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Assessment of Groundwater vulnerability for irrigation use in coastal blocks of Jagatsinghpur District, Odisha, India

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Abstract - Groundwater vulnerability studies are given utmost importance in recent times as a source of essential information for the management of water resources. Since the area of study i.e. a part of the Jagatsinghpur district lies close to the sea (Bay of Bengal), experiences large rate of population growth, increase in agricultural and industrial activities, there is a lot of stress on groundwater quality and quantity. In the present study, the groundwater vulnerability for irrigation use is assessed. In addition to delineation of chemical constituents in ground water, various parameters such as sodium percentage (%Na), Sodium adsorption ratio (SAR), Potential Salinity (PS), residual sodium carbonate (RSC), Magnesium hazard (MH), Kelly's ratio (KR), Permeability Index (PI) are calculated and interpreted to find out the suitability of groundwater for irrigation use.

Keywords: aquifer; residual sodium carbonate; ground water quality; vulnerability; permeability index; below ground level (bgl)

INTRODUCTION:

Groundwater plays more and more important role in recent times for the development and management of water resources. Moreover, the issue of groundwater has become a strategic issue worldwide including India for usage, owing to the deterioration of quality and depletion of surface water resources. Jagatsinghpur is one of the most natural disaster-prone districts of costal Odisha. The district is surrounded by the districts namely Kendrapara, Cuttack, Khurda, Puri and Bay of Bengal. Cyclone and natural calamities regularly devastate the economy of the district. The district spreads over alluvial deposits of river Mahanadi and its distributaries that resulted fertile agricultural land.

Jagatsinghpur district lies over alluvial plains of the river Mahanadi, Kathajodi, Devi, their tributaries and distributaries. Physiographically the district can broadly be divided into two distinct units, viz the saline marshy and swampy strips along the coast covered with wild growth of reeds and tropical jungle and the very gently sloping fertile plain land. The gently sloping alluvial plain occurs to the west of the saline marshy tract and forms the most fertile land of the district. The general slope of this tract is towards east and southeast and varies from 0.50 to 1.60 m/km.

Although the study area comes under coastal tract of Odisha & there is no mining activity or large-scale industrial activities in the area, the groundwater is still contaminated. This is mainly because of frequent cyclone, sea water contamination in the coastal tract of the study area, agricultural activity and rapid population growth in the region.

The basement rocks in the Mahanadi delta are the Eastern Ghats crystallines (khondalites, charnockites and granite gneiss) which were faulted against the Iron Ore Super Group rocks (Archean) of North Odisha along a major fault designated as the North Orissa Boundary fault (Mahalik, N.K. (2000)). Brahmani River valley clearly defines this fault. Marine sedimentation started in this basin since the Upper Cretaceous age. A hinge line separating the continental shelf from the continental slope got established during the Palaeogene period. (Mahalik, N.K. (2000)).

Study area:
Geographically the study area lies between 19°58'N and 20°18'N latitudes and 86°05'2.4"E and 86°25'50.4"E longitudes and covers a total area of about 584.84 sq.km. (Fig. 1). The study area consists of three administrative blocks such as Jagatsighpur, Balikuda and Nuagaon, lies along the south western part of Jagatsinghpur district. The average annual rainfall of mandal is about 1436 mm and the mandal receives seasonal rainfall in south-west

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monsoon periods and about 75% of the total rainfall occurs during the period from June to September. The Bay of Bengal, which forms the South-eastern boundary of the study area, plays a vital role in controlling the climate of the district. The relative humidity varies from 74 to 86 percent during the year and temperature varies from 15°C to 39°C.

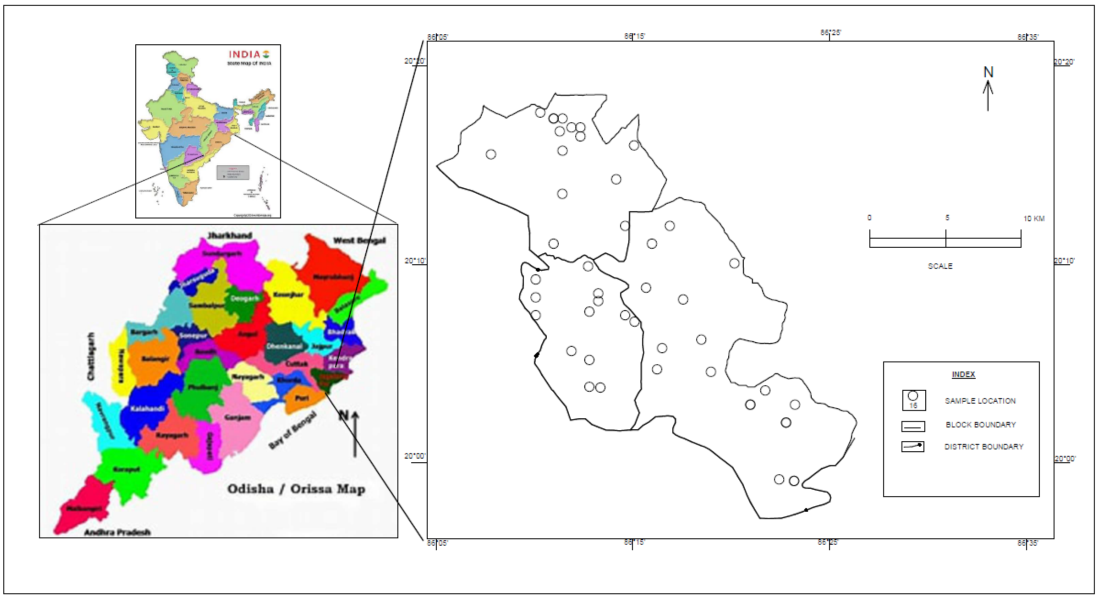

Fig 1: Location Map of the Study area.

The groundwater samples were collected from the study area, field measurements were conducted during the water sampling process such as temperature, pH, EC, by water analysis kit. The sample location coordinate points noted from GPS data.

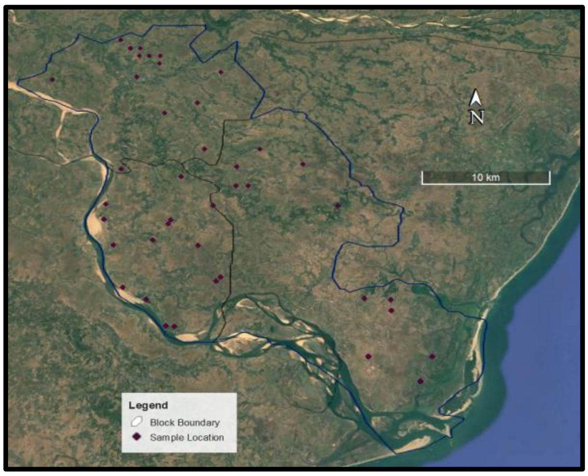

Fig 2: Sample location map of the Study area.

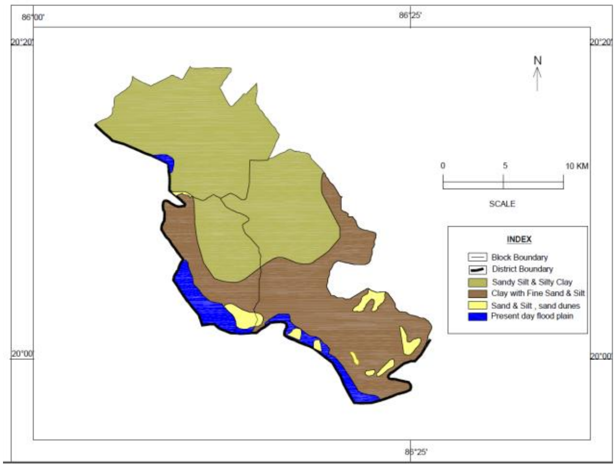

Fig 3: Geological map of the Study area.

