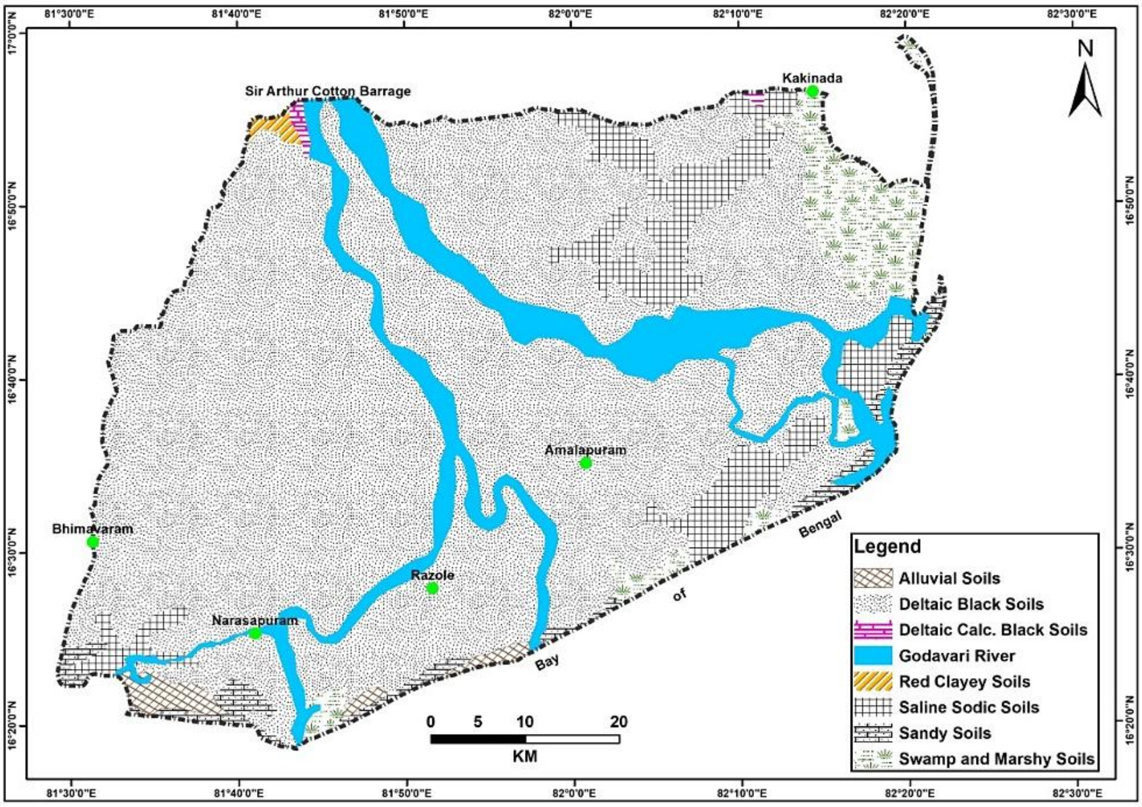

Fig.4.5 Soil map of Godavari delta

4.9 Occurrence of Groundwater in the Godavari Delta

Groundwater in the Godavari delta occurs under unconfined to semi-confined conditions, with impervious clay layers overlying saturated granular zones. Extraction is carried out using open dug wells (approximately 10 m depth), filter point wells (10–30 m depth), and tube wells (30–60 m depth). Depth to water levels ranges from less than 1 m to 22 m, with shallow open wells typically at 3–8 m depth and filter point wells reaching up to 20 m. Near canals and drains, water levels are often <2 m below ground level. The aquifer exhibits permeability ranging from 2 to 75 m/day, a specific yield of 0.05–0.2, and yield prospects of approximately 100 m³/h. Groundwater flow generally follows a NW–SE direction along the drainage pattern. The shallow aquifer occurs between 10–30 m depth, while the deeper aquifer extends from 30–45 m. The century-old canal network contributes significantly to groundwater recharge, reducing the potential for saltwater intrusion into shallow aquifers (Chachadi and Teresa, 2002). Geophysical logs from the Ravva Onshore Terminal indicate that sandy clay is overlain by 45–55 m of clay with fine sand, followed by medium- to coarse-grained sands up to 120 m depth, beneath which saline-saturated clays are found down to 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 (CGWB, 2013), is shown in Fig. 4.6.

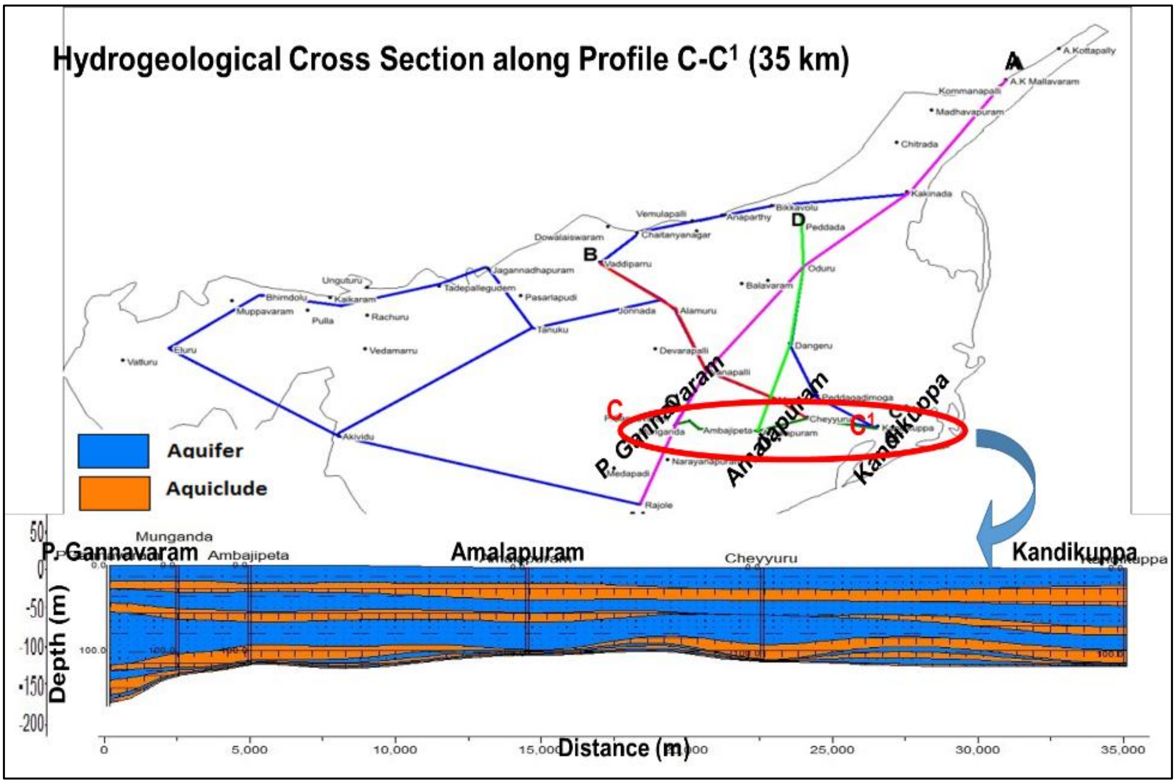

Fig. 4.6 The hydrogeology of the Central Godavari delta (CGWB, 2013)

5. METHODOLOGY

To acquire baseline information on the Godavari delta, topographic sheets covering the study area were georeferenced and mosaicked within a GIS framework. Hydrological boundaries were delineated using a combination of topographic sheets, satellite imagery, and Google Earth data. A Digital Elevation Model (DEM) was generated using ALOS PALSAR data with a 12.5 m resolution. Land use and land cover (LULC) maps were prepared from LANDSAT 5 (30 m resolution) and IRS-LISS IV (5.8 m resolution) satellite imagery. Geomorphology, soil, and drainage maps were digitized from published sources within the GIS framework. Additionally, historical water quality data from eight major drains were obtained from the Andhra Pradesh Pollution Control Board (APPCB) to assess seasonal variations in salinity across the Godavari delta.

The first phase of intensive fieldwork was conducted in the Eastern and Central Godavari deltas in June 2023, during which thirty-five water samples were collected from creeks, drains, and the Godavari River (both fresh and backwater) across the three major branches, along with seawater samples. In-situ measurements of pH, temperature, electrical conductivity (EC), and salinity were recorded. Water samples were collected in 500 ml and 20 ml containers for chemical analyses and stable isotope characterization, respectively. A second field visit was conducted in February 2024 in the Western delta to collect salinity data from creeks and drains. During this visit, fifty-five water samples were collected from major and minor drains, river backwaters, sea, canals, and aquaculture ponds for chemical and isotope analyses. In-situ measurements of salinity, pH, temperature, and EC were also recorded at all sampling points. Based on hydrochemical analysis from these two field campaigns, highly saline creeks and drains were identified. A third field visit in June 2024 focused on these high-salinity sites, during which water samples were collected from sixteen creeks and drains, along with surrounding shallow groundwater from twenty-nine locations, for detailed chemical and isotopic investigation.

Stable isotope data for $\delta^{18}O$ and $\delta^{2}H$ were collected from creeks, drains, river branches, canals, and seawater to assess the impact of salinity from creeks and drains on shallow groundwater in the Godavari delta. In-situ measurements of temperature, pH, electrical conductivity (EC), and salinity were recorded at all sampling locations. Major ion analyses—including bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), chloride (Cl^-), sodium (Na^+), potassium (K^+), sulfate (SO_4^{2-}), and nitrate (NO_3^-), were performed at the Water Quality Laboratory of the DRC, NIH, and Kakinada. Samples for isotope analysis were collected in acid-washed LDPE (Low-Density Polyethylene) Tarson bottles and transported to the National Institute of Hydrology, Roorkee. Ratios of heavy stable isotopes ($\delta^{18}O$ and δD) were measured at the Nuclear Hydrology Laboratory of NIH, Roorkee, using a Dual Inlet Isotope Ratio Mass Spectrometer (DI-IRMS; Isoprime GV Instruments, UK) equipped with automatic sample preparation units. For δD analysis, 400 μL of water was equilibrated with ^2H in the presence of a Pt catalyst at 40 °C for 3 hours, and the gas was then introduced into the mass spectrometer. For $\delta^{18}O$ analysis, 400 μL of water was equilibrated with CO_2 gas at 40 °C for 7 hours, and the equilibrated gas was introduced into the spectrometer. Measured values are reported as delta (δ) values relative to the Vienna Standard Mean Ocean Water (VSMOW) (Huang and Pang, 2012; Krishan, 2021; Gallart et al., 2024).

6. RESULTS AND DISCUSSIONS

The results of historical salinity data of Andhra Pradesh Pollution Control Board (APPCB) of various creeks located in the Eastern Godavari delta, and the salinity values of creeks, drains and river water (backwater) measured during field visits in the Godavari delta are presented and discussed in the subsequent sections.

