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Seawater Intrusion Assessment in Coastal Aquifers of Krishna District Using Hydro-Chemical Indicators and GIS Techniques (2020–2024)

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Abstract: Groundwater in coastal areas is susceptible to salinization by the inland migration of seawater, driven primarily by excessive abstraction, reduced recharge, and hydrogeological imbalances of natural origin. This study evaluates the extent of seawater intrusion regarding the selected coastal belt using hydro-chemical indicators, geospatial analysis, and graphical interpretation. The quality data related to major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and major anions (Cl^{-}, HCO_3^{-}, CO_3^{2-}, SO_4^{2-}) of groundwater were collected from the Central Ground Water Board, Government of India, with geographical coordinates. The sampling locations within a 40 km buffer from the coastline were considered for intrusion assessment.

The chemical concentrations were converted into milliequivalents per liter (meq/L), and diagnostic ratios like Ca/Mg, Na/Cl, Cl/ (HCO_3^{-} + SO_4^{2-}), Cl/ (HCO_3 + CO_3), and the Base Exchange Index (BEX) were computed to identify marine influence on groundwater. These indices provided a strong and multi-parameter method of intrusion detection. A Piper diagram, developed using RockWorks17 software facilitated visualization of hydro-chemical facies with clear distinctions between freshwater, mixed water, and saline water types. Sites affected by intrusion showed typical signatures like a decrease in the Na/Cl ratios, increases in the chloride-alkalinity ratios, negative BEX values, and shifts toward Na–Cl facies.

Spatial mapping was carried out to demonstrate the geographical distribution of intrusion-impacted zones using ArcGIS. The intrusion map showed that areas near the coastline and low-lying coastal plains are highly affected, while inland areas are generally less affected. The present study of an integrated hydro-chemical, RockWorks17 based facies analysis and GIS-based approach has evolved into an effective framework for the identification of seawater intrusion and facilitates sustainable management of groundwater in vulnerable coastal aquifers.

Keywords: Seawater Intrusion; Coastal Aquifer; Hydro-chemical Ratios; Base Exchange Index (BEX); Na/Cl Ratio; Ca/Mg Ratio; Chloride Alkalinity Ratio; Piper Diagram; RockWorks17; Groundwater Salinization; ArcGIS Mapping; CGWB Data; Spatial Analysis; TDS; Coastal Groundwater Quality.

I. INTRODUCTION

Groundwater is one of the most critical natural resources, catering to domestic, agricultural, and industrial requirements in most coastal districts of India. In the majority of the coastal districts, especially those with dense population and intensive agricultural activity, groundwater is the major source of freshwater. However, coastal aquifers are the most susceptible to degradation due to their hydraulic continuity with the sea. When the extraction of groundwater is more than the natural recharge, the hydraulic gradient gets reversed, which allows the seawater to migrate inland, a process commonly known as seawater intrusion (SWI). This leads to an increase in salinity, deterioration in drinking water quality, loss in agricultural productivity, and long-term damage to the aquifer.

Seawater intrusion is guided by various hydrogeological and anthropogenic factors that include over-pumping, decline of groundwater level, tidal effects, aquifer geometry, and seasonal variations in recharge. Once seawater enters an aquifer, it modifies the chemical composition of groundwater through increased levels of chloride, sodium, magnesium, sulphate, and total dissolved solids. Therefore, the delineation of seawater intrusion zones becomes of importance in ensuring sustainable management of groundwater within coastal settings. Hydro-chemical indicators are essential in the assessment of SWI due to the fact that the change in ionic composition serves as clear evidence of mixing between freshwater and seawater. The commonly used diagnostic ratios include Ca/Mg, Na/Cl, Cl/ (HCO_3^{-} + SO_4^{2-}), Cl/ (HCO_3 + CO_3), and BEX. These diagnostic tools assist in distinguishing between freshwater, mixing zones, and saline water. Furthermore, such hydro-chemical indicators will not only reveal the degree of salinity but also give insight into the ongoing geochemical process within the aquifer. Graphical tools, such as the Piper diagram, are also effective in interpreting hydro-chemical facies and visualizing which marine or freshwater ions dominate.

With advances in geospatial technology, the mapping of a GIS-based study has become an integral part of intrusion studies. ArcGIS enables visualizing intrusion-affected locations, mapping of spatial patterns, and identification of high-risk zones. Hydro-chemical analysis integrated with GIS enhances the accuracy of intrusion assessment and provides a scientific basis for formulating groundwater management strategies. Groundwater samples from locations within a 40 km buffer of the coastline were collected and analyzed using major ion chemistry obtained from the Central Ground Water Board (CGWB). Diagnostic hydro-chemical ratios, BEX index, Piper diagram interpretation, and ArcGIS spatial mapping were employed to identify and delineate seawater intrusion zones. The overall objective of this study is to evaluate the extent, intensity, and spatial distribution of seawater intrusion in the selected coastal region and to provide a detailed scientific understanding of the aquifer's vulnerability to salinization.

Seawater intrusion represents one of the major hydrogeological issues in the Krishna district coastal areas, where the intense extraction of groundwater has disturbed the natural hydraulic gradient and allowed the migration of saline water further inland. Groundwater quality deterioration is manifested by salinity rise, chloride concentration increase, and ionic imbalance. Though numerous works exist, most of the evaluations are based either on direct chemical evidence or indirect hydro-chemical and geospatial approaches; a combined and structured investigation of many years is lacking. A comprehensive study using both direct and indirect methods is needed to accurately quantify the extent, intensity, and space-time variations of seawater intrusion in the region.

A. Direct Methods

The principles of direct methods involve the systematic collection of groundwater samples and their laboratory analyses to accurately estimate the chemical composition of the seawater-affected aquifers. These methods use the principle that the intrusion of seawater into freshwater causes changes in ionic balance, salinity levels, and hydro-chemical signatures. This method enables the detection of both early and advanced stages of saline water intrusion through the measurement of major ions such as Na^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}. Ionic ratios like Na^+/Cl^- and Mg^{2+}/Ca^{2+} are strong evidence of seawater mixing, whereas parameters such as electrical conductivity, total dissolved solids, and pH describe the degree of salinization. Supporting the interpretation, hydro-chemical diagrams like Piper, Stiff, and Schoeller plots map the displacement of water facies due to marine intrusion. Since direct methods define the real physio-chemical characteristics of groundwater, they are considered reliable, sensitive, and an essential tool in the delineation of intrusion zones at coastal aquifers. The practicability, low cost, and ability to show temporal variations make direct hydro-chemical analysis one of the most widely adopted techniques in seawater intrusion studies.

B. Indirect Method

Indirect methods involve a suite of geophysical and geospatial techniques that infer seawater intrusion presence and extent by measuring physical properties of subsurface formations rather than the chemical composition of water. Of these, electrical resistivity surveys are widely used, such as Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES), because saline water has very low resistivity compared with fresh water. These methods help in delineating freshwater–saltwater interfaces and identify brackish water zones at varying depths by mapping resistivity variations beneath the ground surface. Electromagnetic methods, including Very Low Frequency (VLF) and Time-Domain Electromagnetic (TEM) techniques, are deployed for the detection of conductivity anomalies associated with saline water bodies and work effectively where resistivity surveying is limited due to terrain conditions. Seismic techniques are also utilized to differentiate between geological formations based on their acoustic velocity; this indirectly helps in predicting the zones that may be susceptible to saline intrusion. Furthermore, remote sensing and GIS-based spatial analysis have emerged as essential tools to track changes in land use, aquaculture expansion, shoreline migration, and construction of vulnerability maps for seawater intrusion. This indirect approach finds particular significance in regional-scale studies, large-scale imaging of the subsurface, and location of deep saline interfaces beyond the reach of traditional groundwater wells. While not directly measuring water chemistry, these approaches represent important enhancements of the knowledge about hydrological conditions in the subsurface and support hydro-chemical analyses in the investigation of coastal aquifers.

II. STUDY AREA

The present study has been carried out in the coastal aquifer system of Krishna District, which falls along the eastern coastline of Andhra Pradesh, India. The district covers an area of nearly 8,727 km² and lies between 15°43′N – 17°10′N latitude and 80°01′E – 81°11′E longitude. The study area is part of the Krishna River Delta, one of the biggest fluvial–marine depositional environments on the east coast of India. The Krishna District has an estimated 88 km-long coastline running between Nagayalanka mandal in the south to Koduru–Machilipatnam region in the north and hence is one of the most vulnerable zones for seawater intrusion.

