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Assessment of Surface Water Quality Using Entropy-WQI, Fuzzy-TOPSIS Analysis, Irrigation Indices and Spatial Interpolation Approaches in Mahanadi River Basin, Odisha, India

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ABSTRACT

The current study is aimed at the assessment of surface water quality in the Mahanadi River, Odisha and its suitability for agricultural and consumption purposes, utilizing various indices of water quality such as Entropy Water Quality Index, Osmotic Pressure, Potential Salinity, Residual Sodium Carbonate, Sodium Adsorption Ratio and Kelly Index. Multi-criteria decision-making (MCDM) mechanisms namely, fuzzy-TOPSIS modeling and GIS tools were used; additionally, the suitability of river water for industrial uses was evaluated using indices such as Ryznar Stability Index and Puckorius scaling index. From 2019 to 2023, samples from 19 sampling stations were collected and 21 physical and chemical parameters were evaluated and compared with the normative recommendations advised by WHO. The dispersion of surface water quality on land use changes was discovered using GIS approaches. Additionally, using ArcGIS software, the spatial variability of hydrological processes was determined using the IDW interpolation approach. The pH levels of certain sampling points were slightly above the acceptable limit. Tests revealed that the Total coliform (TC) and turbidity levels in the water samples exceeded critical limits, particularly in areas of the urban river basin that were irrigated with wastewater. The calculated values of EWQI lie between 14.6 and 1066. Entropy WQI values designated 2 locations (ST-8, 19) out of 19 sampling locations as poor category and another one testing point (ST-9) as extremely poor category. The study found that 84.21% of the water samples were of excellent quality for drinking, while 15.78% of locations had poor or extremely poor water quality. However, some indices were favorable for the usage of the water for irrigation purposes. Magnesium hazard (MH) readings at two sampling sites were above 50%, indicating that they were inappropriate for irrigation. USSL (United States Salinity Laboratory) diagrams categorized the water samples as C1-S1 (low salinity and low sodium) for almost 18 sites and C4-S3 (very high salinity and high sodium) for only ONE sample, respectively, suggesting river water's irrigation suitability. Further, Piper diagrams revealed that most investigated waters were Ca^{2+}-Mg^{2+}-Cl^{-} water type. In a later stage, from Gibb's diagram, it was found that most samples fall under the rock-water dominance. Based on the above and all other investigation results, it was concluded that water is suitable for irrigation and drinking purposes in all sites, except for three locations. The reason may be due to long-term use of wastewater, anthropogenic activities, over-extraction of surface water and changes in land use patterns. To sum up, it is advantageous to combine physicochemical properties, EWQI, fuzzy-TOPSIS, and GIS tools to evaluate surface water suitability for consumption and agriculture and their regulating variables. The strategy utilized in this work will aid the water management authorities in ensuring the supply of safe water for stakeholders.

Keywords: Mahanadi; EWQI; Fuzzy-TOPSIS; GIS; Geogenic; Anthropogenic; Over-extraction.

1. INTRODUCTION

Physical, chemical and biological factors show the state of the water system, which is known as water quality. It also affects the health of humans, animals, and vegetation (Kiss *et al.* 2021). A region's physiochemical properties of water depend on a variety of natural processes as well as manmade causes (Zhou *et al.* 2022). Rivers are the foremost source of fresh water and have been used for municipal water supply, irrigation, transportation, energy production, and for carrying wastewater since ancient times (Wang *et al.* 2022). Moreover, water is the essential ingredient for life on earth, and access to water resources is a prerequisite for the environment's continued sustainability (Zhang *et al.* 2022). Human health, agricultural production, gender equality, poverty alleviation, ecological livelihoods, economic development, and social development in communities are all directly impacted by the quality of the water (Chifflet *et al.* 2023). The presence of natural organic matter, which is a complex mixture of different organic molecules primarily derived from aquatic organisms, soil, and terrestrial vegetation, as well as toxic chemicals that are above the level naturally found in water and may pose a threat to the environment, is referred to as water pollution (Choudhury and Chatterjee, 2022). Surface and groundwater quality and quantity will vary as a result of all these factors. The differences in quantity and quality provide essential data for analyzing the local water resource shortage (Zeng *et al.* 2023).