6.1 Analysis of Salinity in Creeks/Drains Monitored by Andhra Pradesh Pollution Control Board

The for preliminary investigations, historical water quality data from various drains in the Godavari delta were obtained from the Andhra Pradesh Pollution Control Board to assess salinity levels. A total of thirteen water samples from eight drains, including Rangaraju Drain (Katrenikona mandal), North Addalakaluva (I. Polavaram mandal), Vasalatippa Drain (Uppalaguptam mandal), Vrudha Gowthami (Mummidivaram mandal), Vadalanali Drain and Atreya Godavari (Tallarevumandal), and Teki and Andrangi Drains (Kajuluru mandal) (Fig. 6.1)were analyzed for pH, dissolved oxygen (DO), salinity, total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), and ammonia nitrogen (NH_3-N). These samples, collected between April 2018 and March 2023, were evaluated for all major chemical parameters to understand the temporal variation and salinity dynamics of the drains.

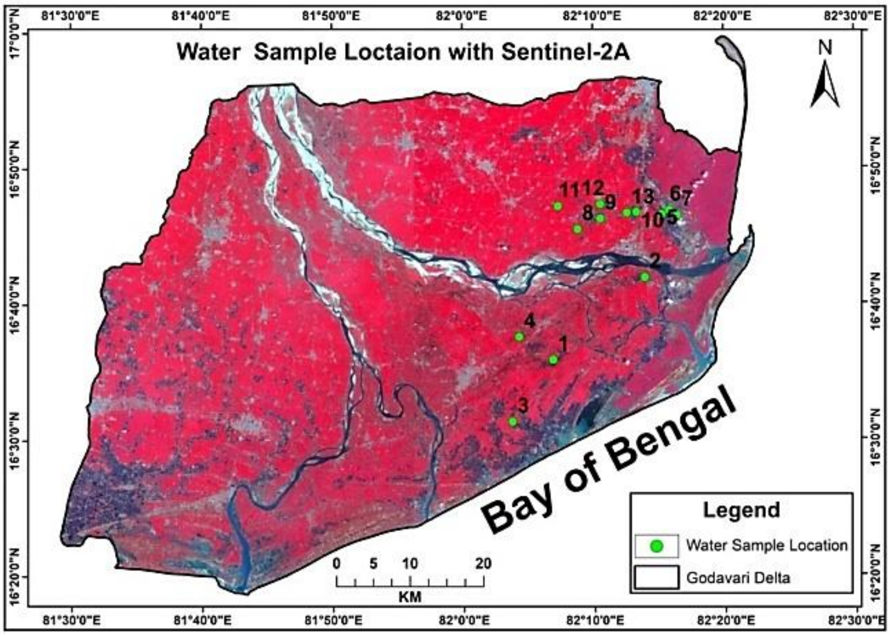

Fig.6.1 Water sample locations (13) of APPCB in various drains in Godavari Delta

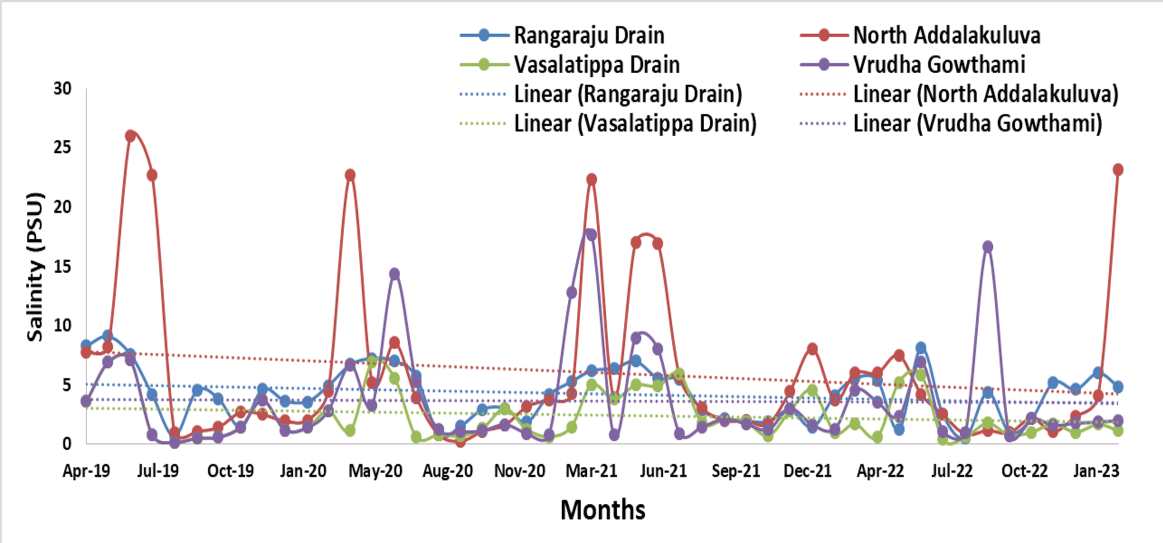

Fig.6.2 Salinity Variation in the four major drains in the Godavari Delta during April 2019 to March 2023

Analysis of the drain water quality data indicates that salinity levels varied widely on a monthly basis between April 2019 and March 2023 (Fig. 6.2). To assess the influence of rainfall on drain water quality, salinity values were compared with monthly rainfall data for the period April 2018–September 2019 (Fig. 6.3). Representative results for the Rangaraju Drain (Katrenikona mandal) and Vadalanadi Drain (Tallarevu mandal) are shown in Fig. 6.3. High salinity levels were observed during months with low rainfall, whereas during the monsoon season, dilution by rainwater resulted in lower salinity values. In the pre-monsoon season, elevated salinity may be attributed to backwater effects and anthropogenic influences, such as discharges of brackish groundwater from aquaculture ponds. The sources of high and low salinity in major and minor creeks and drains were further investigated through extensive fieldwork. All major creeks, drains, and river branches across the Godavari delta were demarcated to facilitate a comprehensive understanding of spatial salinity distribution.

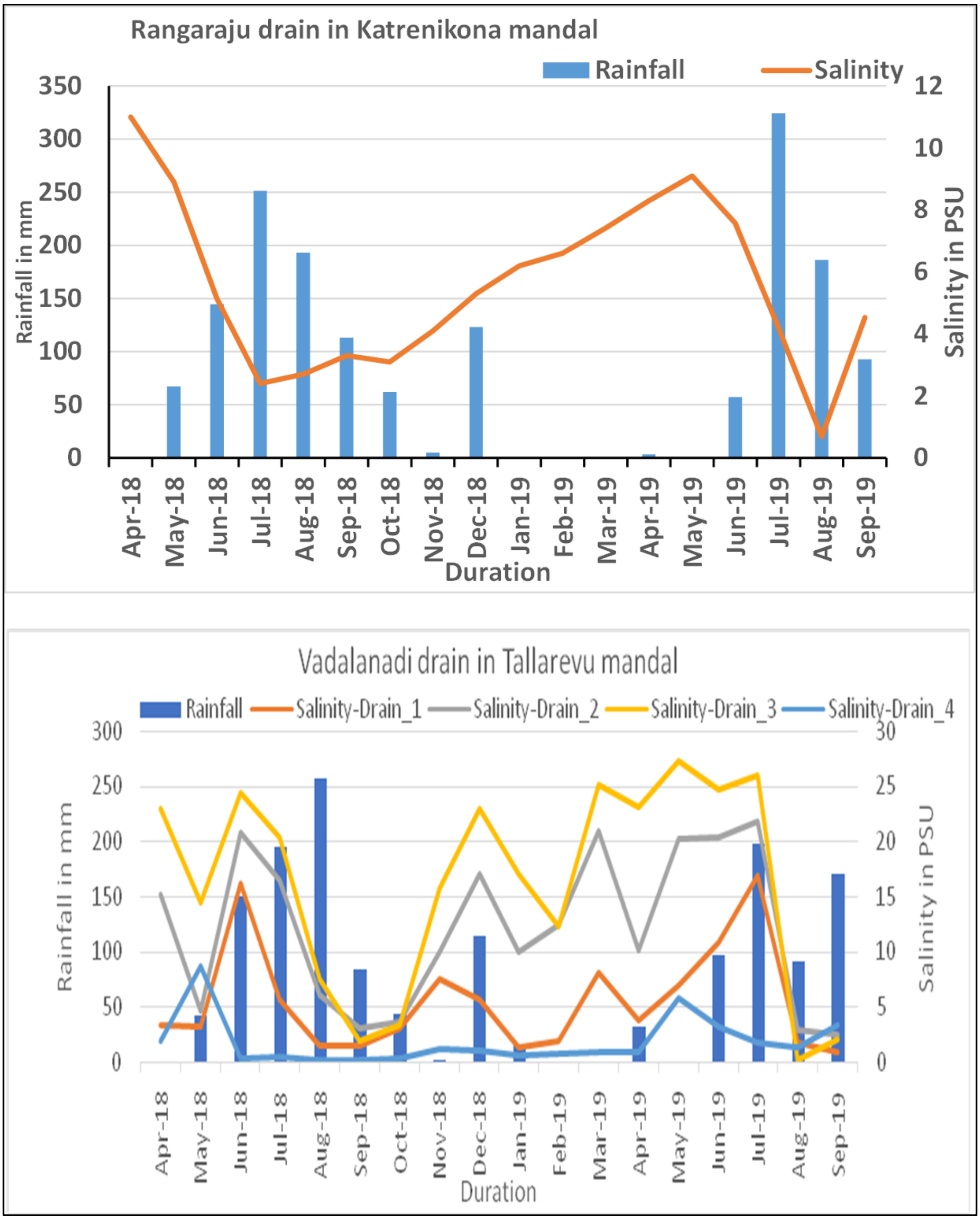

Fig.6.3 Mandal rainfall (mm) and drain water salinity (PSU) variations

6.2. Assessment of Salinity in Creeks, Drains, and Backwater through River Branches during Field Visits

Based on Electrical Conductivity (EC) and salinity measurements, a total of fifty-six backwater (saline) samples were collected from creeks (11), drains (34), and Godavari river branches (11) across the Godavari delta (Fig. 6.4). Of these, thirty-one samples were from the Eastern and Central deltas, and twenty-five from the Western delta. The detailed sample numbers for these backwater samples are presented in Table 6.1 and illustrated in Fig. 6.4. Analysis of EC and salinity values indicates a strong correlation between these parameters as shown in Fig. 6.5(a) and 6.5(b). The results show that backwater salinity in creeks, drains, and river branches is generally higher in the Eastern and Central deltas compared to the Western delta.