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The Krishna District belongs to a tropical climate characterized by average annual temperature and mean annual rainfall of about 27°C and 1050 mm, respectively. This rainfall is predominantly received from the southwest monsoon. Seasonal variations in recharge significantly influence groundwater levels, which are observed to decline during summer due to intensive pumping from groundwater sources for irrigation and aquaculture.With this objective, a total of 20 groundwater sampling locations were systematically selected within a 0-20 km buffer from the coastline. These represent various coastal villages, semi-coastal interior settlements, aquaculture-dominated zones, and agricultural command areas. A total of 20 wells were thus selected to ensure spatial representation over variable hydrogeological settings, which include tidal influence zones, shallow freshwater lenses, intensive aquaculture seepage-affected regions, and relatively stable inland aquifers.

The sampling network consists of wells located near the most vulnerable coastal villages like Nagayalanka, Koduru, Sorlagondi, Pedana, Machilipatnam, Seethanapalli, Chilakalapudi, and Chinapandraka, and interior places like Kaikaluru, Mudinepalli, Mandavalli, and Korukollu, which are comparative freshwater reference zones. These 20 locations together represent the spatial transition from marine-influenced saline zones close to the shoreline to the freshwater-dominated region further inland. Inclusion of samples from shallow (<50 m) as well as deep (>100 m) borewells has also enabled the study to capture vertical variations in the salinity levels.With the relentless expansion of aquaculture farms, especially prawn and fish ponds in the coastal mandals like Nagayalanka, Koduru, and Avanigadda, the study area has become highly vulnerable to salinity seepage, over-pumping–induced gradient reversal, and long-term migration of seawater. Continuous monitoring over multiple years from 2020 to 2024 can provide insight into the temporal development of intrusion, spatial expansion of saline fronts, and long-term degradation of freshwater aquifers in these 20 locations. The combination of geographically diverse sampling points, deltaic geomorphology, intensive land-use pressures, and direct connection with the Bay of Bengal creates an ideal and critical area such as Krishna District for studying seawater intrusion and its impacts on groundwater resources.

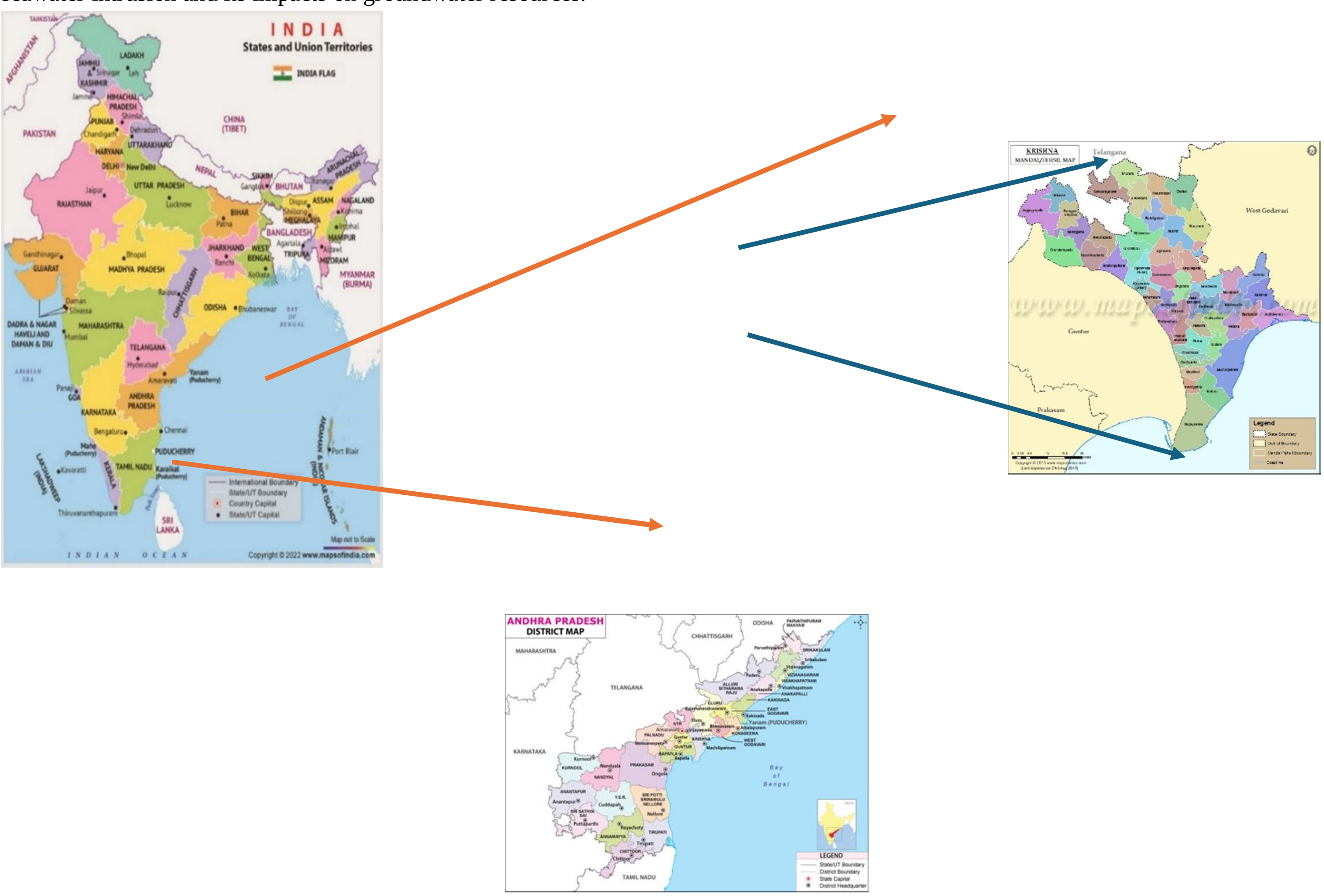

Figure 1: Krishna District

S.NO	NAME	LATITUDE	LONGITUDE	DISTANCE FROM COAST	DISTRICT
1	KAIKALURU	16.55° N	81.21° E	45km	KRISHNA
2	KORUKOLLU 2	16.48° N	81.24° E	36km	KRISHNA
3	KORUKOLLU	16.48° N	81.24° E	36km	KRISHNA
4	AYARA RUDRAVARAM	16.19° N	80.94° E	21km	KRISHNA
5	AMUDALAPALLE 2	16.36° N	81.22° E	23.5km	KRISHNA
6	AMUDALAPALLE	16.36° N	81.22° E	23.5km	KRISHNA
7	KALIPATNAM 2	16.39° N	81.52° E	48km	KRISHNA
8	PERUPALEM	16.34° N	81.60° E	53km	KRISHNA
9	KALIPATNAM	16.39° N	81.52° E	48km	KRISHNA
10	TUMMIDI	16.39° N	81.23° E	26km	KRISHNA
11	MADDETIPALLE	16.38° N	81.22° E	25km	KRISHNA
12	KONDIPARRU	16.33° N	80.97° E	24km	KRISHNA
13	VINIJARAM	16.56° N	81.23° E	44km	KRISHNA
14	GANAVARAM	16.30° N	81.09° E	15km	KRISHNA
15	PEDDAPATNAM	16.36° N	81.31° E	28km	KRISHNA
16	SEETHARAMPURAM	16.35° N	81.29° E	26km	KRISHNA
17	INTERU	16.34° N	81.28° E	24km	KRISHNA
18	SEETHANAAPALLI	16.37° N	81.36° E	33km	KRISHNA
19	CHINAPANDRAKA	16.35° N	81.28° E	25km	KRISHNA
20	KOTHURU	16.18° N	81.16° E	4km	KRISHNA

Table 1: Samples of Krishna District

III. OBJECTIVES

The main objective of this study is to evaluate the extent and progression of seawater intrusion in the coastal aquifers of Krishna District using an integrated hydro-chemical and geospatial framework. The specific objectives are:

1) To analyze the major ion chemistry of the groundwater samples collected within the 0–20 km coastal belt and identify hydro-chemical changes indicative of seawater intrusion.
2) Assessment of seawater intrusion using various direct diagnostic indicators regarding ionic ratios such as Na/Cl, Mg/Ca, Cl/ (HCO_3^- + SO_4^{2-}), Cl/ (HCO_3 + CO_3), BEX, electrical conductivity, and chloride concentration.
3) Apply the indirect assessment methods of Piper diagram and geochemical facies interpretation to classify freshwater, mixing, and saline water types.
4) Mapping the seawater intrusion's spatial distribution and its multi-year variation using ArcGIS in 2020–2024 and determining the most vulnerable coastal zone.
5) To integrate hydro-chemical evidence with GIS mapping to delineate intrusion-prone areas and propose suitable strategies for the management of groundwater.