Geology:
The study area consists of vast pile of sediments ranging in age from pre-Tertiary to Recent deposited over an uneven block faulted basement with a series of horsts and grabens. The area is covered by soft Quaternary sediments overlain by Baripada beds of Tertiary age (Mahalik, N.K. (2000)). The geological map of the study

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region (Fig. 3) showed that it is overlain by Quaternary unconsolidated formations (a mixtures of sand, gravel, clay, and silt) belonging to the flood deposits of the Mahanadi and Devi rivers (Behera et al., 2022; GSI 2023). A total five Quaternary formations are identified namely, Older beach deposit, Lower delta deposit, Upper delta deposit, Younger beach deposit and Present Day coastal & flood plain deposit.

Older Beach deposit consisting of compact sand & silt of Late Pleistocene to early Holocene age occurs as small patches (mainly as small ridges within lower delta deposit. Lower & upper delta consists of clay with fine sand & silt and alternating layers of sandy silt & silty clay respectively. Major difference between them is that lower delta is a marine deposit whereas upper delta is typically fluvial deposit. Areas near the Bay of Bengal seashore is mainly occupied by younger beach deposit consisting of very fine sand and silt. This is a marine-aeolian deposit & occurs as small ridges. Present day coastal deposit occurs within narrow zone & consists of medium grained sand with heavy minerals. Present day fluvial deposit consisting of sand & silt occurs at the bank of the rivers. Both younger beach deposit & present day coastal & fluvial deposits are of late Holocene age.

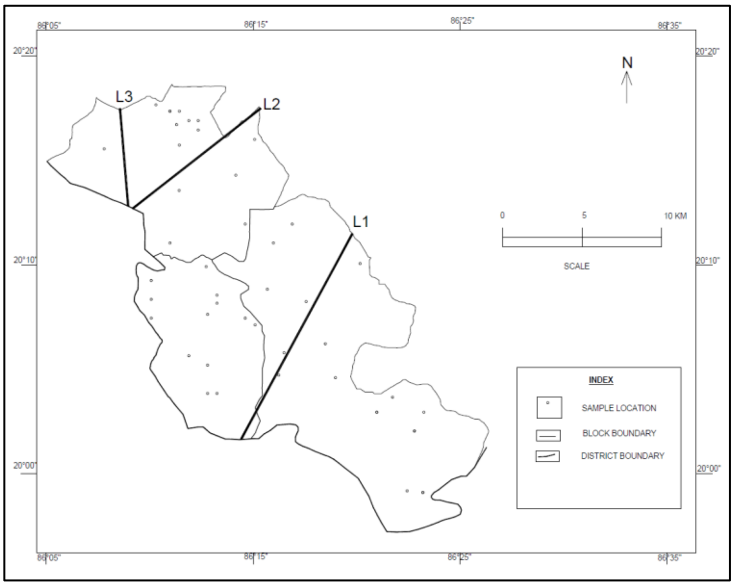

Fig 4: Lineament map of the Study area.

Table 1: Stratigraphical Succession of the study area

Lithology	***Morphology***	***Age***
Sand & silts (flat surface with Occasional dunes/point & lateral bars & meanders	Present day coastal/flood Plain deposit	Late Holocene
Very fine sand, silt & clay (Older dunes)	Younger beach deposits	
Sandy silt & silty clay	Upper Delta Deposit	Middle to Lower Holocene
Clay with fine sand & silt	Lower Delta Deposit	
Compact Sand & Silt	Older Beach Deposit	Late Pleistocene To Early Holocene

Hydrogeology: The aquifers in the recent alluvial tracts are very extensive, often inter- connected and display wide variation in the texture of the formation materials. Different granular zones have been identified with in the depth of 400 m. The depth and thickness of these granular zones vary laterally. Facies variation and lateral intercalation are prevalent in the area. In general the cumulative thickness of granular zones has a tendency to

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increase towards the coast in the Mahanadi delta region. The occurrence of fresh water granular zones in the coastal alluvial tract of the area is restricted as saline zones are encountered in the east.

Based on behaviour, occurrence & movement of groundwater, the aquifers of the study area have been described under two distinct categories:

a) Shallow Aquifer zones (Occurring within the depth of 50 m bgl).
b) Deeper Aquifer zones (Between 50-300 m bgl).

The area has number of nalas, ponds etc besides two major rivers Mahanadi & Devi. These water bodies help in recharge and in increasing the groundwater potential of the area. The shallow aquifers occurring within a depth of 50m below ground level consists of sand, clay and gravel at some places. The thickness of saturated zone varies from 10-35 m & occurs under water table condition in northern part of study area whereas along the coastal tract it occurs under perched water table condition underlain by clay beds in sand dune areas. The water yielding capacity is around 30-40 lps in this zone which favours shallow depth tube wells and dug wells in these regions.

The deeper aquifers occurring at a depth of 50 to 300 m bgl is confirmed by bore holes drilled by C.G.W.B, RWS & S of Govt of Odisha. The lithologs recovered from these zones indicate that the aquifer zones become thicker with depth but the alternation of clay bands still continue except some areas where there is no clay bands even up to a depth of 200 m bgl.

Materials & methods

Collection of groundwater samples: Forty-five (45) groundwater samples were collected from the locations of Tubewells distributed in three blocks of southern part of Jagatsinghpur district in 2019, post monsoon season as shown in Fig 2. The samples of groundwater were collected based on the standard methods of quality control as follows:

- For physicochemical analysis, the water samples were collected in clean plastic bottles of 1L capacity.
- Plastic bottle used was cleaned with nitric acid and rinsed with actual water samples to maintain the water quality according to APHA (2012).
- Some field measurements were conducted during the water sampling process such as temperature, pH, EC, by water analysis kit (Systronics make) and the total dissolved solids (TDS) values are calculated by multiplying EC with factor 0.64.

Remote sensing techniques: For the exploration of groundwater resources satellite imageries are of immense help. Hydro-geomorphological maps are prepared from satellite imageries which helps in interpretation of different lithological, structural and morphological units. Remote sensing data have been increasingly used in groundwater targeting by Mabee et al (1994), Behera et al (2000), Hari Narayan et al (2000), Kar (2000), Mahapatra (2000), and Gopinath et al (2003).

Regional trends of lineaments can be best studied with the help of satellite imageries and hydro potentialities in the study area can also be interpretated. The combination of landform cum lineament mapping and electrical resistivity studies are very much successful in areas where the overburden and /or weathered rock as well as partly weathered rock contains adequate quantities of groundwater. Based on these factors the remote sensing techniques has been applied for the study area to target groundwater potential.

The hydro-geomorphological map of the study area prepared from the IRS-IA (LISS-II) imagery and survey of India sheets of 1:2,50,000 scale depicts the landforms of the area and their groundwater potentialities. The geomorphological features include Young coastal plain, Younger mud flat, Back swamp, Channel Bar, Natural levee, Old coastal plain, Palaeo beach ridge and Point bar interpreted from the map by remote sensing method in the area of study.

The geomorphic units such as younger and older alluvium, marshy tracts, sand dunes are areas of good ground water potentialities. In contrast to above unit clay zones can be identified which creates water logging in the area. The lineament map of the study area (Fig.4) indicates that predominantly the three lineaments (L1, L2 & L3) trend NE-SW and N-S. The field studies reveal that better yields are received from the areas of N-S trending lineaments.