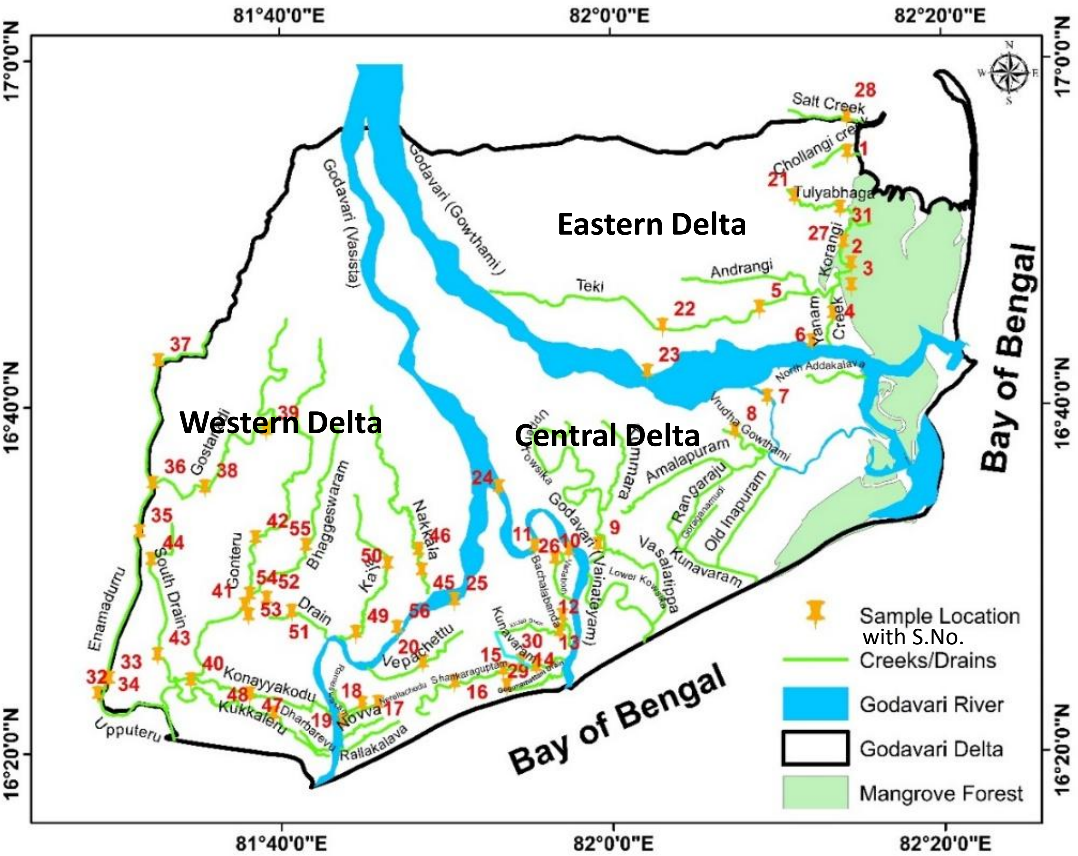

Fig.6.4 Water sampling locations at creeks, drains, and Godavari River (Backwater) in the Godavari delta

Table 6.1. Sampling locations at various creeks/drains in the Godavari delta

S.No.	Name of the Creek/Drain	Sampling Location	Delta zone	S.No.	Name of the Creek/Drain	Sampling Location	Delta zone
ECR1	Chollangi Creek	Chollangi	Eastern Delta	CCR29	Minor Drain	Kesanapalli	Central Delta
EDR2	Corangi River	Tallarevu	Eastern Delta	CCR30	Kunavaram (minor) Drain	Kunavaram	Central Delta
EDR3	Teki-Corangi Confluence	Tallarevu	Eastern Delta	ECR31	Creek	Matlapalem	Eastern Delta
ECR4	Creek	Yanam	Eastern Delta	WCR32	Upputeru	Losari	Western Delta
EDR5	Teki Drain	Goppirevu	Eastern Delta	WDR33	Mandachedu Drain	Nagidipalem	Western Delta
EGG6	Gowthami Godavari	Yanam	Eastern Delta	WDR34	Yenamadurru Drain	Nagidipalem	Western Delta
CGG7	Gowthami Godavari	Muramalla	Central Delta	WDR35	Yenamadurru Drain	Bhimavaram	Western Delta
CDR8	VruddaGowthami Drain	Bandarupalem	Central Delta	WDR36	Yenamadurru Drain	Palakoderu	Western Delta
CDR9	Peruru Drain	Bodasakurru	Central Delta	WDR37	Yenamadurru Drain	Pippara	Western Delta
CVG10	Vainateyam Godavari	Pasarlapudi	Central Delta	WDR38	GostaniNadi Drain	Palakoderu	Western Delta
CDR11	Vodabodi Drain	Pasarlapudi	Central Delta	WDR39	GostaniNadi Drain	Mamiduru	Western Delta
CCR12	Bacholabanda Drain	Morupolaram	Central Delta	WDR40	Gonteru Drain	Koththata	Western Delta
CCR13	Kadali medium Drain	Gogannamattam	Central Delta	WDR41	Gonteru Drain	Matsyapuri	Western Delta
CCR14	Shankarguptam Drain	Karavaka	Central Delta	WDR42	Gonteru Drain	Veeravasaram	Western Delta
CCR15	Shankarguptam Drain	Kesavapalli	Central Delta	WDR43	South Drain	Komatitippa	Western Delta
CCR16	Shankarguptam Drain	Battalanka	Central Delta	WDR44	South Drain	Taderu	Western Delta
CDR17	Gondi Drain	Gondi	Central Delta	WDR45	Nakkala Drain	Kottukalva	Western Delta
CDR18	Novva Drain	Gudimula	Central Delta	WDR46	Nakkala Drain	Penumarru	Western Delta
CCR19	Rameswaram Drain	Gudimella	Central Delta	WDR47	Marteru Drain	Turputallu	Western Delta
CDR20	Malikipuram Drain	Malikipuram	Central Delta	WDR48	Konayyakodu Drain	Pasaladeevi	Western Delta
EDR21	Tulyabhaga River	Gorrepudi	Eastern Delta	WDR49	Kaja Drain	Navarasapuram	Western Delta
EDR22	Taki Drain	K Gangavaram	Eastern Delta	WDR50	Kaja Drain	Medapadu	Western Delta
EGG23	Gowthami Godavari	Kotipalli	Eastern Delta	WDR51	Minor Drain	Saripalli	Western Delta
EVG24	Vainateyam Godavari	P. Gangavaram	Eastern Delta	WDR52	Mogalthuru Drain	Mallavaram Pedalanka	Western Delta
CVG25	Vashista Godavari	Razole	Central Delta	WDR53	Mogalthuru Drain	Kopparru	Western Delta
CVG26	Vainateyam Godavari	Appanapalli	Central Delta	WDR54	Bhaggeswaram Drain	Mallavaram	Western Delta
EDR27	Corangi Creek	Corangi	Eastern Delta	WDR55	Bhaggeswaram Drain	Kapavaram	Western Delta
ECR28	Salt Creek	Kakinada	Eastern Delta	WVG56	Vasishta Godavari	Chinchinada	Western Delta

Note: ECR– Eastern delta Creek; CCR– Central delta Creek; EDR– Eastern delta Drain; CDR– Central delta Drain; EGG– Eastern delta Gowthami Godavari; CGG– Central delta Gowthami Godavari; EVG– Eastern delta Vainatheyam Godavari; CVG– Central delta Vainatheyam Godavari; WDR– Western delta Drain; WVG– Western delta Vasista Godavari

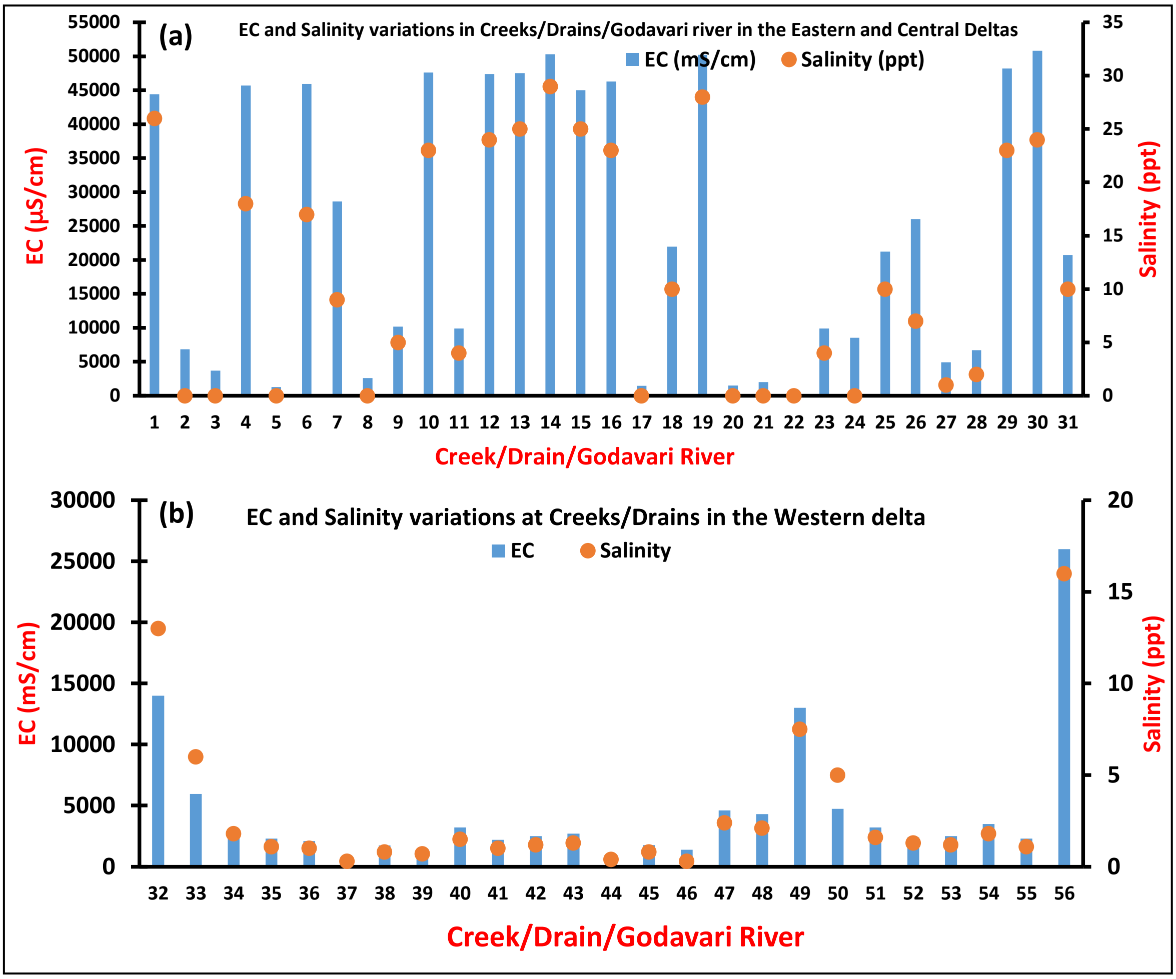

Fig.6.5 EC and Salinity variations in creeks, drains, and Godavari backwater in the (a) Eastern and Central deltas and (b) Western delta

The average salinity parameters of water samples collected during the two field visits are summarized in Table 6.2. Among eleven creek water samples (average EC: 45,136 µS/cm; salinity: 23.3 ppm), three were collected from the Shakaraguptham major drain in the Central delta, while the remaining eight samples were from the Central (4), Eastern (3), and Western (1) deltas. All these creeks are directly connected to the sea, allowing seawater inflow (backwater) several kilometres inland. Drain water represents a mixture of return flows from irrigation and aquaculture with backwater, resulting in comparatively lower average EC (3,764 µS/cm) and salinity (1.53 ppm) than creek water. Nine backwater samples from river branches revealed that backwater intrusion extends nearly 35 km upstream from the sea along the three major Godavari branches—Gautami, Vainateyam, and Vasista. High salinity was observed at Yanam in the Gautami Godavari (EC: 45,900 µS/cm; salinity: 17 ppm) and at Pasarlapudi in the Vainateyam Godavari (EC: 47,600 µS/cm; salinity: 23 ppm), indicating strong backwater influence at these locations.EC values of backwater in other locations within the three major river branches ranged from 21,210 to 30,000 µS/cm. In contrast, Godavari River water at Kotipalli and P. Gannavaram (Gautami branch) recorded EC values of 9,890 µS/cm and 8,550 µS/cm, respectively, with salinity effectively zero, suggesting minimal backwater influence approximately 35 km from the sea coast.