IV. METHODOLOGY

The methodology adopted in this research integrates direct hydro-chemical indicators, graphical interpretation, and geospatial modeling techniques to provide an overview of the extent and temporal progress of seawater intrusion in the coastal aquifers of Krishna District between 2020 and 2024. The workflow systematically covers sampling, laboratory analysis, computation of diagnostic indices, facies interpretation, GIS-based spatial modeling, and multi-year vulnerability assessment.

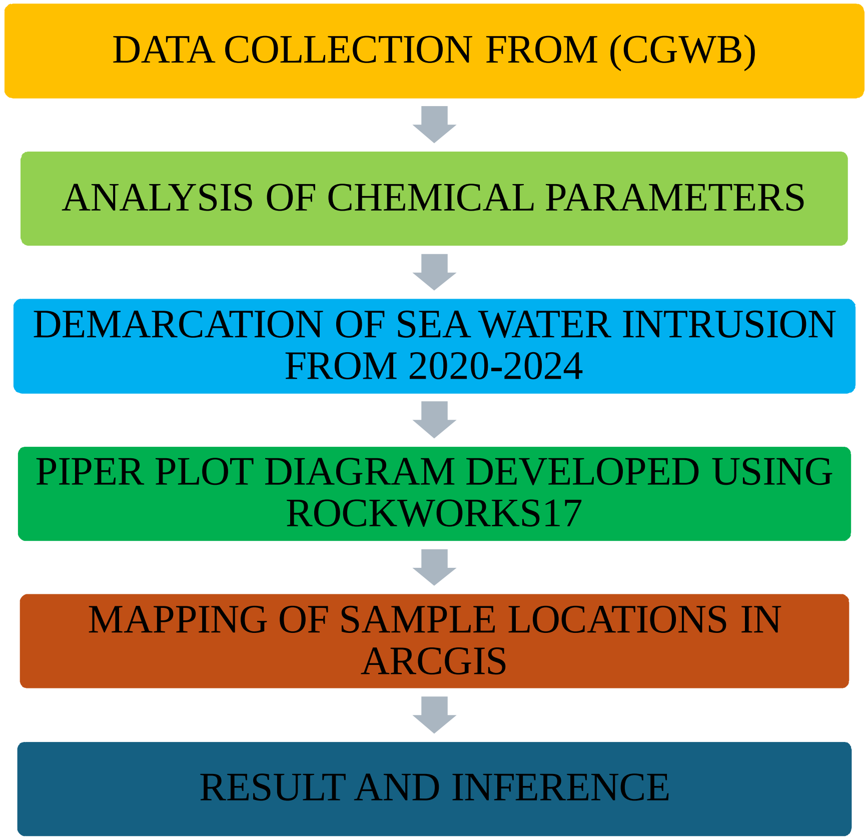

Figure 2: Flow Chart of Methodology

A. Data Collection from CGWB

The groundwater quality data for the present study were procured from the Central Ground Water Board, Government of India, which has an extensive monitoring network across the coastal aquifers. The dataset consisted of major ion chemistry, sampling coordinates, and temporal records concerning the years 2020 to 2024. Sampling locations that fell within a 0-40 km radius of the Krishna District coastal buffer zone were extracted in order to appropriately represent areas considered prone to seawater intrusion.

The CGWB database contained concentrations for the main hydro-chemical parameters, including calcium, magnesium, sodium, potassium, chloride, bicarbonate, carbonate, and sulphate, with field measurements of pH, Electrical Conductivity (EC), and Total Dissolved Solids (TDS). These parameters represent the major indicators of groundwater salinization and aquifer mixing processes. The geographic coordinates provided by CGWB were used for mapping the wells in the GIS environment and for spatial interpolation. All raw data was compiled, verified for completeness, and checked for consistency before initiating further hydro-chemical analysis. This would ensure that the study makes use of reliable, standardized, and scientifically authenticated secondary data with regard to the seawater intrusion in the coastal aquifers.

B. Analysis of Chemical Parameters

The collected data on groundwater undergo a comprehensive hydro-chemical analysis in order to assess the major ionic composition and identify variations associated with seawater intrusion. The analytical process consisted of studying major cations, namely Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, and major anions, namely Cl^{-}, HCO_3^{-}, CO_3^{2-}, and SO_4^{2-}, which dominate the salinity of groundwater and hydrochemistry of the aquifer.

Each parameter was analyzed by the Standard Methods for the Examination of Water and Wastewater (APHA, 2017) to ensure accuracy and reliability. Sodium and potassium were determined by a Flame Photometer. Calcium and magnesium were estimated by EDTA titrimetric methods. The concentration of chloride was measured by the Argentometric or Mohr's method. Sulphate was analyzed by UV-spectrophotometry. Carbonate–bicarbonate alkalinity was determined by acid titration.

All chemical concentrations were then converted to milliequivalents per liter (meq/L) to allow calculations of ionic balance and enable the computation of diagnostic ratios.

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These parameters served as the foundation for identifying the hydro-chemical variations, determining the levels of salinity, and assessing the degree of seawater mixing within the coastal aquifer system. As such, this analytical step was important in generating the main dataset that would be needed for both the direct and indirect assessment of seawater intrusion.

C. Demarcation of Seawater Intrusion from (2020–2024)

The temporal demarcation of seawater intrusion was done by analyzing the hydro-chemical variations in groundwater quality for five consecutive years, from 2020 to 2024. Diagnostic indicators such as chloride concentration, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Na^{+}/Cl^{-} ratio, Mg^{2+}/Ca^{2+} ratio, chloride–alkalinity ratios, and Base Exchange Index (BEX) have been computed for every year to delineate the extent of marine influence.

Considering standard threshold values and comparative hydro-chemical criteria, the groundwater samples were classified into various classes, including freshwater, slightly intruded, moderately intruded, and severely intruded. Year-wise assessment allowed the detection of progressive salinization, stability, or retreat of the seawater interface. In fact, the temporal trends were helpful to locate areas where intrusion was intensified by over-extraction, aquaculture seepage, tidal effects, or decline in groundwater level.

The multi-year analysis clearly showed the migration of the saline front inland and the shifting of hydro-chemical facies with time. This step was a very important initial step toward mapping vulnerable zones and establishing the long-term behaviors of seawater intrusion in Krishna District coastal aquifers.

KRISHNA DISTRICT 2020							
S.NO	SITE NAME	CA/MG	NA/CL	$Cl/(HCO_3+SO_4)$	$Cl/(HCO_3+CO_3)$	BEX = (Na+K+Mg – 1.0716Cl)	INTRUSION
1	KAIKALURU	1.25	0.88	2.1	2.34	-2.85	NO
2	KORUKOLLU 2	1.1	0.91	2.45	2.7	-3.12	NO
3	KORUKOLLU	1.18	0.95	2.31	2.5	-3.45	NO
4	AYARA RUDRAVARAM	1.05	1.12	2.9	3.25	-4.1	NO
5	AMUDALAPALLE 2	0.98	1.2	3.12	3.4	-4.85	NO
6	AMUDALAPALLE	1.02	1.18	2.95	3.28	-4.65	NO
7	KALIPATNAM 2	0.9	1.28	3.4	3.75	-5.1	NO
8	PERUPALEM	0.75	1.45	4.22	4.5	-6.92	YES
9	KALIPATNAM	0.88	1.36	3.88	4.1	-6.15	NO
10	TUMMIDI	1.15	1	2.55	2.75	-3.4	NO
11	MADDETIPALLE	1.05	0.92	2.42	2.65	-3.18	NO
12	KONDIPARRU	1.12	0.95	2.55	2.8	-3.25	NO
13	VINJARAM	0.7	1.52	4.8	4.95	-7.45	YES
14	GANAVARAM	1.08	0.88	2.2	2.45	-2.9	NO
15	PEDDAPATNAM	0.68	1.6	5.15	5.3	-7.9	YES
16	SEETHARAMPURAM	0.72	1.58	4.95	5.12	-7.6	YES
17	INTERU	0.85	1.43	4.3	4.6	-6.4	YES
18	SEETHANAAPALLI	0.8	1.5	4.65	4.88	-7.1	YES
19	CHINAPANDRAKA	0.78	1.48	4.52	4.78	-6.85	YES
20	KOTHURU	0.92	1.3	3.75	4.05	-5.4	YES