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Irrigational Use:
Various factors such as nature and characteristics of soil, topography, drainage, crop pattern, types of well, cultural practices which decide whether a particular type of soil is suitable for irrigation purpose or not. The presence of a salt type may affect the plant growth as it may be toxic for any plant if it is present beyond certain permissible limit. Soil with low permeability, flat topography, shallow water table and arid climate favours accumulation of salts at the root zones of plants. Salt tolerance varies from species to species. The different Physico-chemical parameters of the ground water samples analysed are pH, EC, TDS, Total alkalinity, Total hardness, Ca, Mg, Na, K, Cl, HCO_3, CO_3, SO_4 are represented in Table 3.

Total Dissolved Solids & Electrical conductivity: In natural water total dissolved solids contains of minerals, nutrients that have dissolved in water, and also includes major ions (Cations & anions). Weathering or dissolution of soil and rocks also generates ions in water. The high concentrations of TDS reduce water clarity, giving the water its color and determining the salinity behaviour of water. Conversely, electrical conductivity (EC) indicates the total salt concentration, which is dependent on the charges from dissolved ions in water. The TDS concentration value < 450 mg/l is preferred for irrigation whereas value > 450–2000 mg/l is slight to moderate and > 2000 mg/l is unsuitable for agricultural purpose (FAO, 2006). A high EC of water indicates a high concentration of ions, representing the higher TDS in water. A relationship exists between TDS and EC as defined in Eq. (1)

$$\text{TDS}\left(\frac{mg}{L}\right) = EC\left(\frac{dS}{m}\right) \times K \qquad (1)$$

where K =800 when EC > 5 dS/m, 735 for mixed waters and 640 if EC: 0.5‑5.0 dS/m.

Total hardness (TH): Water hardness is a result of existence of divalent metallic cations (Ca^{2+} and Mg^{2+}) and it can be calculated as the sum of $Ca^{2+}$and Mg^{2+} concentration as meq/l equivalent to $CaCO_3$ (Todd 1980) and expressed by (Eq. 2):

$$TH = (2.5 \times Ca^{2+}) + (4.1 \times Mg^{2+}) \qquad (2)$$

TH is usually classified as soft (0–60 mg/l), moderately hard (60–120 mg/l), hard (120–180 mg/l) and very hard (> 180 mg/l) (EPA, 1986).

Hardness is of two types i.e. temporary hardness (carbonate hardness) & permanent hardness. Temporary hardness caused by bicarbonates of calcium and magnesium can be largely removed by simply boiling the water, where the bicarbonates precipitated as carbonates. However, the Permanent Hardness (Non-carbonate hardness) caused by sulphates, chlorides, and nitrates of calcium and magnesium can't be removed by boiling.

Different parameters are proposed for evaluating the suitability of water for irrigation use are described below.

Sodium Adsorption Ratio: For quality assessment of water for irrigation, sodium content is an important criterion. By the process of exchange sodium replaces calcium from soil due to which permeability of soil is reduced. This is known as "Sodium/Alkali Hazard", because the degradation process helps in formation of alkaline soil. The sodium concentration is expressed by SAR (Sodium Adsorption Ratio) by the following formulae, where the concentrations are expressed in meq/l. (Fig 10.(a))

$$SAR = \frac{Na^{+}}{\sqrt{([Ca^{2+}] + [Mg^{2+}])/2}} \qquad (3)$$

The SAR assessment of irrigation water by this index is such that the water is excellent, good, suspicious and inappropriate for SAR value below 10 meq/L, 10 to 18 meq/L, 18 to 26 meq/L and above 26 meq/L respectively as a classification for its salinity hazard.

Sodium Percentage (Na%): This is calculated by applying the formula as given below. High sodium percentage can lead to deflocculation of soil particles, reducing permeability and affecting plant growth. Groundwaters can be classified on the basis of percentage of sodium (%Na) vrs electrical conductance according to Wilcox (1955). When these values are plotted in the diagram (Fig 8), the samples occupy fields of "Excellent", "good",

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"permissible", "doubtful" and "unsuitable classes". High Na% leads to soil *sodicity,* displacing Ca^{2+} and Mg^{2+}, which causes clay dispersion, sealing, reduced infiltration, hardpan formation, and eventual crop failure.

$$\%Na = \frac{(Na^{+}+K^{+})\,X100}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} \qquad (4)$$

Where concentration is expressed in meq/l.

Based on this index, the irrigation water is classified as excellent, good, permissible, doubtful and unsuitable for Na% < 20, Na% 20-40, Na% 40-60, Na% 60-80 and Na% > 80 respectively. (Raghunath, 1987), (Bhatti E-H, et al 2019)

Soluble Sodium Percentage (SSP): It is a crucial water quality parameter used to evaluate the sodium hazard in irrigation water, indicating the potential negative impact of sodium on soil structure and crop productivity. SSP represents the proportion of sodium ions relative to the total concentrations of major cations—sodium (Na^{+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^{+})—present in irrigation water. It is expressed as a percentage and reflects the tendency of sodium to accumulate in soils when irrigation water contains high sodium levels. SSP < 50%: Generally considered good to safe & SSP > 50%: Indicates that the water is unsafe.

$$SSP = \frac{(Na^{+}+K^{+})}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})}\,X100 \qquad (5)$$

Permeability Index (PI): The permeability of soil is affected if they contain higher levels of TDS, sodium, bicarbonate etc. Doneen,(1964) developed a criterion to assess the suitability of water for irrigation based on permeability index which can be determined from the expression given as follows where the concentration of ions are expressed in meq/l.

$$PI = \frac{Na^{+}+\sqrt{HCO3^{-}}}{Ca^{2+}+Mg^{2+}+Na^{+}}\,X100 \qquad (6)$$

Where:PI = Permeability Index (expressed as a percentage)
Na^{+} ,HCO_3^{-} ,Ca^{2+} & Mg^{2+} ion concentration expressed in meq/L.

The PI levels are categories into three classes where class III (below 25%)is unsuitable while both I and II classes (above 75% and 25%−75% respectively) are considered suitable for irrigation (Panneerselvam B et al, 2021) , (El Tahlawi, et al (2014)).

Residual Sodium Carbonate (RSC): The relative abundance of Sodium with respect to excess of carbonate and bicarbonate over alkaline earth also affects the suitability of water for irrigation purpose and this excess is denoted by Residual Sodium Carbonate (RSC) and is determined by the formula (Richards,1954), where the concentrations of ions are expressed in meq/l.

$$(CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+}) \qquad (7)$$

Occurrence of CO^3 and HCO^3 that reduce free Mg and Ca results to positive RSC values leading to an abundance of Na in form of a predominant salt (sodium carbonate) and a consequential corrosive impact within laterals and emitter materials. (Kumari D et al, 2022)

The water is classified in to three categories safe (good) , marginal (doubtful) and unsuitable (hazardous) on the RSC value of <1.25, 1.25-2.50 and >2.50 respectively. The unsuitable category is not suggested for irrigation while the marginal category should be used with caution. Richards (1954)

Residual Sodium Bicarbonate (RSBC) is an irrigation water quality index that measures the excess of bicarbonate relative to calcium in groundwater, responsible factor to determine water quality according to bicarbonate ion concentration. High RSBC implies bicarbonates exceed calcium, causing sodium bicarbonate formation, which can destabilize soil structure and harm permeability and plant growth. Groundwater classified as RSBC < 5 meq/L: Safe for irrigation, RSBC between 5–10 meq/L: Marginal suitability and RSBC > 10 meq/L : Unsuitable for irrigation.

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$$RSBC=[HCO_3^-]-[Ca^{2+}] \quad (8)$$

Where Concentrations are expressed in milliequivalents per liter (meq/L)

Magnesium Hazard: Magnesium (Mg^{2+}) in irrigation water can contribute to soil degradation and reduced crop productivity, especially when present in excess relative to calcium (Ca^{2+}). Although magnesium is an essential plant nutrient, high levels can negatively affect soil structure and water infiltration. The index of Magnesium Hazard of irrigation water is given as a ratio (Mg^{2+} X 100)/ (Ca^{2+} + Mg^{2+}) where concentration is expressed in meq/l. Generally, MH < 50%, considered suitable for irrigation where as in case MH > 50%, water is considered problematic or unsuitable for irrigation.