Table 6.2.Average salinity parameters of various types of water samples in Godavari delta

Sample	No.	Temp (^{0}C)	pH	EC (µS/cm)	Cl (mg/L)	HCO_3 (mg/L)	Salinity (ppm)
Creeks (backwater)	11	31.47	7.07	45136	18772	329	23.3
Drains (Mixing of Return Flows & backwater)	36	29.81	6.97	3764	1227	342	1.53
Godavari (Backwater)	9	31.44	6.95	27083	11298	273	12.4
Godavari (Freshwater)	3	32.5	7.75	246	68	250	0
Groundwater (deep)	3	29.38	6.65	9788	3228	500	7.52
Groundwater (shallow)	29	31.0	7.0	6100	1479	727	4.0
Canal water	16	29.12	7.31	265	104	80	0.1
Aqua pond water	5	27.93	6.18	7433	2333	255	3.86
Seawater	3	28.83	8.2	29666	-	-	27.6

Freshwater samples from the Godavari River were collected at three locations, Kapileswarapuram, Siddhantham, and Dhawaleswaram, with EC values ranging from 230 to 271 µS/cm. Canal water samples exhibited similar characteristics, reflecting the freshwater quality of the Godavari River. Near creeks and drains, twenty-nine shallow groundwater samples were collected from hand pumps and dug wells (less than 10 m depth), along with three deep groundwater samples from tube wells (depths exceeding 100 m). Shallow wells are primarily used for domestic purposes, whereas deep tube wells serve aquaculture practices due to higher salinity. High salinity was observed in shallow aquifers (average EC: 6,100 µS/cm; salinity: 4 ppm), while deeper aquifers (~115 m) showed significantly higher salinity (average EC: 31,600 µS/cm; salinity: 22 ppm). At depths near 150 m, salinity decreased (average EC: 6,600 µS/cm; salinity: 4 ppm), indicating that deep groundwater is a source for aquaculture ponds in the Western delta, helping to maintain optimal salinity levels. The average EC of three seawater samples was 29,666 µS/cm, which is lower than that observed in creek backwater (Table 6.2). The lower salinity of seawater, relative to creek backwater, is further explained through stable isotope analysis.

Analysis indicates that the average salinity in drains of the Western delta (EC: 3,490 µS/cm; salinity: 2.3 ppm) is lower than that in the Eastern and Central deltas (EC: 4,314 µS/cm; salinity: 2.8 ppm). This difference is likely due to greater mixing of irrigation return flows with comparatively lower inflows of saline backwater in the Western delta drains, compared to the Eastern and Central deltas. The average EC and salinity values for creeks, drains, and river branches in the Western delta and the Eastern and Central deltas are presented in Table 6.3 and Table 6.4, respectively. Seawater samples were collected from one location in the Western delta (near Perupalem) and two locations in the Central delta (near Antarvedi). The lower seawater salinity observed at the river-sea confluence in the Western delta (EC: 28,500 µS/cm) compared to the Central delta (EC: 32,000 µS/cm) reflects dilution effects at these points of freshwater-seawater interaction.

Table 6.3. Average salinity parameters of water samples in the Western delta

Sample	No. of samples	Temp (^{0}C)	pH	EC (µS/cm)	Cl (mg/L)	HCO_3 (mg/L)	Salinity (ppm)
Creeks	1	26.9	6.47	14000	4500	472	13
Drains (Mixing of Return Flows & backwater)	22	28.65	6.64	3490	1055	352	2.3
Vasista Godavari (Backwater)	2	30.6	6.8	23605	9850	268	13
Godavari (Freshwater)	1	32.7	7.6	222	68	253	0
Groundwater (deep, 375 ft)	1	28.8	5.83	31600	12300	526	22
Groundwater (deep, 500 ft)	2	29.5	6.26	6660	1460	460	3.75
Aqua pond water (brackish)	4	27.93	6.18	7433	2333	255	3.86
Aqua pond water (Freshwater)	2	28.5	6.69	2100	504	484	1
Canal water	8	29.15	7.7	286	104	80	0.1
Seawater	1	29	7.9	32000	-	-	30

Table 6.4 Average salinity parameters of water samples in the Eastern and Central deltas

Sample	No. of samples	Temp (^{0}C)	pH	EC (µS/cm)	Cl (mg/L)	HCO_3 (mg/L)	Salinity (ppm)
Creeks (backwater)	10	31.47	7.07	47580	19750	314	24.6
Drains (Mixing of Return Flows & backwater)	11	31.88	7.57	4314	1571	323	2.8
Gowthami and Vainateyam Godavari (Backwater)	7	31.68	7	28077	11711	275	16.9
Godavari (Freshwater)	1	30.65	7.41	250	68	247	0
Canal water	8	29.1	7.45	249	105	40	0.1
Seawater	2	28.7	8.3	28500	-	-	25

The water sampling locations for creeks, drains, and various branches of the Godavari River, along with their salinity values (ppt), are shown in Fig. 6.6. Low-salinity drains (0.3–2.4 ppt) are observed throughout the Western delta, with the exception of the Kaja Drain, which exhibits higher salinity (5–7.5 ppt). High-salinity creeks are predominantly located near the mouths of the Gowthami and Vainateyam rivers in the Eastern and Central deltas, and these zones are highlighted in Fig. 6.6. The influence of these high-salinity creeks and drains on shallow groundwater was assessed on either side of the identified water bodies during the third field visit conducted in June 2024.

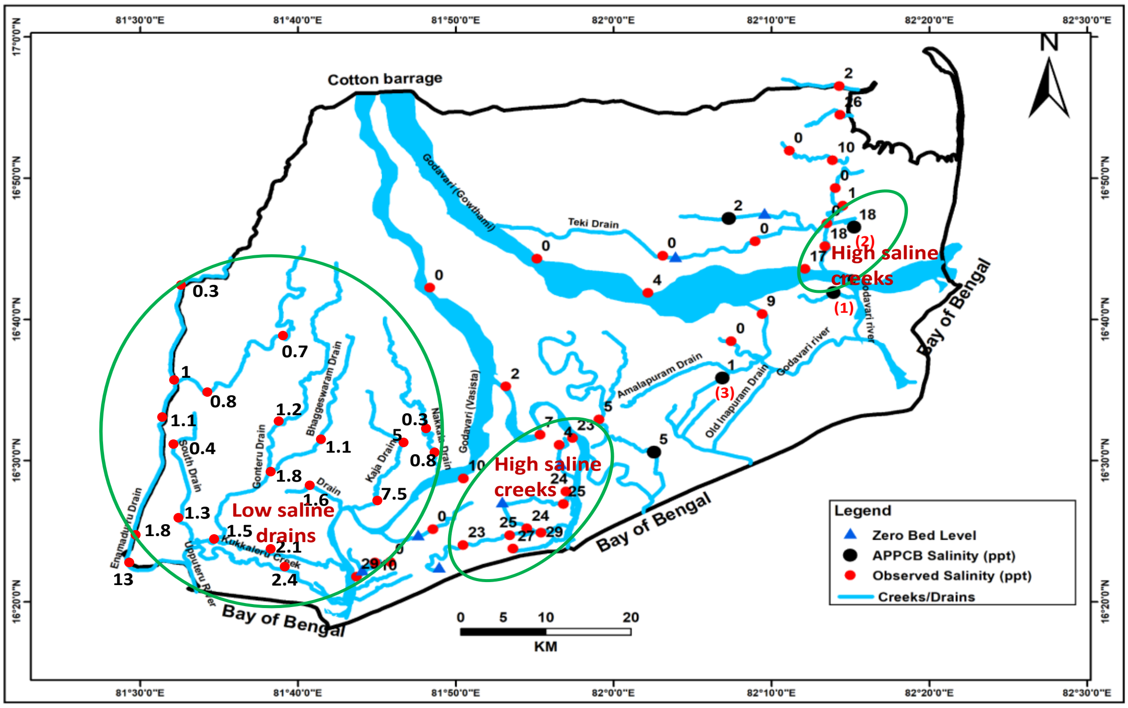

Fig.6.6 Water sampling points at creeks/drains and salinity in Godavari delta

6.3. Assessment of Seawater influence in the Drains, Creeks and Godavari Backwater on Shallow Groundwater

The seawater fraction in groundwater samples can be estimated using chloride (Cl^-) as a conservative tracer, based on the following mixing equation (Appelo and Postma, 2005).

$$fsea\% = (m_{sample} - m_{fresh}) / (m_{sea} - m_{fresh})$$

Where m_{sample} is the sample Cl^- concentration, $m_{fresh}$is the freshwater Cl^- concentration, and m_{sea} is the seawater Cl^- concentration.

Table 6.5 presents the seawater fraction in creeks, drains, and Godavari backwater across the Godavari delta. The seawater contribution to the 36 drains shows a wide range, from less than 1% to 24%. High seawater fractions were observed in CDR9 and CDR11 (24%) in the Central delta, and in WDR32 (21%) and WDR49 (20%) in the Western delta. Conversely, lower seawater fractions (<1%) were recorded in EDR22 in the Eastern delta and WDR37 and WDR44 in the Western delta. Relatively low seawater fractions (0.3–6%) were found in 18 drains of the Western delta. Among backwater locations, EVG24 and EGG23 exhibited the lowest seawater fractions (11% and 24%, respectively), whereas EGG6 showed the highest fraction at 98%. CVG25 and WVG56 recorded seawater fractions of 46%, indicating moderate seawater influence at these sites.

Table 6.5. Seawater fraction (%) in the creeks, drains and Godavari backwater

Water sample	Delta Region	Fsea% (Min to Max)	Different Range of seawater fraction in %			
			0-1	1-10	10-30	>30
Creeks (10)	Eastern and Central delta	86-99	-	-	-	10
Drains (12)	Eastern and Central delta	0.28 to 24	1	9	2	-
Godavari (Backwater) (7)	Eastern and Central delta	11.8 to 98	-	-	2	5
Drains (24)	Western delta	0.32-21	2	20	2	-
Godavari (Backwater) (2)	Western delta	45-46	-	-	-	2

The molar ratio of Cl^-/HCO_3^- (Todd, 1959) was calculated to assess the influence of seawater on creeks, drains, Godavari river branches, aquaculture pond water, and shallow groundwater. Chloride is the predominant anion in seawater, whereas bicarbonate dominates in freshwater and groundwater. The Cl^-/HCO_3^- ratio serves as a reliable indicator of salinization due to seawater encroachment (Nwankwoala and Judom, 2011; Demirel, 2004). A plot of Cl^- versus Cl^-/HCO_3^- provides a clear understanding of seawater influence, showing a positive correlation between the ratio and chloride concentration (Fig. 6.7). The results indicate that all creeks are severely affected by seawater. Godavari backwater in the Eastern (Gautami) and Central (Vainateyam) deltas is highly to severely affected. In the Western delta, WCR32 (Upputeru) and WDR49 (Kaja drain) show strong seawater influence, whereas the remaining drains are slightly affected. In the Central delta, CDR9 and CDR11 are confirmed to be highly affected, with other drains exhibiting minor seawater influence.