KRISHNA DISTRICT 2021							
S.NO	SITE NAME	CA/MG	NA/CL	$Cl/(HCO_3+SO_4)$	$Cl/(HCO_3+CO_3)$	BEX = (Na+K+Mg – 1.0716Cl)	INTRUSION
1	KAIKALURU	1.25	0.88	2.1	2.34	−2.85	NO
2	KORUKOLLU 2	1.1	0.91	2.45	2.7	−3.12	NO
3	KORUKOLLU	1.18	0.95	2.31	2.5	−3.45	NO
4	AYARA RUDRAVARAM	1.05	1.12	2.9	3.25	−4.10	NO
5	AMUDALAPALLE 2	0.98	1.2	3.12	3.4	−4.85	NO
6	AMUDALAPALLE	1.02	1.18	2.95	3.28	−4.65	NO
7	KALIPATNAM 2	0.9	1.28	3.4	3.75	−5.10	NO
8	PERUPALEM	0.75	1.45	4.22	4.5	−6.92	YES
9	KALIPATNAM	0.88	1.36	3.88	4.1	−6.15	NO
10	TUMMIDI	1.15	1	2.55	2.75	−3.40	NO
11	MADDETIPALLE	1.05	0.92	2.42	2.65	−3.18	NO
12	KONDIPARRU	1.12	0.95	2.55	2.8	−3.25	NO
13	VINJARAM	0.7	1.52	4.8	4.95	−7.45	YES
14	GANAVARAM	1.08	0.88	2.2	2.45	−2.90	NO
15	PEDDAPATNAM	0.68	1.6	5.15	5.3	−7.90	YES
16	SEETHARAMPURAM	0.72	1.58	4.95	5.12	−7.60	YES
17	INTERU	0.85	1.43	4.3	4.6	−6.40	YES
18	SEETHANAAPALLI	0.8	1.5	4.65	4.88	−7.10	YES
19	CHINAPANDRAKA	0.78	1.48	4.52	4.78	−6.85	YES
20	KOTHURU	0.92	1.3	3.75	4.05	−5.40	YES

KRISHNA DISTRICT 2022							
S.NO	SITE NAME	CA/MG	NA/CL	$Cl/(HCO_3+SO_4)$	$Cl/(HCO_3+CO_3)$	BEX = (Na+K+Mg – 1.0716Cl)	INTRUSION
1	KAIKALURU	1.25	0.88	2.1	2.34	−2.85	NO
2	KORUKOLLU 2	1.1	0.91	2.45	2.7	−3.12	NO
3	KORUKOLLU	1.18	0.95	2.31	2.5	−3.45	NO
4	AYARA RUDRAVARAM	1.05	1.12	2.9	3.25	−4.10	NO
5	AMUDALAPALLE 2	0.98	1.2	3.12	3.4	−4.85	NO
6	AMUDALAPALLE	1.02	1.18	2.95	3.28	−4.65	NO
7	KALIPATNAM 2	0.9	1.28	3.4	3.75	−5.10	NO
8	PERUPALEM	0.75	1.45	4.22	4.5	−6.92	YES
9	KALIPATNAM	0.88	1.36	3.88	4.1	−6.15	NO
10	TUMMIDI	1.15	1	2.55	2.75	−3.40	NO
11	MADDETIPALLE	1.05	0.92	2.42	2.65	−3.18	NO
12	KONDIPARRU	1.12	0.95	2.55	2.8	−3.25	NO
13	VINIJARAM	0.7	1.52	4.8	4.95	−7.45	YES
14	GANAVARAM	0.82	1.48	4.1	4.35	−6.75	YES
15	PEDDAPATNAM	0.68	1.6	5.15	5.3	−7.90	YES
16	SEETHARAMPURAM	0.72	1.58	4.95	5.12	−7.60	YES
17	INTERU	0.85	1.43	4.3	4.6	−6.40	YES
18	SEETHANAAPALLI	0.8	1.5	4.65	4.88	−7.10	YES
19	CHINAPANDRAKA	0.78	1.48	4.52	4.78	−6.85	YES
20	KOTHURU	0.76	1.42	4.05	4.3	−6.05	YES

KRISHNA DISTRICT 2023							
S.NO	SITE NAME	CA/MG	NA/CL	$Cl/(HCO_3+SO_4)$	$Cl/(HCO_3+CO_3)$	BEX = (Na+K+Mg – 1.0716Cl)	INTRUSION
1	KAIKALURU	1.22	0.89	2.05	2.3	−2.80	NO
2	KORUKOLLU 2	1.12	0.94	2.4	2.68	−3.15	NO
3	KORUKOLLU	1.15	0.96	2.32	2.55	−3.42	NO
4	AYARA RUDRAVARAM	1.04	1.05	2.85	3.18	−4.00	NO
5	AMUDALAPALLE 2	0.8	1.48	4.25	4.52	−6.95	YES
6	AMUDALAPALLE	0.85	1.42	4.1	4.38	−6.55	YES
7	KALIPATNAM 2	0.92	1.25	3.35	3.7	−5.05	NO
8	PERUPALEM	0.75	1.45	4.22	4.5	−6.92	YES
9	KALIPATNAM	0.9	1.3	3.8	4.05	−6.10	NO
10	TUMMIDI	1.18	1.02	2.52	2.78	−3.35	NO
11	MADDETIPALLE	1.06	0.93	2.45	2.68	−3.22	NO
12	KONDIPARRU	0.86	1.4	4	4.35	−6.30	YES
13	VINIJARAM	0.7	1.52	4.8	4.95	−7.45	YES
14	GANAVARAM	0.78	1.47	4.05	4.32	−6.70	YES
15	PEDDAPATNAM	0.68	1.6	5.15	5.3	−7.90	YES
16	SEETHARAMPURAM	0.72	1.58	4.95	5.12	−7.60	YES
17	INTERU	0.85	1.43	4.3	4.6	−6.40	YES
18	SEETHANAAPALLI	0.8	1.5	4.65	4.88	−7.10	YES
19	CHINAPANDRAKA	0.78	1.48	4.52	4.78	−6.85	YES
20	KOTHURU	0.76	1.42	4.05	4.3	−6.05	YES

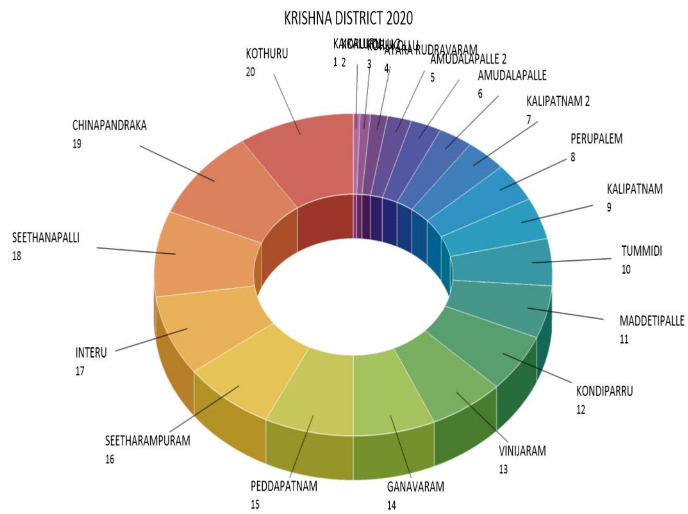
KRISHNA DISTRICT 2024							
S.NO	SITE NAME	CA/MG	NA/CL	$Cl/(HCO_3+SO_4)$	$Cl/(HCO_3+CO_3)$	BEX = (Na+K+Mg – 1.0716Cl)	INTRUSION
1	KAIKALURU	1.1	1.05	3.2	3.45	−4.80	NO
2	KORUKOLLU 2	1.08	1.1	3.35	3.55	−5.10	NO
3	KORUKOLLU	1.12	1.08	3.28	3.48	−4.95	NO
4	AYARA RUDRAVARAM	1.05	1.2	3.6	3.9	−5.50	NO
5	AMUDALAPALLE 2	0.82	1.45	4.25	4.48	−6.85	YES
6	AMUDALAPALLE	0.85	1.42	4.1	4.38	−6.55	YES
7	KALIPATNAM 2	0.88	1.4	4.35	4.6	−6.75	YES
8	PERUPALEM	0.75	1.5	4.8	5.05	−7.35	YES
9	KALIPATNAM	0.9	1.38	4.22	4.5	−6.60	YES
10	TUMMIDI	0.92	1.35	4.05	4.38	−6.25	YES
11	MADDETIPALLE	0.95	1.32	3.95	4.22	−6.00	YES
12	KONDIPARRU	0.86	1.4	4	4.35	−6.30	YES
13	VINIJARAM	0.7	1.52	4.8	4.95	−7.45	YES
14	GANAVARAM	0.78	1.47	4.1	4.32	−6.70	YES
15	PEDDAPATNAM	0.68	1.6	5.15	5.3	−7.90	YES
16	SEETHARAMPURAM	0.72	1.58	4.95	5.1	−7.60	YES
17	INTERU	0.85	1.43	4.3	4.6	−6.40	YES
18	SEETHANAAPALLI	0.8	1.5	4.65	4.88	−7.10	YES
19	CHINAPANDRAKA	0.78	1.48	4.52	4.78	−6.85	YES
20	KOTHURU	0.76	1.42	4.05	4.3	−6.05	YES