Potential soil salinity (PS): Potential soil salinity" refers to the likelihood or risk of a soil developing or experiencing problems due to an accumulation of soluble salts. It's not just about the current salt levels, but also the factors that could lead to increased salinity over time.

Soil salinity is the presence of excessive concentrations of soluble salts in the soil solution, primarily in the root zone which negatively impacts plant growth and soil productivity. These salts can include chlorides, sulphates, carbonates, and bicarbonates of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K+). It is an important factor for classification of irrigation waters. It is determined by adopting the formula suggested by Doneen (1962)

$$Cl^- + \frac{1}{2} SO_4^{\ 2-} \quad (9)$$

where concentration is expressed in meq/l.

The water classified excellent to good(<5), good to injurious (5-10) and injurious to unsatisfactory (>10) based on PS value in meq/l.

Salinity Hazard: Total dissolved solids (TDS) content if present beyond a certain limit may be responsible for salinity hazard. Soils which contain exchangeable calcium and magnesium ions may be unsuitable if excess sodium is present in the water. Suitable water management practices and soil management practices have to be adopted if the irrigation water contains high sodium. Such practices include application of Gypsum (Karanth, 1997). TDS (Total Dissolved Solids) <450 ppm is excellent to good for irrigation whereas TDS more than 450ppm creates salinity hazard and decreases yield.

Kelly's Ratio (KR): It is an important parameter introduced by Kelley (1940) and Paliwal (1967) in order to assess the irrigation water quality based on the concentration of Na versus the sum of Ca and Mg. It helps determine the excess of sodium ions in irrigation water, which can negatively affect soil permeability and crop development, as an excess of sodium can lead to soil deflocculation and reduced permeability.

$$\text{Kelly's Ratio KR} = Na^+/ (Ca^{2+}+Mg^{2+}) \quad (10)$$

where concentration is expressed in meq/l.

Water with KR value of less than 1.0 is generally considered suitable for irrigation and KR value more than 1.0 is generally considered unsuitable for irrigation.

Chloro-alkaline indices (CAI-1): Schoeller (1967) evolved a formula to study the ion exchange between the groundwater and its surroundings during residence or movement in the aquifer. Chloro-alkaline indices (CAI-I) is measured using Equation (11). The negative values of CAI mean the occurrence of sodium and potassium exchange with calcium and magnesium in the rocks by a base exchange type. Meanwhile, a positive value of CAI indicates the absence of base-exchange reactions and the existence of cation–anion exchange type of reactions (El Tahlawi et al, 2014).

$$CAI(I) = \{Cl^- - (Na^+ + K^+)\} / (Cl^-) \quad (11)$$

CAI > 0: Suggests reverse ion exchange**,** i.e., Na^+ and K^+ from water are being replaced by Ca^{2+} and Mg^{2+} from host rock, saline intrusion or Contamination from industrial/agricultural sources. CAI < 0: Indicates normal ion exchange, i.e., Ca^{2+} and Mg^{2+} in water are replaced by Na^+ and K^+ from host rock, natural weathering of carbonates or silicates and fresh recharge from precipitation or rivers. CAI ≈ 0: Suggests no significant ion exchange**.**

A negative CAI can help distinguish salinization from seawater intrusion (which would have a characteristic ratio of ions) from salinization caused by dissolution of evaporite rocks (like halite, which would show a very strong negative CAI with a massive excess of Na^+ and Cl^-).A strongly positive CAI would be a tell-tale sign that the saline water has been in the aquifer for a long time, undergoing extensive base exchange, releasing Ca^{2+} and Mg^{2+}, and retaining Na^+ on the clay surfaces.

chloro-alkaline indices are vital geochemical tools for diagnosing ion exchange processes, understanding the evolution of water chemistry, and identifying sources of aquifer salinization.

Table 2: Groundwater Parameters

Sl. No	*Parameters*	*Water type*	*Quality*	*Suitability for irrigation*
1	*Total Dissolved Solids (mg/l)*	< 450	Preferred	Suitable for irrigation
		450-2000	moderate	Moderately tolerant plants show injury
		>2000	Unsuitable	Unsuitable for irrigation
2	*Total hardness (TH) (mg/l)*	0-60	Soft	
		60-120	Moderately hard	
		120-180	Hard	
		>180	Very hard	
3	*Sodium Adsorption Ratio*	<10	Excellent	
		10 -18	Good	
		18-26	Doubtful	
		>26	Unsuitable	
4	*Sodium Percentage (Na%)*	<20	Excellent	
		20-40	Good	
		40-60	Permissible	
		60-80	Doubtful	
		>80	Unsuitable	
5	*Soluble Sodium Percentage (SSP) (%)*	< 50%	Good to safe	
		>50%	Unsafe	
6	*Permeability Index (PI) (%)*	>75%	Class I (Excellent to Good)	Suitable
		25-75 %	Class II (Good to permissible)	Use with caution
		<25%	Class III (Unsuitable)	Not Recomended
7	*Residual Sodium Carbonate (RSC)(meq/L)*	<1.25	Safe (Good)	Suitable
		1.25-2.50	Marginal (Doubtful)	Use with caution
		>2.50	Unsuitable (Hazardous)	Not Recomended
8	*Residual Sodium Bicarbonate (RSBC)*	< 5	Safe	Suitable
		5-10	Marginal suitability	Use with caution

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		>10	Unsuitable	Not Recommended
9	*Magnesium Hazard (%)*	< 50%	Suitable	Suitable
		> 50%	Unsuitable	Unsuitable
10	*Potential soil salinity (PS):*	<5	Excellent to Good	Safe
		5-10	Good to injurious	
		>10	Injurious to unsatisfactory	Sensitive plants show injury
11	*Salinity Hazard (mg/l)*	<450	Suitable	Suitable
		>450	Unsuitable	Unsuitable
12	*Chloride Hazard (mg/l)*	<70	Safe	Safe
		70-140	moderate hazard	Sensitive plants show injury
		>140	Severe hazard	Moderately tolerant plants show injury
13	*Kelly's Ratio (KR)*	< 1	Suitable	Suitable
		> 1	Unsuitable	Unsuitable
14	*Chloro-alkaline indices (CAI-1)*	> 0	saline intrusion	
		<0	natural weathering of carbonates	
		0	no significant ion exchange	

Results & Discussion:

It is quite evident that most of the available indicators are not comprehensive due to the limitations in parameters involved and computational reliabilities. The indicators like USSL and Wilcox diagram are primarily relevant in situations of EC and SAR and It is prudent to be flexible, incorporating several irrigation water quality parameters and consolidating them to one value, which makes it more comprehensive but simple. Situations of observable contamination can be handled by the discussed water management practices similarly applied in precision irrigation, land use planning, and nonpoint source pollution detection.

Forty-five water samples representing the study area are analyzed and summarised result depicted in Table (3). The analytical value of samples is assessed for their suitability for irrigational use.

Spatial distribution of water quality parameters

Based on the results of groundwater quality parameters of the selected wells of the study area, the spatial distribution maps have been prepared using ArcGIS 10.1 program, as illustrated in Fig 9(a, b, c & d). The data presented in the table and figures reveal the following:

The pH of groundwater of the studied wells varies from 6.367– 7.75, which means that most of the groundwater samples are suitable for irrigation according to FAO (2006).