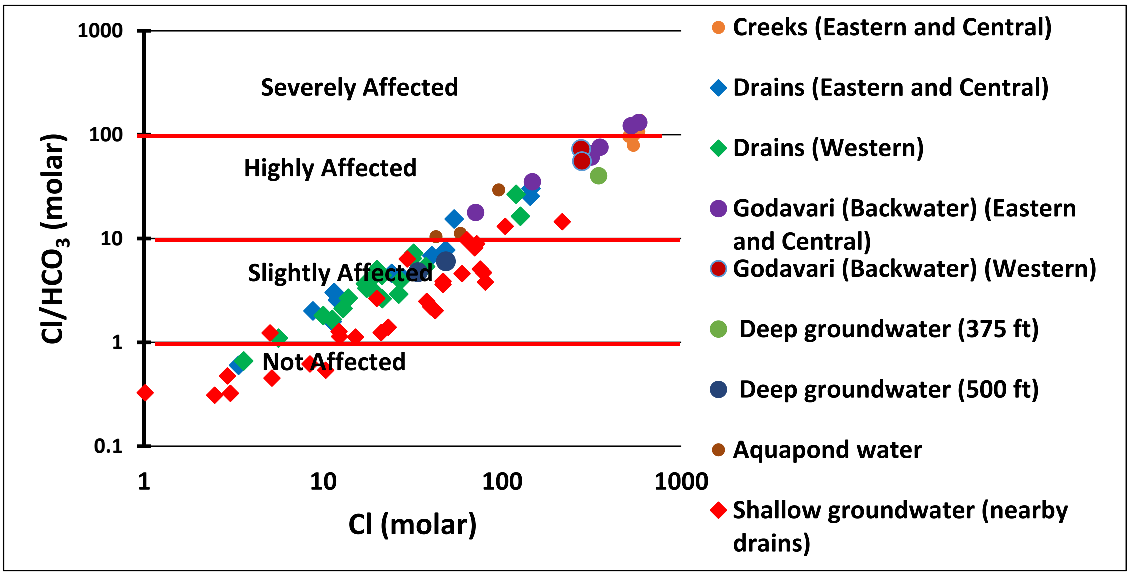

Fig.6.7 Geochemical facies distribution from the scatterplot of Cl/HCO_3 Versus Cl

6.4. Analysis of Hydrochemistry of High Saline Creeks/Drains on Surrounding Shallow Groundwater

To assess the impact of salinity on surrounding shallow aquifers, eight high-salinity creeks and drains, including the Vainateyam Godavari back water were identified from the previous analyses. Additionally, five high-salinity drains (Kummara Drain, Kadali Drain, Old-Inapuram Drain, Rangaraju Drain, Kunavaram Major Drain, and Lower Kowshika Drain) were included, resulting in a total of thirteen high-salinity creeks and drains selected for further analysis in the Godavari delta. Of these, two are located in the Eastern delta, two in the Western delta, and the remaining nine in the Central delta. In-situ measurements of pH, temperature, EC, and salinity were carried out in twenty-nine surrounding shallow wells (hand pumps, dug wells, and shallow bore wells) to evaluate the influence of these creeks and drains on shallow groundwater salinity. These twenty-nine shallow wells are located within 50 m of the nearby creeks/drains**.** Major ion chemistry analyses were performed at the Water Quality Laboratory of the Deltaic Regional Centre (DRC), National Institute of Hydrology (NIH), Kakinada, while stable isotope analyses were conducted at the Isotope Laboratory, NIH Roorkee. In addition, heavy metals were analysed at the Water Quality Laboratory of the Environmental Hydrology Division, NIH, Roorkee. The major ion chemistry of high-salinity creek and drain samples, along with their corresponding nearby shallow groundwater samples, is presented in Table 6.6.

Table 6.6. Major ion chemistry in high saline creeks/drains and surrounding shallow groundwater in the Godavari delta

S.No	Location	Source	pH	EC (µS/cm)	Cl (ppm)	Na (ppm)	K (ppm)	HCO3 (ppm)	Ca (ppm)	Mg (ppm)
1	Matlapalem	**Creek-1**	**7**	**5030**	**1310**	**816**	**23**	**324**	**148**	**166**
		DW	6.9	4900	1350	884	180	936	64	98
		HP	6.95	4220	710	652	138	460	133	98
2	Yanam	**Creek-2**	**7.5**	**13560**	**3760**	**2460**	**96**	**212**	**114**	**299**
		DW	7.5	1400	180	92	20	250	26	56
3	Kodurupadu	**Kummara drain**	**7.1**	**22800**	**6000**	**3500**	**140**	**184**	**242**	**509**
		DW-1	7	3770	1050	698	9	284	101	108
		HP-1	6.9	8090	2250	1388	48	396	160	179
		DW-2	7.5	13870	3700	1966	23	484	321	61
		HP-2	7.5	11890	2500	1350	44	528	274	310
4	Kithana cheruvu	**Kummara drain**	**7.3**	**3290**	**916**	**596**	**10**	**124**	**88**	**99**
		SW	6.9	14900	2864	2520	56	1288	82	343
5	Pasarlapudi	**Vainateyam Godavari**	**7**	**41200**	**12000**	**5260**	**264**	**172**	**282**	**893**
		HP	8.1	1050	88	65	5	488	22	44
6	Morupolam	**Bachalabanda drain**	**7.6**	**7840**	**1700**	**650**	**28**	**1128**	**40**	**103**
		SW	7.1	3230	540	210	19	820	47	50
7	Gogannamatam	**Kadali drain**	**7.5**	**47500**	**20600**	**2445**	**146**	**329**	**-**	**-**
		DW	7	3130	440	98	80	660	58	93
		HP-1	7	1262	108	86	7	572	27	28
		SW	6.5	8230	2120	1288	264	792	66	262

		HP-2	7.5	11800	2560	1602	314	492	186	159
8	Kunavaram	**Minor drain**	**7**	**7350**	**1120**	**1348**	**30**	**256**	**107**	**132**
		HP	7.6	386	36	26	4	188	69	-18
		SW	6.8	1066	104	68	58	376	64	30
9	Katrenikona	**Old Ina- puram drain**	**6.9**	**13630**	**2600**	**2380**	**82**	**208**	**132**	**285**
		HP-1	7	2750	368	198	156	1172	30	87
		HP-2	7	14920	2800	2620	72	1020	64	164
10	N.Kothapalli	**Old Ina-puram drain**	**7**	**11180**	**2560**	**1968**	**62**	**228**	**135**	**242**
		SW	6.9	12290	2684	2160	102	908	21	295
		DW	6.9	6140	1500	880	346	1276	48	207
11	Sannavelli	**Rangaraju drain**	**7**	**7300**	**2780**	**1094**	**17**	**144**	**210**	**106**
		HP	7.1	4500	1660	822	24	736	40	138
		SW	6.9	14900	2864	2520	56	1288	82	343
12	Kunavaram	**Major Drain**	**7**	**6650**	**2540**	**940**	**17**	**164**	**176**	**194**
		SW	7.4	18450	7700	2200	64	908	104	466
		HP	6.9	4740	1660	958	48	788	32	107
13	Mogallamuru	**Lower Kowshika drain**	**7.1**	**9200**	**-**	**-**	**-**	**-**	**-**	**-**
		SW	7	4490	1420	954	23	1108	21	64
		HP	6.9	3820	820	158	22	1004	42	52
		HP	7.3	2200	436	98	17	588	43	83
14	Losari	**Upputeru creek**	**7.3**	**20800**	**5600**	**2900**	**142**	**244**	**184**	**450**
		HP	7.2	4860	750	350	158	1036	72	60
15	Navarasapuram	**Kaza drain**	**7.5**	**11660**	**2510**	**1984**	**64**	**192**	**150**	**200**
		HP-1	7.3	1900	184	454	33	696	56	47
		HP-2	7	2660	300	554	60	832	48	54
16	Medapadu	**Kaza drain**	**6.9**	**5670**	**850**	**894**	**15**	**268**	**192**	**87**
		SW	6.5	8230	2120	1288	264	792	66	262
		HP	7.5	11800	2560	1602	314	492	186	159

Note: DW, HP and SW refers Dug Well, Hand Pump and Shallow tube Well, respectively

Shallow groundwater was collected from dug wells, hand pumps, and shallow tube wells with depths of less than 6 m, all located within 100 m of creeks and drains. The EC values of the creeks and drains range from 3,290 to 47,500 µS/cm, while most shallow wells exhibit EC values between 2,660 and 18,450 µS/cm, indicating saline to highly saline conditions. The EC values of sixteen creeks and drains and their surrounding twenty-nine shallow wells are presented in Fig. 6.8. Locations of these sixteen creeks and drains along with their EC values are shown in Fig. 6.9. Among them, Kadali Drain (Gogannamatam) and Kummara Drain (Kodurupadu) show the highest EC values of 47,500 µS/cm and 22,800 µS/cm, respectively. In contrast, Kunavaram Minor Drain and Vainateyam Godavari backwater exhibit minimal influence on nearby shallow wells, as evidenced by low EC values ranging from 386 to 1,000 µS/cm, which are considered freshwater conditions.