Globally, the rise of industrial and agricultural operations has resulted in a significant decline in surface water quality (Sharma *et al.* 2023a). Nowadays, water quality has become a serious issue and has garnered worldwide consideration for its preservation and protection (Peiravi-Rivash *et al.* 2023). River water quality is also being negatively impacted by several anthropogenic and natural processes, preventing rivers from being used for multiple purposes (Sun *et al.* 2023). It is also one of the main issues in managing and planning for water resources. Through the inhalation of poisonous fumes, ingestion of pollutants both directly and indirectly, and skin contact with toxic water and soil, open dumps present a variety of health risks. Consequently, the quality of water deteriorated increasingly (Kapoor and Singh, 2021). Additionally, the condition of both surface and groundwater, as well as how it affects people's health, have been negatively impacted by an increase in urbanization, construction, agricultural processes, engineering products, natural processes such as volcanic eruption, weathering of bedrock and earth crust erosion, and human impacts such as pollution from coal combustion, metallurgy, mining, and smelting of metals (Nour *et al.* 2022).

It has been noticed that surface water quality has grown extremely important in recent decades, especially in emerging nations like India. It has also become a touchy subject (Yang *et al.* 2022). The process of selecting a specific corrective action for a polluted site is difficult because of the many variables that must be taken into consideration, including the type of soil, the pollutant and the concentration of pollution at the site. Therefore, monitoring the level of components, their concentration, sources, and distribution is crucial to managing water resources and preventing water pollution (Zaynab *et al.* 2022). Due to internal waste stabilization processes that take place as the landfill gets older, the concentration of leachate decreases.

Researchers face a difficult problem when it comes to elucidating monitored data (Hossain *et al.* 2022a). As a result, Water Quality Indices (WQIs) were designed, which combine a vast number of observed characteristics into a single numerical score; also, these are quite user-friendly and can be handled by computational tools with ease (Fan *et al.* 2023a). Further, WQI has made significant contributions to the management of water resources. It is a quantitative technique that enables accurate reporting of water quality data and has been widely used for water quality evaluation of various water resources, including groundwater and surface water, primarily rivers. This method is thought to be the most effective one for determining whether a water source is suitable for human consumption (Leads *et al.* 2023). Horton (1965) made the first modern WQI proposal to predict the variations in water quality status. Since then, scholars have used several indices to classify the water quality in their area, but there is no WQI which is universally recognized.

The creation of WQI involves a lot of subjectivity and uncertainty. Maintaining water quality at a specific level requires constant monitoring. The complexity brought on by a lot of data and multiple factors is a significant downside of water quality monitoring (Shil *et al.* 2019). Nowadays, a Geographical Information System (GIS) is a key surface WQ tool that is extensively utilized. Scientists from several disciplines have created the GIS over the past few decades for geographical research, study and integration (Menberu *et al.* 2021). This was achieved by the Inverse Distance Weighted (IDW) interpolation technique. It is effective in interpreting and analyzing spatial data when used in conjunction with GIS technology. Large datasets can be quickly and affordably transformed into various projections and images of spatial variability, that show patterns, correlations, and many polluting factors (Ustaoglu *et al.* 2021).

Ramachandran *et al.* (2020) investigated the Adyar River basin's seasonal drinking quality using the WQI and GIS in Chennai, Tamil Nadu, India, and showed that most of the investigated area depicts water quality as unsuitable for consumption. The use of diverse methodologies enables in identification of potential components that could hamper the water quality and aids in the interpretation of huge and complicated data sets for a better knowledge of water quality. The WQI and IDW interpolation in GIS systems has been utilized by numerous researchers who are interested in analyzing surface water for drinking reasons. Using the WQI and IDW methods, the Tigris River in Iraq as per Chabuk *et al.* (2020), has been evaluated for water quality, and the findings revealed that the river's downstream waters were getting worse. Furthermore, Magesh *et al.* (2013) reviewed groundwater quality using the WQI and GIS in Tamil Nadu, India, and the findings revealed that the majority of the samples are safe for consumption. However, greater quantities of hydraulics and hydrodynamics data, as well as widespread validation are needed for the mathematical modeling of river water quality (Madhloom and Alansari, 2018), which shows most of the aforementioned issues can be resolved using the WQI in conjunction with GIS.