The range of EC values of the groundwater of the studied wells is 287.85 µs/cm–12936 µs/cm in the study area. High values of EC are located in some locations in the southern parts of the study area adjacent to the Bay of Bengal.

The values of TDS ranged between 184.22 and 8279.04 ppm for the study area. Fig 9 (a) illustrates the spatial distribution of TDS in the study area, where TDS values are generally low but increased values are seen in the south-eastern part of the study area.

The predominant cations include Na, K, Ca, and Mg. The concentration of Na in ground water samples ranged between 10.05 and 1020.20 mg/l in the study area. The distribution of Na values in the study area indicates low concentration in the northern part and increased concentration in the southern part. The values of calcium in the groundwater sample ranged between 15 and 105 ppm across the study area. Fig 9 (b) illustrates the distribution of Ca values, where its values are generally low in the southern part and increased toward the northern part. From

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the data presented in Tables (3), it is clear that sodium cations (Na) are the dominant cations compared to the other measured cations in the southern part of the study area, while calcium is the dominant cation in some locations in the northern part.

The predominant soluble anions in the groundwater include CO_3, HCO_3, SO_4, and Cl but CO_3 was absent in all the studied locations. The values of bicarbonate (HCO_3) ranged between 24.40 and 158.60 mg/l and it is considered the prominent anion in most of the studied locations. The chloride (Cl) concentration in groundwater samples of the study area ranged from 10 to 2345 mg/l. The data shows that the highest value of 2345 mg/l is located in the southern part of the study area near to Bay of Bengal as shown in Fig 9 (c). The total hardness range varies from 60 mg/l to 785 mg/l. (Fig 9d).

SAR varied from one location to the other in the study area; the data presented in Table (4) show that the highest values were 18.49 for the wells located in the southern part of study area. This is attributed to the high value of Na and the low values of Ca and Mg.

The anomalies of TDS, Na, Ca, HCO3, and Cl in the groundwater in the study area are related to the surface activities, especially the sea water freshwater influence and the sources of irrigation. The anomalies of the different parameters are related to the quality of the irrigation water as follows: The values of TDS are high, where the aquifer is in close contact with sea water and subsequently the values of Na and Cl are high. The values of the TDS are low when the source of irrigation is canal water, and subsequently the dominant cation is Ca and the dominant anion is HCO_3.

Gibbs' diagram

The Gibbs diagram is widely used to establish the intricate relationship of water composition and aquifer lithological characteristics (Gibbs,1970). Three distinct fields such as "precipitation dominance", "evaporation dominance" and "rock–water interaction dominance" areas are shown in the Gibbs diagram (Fig.5).

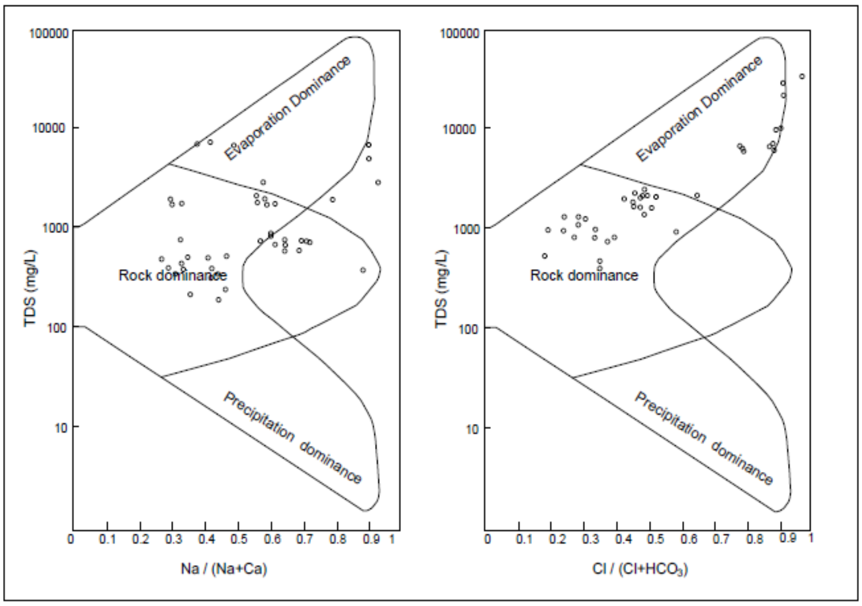

Fig 5: Gibbs Diagram Showing water quality for irrigation purpose.

Most of the groundwater samples fall in the "rock dominance" field of Gibbs diagram (1970) indicating that lithology of the area is responsible for different constituents in the groundwater of the area but some plots are found outside the "rock dominance" field indicating influence of saline water changing the quality.

Piper Trilinear diagram

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The geochemical evolution of ground water can be interpreted by plotting the concentrations of major cations and anions in the Piper trilinear diagram (Piper, 1994). It is a combination of anion and cation triangle that lies on a common base line and diamond shaped field space. The concentrations are plotted on a Piper diagram can be used to make a tentative conclusion as to the origin of the water.

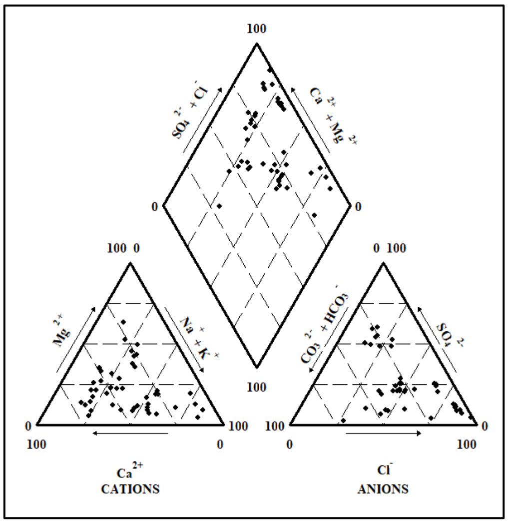

Fig 6: Piper Trilinear Diagram

The hydrochemical facies of the groundwater of the study area is determined using Piper's classification. In the area of study it is observed that most of the well waters are characterized by Ca-Cl type facies followed by Na-Cl, Ca-Mg -Cl (mixed type) and Ca- SO_4. The chemical nature of groundwater can also be interpreted by Piper's trilinear diagram based on mazor ions such as SO_4, HCO_3 and Cl among anions and Na+K, Ca and Mg among cations which are expressed in meq/l. The data plot indicate that major part of the area is occupied by sodium in form of bicarbonate and chloride. From the fig, it can be seen that the peaks of the anions and cations do not match exactly indicating presence of mixed facies of Na-HCO_3, Na-Cl, Ca-SO_4, Na-SO_4 etc. Presence of dominant facies can be explained due to sodium bearing minerals such as sodic plagioclases, clay minerals as the most important minerals in addition to influence of saline water rich in Na and Cl.

Table 3: Chemical analysis of groundwater samples in the study area.

	PH	E.C in µs/cm	TDS (mg/l)	Total alkalinity (mg/l)	T.H (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	HCO_3 (mg/l)	SO_4 (mg/l)
Min	6.37	287.86	184.23	20.00	60.00	15.00	2.10	10.05	2.03	10.00	24.40	2.11
Max	7.75	12936.00	8279.04	355.00	785.00	105.00	136.60	1020.22	160.45	2345.00	158.60	215.14
Mean	6.75	2438.97	1560.94	176.67	228.33	47.67	26.63	101.63	17.40	344.78	80.29	92.13
Median	6.74	1154.00	738.56	170.00	120.00	42.50	7.90	35.76	6.04	85.00	79.30	70.25
Stand. Deviation	0.23	3095.38	1981.04	60.38	200.15	28.29	35.65	222.31	34.80	540.05	28.20	67.49

U.S. Salinity Laboratory (USSL) diagram

The United States Salinity Laboratory (USSL) diagram can be used to present irrigation water parameters similar to the attributes in the Wilcox's diagram, viz. the EC and SAR relationship.