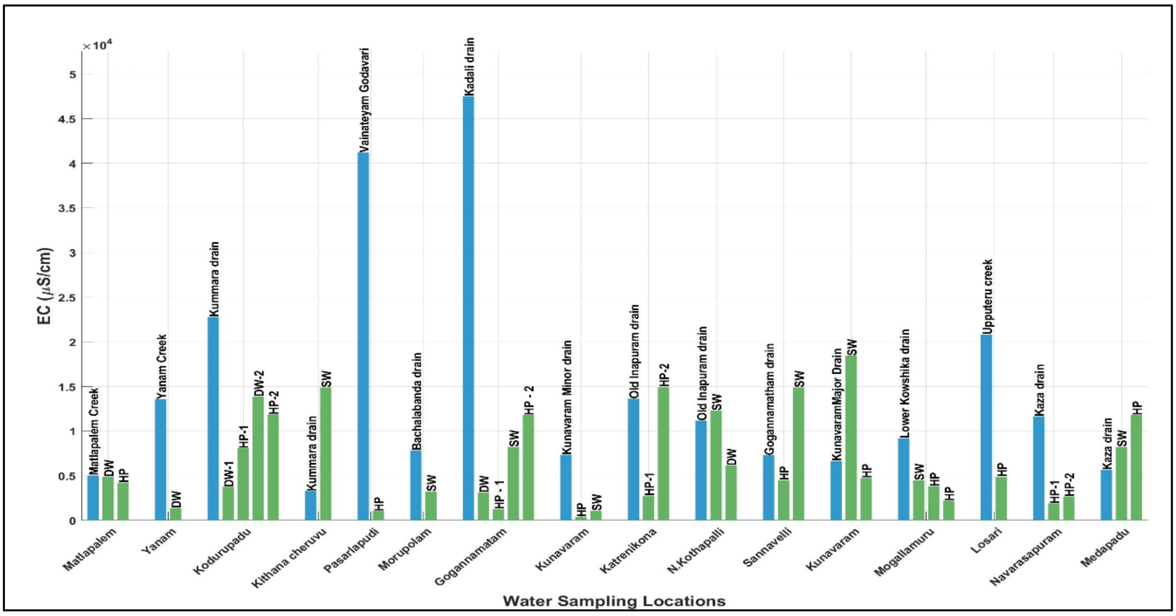

Fig.6.8. EC values of high saline creeks/drains and surrounding shallow wells

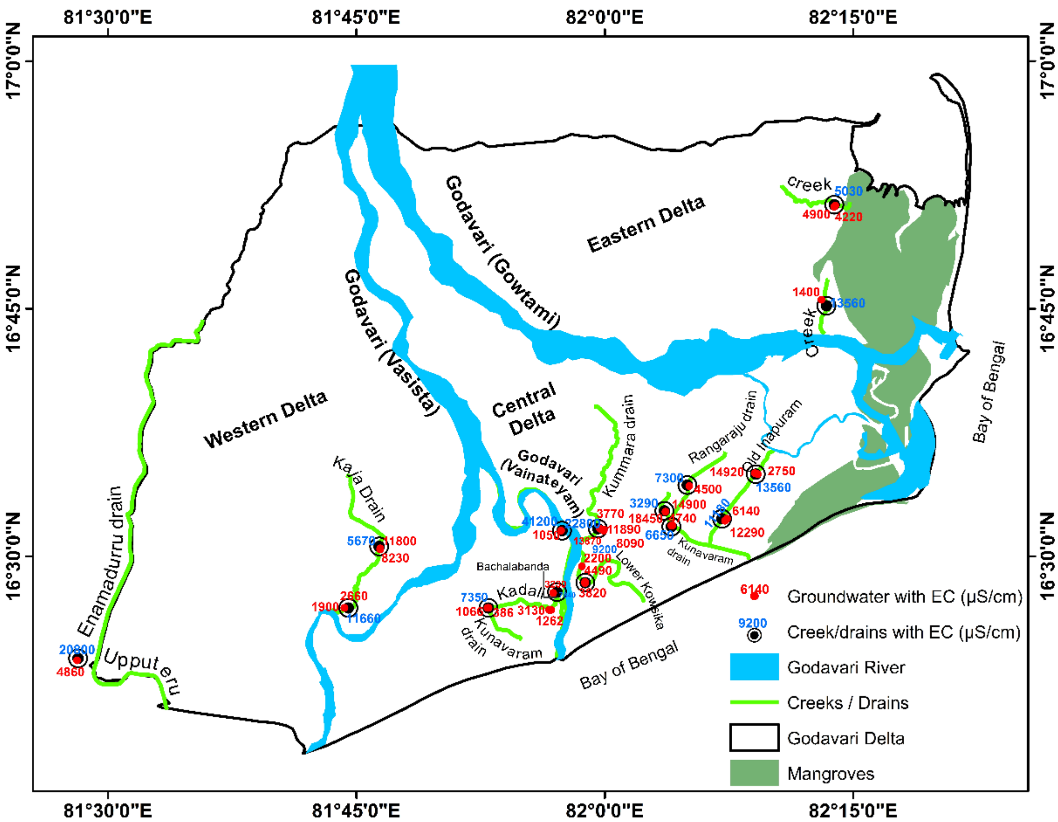

Fig.6.9. EC values of shallow groundwater and nearby creek/drain samples

Shallow wells are plotted on the Cl^- versus Cl^-/HCO_3^- graph as presented in Fig.6.7 to assess the influence of saline water. The analysis indicates that the majority of wells are slightly affected by saline water, with a positive correlation between the

Cl^-/HCO_3^- ratio and Cl^- concentration in these wells, suggesting mixing of fresh groundwater with saline water. Two groundwater samples, one shallow well in Kunavaram and one deep well in Kodurupadu, are highly affected by saline water, being located adjacent to the Kunavaram Major Drain and Kummara Drain, respectively. Seven shallow wells show no signs of saline influence, representing freshwater conditions.

6.4.1. Piper's Hydrogeochemical Process Evaluation

Hydrogeochemical facies are defined as zones within a groundwater system characterized by distinctive combinations of cation and anion concentrations, which help explain the distribution of principal groundwater types (Piper, 1944). The characteristics of shallow wells in each hydrochemical facies, as illustrated using Piper's trilinear diagram, are shown in Fig. 6.10. In the cationic triangle, most groundwater samples (>90%) fall into the Na-dominant type, while in the anionic triangle, the majority are Cl^--dominant, followed by HCO_3^--dominant zones. Most samples belong to the Na–Cl type (or Na–Cl mixed seawater), indicating that non-carbonate alkali (primary salinity) exceeds 50% and representing the seawater mixing zone. The remaining samples exhibit mixed chemical character, primarily as Ca–Mg–Cl type and Na–HCO_3–Cl type, where no single cation–anion pair exceeds 50%. No samples were observed in the Ca–Cl_2 or Na–HCO_3 types. Two samples fall into the Mg–HCO_3 type, indicating carbonate hardness (secondary alkalinity) exceeding 50%.

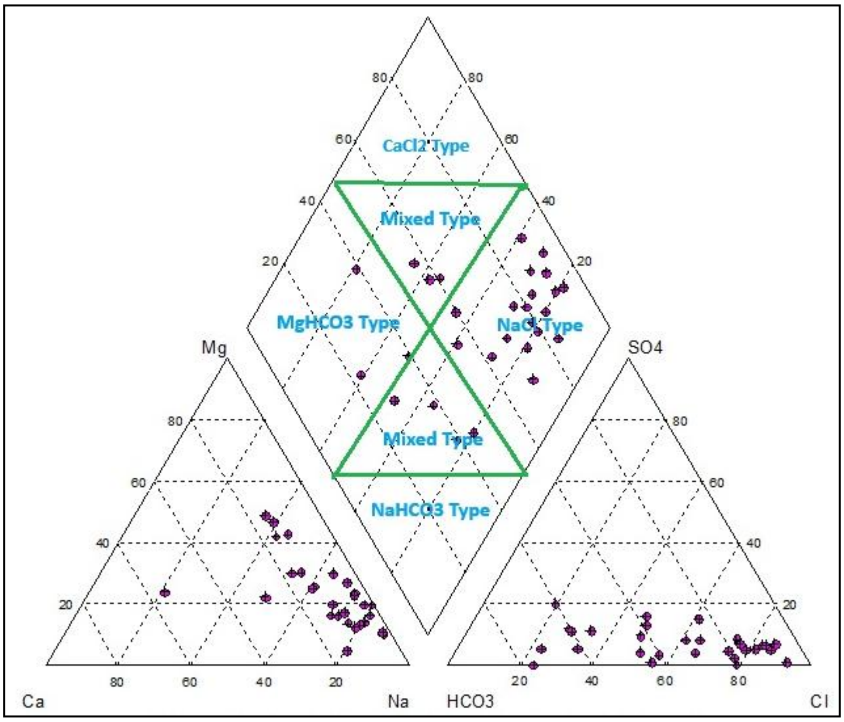

Fig.6.10. Piper trilinear diagram for hydrochemical facies of shallow groundwater

6.4.2. Mechanisms Controlling Shallow Groundwater Chemistry

The molar ratios of ($Na^+ + K^+$)/($Na^+ + K^+ + Ca^{2+}$) and Cl^-/($Cl^- + HCO_3^-$) were plotted as a function of TDS (mg/L) using Gibbs diagrams (Gibbs, 1970) (Fig. 6.11) to identify the dominant processes controlling dissolved chemical constituents in shallow groundwater near creeks and drains, including precipitation, rock-water interaction, and evaporation. The Gibbs diagrams indicate that the majority of samples fall within the evaporation-dominated region for both cationic and anionic plots, suggesting that evaporation is a significant process contributing to the salinity of shallow wells. A smaller number of samples fall within the rock-water interaction region, indicating groundwater chemistry influenced primarily by mineral dissolution, with negligible contributions from direct evaporation or precipitation processes.

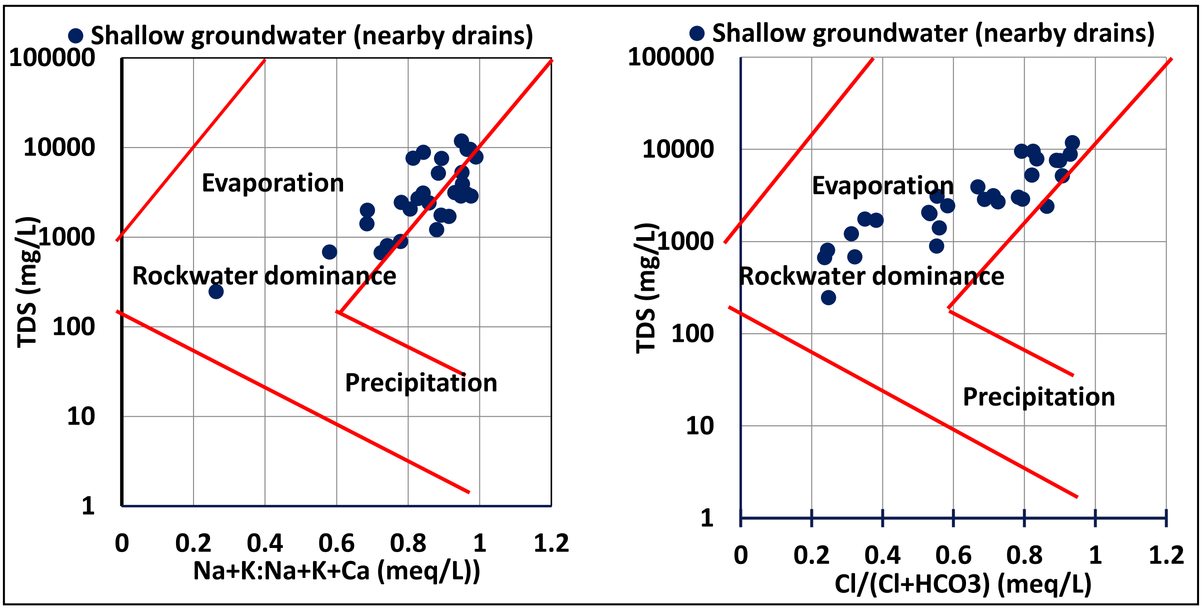

Fig.6.11 Mechanisms controlling the shallow groundwater chemistry using Gibbs diagrams

6.4.3. Hydogeochemical Processes

The Na^+/Cl^- molar ratio was plotted (Fig. 6.12a) to investigate rock–water dissolution characteristics in shallow groundwater. A Na^+/Cl^- ratio of ~1 indicates halite dissolution as the primary sodium source, whereas a ratio >1 suggests sodium release from silicate (e.g., feldspar) weathering (Meybeck, 1987). When Na^+ is plotted against Cl^-, several samples lie on or above the 1:1 trend line, indicating that both halite dissolution and silicate weathering contribute to the sodium content. This suggests that soil salts, deltaic clayey sands, and coastal clayey sands are significant contributors to elevated Na^+ concentrations in groundwater. A few samples below the 1:1 line with higher Na^+/Cl^- ratios may indicate additional salinization factors. The median Na^+/Cl^- ratio of ~1 further confirms the influence of seawater on groundwater chemistry. Seawater mixing is also supported by the strong correlation between (Na^++ K^+) and the major strong acid anions (Cl^- + SO_4^{2-}) (Ahamed et al., 2015) (Fig. 6.12b).