Numerous studies have been conducted using various agricultural water quality indices, and physical and chemical parameters, to monitor and evaluate the quality of water for agricultural use (Egbueri *et al.* 2021). Irrigation parameters namely, Sodium absorption ratio (SAR), Salt Index (SI), Residual sodium carbonate (RSC), Percent sodium (% Na), Magnesium hazard ratio

(MHR), Residual sodium bicarbonate (RSBC), Corrosivity ratio (CR), Kelley's index (KI), Osmotic Pressure (OP), Chloroalkaline indices such as CAI-1 and CAI-2, Potential salinity (PS) and Permeability index (PI), have been extensively used to classify irrigation system's suitability, which helps determine the rate of aquifer infiltration. It is vital to remember that monitoring the quality of surface water resources should be included as a crucial stage for managing water resources because surface water is a significant source of water for drinking and agriculture. The type and amount of rainfall, the geological structure, and aquifer mineralogy are the main factors that can change the chemical composition of surface water.

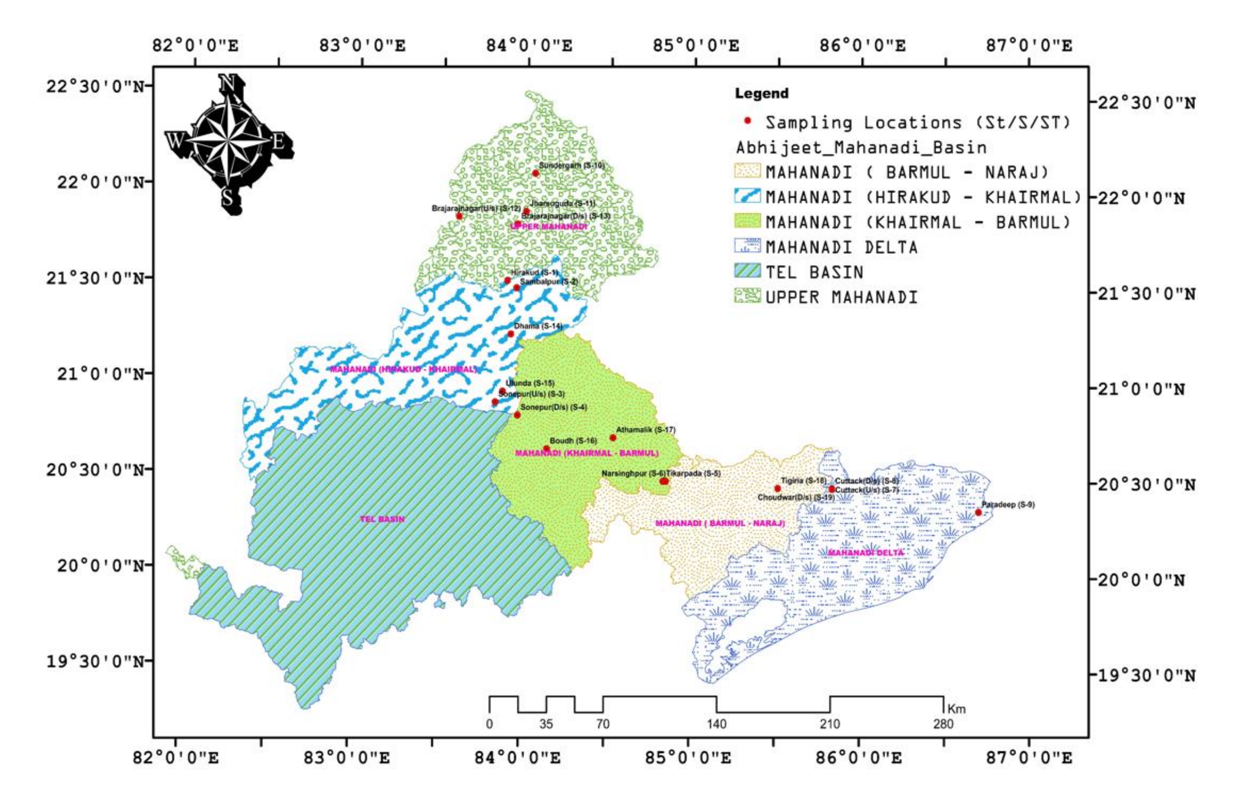

Fig. 1: Location of the study area with surface water sampling points

A surface, and the materials it is surrounded by, may experience corrosion, a physicochemical process that alters the properties of the materials (Wali *et al.* 2020). Corrosion, on the other hand, has a significant impact in drinking water quality. Scaling, a thin coating that forms in pipes and other facilities, because of the interaction between dissolved cations and water-soluble chemicals, is another significant contributor to corrosion (Shil *et al.* 2019). It can lead to several problems in the water distribution system, including clogging of the pipes and channels, decreased equipment life, increased head loss, and increased maintenance and operational costs (Weldeyohanis *et al.* 2020). All these effects can be evaluated using a straightforward mathematical technique that reduces a huge number of water characteristics to a single value that represents the overall impact of water quality values (Preisner, 2020).

Decision-makers can construct important water quality indicators methodically using these techniques. For decision-makers to adopt or implement solutions related to water pollution and scarcity, the combination of WQIs, irrigation parameters, and GIS delivers detailed, rapid, and trustworthy information (Asnake *et al.* 2021). Subjective disturbances would be reduced by assigning fixed weights to indices based on their inherent information. This information could be clarified by Shannon entropy (Negi *et al.* 2020). In their applications, researchers utilized the effectiveness of information entropy. All the parameters' weights and quality rating scales are combined to calculate a numerical score based on cumulative data, which is known as the entropy-weighted water quality index (EWQI). This approach is also termed as Object emancipating method (Pandey *et al.* 2020). The goal of this method is to offer a better way to deliver a cumulatively determined, numerical expression that describes a certain degree of water quality based on information entropy. As a result, the data item relationships are maintained in balance while taking into account the information in the data that is related to the factors. Therefore, it was evident that entropy produced useful outcomes in the examination of indicators (Sajil Kumar *et al.* 2020). These are a step up from conventional WQIs that rely on the Delphi method, the

Analytical hierarchy process (AHP), and the Expert survey method (ESM), which otherwise base parameter weighting on expert analysis and subjective assessment (Kadam *et al.* 2019).