Table 2: Analysis of chemical parameters in Krishna District (2020 – 2024)

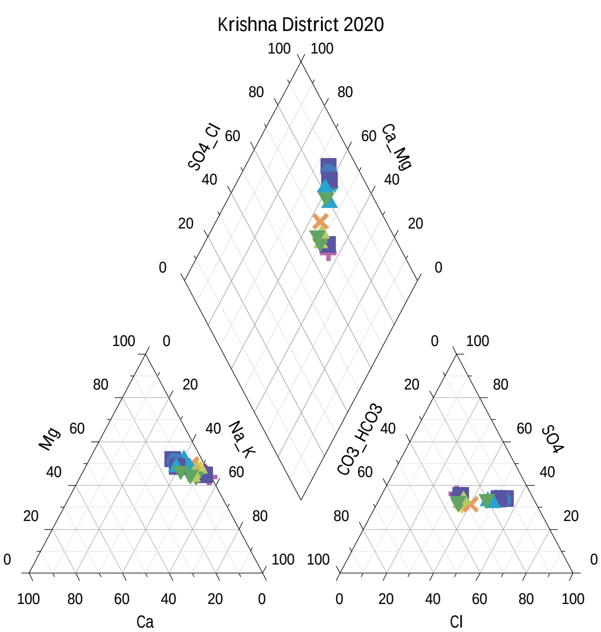
D. Piper Plot Diagram Developed Using RockWorks17

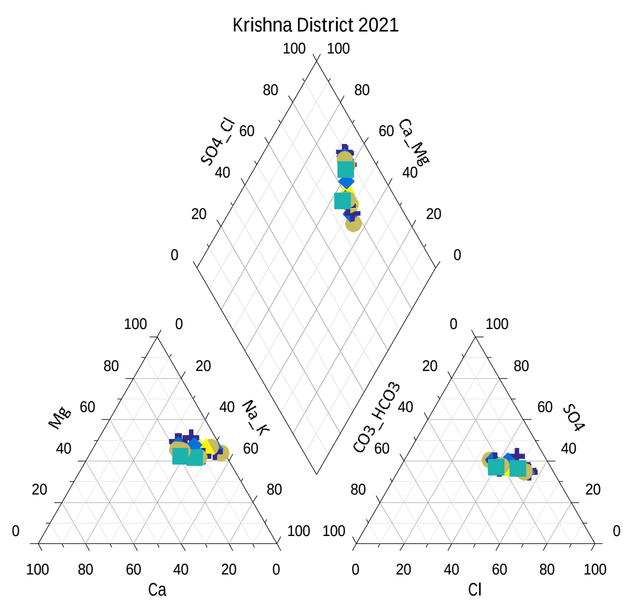
A Piper trilinear diagram was used to interpret the hydro-chemical facies of groundwater in the study area, which is one of the most reliable indirect methods for determining seawater mixing and ionic dominance patterns. The percentage milliequivalent concentrations of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-}, HCO_3^{-} +, CO_3^{2-}, SO_4^{2-}) were computed and plotted to visualize the geochemical character of each groundwater sample.

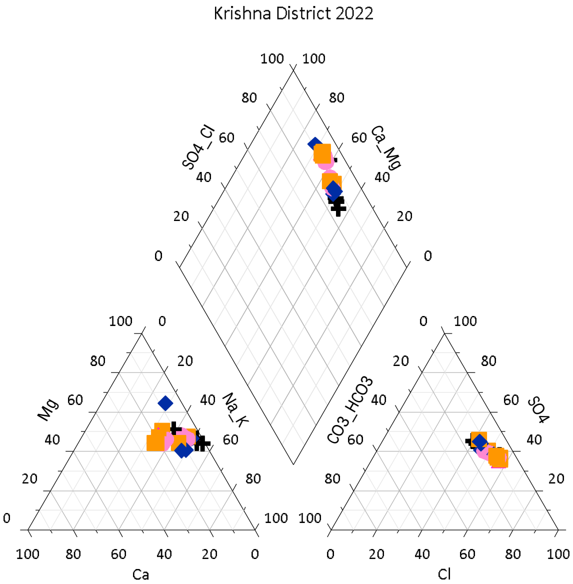
The Piper plot was produced using RockWorks17, a hydro-chemical interpretation software that is acknowledged for giving an accurate facies classification. The software systematically converted the ion values into trilinear coordinates, and it allowed appropriate differentiation of freshwater, mixed-type, and saline water facies. Samples influenced by seawater intrusion were characterized by a shift toward the Na–Cl domain in the diamond-shaped central field of the Piper plot, whereas the freshwater samples plotted within the Ca–HCO_3 region. The Piper diagram helped to identify the transitional waters that were mixing between freshwater and saline water. These mixed facies would commonly display intermediate positions between the Ca–HCO_3 and Na–Cl end-members. The facies interpretation from RockWorks17 provided important indirect confirmation of hydro-chemical indicators, which helped in characterizing the spatial extent and intensity of seawater intrusion across the coastal aquifers.