Rock–water interactions via silicate weathering are further evidenced by the scatter plot of (Ca^{2+} + Mg^{2+}) versus HCO_3^- (Fig. 6.12c), where most samples lie above the 1:1 equiline, indicating a predominance of alkali earth cations (Ca^{2+} and Mg^{2+}) over bicarbonate due to silicate weathering (Elango et al., 2003). To distinguish the dominant source of major ions, (Ca^{2+} + Mg^{2+}) was plotted against (Na^+ + K^+) (Hidalgo and Cruz-Sanjulian, 2001). Most samples fall along or above the 1:1 line (Fig. 6.12d), confirming that silicate weathering is the dominant process over carbonate weathering in controlling groundwater chemistry.

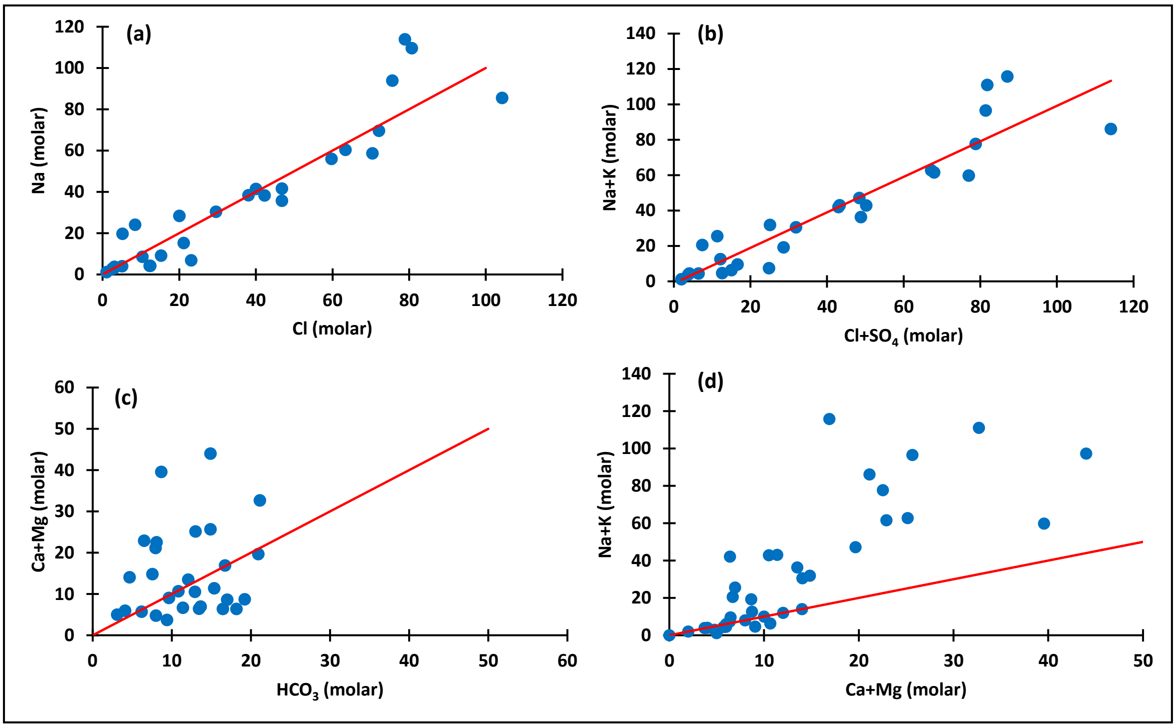

Fig.6.12. Scatter plots of (a) Na^+ vs Cl^-; (b) (Na^++K^+) vs (Cl^-+SO_4^{2-}); (c) (Ca^{2+}/Mg^{2+}) vs HCO_3^- (d) (Na^++K^+) vs (Ca^{2+}/Mg^{2+})

Based on Piper diagram classification, the dominant water type in the shallow groundwater is Na–Cl, indicating significant mixing with seawater. Hydrogeochemical analysis suggests that while several shallow wells are influenced primarily by seawater intrusion, others are governed by rock–water interactions and mineral dissolution processes. To further differentiate these salinity sources and to assess the specific impact of creeks and drains on shallow groundwater, stable isotope characterization of the wells has been conducted.

6.4.4. Stable Isotopic Characterization of Shallow Groundwater, Creeks and Drains

Stable isotopes (^2H and ^{18}O) in groundwater provide valuable information about the origin and source of recharge, including insights into salinity processes (Krishan, 2021). In this study, the isotopic composition ($\delta^{18}O$ and δ^2H) of samples from creeks, drains, canals, and Godavari river water (both backwater and freshwater) as well as shallow wells in the Godavari delta were compared against the Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) (Fig. 6.13). The average EC values of these water samples are also presented in Fig. 6.13. It was observed that the stable isotopic signatures of creeks and Godavari river backwater within 20 km from the sea are highly enriched, reflecting seawater characteristics and representing direct seawater influence. Backwater samples collected at 35 km from the coast (EGG23 and EVG23) showed isotopic values intermediate between those collected at 20 km (5 samples) and 50 km (2 samples) from the coast. Freshwater in the Godavari river, located 50 km from the seacoast, exhibited depleted isotopic values ($\delta^{18}O$: -1.06 to -1.20 ‰, δ^2H: -12.21 to -12.59 ‰).

The observed enrichment in creeks and backwater ($\delta^{18}O$: +0.28 to +1.38 ‰, δ^2H: +2.43 to +7.42 ‰) is likely due to evaporation during the long residence time of backwater in the creeks. All creeks and Godavari river backwater within 20 km of the seacoast fall into Group 'A', with high salinity values (EC: 44,400–50,800 µS/cm), exceeding the salinity measured in seawater samples (EC: 32,000 µS/cm). This difference may be attributed to the collection of seawater samples near the coast and to the inflow of highly saline backwater through well-connected creeks and river mouths. In contrast, drains are well-connected to the inland delta and receive substantial irrigation return flows, which dilute the backwater influence. As a result, drain water shows lower salinity (EC: 711–10,190 µS/cm; average 5,381 µS/cm) but still exhibits enriched isotopic values ($\delta^{18}O$: -2.18 to +0.33 ‰, δ^2H: -15.80 to -3.34 ‰), reflecting a mixture of freshwater and saline backwater.

Isotope analysis indicates that thirteen groundwater samples exhibit enriched isotopic signatures and fall within the zone influenced by drains (Group B, Fig. 6.13). These shallow wells, including hand pumps and dug wells, show EC values ranging from 3,700 to 18,000 µS/cm and are located near six major creeks/drains:

1. Old Inapuram drain (N. Kottapalli and Katrenikona)
2. Kummara drain (Kodurupadu)
3. Kunavaram major drain (Kunavaram, Kithana Cheruvu)
4. Lower Kowsika drain (Mogalamuru)
5. Rangaraju drain (Sannavelli)
6. Kaja drain (Navarasapuram and Medapadu)

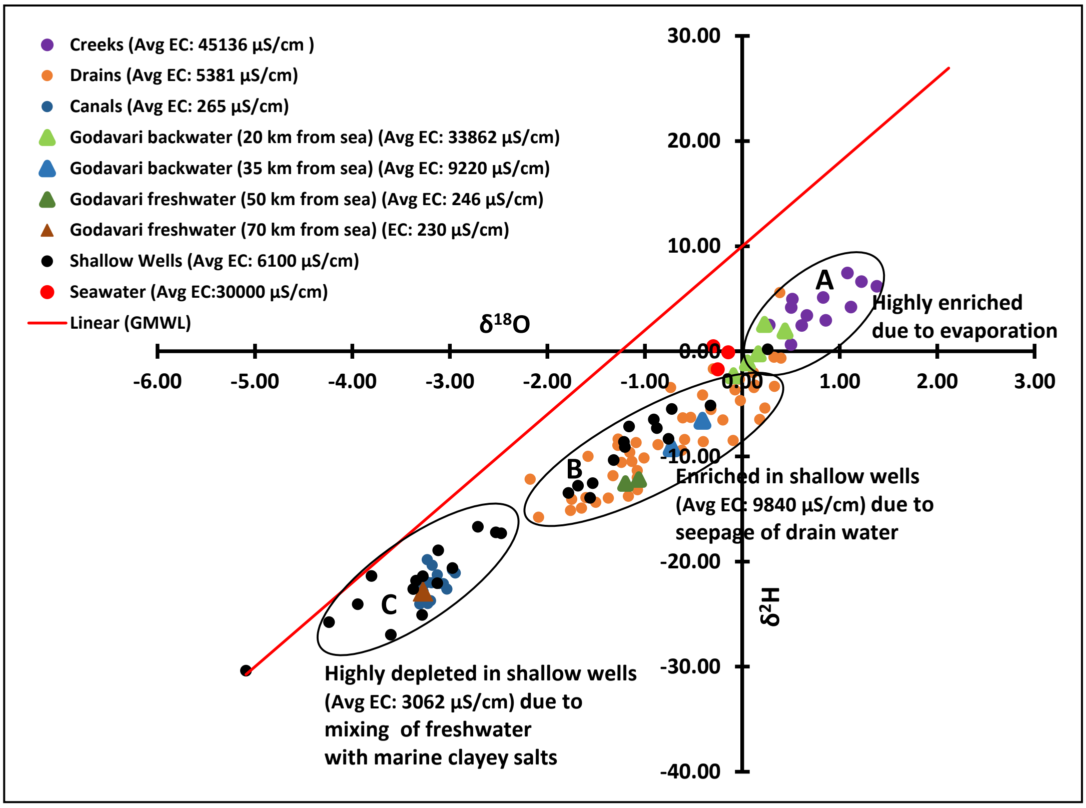

Fig.6.13 $\delta^{18}O$–$\delta^{2}H$ relationship of creek, drains, Godavari backwater and shallow groundwater in the Godavari delta

The locations of these drains are shown in Fig. 6.14. Among these six drains, Kaja drain belongs to the Western delta, while the remaining five are located in the Central delta. The shallow wells in the vicinity of these drains exhibit similar stable isotopic characteristics, suggesting that saline backwater from the drains is influencing the shallow aquifers through seepage. Freshwater samples from the Godavari River at Dhawaleswaram and canal waters show depleted stable isotopes and cluster in Group C, representing unimpacted freshwater. The remaining sixteen shallow wells, with EC values ranging from 380 to 12,000 µS/cm, also display depleted isotopes and are scattered within Group C.