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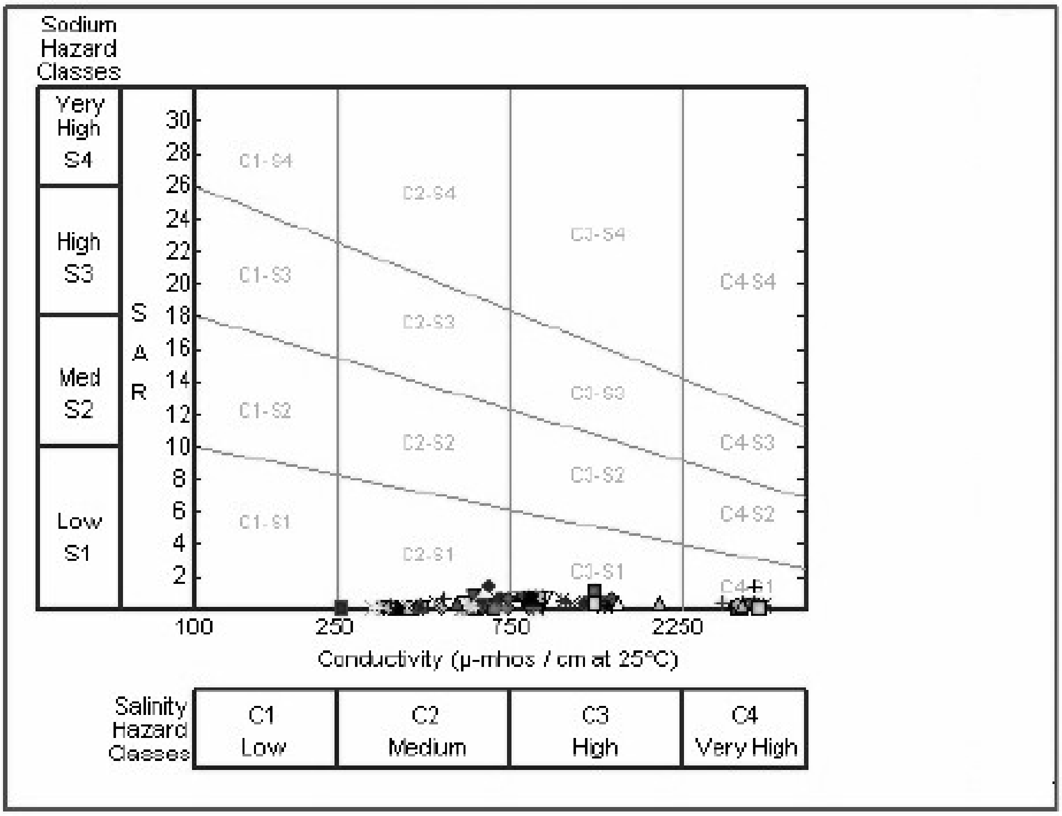

Fig 7: US Salinity Diagram for Classification of Irrigation Water

There is a direct correlation between the SAR values and the extent to which sodium is absorbed by the soil. Plotting the SAR values and EC values Fig (7) of groundwater samples of the study area in the US salinity diagram (Richards, 1954) indicates that the samples occupy C2-S1, C3-S1 & C4-S1 field. Seven out of 45 samples indicate medium to high salinity water class. The high salinity water cannot be used on soils with restricted drainage. Even if there is adequate drainage due to presence of alluvial soils, special management for salinity control shall be required in case of samples of these seven areas and plants with high salt tolerance should be selected in such areas.

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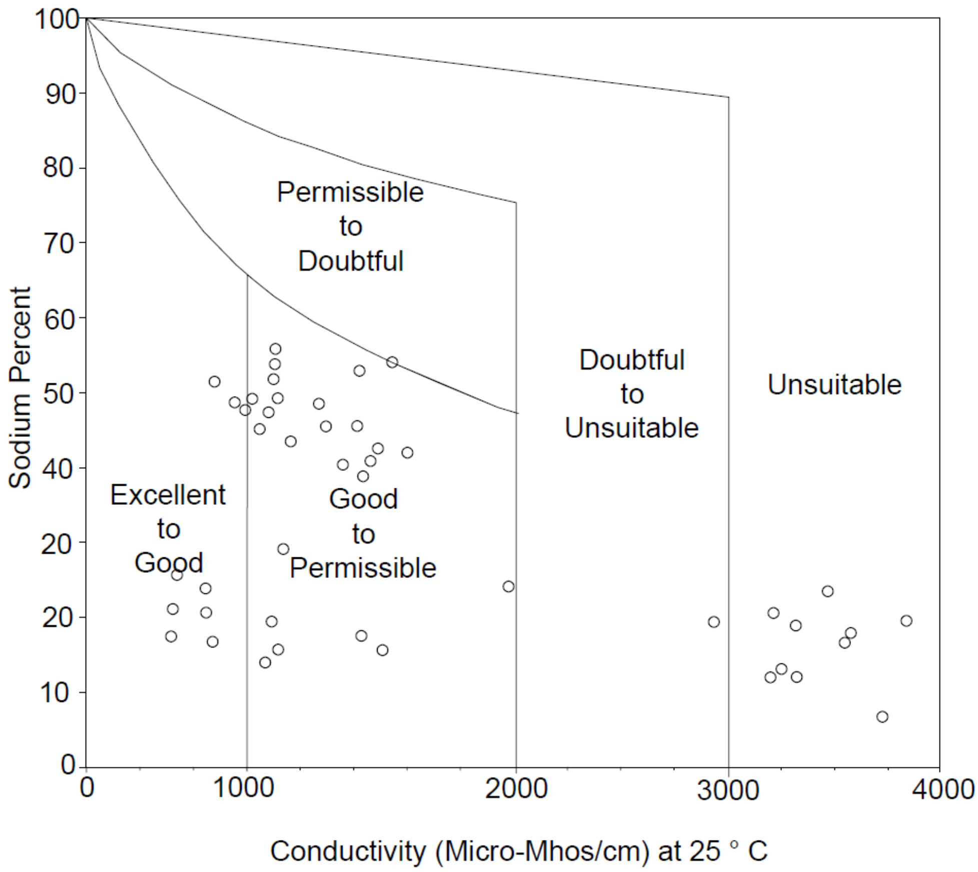
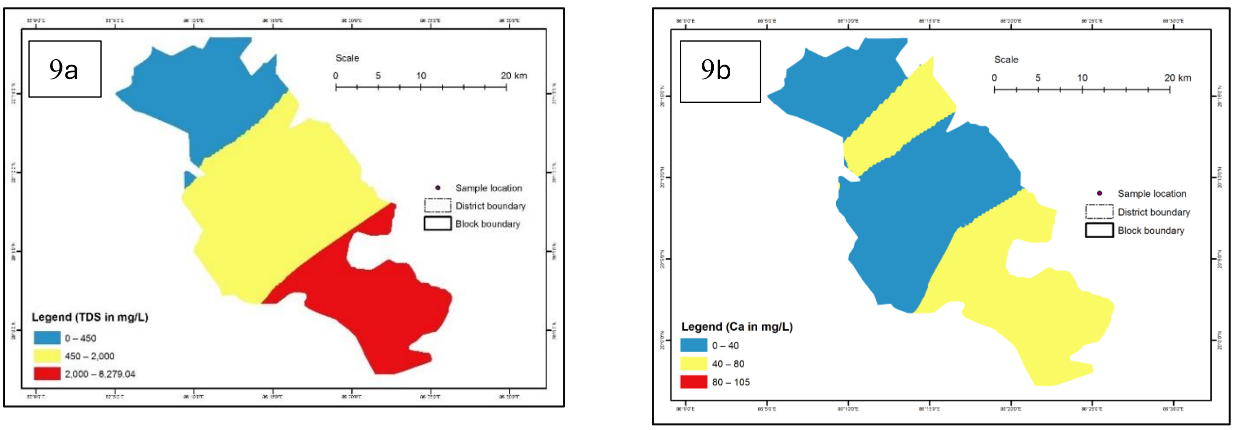


Fig 8: Classification of irrigation water based on electrical conductivity & percent sodium (Wilcox, 1955)

Groundwaters can be classified on the basis of percentage of sodium (%Na) vrs electrical conductance according to wilcox (1955). When these values are plotted in the diagram (Fig 8), most of the samples occupy fields of " Excellent to good", "Good to permissible" and "unsuitable classes".