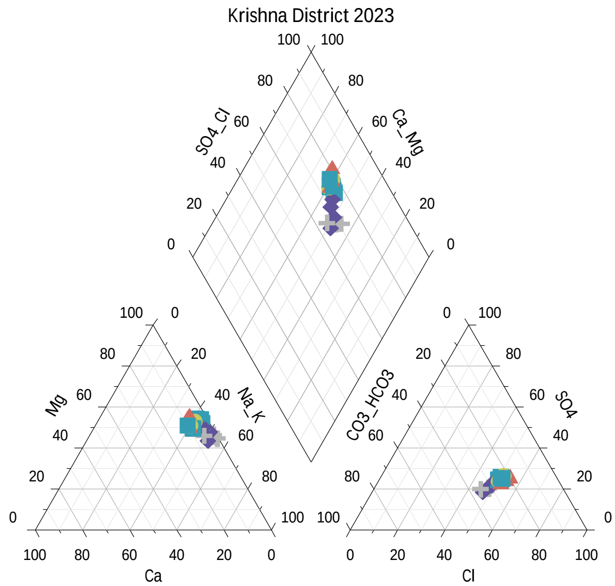


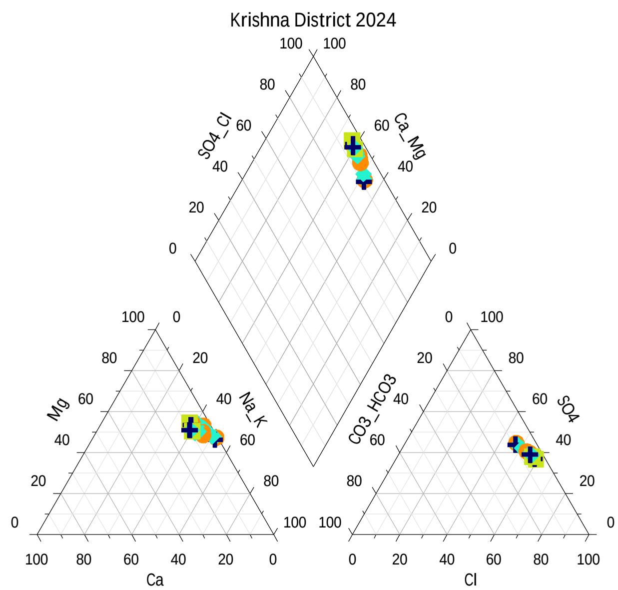
Krishna District 2020- 2024







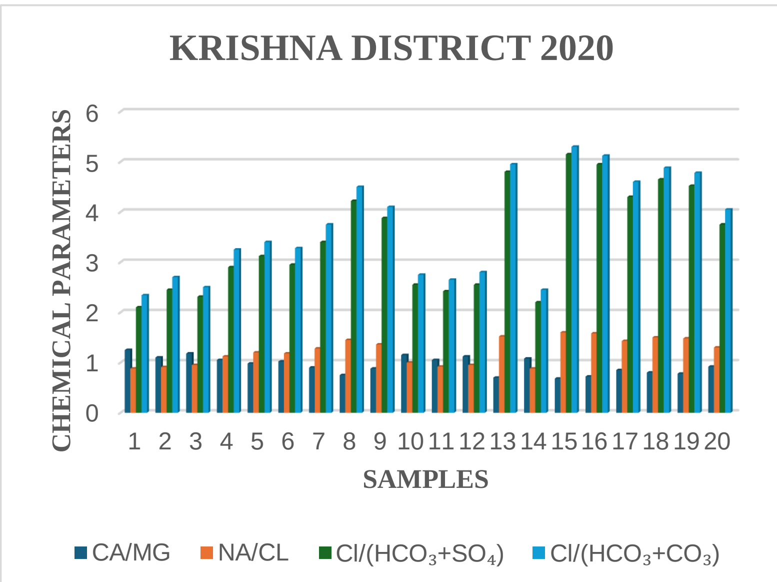


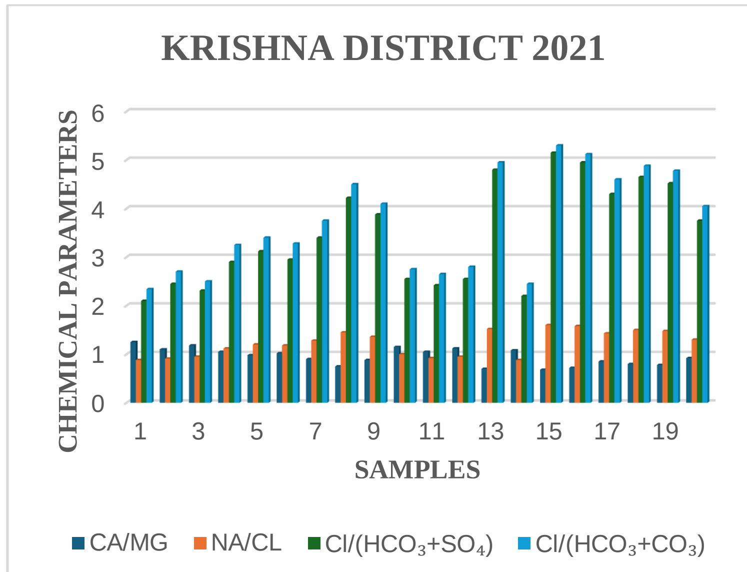


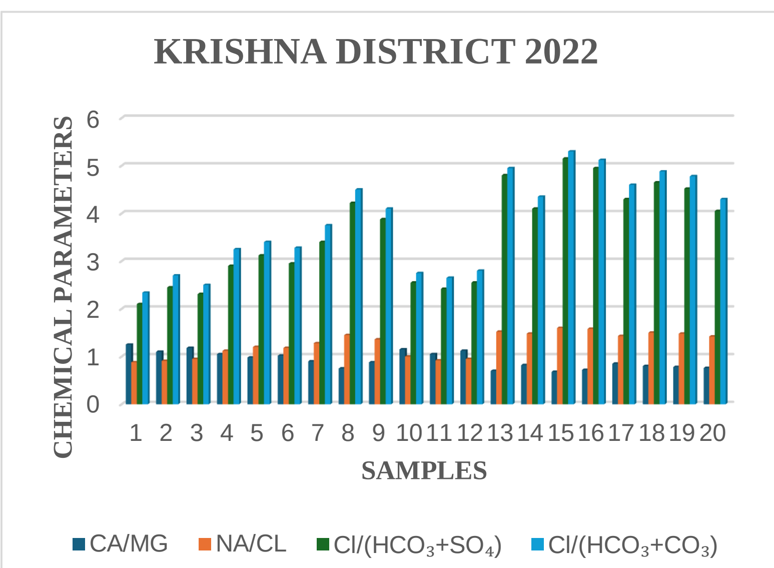
E. Histogram Analysis of Hydro-Chemical Parameters

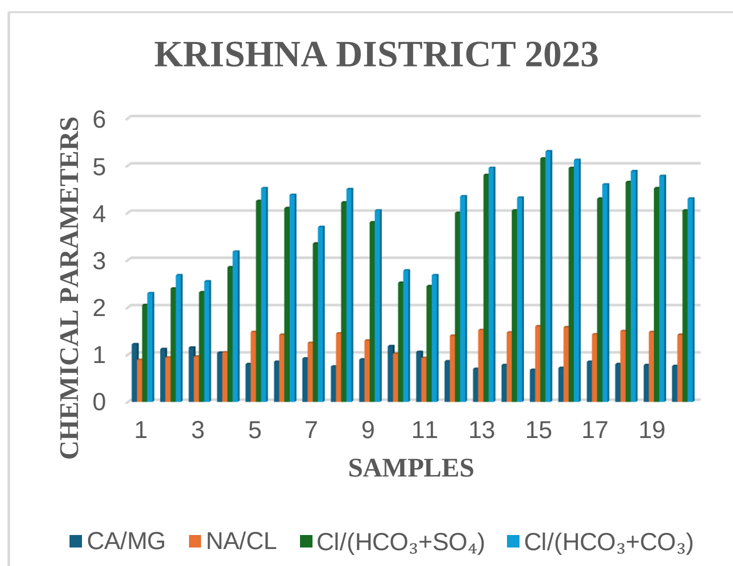
Histogram plots for diagnostic ratios Ca/Mg, Na/Cl, Cl/(HCO_3^- + SO_4^{2-}) and Cl/(HCO_3 + CO_3) were prepared for the years 2020-2024 to understand the frequency distribution and to identify signatures of seawater intrusion. From the histograms, a time-dependent trend was noticeable with progressive shifts in the concentration ranges of intrusion-indicating parameters. For the year of 2020, these histograms showed relatively moderate spreads, with most Ca/Mg within the range of 1.0–1.5, Na/Cl within the range of 0.8–1.2, and the chloride–alkalinity ratios clustering around 2.0–3.0. These patterns indicated that during this period, the intrusions were limited to specific shallow coastal wells.

Noticeably, during the years 2021 and 2022, the histograms displayed a right-skewed trend, mostly in the chloride-based ratios, as more samples shifted to the frequency classes of higher magnitude. This shift suggested the gradual intensification of the salinity influence, probably driven by seasonal groundwater withdrawal and reduced recharge. By 2023 and 2024, the histograms showed a significant shift to the higher classes of concentration for Cl/(HCO_3^- + SO_4^{2-}) and Cl/(HCO_3 + CO_3), particularly for samples between 14 and 20. These higher ratios dominated the frequency of the upper-class intervals, indicating strong marine influence and mixed-type water conditions. Ca/Mg and Na/Cl ratios also showed larger dispersions, reflecting increased ion exchange and seawater mixing processes. The general patterns in the histogram reflected an increase in frequency over the 5-year period for saline-affected samples along the coast. Thus, the histogram analysis efficiently captured the overall temporal progression and spatial intensification of seawater intrusion, besides the output provided by Piper facies and GIS mapping.









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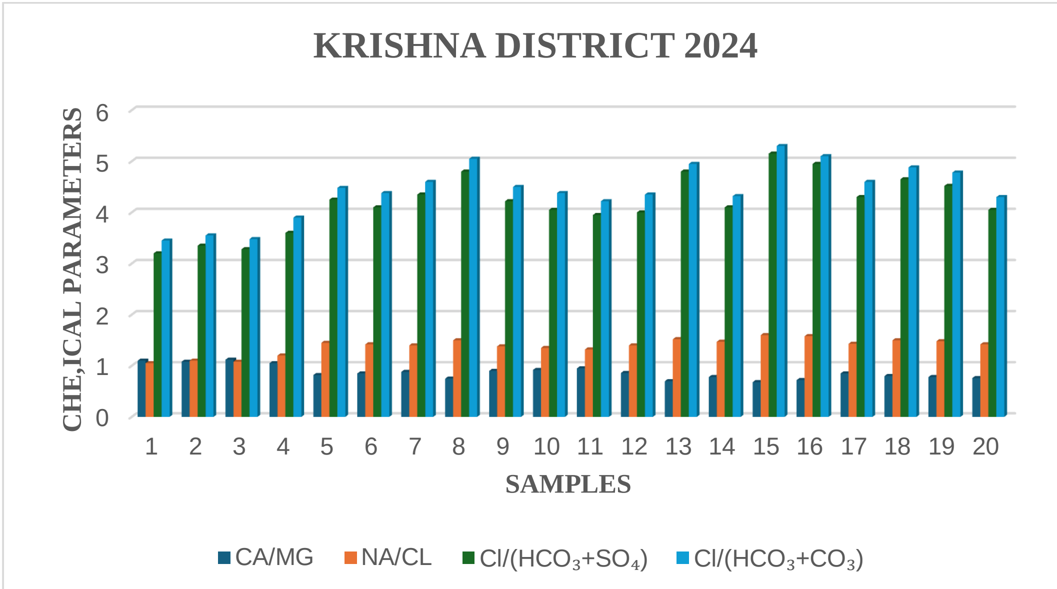
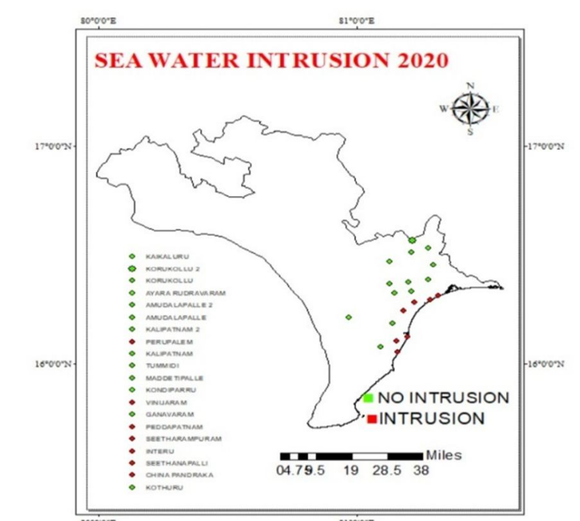