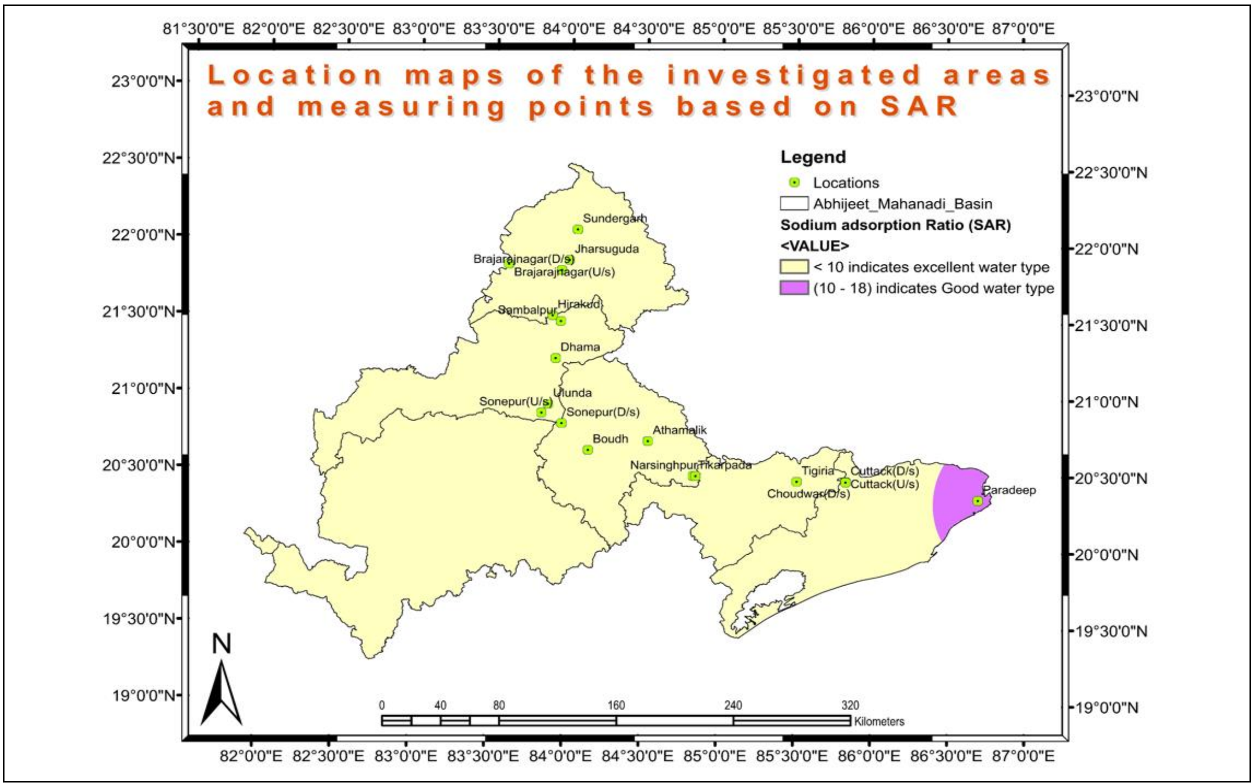

Fig. 2a: Spatial SAR map

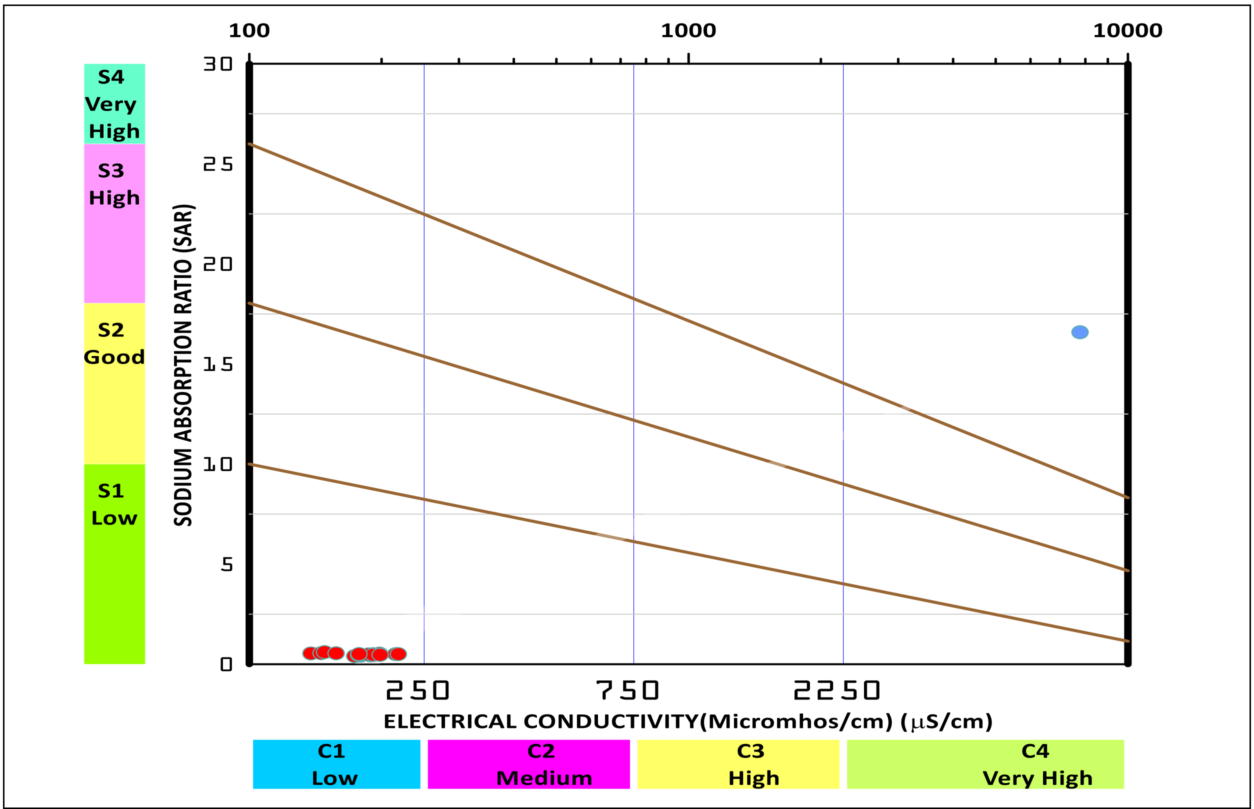

Fig. 2b: USSL map of all chosen sites

Researchers have assessed the possibilities of multi-objective decision-making strategies in stream restoration initiatives in addition to WQIs, including demand response, redressing management, renewable energy sources, and WQI ranking modifications (Saha and Paul, 2019). Each sampling site's overall ranking in terms of pollution level was determined by TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution). It uses information entropy and seeks to create a scenario closest to the Positive ideal solution (PIS) and longest from the Negative ideal solution (NIS) (Hwang and Yoon, 1981). Its capacity to handle uncertainty across a range of sciences, including water quality management, has led to its quick acceptance by researchers and decision-makers.

Fuzzy-TOPSIS logic can be utilized in conjunction with in-depth data analysis for long-term water quality assessment (Van and Pedrycz, 1983). Although earlier studies concentrated on modifying anticipated conflicts in the context of drinking water quality indices and their validation of water quality indices and their classes by the application of TOPSIS, no study to date has identified relatively less polluted sites and relatively more polluted studies by removing conflicts in drinking water quality indices (Sener and Sener, 2015). This calls for the use of the Fuzzy-TOPSIS method to address this weakness and make effective decisions. This method not only provides an overall ranking of the sites by taking into account both physicochemical parameters and heavy metals, but it also prioritizes decisions in the event of contingencies (Goodarzi *et al.* 2022). This is one of the judgment models that has the potential to address many of the issues that planners and decision-makers encounter. It cleared the door for planners to use it as one of the best and most precise models for multi-index decision-making (Tseng *et al.* 2008).

The Arc GIS software's spatial analysis module was used to plot several thematic layers. It enables the statistical development of a relationship to provide a simplified visual representation of the area's WQ. The most popular and reliable technique for producing spatial distribution maps is Inverse Distance Weighted (IDW). Using GIS, this method was utilized to produce geographic variation plots of EWQI categories. With the nearest point receiving more weight, this is used to calculate the indeterminate values concerning the distance. Surface water quality evaluation has made substantial use of MCDMs during the past three decades. The weights of water properties have also been determined using the entropy technique. However, the weights of water quality criteria were subsequently generated by various researchers using the TOPSIS technique; however, this system does not solely rely on human judgment. Several researchers like Chen (2015) intended to classify data using TOPSIS and entropy approaches, resulting in logical conclusions to assess the sustainability of surface water using both quantitative and qualitative indicators. According to them, the most crucial stage in doing such analysis and thorough evaluations is defining the factor weights, which demonstrate the factors' contributions to the evaluation conclusion.