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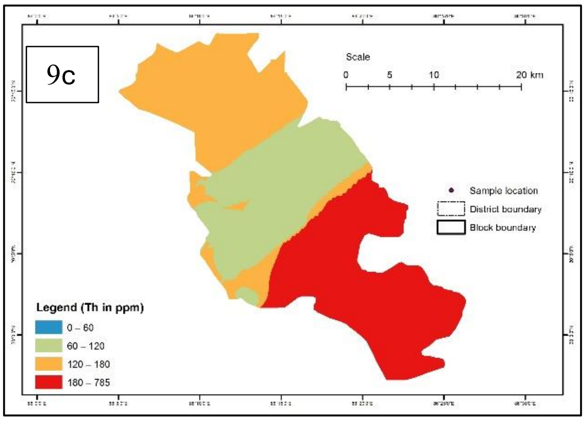

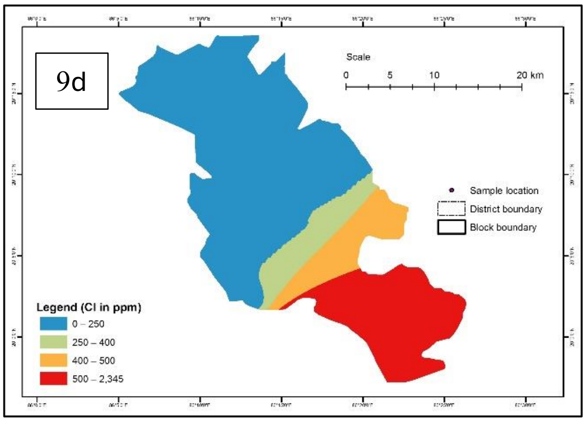

Fig. 9. Concentration maps of major analytes in ppm/L or (mg/L) [a)TDS, b) Total Hardness, c) Calcium, d) Chloride]

Sodium adsorption ratio (SAR): SAR also influences percolation time of water in the soil. Therefore, the low value of SAR of irrigation water is desirable. Based on the analysis result of 45 samples, 42 samples fall under excellent, 2 samples under good and one sample fall under fair category as depicted in fig-10 (a).

Percentage of sodium (Na%): The values of Na% at the studied wells are presented in Tables 4. The results reveal that the water samples are classified as 13.33 (excellent),46.67% (good), 26.67% (permissible) limits of Na%. The remaining of the samples 8.89% and 4.44% are under doubtful and unsuitable category respectively (fig-10 b), concentrated at the southern part of the study area.

Soluble Sodium Percentage (SSP): The values of SSP varies between 11.51 %-79.05 %, 35 samples may be categorised as safe as the value is less than 50% whereas 10 samples are categorised as unsafe for irrigation purpose, indicating the potential negative impact of sodium on soil structure and crop productivity.

Permeability index: The values of PI are presented in Table 4 and fig. 10c. The data show that the values of fifteen samples are higher than 75, while the values of the majority of samples (30 samples) are less than 75 and ranged between 17.21 and 73.68. This means that about 33.33% of the total studied samples are ordered as class I and 64.44% of the total studied samples are ordered as class II are classified as permissible and good for irrigation, respectively. However, only one no of sample collected from Devi river is considered as unsuitable for irrigation and is due to intermixing of sea water with river water.

Residual sodium carbonate (RSC)/Residual alkalinity (RA): A high range of RSC in irrigation water means an increase in the adsorption of sodium on the soil. Water having RSC > 5 has not been recommended for irrigation because of damaging effects on plant growth. Generally, any source of water in which RSC is higher than 2.5 is not considered suitable for agriculture purpose, and water < 1.25 is recommended as safe for irrigation purpose. As per analysis result, all the sample falls under safe category.

Magnesium hazard: The values of MH are presented in Table 4 and fig 10 (d). The results show that the number of water samples that recorded values of MH less than 50 are 34 samples from the total number of samples in the study area. The percentage of samples suitable for irrigation due to MH is 75.55%, however 24.45 % of samples i.e. 11 nos are unsuitable for irrigation concentrated mainly in central and southern part of the study area.

Table 4: The groundwater quality parameters of suitability for irrigation.

	EC	SAR	%Na	SSP	PI	RSC (meq/l)	RSBC	MH	PS (meq/l)	KR	CAI (I)
Min	287.86	0.46	15.09	11.51	17.21	-14.14	-3.44	7.59	0.44	0.14	-2.42
Max	12936.00	18.49	84.51	79.05	99.52	0.30	0.65	74.12	67.61	4.93	0.96
Mean	2438.97	2.50	38.78	34.78	61.67	-3.24	-1.06	35.93	10.67	0.87	0.14
Median	1154.00	1.37	31.86	28.15	62.13	-1.39	-0.82	32.63	3.10	0.41	0.21
Standard Deviation	3095.38	4.09	19.34	18.35	22.94	3.79	1.25	18.47	15.65	1.10	0.66

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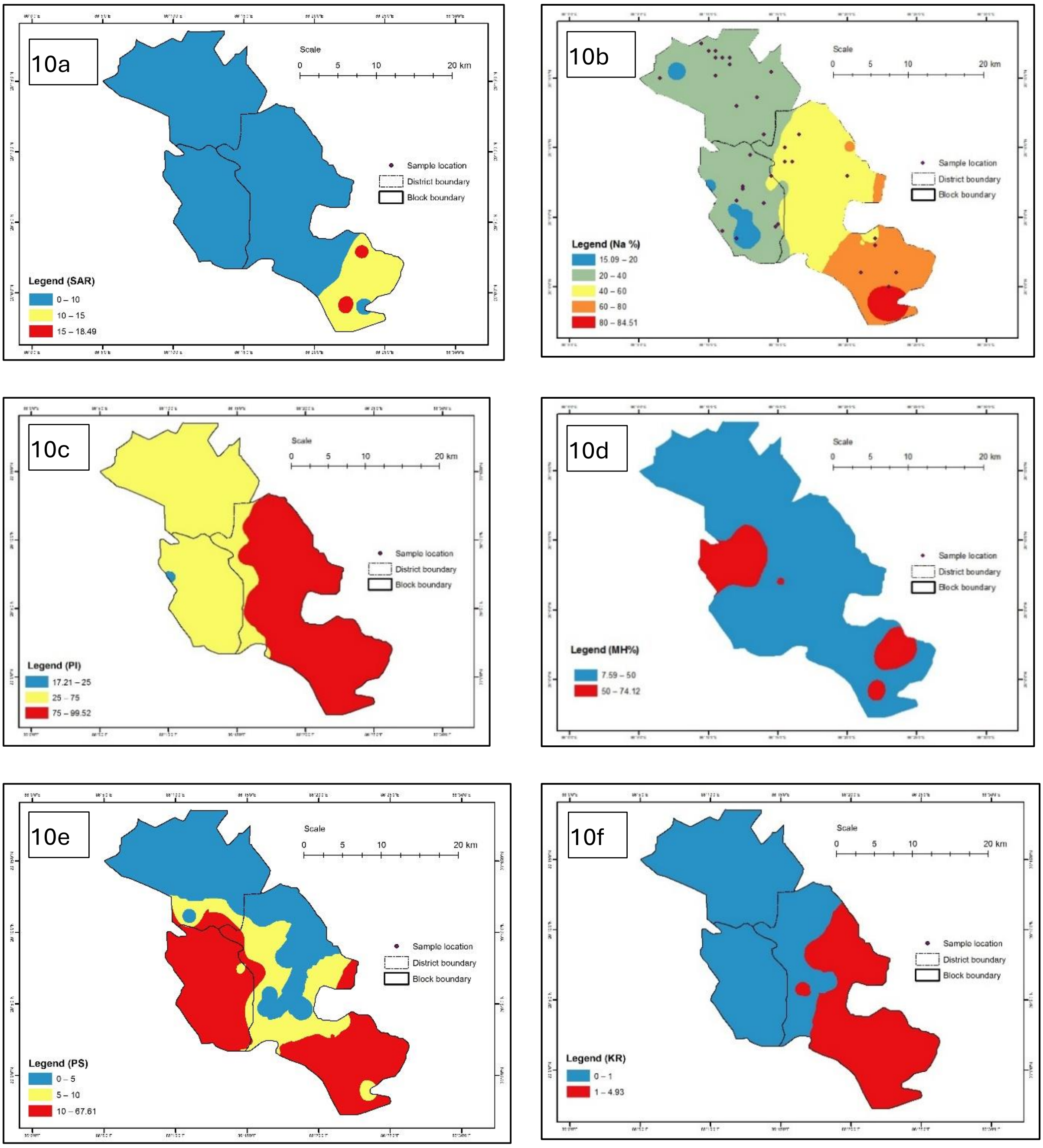