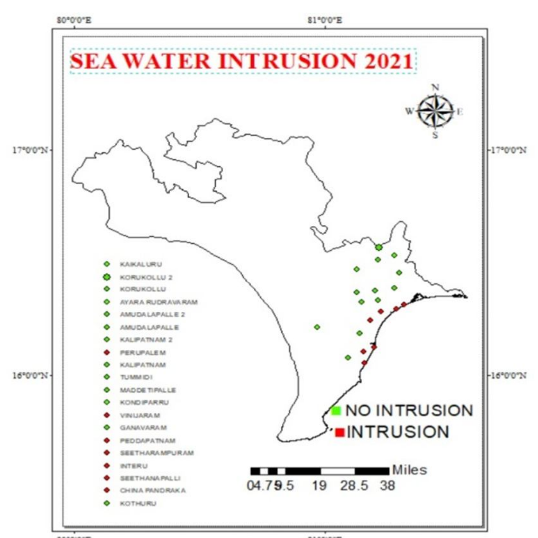
Figure 4: Histograms of Chemical Parameters and Samples Krishna District (2020 – 2024)

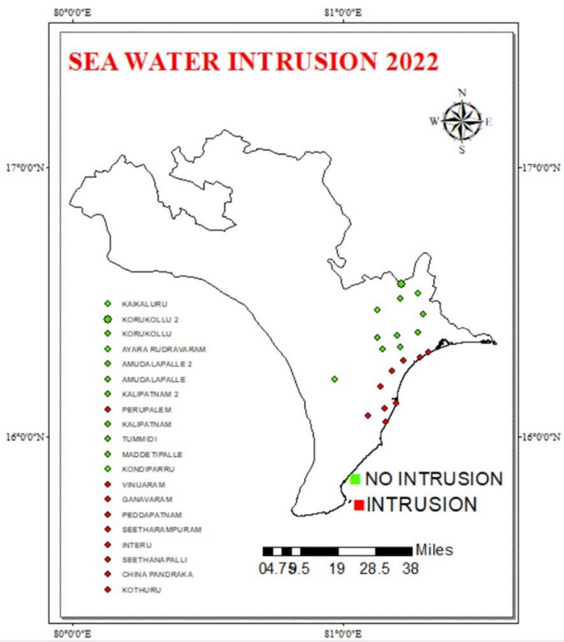
F. Mapping of Sample Locations in ArcGIS

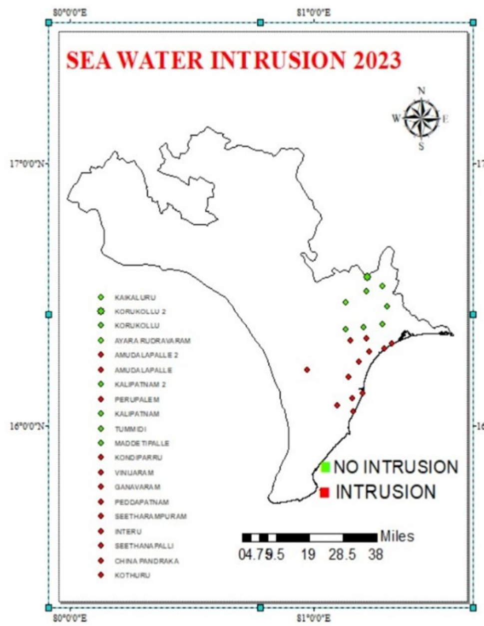
Spatial distribution mapping of groundwater sampling locations was done using ArcGIS 10.x to visualize the geographical layout of wells and to support the geospatial analysis of seawater intrusion. The geographic coordinates extracted from the CGWB database were imported into ArcGIS and converted into point shapefiles representing monitoring wells across the study area. These were overlaid on administrative boundaries, coastal buffers, and base maps to demarcate their respective positions in relation to the shoreline. To isolate wells falling within the intrusion-prone region, a 40 km coastal buffer zone was generated around the coastline. This buffering technique has made the selection of wells that are most vulnerable to tidal influence, over-extraction, and saline water migration possible. The spatial arrangement of sampling points further assisted in understanding data clusters, gaps in coverage, and the way in which wells are spread over the deltaic plains, inland villages, and aquaculture-dominated regions.

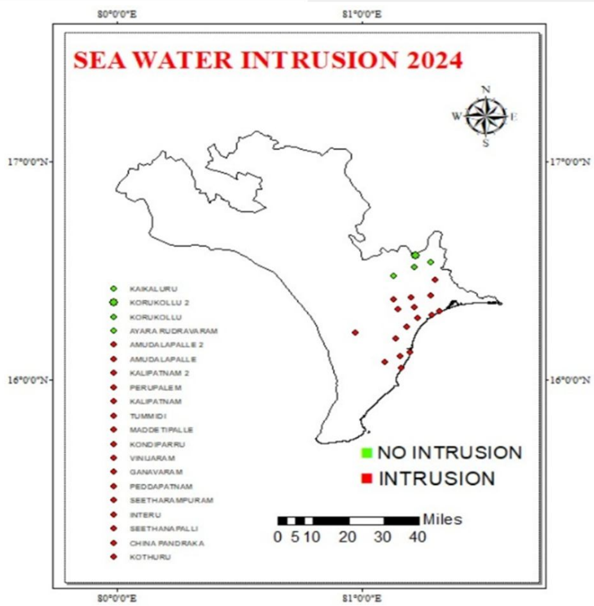
Thereafter, the sampled location points acted as control points for the development of thematic layers related to hydro-chemical parameters like chloride, EC, TDS, and ionic ratios. Spatial interpolation techniques, such as Inverse Distance Weighting, were employed to produce continuous surfaces representing the intensity and pattern of seawater intrusion along the Krishna District coastal belt. These maps allowed for the demarcation of highly intruded, moderately affected, and freshwater-dominant zones, enhancing the spatial understanding of intrusion dynamics. The GIS-based mapping integrated field data, hydro-chemical interpretation, and temporal trends that contributed to delineating saline-impacted aquifers and also assisted in the sustainable management of groundwater.











V. RESULT AND INFERENCE

The integrated hydro-chemical, graphical, and geospatial analyses provided a comprehensive understanding of seawater intrusion dynamics in the coastal aquifers of Krishna District for the period 2020-2024. Temporal evaluation of the diagnostic ratios presented an increasing trend in different parameters like $Cl/(HCO_3^- + SO_4^{2-})$,$Cl/(HCO_3 + CO_3)$, and Na/Cl, especially in wells belonging to the 0-20 km coastal zone. The increasing trends of these parameters reveal the inland migration and mixing of fresh and saline waters over the period of the study.

The Piper diagrams developed with RockWorks17 confirmed significant shifts in the hydrochemical facies. Whereas the early years (2020–2021) were dominated by Ca–HCO_3 and mixed facies, later years (2023–2024) showed a strong transition towards Na–Cl-type water, which is a typical indicator of seawater intrusion. This transition reflects the ion exchange processes and encroachment of the saline water directly into shallow and intermediate aquifers. Spatial interpolation using ArcGIS further indicated that there are distinct intrusion-impacted zones across the coastline. High chloride and EC were found to be concentrated near low-lying areas, aquaculture regions, and zones with intensive groundwater extraction. Inland wells showed relatively stable freshwater conditions, confirming that the degree of intrusion decreases with increasing distance from the coastline.