A few of these shallow wells are classified as freshwater, with EC values ranging from 380 to 1,400 µS/cm, whereas many others exhibit high salinity. The elevated salinity in some wells may result from the mixing of freshwater, derived from precipitation, with marine clayey salts through rock–water interactions (mineral dissolution). The contribution of mineral dissolution to groundwater salinity is further supported by the hydrogeochemical processes and evolutionary patterns discussed in the previous sections. Thus, the combined interpretation of stable isotope analysis and hydrochemistry effectively distinguishes the sources of salinity in shallow wells and allows for the assessment of the influence of high-salinity creeks and drains on the surrounding shallow aquifers in the Godavari Delta.

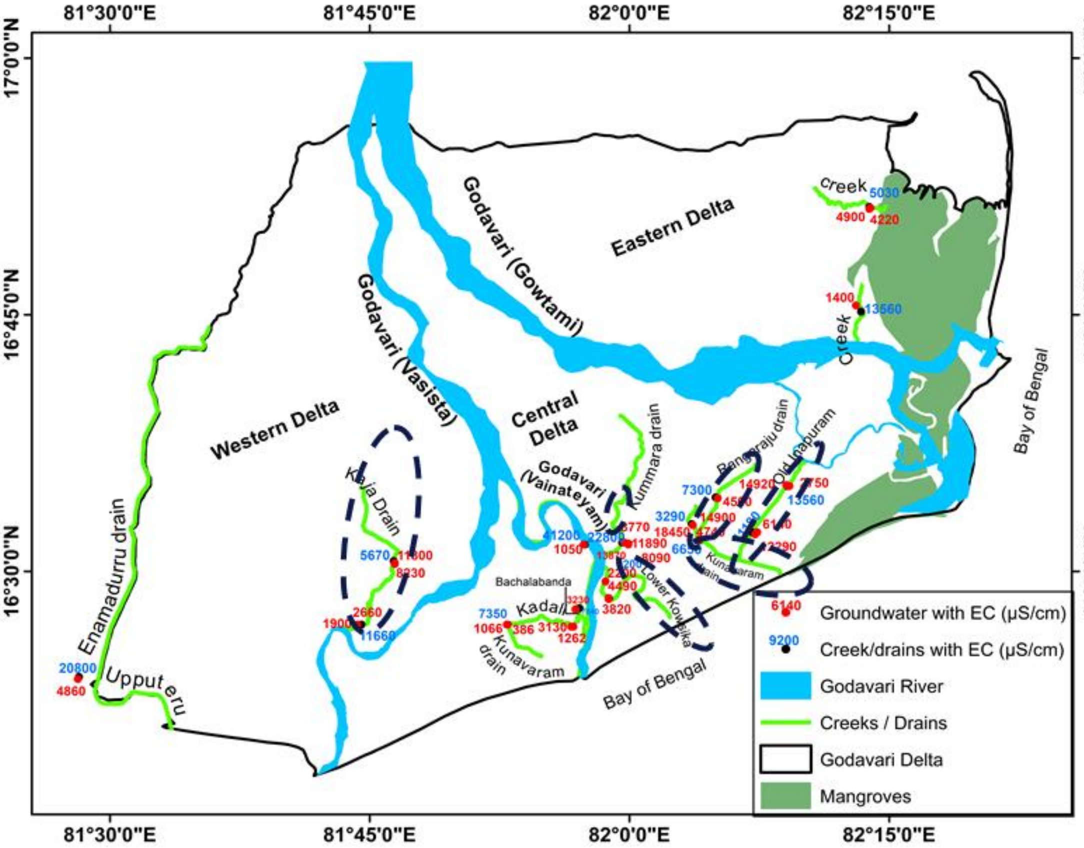

Fig.6.14 Six creeks (marked with dotted circles) influence the nearby shallow groundwater salinity in the Godavari delta

Shallow groundwater in the nine villages namely N. Kottapalli and Katrenikona (at Old Inapuram drain), Kodurupadu (at Kummara drain), Kunavaram and Kithana Cheruvu (at Kunavaram major drain), Mogalamuru (at Lower Kowsika drain), Sannavelli (at Rangaraju drain) and Navarasapuram and Medapadu (at Kaja drain) is unsuitable for drinking due to anthropogenic contamination caused by saline water seepage from the six identified drains/creeks. Therefore, treated surface water supplied through canal systems should be considered as the primary source of drinking water in these villages.

7. SUMMARY AND CONCLUSIONS

High salinity values in the drains monitored by the APPCB in the Godavari delta are observed during months with low rainfall, whereas monsoon rainfall events dilute drain water, resulting in lower salinity. In the pre-monsoon season, elevated salinity is attributed to intense backwater effects and anthropogenic influences. Based on Electrical Conductivity (EC) and salinity measurements from field visits, A total of 116 water samples were collected, comprising 11 creek water samples, 47 drain water samples, 29 shallow groundwater samples (near drains/creeks), 16 canal water samples, 7 backwater samples from Godavari river branches, 3 freshwater river samples, and 3 seawater samples. Of the 11 high-salinity creeks, ten (average EC: 45,136 µS/cm; Salinity: 23.3 ppm) are located in the Eastern and Central deltas, while one is from the Western delta. Drain water, representing a mixture of irrigation return flows and backwater, exhibits lower average values (EC: 3,764 µS/cm; Salinity: 1.53 ppm). Freshwater in the Godavari River is found approximately 50 km from the sea, whereas the influence of backwater extends up to 35 km along the Gowthami, Vainatheyam, and Vasishta river branches.

In the Western delta, mixing of low-salinity backwater with higher irrigation return flows results in relatively lower drain salinity (EC: 3,490 µS/cm; Salinity: 2.3 ppm) compared to the Eastern and Central deltas (EC: 4,314 µS/cm; Salinity: 2.8 ppm). Groundwater in the Western delta shows very high salinity at deeper levels around 115 m (EC: 31,600 µS/cm; Salinity: 22 ppm), while lower salinity values (EC: 5,500–7,800 µS/cm; Salinity: 3.5–4 ppm) are observed near 150 m depth. Except for Kaja drain and Upputeru creek, most drains in the Western delta exhibit low salinity (0.3–2.4 ppt). Overall, the salinity of backwater in creeks and drains is higher in the Eastern and Central deltas compared to the Western delta. The Cl^- vs Cl/HCO_3^- plot confirmed that all creeks are severely affected by seawater intrusion. In the Western delta, Kaja and Upputeru drains show a high degree of seawater influence, whereas the remaining drains are slightly affected. In the Eastern and Central deltas, Peruru drain (CDR9), and Vadabodi drain (CDR11) are highly affected by seawater, while the others show minor influence. The seawater fraction (%) varies widely across the delta, ranging from <1% to 24% in drains and 89–98% in creeks. The highest seawater fractions are observed in Peruru drain (CDR9: 24%), Vadabodi drain (CDR11: 24%), and Kaja drain (WDR49: 20%), whereas the lowest fractions (<1%) are found in Teki drain (EDR22), Yenamaduru drain (WDR37), and South drain (WDR44). In the Western delta, 18 drains exhibit low seawater fractions in the range of 0.3–6%.

Stable isotope analysis indicates that the creeks and backwater in the Godavari River (20 km from the seacoast) exhibit highly enriched isotopic signatures, suggesting evaporation effects due to the long residence time of backwater in the creeks. Dilution of backwater in drains also leads to enriched isotopic values.

Thirteen shallow groundwater samples near six creeks/drains namely Old Inapuram drain (at N. Kottapalli and Katrenikona), Kummara drain (at Kodurupadu), Kunavaram major drain (at Kunavaram, Kithana Cheruvu), Lower Kowsika drain (at Mogalamuru), Rangaraju drain (at Sannavelli), and Kaja drain (at Navarasapuram and Medapadu), display enriched isotopic signatures and EC values ranging from 3700 to 18000 µS/cm, indicating that saline backwater from these drains is influencing the surrounding shallow groundwater. Anthropogenic contamination resulting from saline water seepage from these six drains/creeks has rendered the shallow groundwater unsuitable for drinking purposes in nine villages, namely N. Kottapalli, Katrenikona, Kodurupadu, Kunavaram, Kithana Cheruvu, Mogalamuru, Sannavelli, Navarasapuram, and Medapadu. Hence, treated surface water supplied through canal systems may be adopted as the primary drinking water source for these villages. The remaining sixteen shallow wells, with EC values of 380–12000 µS/cm, show depleted isotopic signatures. Their high salinity is likely caused by the mixing of freshwater (from precipitation) with marine clayey salts through rock–water interactions and mineral dissolution. Overall, the combination of stable isotope analysis and hydrochemical data effectively distinguishes the sources of salinity in shallow wells and identifies the impact of creeks and drains on the surrounding shallow aquifer in the Godavari delta.

8. WAY FORWARD / SCOPE FOR FURTHER WORK

Anthropogenic contamination resulting from saline water seepage from the six drains/creeks has rendered the shallow groundwater unsuitable for drinking purposes in nine villages, namely N. Kottapalli and Katrenikona (at Old Inapuram drain), Kodurupadu (at Kummara drain), Kunavaram and Kithana Cheruvu (at Kunavaram major drain), Mogalamuru (at Lower Kowsika drain), Sannavelli (at Rangaraju drain) and Navarasapuram and Medapadu (at Kaja drain). Hence, treated surface water supplied through canal systems may be adopted as the primary drinking water source for these villages.

Very high salinity has been observed in certain creeks, particularly the Shakkaraguptham major drain. The potential seepage of saline water from these creeks into the shallow aquifer system needs to be systematically investigated along the entire course of the drains as a pilot study to delineate the extent and pathways of salinity intrusion.

Further work is required to operate tidal gates to control backwater from the Bay of Bengal by incorporating sea level rise.

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REFERRED LETTER FROM END-USER AGENCY

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ANNEXURES

 **Interaction with DE of Drainage Division, Central Godavari Delta on drainage network and local Salinity issues**	 **Sample Collection at Peruru drain**
 **Salinity measurement at Gowthami Godavari, Yanam**	 **Kaja drain, Navarasapuram**
 **Interaction with local farmers on salinity in Upputeru creek**	 **In-situ salinity measurements in the field**

Water sample collection from the handpumps nearby creeks

Sample collection from the creek, Matlapalem

Backwater in Vainatheyam Godavari, Pasarlapudi

Sample Collection at drain, Desakodu

PUBLICATIONS FROM THE STUDY

SOFTWARES / DATA USED IN THE STUDY

(1) Historical salinity data of Andhra Pradesh Pollution Control Board (APPCB)
(2) Hydrochemistry data of creeks/drains and shallow groundwater
(3) Stable Isotopes ($\delta^{18}O$, $\delta^{2}H$) data of creeks/drains and shallow groundwater

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