Fuzzy-TOPSIS framework which uses pair-wise comparisons is a well-known MCDM technique for formulating and analyzing decisions. It may be used to rank alternatives and estimate criteria weights (Guo *et al.* 2008). Further, using multi-criteria analysis and GIS, Siefi *et al.* (2017) recommended the best potential thermal power plant sites in Kahnuj Country, Southeast Iran. In the GIS environment, each criterion was mapped. Tabesh *et al.* (2020) conducted a study by employing the TOPSIS technique; he found that researchers have examined the effectiveness of the reduction policies for the apparent and real losses of non-revenue water. Then, Lermontov *et al.* (2009) described a study that evaluated the water quality of a river in Brazil; the development of a quality index showed that this new index might be an effective tool for monitoring the quality of the river under consideration. Dortaj *et al.* (2020) utilized MCDM to choose potential subsurface dam construction (SSD) sites. They claimed that by using an advanced technique, some ambiguities in the selection of SSD sites might be reduced and that the created methodology could serve as the foundation for more in-depth field experiments.

On the other hand, numerous investigations on infrastructure management and rehabilitation have been done, including the replacement of water distribution pipes based on seismic risk, risk-based algorithms, and modeling techniques. Hence, Fuzzy-TOPSIS has been used as a result because interval judgments are more accurate than fixed value judgments. To lessen human ambiguity, the fuzzy set and Saaty's priority theory were integrated (Sadi and Damghani 2010). Seemingly, no study has attempted to realize the scope of its applicability, particularly about the quantification of physiochemical contamination. In addition, very limited literature is available on the feasibility of the combined use of these tools.

The present study was conducted during 2019-2023 to assess the water quality of the Mahanadi River (Odisha, India) and to identify numerous elements contributing to the changes in water quality. 21 physical and chemical parameters in water samples were analyzed during this 4-year study. The uniqueness of the current study lies in the integration of EWQI, GIS and MCDM techniques in the management and monitoring of water quality. WQI rates the water's quality, and MCDMs identify the water bodies' latent, invisible sources of contamination. The main agenda of this innovative work is to analyze irrigation indices such as SAR, % Na, RSC, PI, KR, MR, OP, SI, RSBC and PS as well as determine the river's water quality for industrial uses with LSI, AI, RSI, PSI and LS indices. Piper diagrams were employed to Fig. out the hydro-chemical makeup of the pollutants in water. Gibb's diagrams were used to evaluate the causes of pollution and to assess the suitability of surface water. These analytical methods have all been used to categorize the contaminants and pinpoint potential sources of pollution. This study will set a standard for prospective future studies by thoroughly examining the state of the river water quality and its sources of pollution.

2. SITE DESCRIPTION

Mahanadi River System (MRS) is the third largest in the Indian Peninsula and has historically irrigated agricultural land in the Indian States of Chhattisgarh and Odisha. It is the largest river in the State of Odisha and serves as the domestic water supply to main cities (Pandey *et al.* 2022). The basin is located between the following latitude and longitude: 80°30'E to 86°50'E and 19°20'N to 23°35'N. The area covered by this river measures around 141,600 sq. km. Its entire length spans 851 km, with 357 km running through Chhattisgarh and 494 km through Odisha. The climate in the basin is tropical and receives an average annual rainfall of 1200 to 1400 mm. It is in the subtropical temperature zone, and the placement of the watershed from the Bay of Bengal has a significant impact on the local climate. More than 90% of the total precipitation falls during the monsoon season, which starts in June and lasts until October, even if it happens in spells of varying lengths and intensities.

The basin's economy is largely based on agriculture, with a mixture of commercial and subsistence farming. Rice farming is the primary form of agriculture (Sahoo *et al.* 2023). As a result, the basin's two primary land uses are agriculture and forest, which are both supported by extensive irrigation infrastructure created by major and medium-sized projects. Using the typical annual runoff as a basis, the water availability per person is 1826 m^3. In the basin, there are roughly 54 medium irrigation projects, 22 big irrigation projects, and 5 hydroelectric projects. The basin's projected total live storage capacity is 14.244 BCM, of which 12.799 BCM is finished and 1.465 BCM is under development. This equates to 21.32% of the average annual flow and 28.4% of the reliable usable water, which accounts for 75% of the water supply. According to estimations from this river's per-person irrigation withdrawal of 686 m^3 and its net area irrigated of 1.85 million hectares (Samal *et al.* 2022), respectively. While the predicted ground water share in irrigation is 34%, the intensity of irrigation was determined to be 112%. Cereals are found to use 76% of the irrigation area, with a 47% irrigation efficiency rate. Red and yellow as well as mixed red and black soils are the two main types of soil. Fig. 1 depicts the locations of the study area and the water quality monitoring stations.