The overall study establishes that seawater intrusion in the Krishna coastal belt is active, spatially variable, and gradually intensifying. The combination of hydro-chemical indicators, Piper facies, histogram distribution, and GIS mapping proves to be an effective framework for the detection and monitoring of seawater intrusion. This study emphasizes controlled groundwater abstraction and artificial recharge measures with periodical monitoring for sustainable management of the coastal aquifers and minimization of further saline water migration.

VI. CONCLUSION AND CONTROL MEASURES

The present research work attempts an integrated approach for the evaluation of seawater intrusion within the coastal aquifers of Krishna District by adopting hydro-chemical indicators, Piper facies interpretation using RockWorks17, histogram analysis, and GIS-based spatial mapping. The multi-year assessment from 2020 to 2024 reflects a definite enhancement in the encroachment of saline water, mainly within the first 20 km from the coastline. Progressive increases in the diagnostic ratios of Cl/ (HCO_3^- + SO_4^{2-}), Cl/ (HCO_3 + CO_3), and Na/Cl, coupled with negative BEX values, strongly establish the marine influence.

The Piper plots indicate a clear evolution from Ca–HCO_3 freshwater facies to mixed and Na–Cl saline facies through time, suggesting both ion exchange and direct mixing with seawater. The spatial analysis reveals that the lower-lying coastal plains, aquaculture-dominated areas, and areas of high extraction of groundwater have been most affected. The study confirms seawater intrusion in Krishna District is active, expanding, and strongly controlled by anthropogenic pressures coupled with hydrogeological conditions. The integrated methodology adopted herein offers a robust framework for intrusion monitoring, early detection, and sustainable groundwater planning. The results clearly indicate the urgency of regulatory and scientific interventions to preserve the coastal aquifers from further salinization.

A. Control Measures to Mitigate Seawater Intrusion:

Effective management of seawater intrusion calls for concerted hydrogeological, engineering, and policy-based interventions. To manage the Krishna coastal belt, the following are recommended:

1) Regulation of Groundwater Pumping: Limit excessive extraction of groundwater in coastal zones. Enforce pumping permits and restrict large-scale private borewell development. Promote conjunctive use of surface and groundwater to reduce aquifer stress.
2) Artificial Recharge and Aquifer Replenishment: Construct recharge wells, check dams, percolation tanks and recharge trenches. Utilize stormwater and surplus monsoon runoff for artificial recharge. Managed Aquifer Recharge Promotion in critical zones
3) Creation of Protective Barriers: Develop subsurface hydraulic barriers to prevent the inland migration of seawater. Promote the injection wells of freshwater to maintain seaward hydraulic gradients.
4) Monitoring and Early Warning Systems: Install continuous monitoring wells along the 0–20 km coastal buffer. Testing for EC, Cl^-, Na^+, SO_4^{2-}, and diagnostic ratios should be conducted quarterly. Integrate GIS-based real-time mapping for intrusion detection.
5) Control of Aquaculture Practices: Regulate saline-water aquaculture ponds near the coast. Line aquaculture ponds to reduce seepage of saline water into groundwater.
6) Land-Use Planning and Zoning: Restrict groundwater-dependent industries and commercial activities in vulnerable zones. Promote coastal vegetation and restore sand dunes to improve natural recharge.

VII. FUTURE SCOPE

The present study lays a firm basis for the understanding of seawater intrusion in the Krishna coastal aquifers, but quite a few avenues remain for further improvement and advanced research. Future work should be oriented toward the development of predictive modeling frameworks like MODFLOW-SEAWAT, FEFLOW, or MT3DMS, which can simulate the future extent of saline intrusion under varying pumping, recharge, and climate scenarios. Such models can be used to design long-term management strategies and evaluate the effectiveness of the proposed control measures.

Additional field-based research could be added, such as isotopic analysis ($\delta^{18}O$, δ^2H) and trace element studies, in order to clearly distinguish marine signatures from other anthropogenic sources like aquaculture seepage or industrial discharges. It is also possible to conduct a high-resolution geophysical survey, like electrical resistivity tomography (ERT), electromagnetic profiling, or 2D/3D subsurface imaging, to map the freshwater–saltwater interface more accurately. Future research should include, for this purpose, remote sensing datasets such as satellite-derived groundwater storage anomalies, land-use changes, and coastal morphology dynamics to better understand seawater intrusion driven by these external factors. Long-term monitoring networks with automated sensors for EC, TDS, and water levels can improve real-time intrusion detection and support the development of early warning systems.

Future research should, therefore, be focused on socio-economic aspects, assessing community water-use patterns, agricultural dependence, and local adaptation measures to develop holistic and sustainable policies for the management of groundwater. The linkage of scientific assessment to policy implementation will be increasingly crucial in securing the long-term resilience of the Krishna coastal aquifer system.

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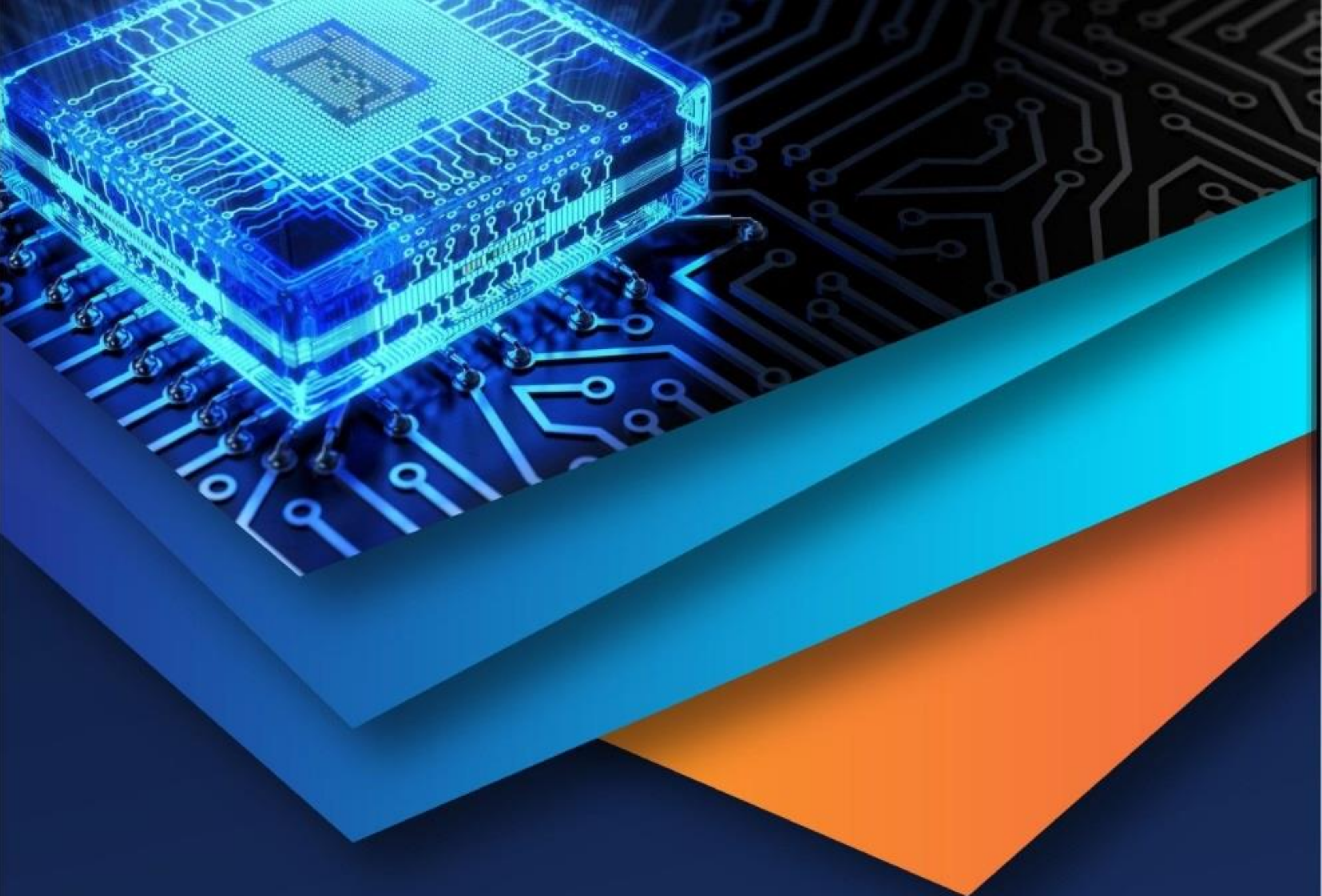

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