Fig. 10. Different Ratios maps[a)SAR, b) Na%, c) PI , d) MH %, e) PS and f) KR]

Potential soil salinity (PS): With respect to PS, out of 45 samples, 28 samples of can be classified as excellent to good and 1 sample as good to injurious and 16 samples as injurious to unsatisfactory as shown in fig. 10(e).

Kelley ratio: The values of KR are presented in Table 4 and Fig. 10 (f). It shows that about 34 samples have KR values less than 1 and the rest of the values (11 samples) are higher than 1. This means that 75.55% of the studied samples are suitable for irrigation from the viewpoint of KR, while 24.45% of the studied samples are unsuitable for irrigation and cover the end of the central and northern part of the aquifer system.

Chloro alkaline indices: The CAI (I) is calculated for 45 samples as per Schoeller (1967) equation and the value varies from 0.96 to -2.42. The results presented in Table 4 show that CAI values were positive for 23 wells, which are distributed mostly in the northern side of the study area, implies that there was no considerable base- exchange reaction with the rocks and soils of the aquifer. The CAI values are positive for 51.11 % of the total collected

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samples, while the CAI values of the other wells, 48.89%, are negative. This means that there was a base-exchange reaction in the groundwaters.

Correlation matrix: To find out the relationship between the different irrigation quality parameters of the water samples, a correlation matrix (r) was constructed. This matrix was calculated from 45 groundwater samples and is presented in Table 5.

The EC was highly significant and positively correlated with MH and PS (r = 0.730, and r = 992, respectively) and significantly negatively corelated with RSC & RSBC. SAR had a highly significant and positive correlation with Na, SSP and KR. Sodium has positive corelation with SSP, PI & KR. SSP has strong positive corelation with PI & KR. PI has positive corelation RSC, RSBC & KR and there is no significant negative corelation except with CAI. RSC has significantly positive corelation with RSBC (r = 0.786) & high negative corelation with MH (r = -0.765) & PS (r = -0.947). RSBC has significant negative corelation with PS (r =-0.587). Similarly, MH has positive corelation with PS (r = 0.760) and KR has negative corelation with CAI (r = -0.569).

Table 5: Correlation matrix for all the irrigation water quality indices.

	EC	*SAR*	*%Na*	*SSP*	*PI*	*RSC*	*RSBC*	*MH*	*PS*	*KR*	*CAI (I)*
EC	1										
SAR	0.458	1									
%Na	0.092	0.753	1								
SSP	0.098	0.748	0.991	1							
PI	-0.328	0.354	0.818	0.812	1						
RSC	-0.932	-0.408	0.085	0.077	0.567	1					
RSBC	-0.574	-0.227	0.331	0.317	0.743	0.786	1				
MH	0.730	0.369	0.072	0.078	-0.335	-0.765	-0.374	1			
PS	0.992	0.428	0.058	0.064	-0.371	-0.947	-0.587	0.760	1		
KR	0.196	0.870	0.879	0.881	0.577	-0.097	0.059	0.162	0.169	1	
CAI (I)	0.326	-0.340	-0.430	-0.416	-0.468	-0.386	-0.324	0.303	0.357	-0.569	1

CONCLUSION:

The present study aims to assess the groundwater suitability for irrigation in the southern part of the Mahanadi Delta region and its fringes through chemical analysis of 45 groundwater samples. Ground water quality results and groundwater quality parameters such as TDS, %Na, Ca, Cl, PI, and KR for the study area are presented in spatial distribution maps using ArcGIS 10.1.

The chemical composition of groundwater of the study area is more influenced by rock–water interaction and partially by propagation and sea water. In piper diagram, 70% samples indicates either salinisation of coastal aquifers or influence of the connate waters of marine origin. However around 30% samples reflect aquifer processes like carbonate dissolution and effects of anthropogenic activity. The area adjacent to lineaments shows water at an elevated level in comparison to other areas.

The spatial distribution of groundwater quality parameter maps provides a clear vision of groundwater quality in the study area for its suitability for use in irrigation. Based on the indices such as SAR, SSP (or %Na), RSC (RA), KR, PI, CAI, PS, MH, TDS and TH groundwater in majority of the wells fall under suitable category but about 40 % of the water samples fall in moderate to the unsuitable category for irrigation purposes. Thus, the use of groundwater for irrigation (without treatment) near the coastal tract of study area may damage crops and reduces production.

PI, percent sodium (Na%), and KR present the suitability of groundwater for irrigation through maps and tables, which illustrated that groundwater in the northern part of study area is suitable for irrigation except some samples located at the southern edge of the study area due to contamination of aquifer system depicted from high TDS and electrical conductance and increasing value of sodium in some water samples.

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More investigation and continuous monitoring are needed to detect the change in groundwater quality and its suitability for irrigation and other different uses due to sharp increase of the population and intensive agricultural activities that could lead to the deterioration of the water quality in the area.

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DECLARATIONS:

Ethics approval and consent to participate:

The original author and co-authors State that the study was conducted in accordance with relevant international and/or national ethical guidelines. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee. We Ensure that any data sharing adheres strictly to the ethical approvals and consent obtained from participants.

Consent for publication:

Every individual named as an author has reviewed, approved, and agreed to be associated with the final version of the manuscript before submission. The manuscript includes original work of authors and the work described has not been published previously else where.

Availability of data and material:

All data generated or analyzed during this study are included in this published article and its supplementary information files. The datasets generated and/or analyzed during the current study are not publicly available but shall be available from the corresponding author on reasonable request.

Declaration of competing interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contribution:

Contributions: SAHU J. K: Designed the study, Conceptualization, Field investigation, Sample analysis, Validation, Writing – original draft, review & editing. SAHOO H K: Conceptualization, Methodology, Supervision, Writing – original draft, review & editing. SAHOO S: Field investigation, Arc GIS Software plotting. Writing - review and editing. All the authors read and approved the final manuscript.