3. SAMPLE COLLECTION, PRESERVATION AND ANALYSIS

The catchment area was first surveyed to determine the sampling site's location and to identify the different point and non-point sources of pollution. The selection of appropriate sampling locations was based on the information gathered. Based on the dense population, agricultural activity, and garbage disposal sites in the study area, 19 locations were chosen. A weighted bottle sampler was used to gather water samples in triplicates from 2019 to 2023. Before taking the samples, the vials were cleaned and immersed in HCL (Hamid *et al.* 2020). After collection, the bottles were firmly shut and maintained in a refrigerator at 4 °C. To increase the precision of the data, the bottles were labeled with the site number and date, and preserved. Deionized water was used for carrying out the dilutions. Standard solutions were created by mixing the stock concentrations. During sampling and testing, monitoring of quality and quality control are effective ways to get more precise data (Zaman *et al.* 2018). Quality control as per Standard Methods for the Examination of Water and Wastewaters, 20^{th} edition, published by APHA (2017), has been followed throughout the analysis. Further, the selection of a sampling location is one of the most crucial processes involved in achieving the goal of the current study. The techniques used to determine 21 water quality characteristics include pH, turbidity, TDS, TSS, EC, DO, alkalinity, BOD, TH, HCO_3^-, SO_4^{2-}, NO_3^-, PO_4^{3-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, TC, Fe^{2+} and Cr^{2+} of the collected samples are estimated as per APHA (2017). Water quality parameters were compared using ionic balance error (IBE) i.e., IBM = [(∑cations - ∑anions)/ (∑cations + ∑anions)] *100, to accurately evaluate chemical data, where the unit of measurement for cations and anions is mg/l). The IBE value must stay within the permissible range of ± 5%.

4. METHODOLOGY

Information entropy is a quantitative measure of knowledge, disorder or uncertainty related to the occurrence of a random process. The EWQI is often employed for evaluating the quality of water (Fagbote *et al.* 2014). It is an improvement over the current traditional WQIs, which are otherwise dependent on weighting parameters based on subjective judgments and professional opinion (Li *et al.* 2010). According to the degree of uncertainty reduction, it can be argued that the amount of information can be analyzed indirectly; specifically, a higher entropy tends to result in a higher reduction of spatial uncertainty. Steps involved in the calculation of EWQI are as follows: to remove errors brought on by varying dimensions and units, the first step entails creating an initial matrix of the water samples and the evaluated parameters; the second step lies in creating a normalized matrix that contains the normalized value of each evaluated parameter in a specific sample (Amiri *et al.* 2014; Singh *et al.* 2019; Yu and Tang, 2013). The third step requires the calculation of the information entropy (E) of each parameter that can be assessed, using the formula presented by Claude Shannon (1948):

$$E_n = -(1/\ln n) \sum_{i=1}^{m} Vij * \ln Vij \quad (1)$$

where, n indicates the number of sampling sites and V_{ij} indicates the likelihood that the examined parameter's normalized value (v_{ij}) will occur:

$$V_{ij} = v_{ij}/\sum v_{ij} \quad (2)$$

The fourth step involves the computation of entropy weights (W) such that parameters with lower entropy or disorder are assigned more weightage in the following manner:

$$W_j = (1-E_j)/\sum(1-E_j) \quad (3)$$

Lastly, EWQI is calculated by adding together entropy weights and a quality rating scale:

$$EWQI = \sum W_j * U_j \quad (4)$$

where, U_j for each parameter is given as the ratio of the monitored value (I_j) to its standard value (S_j) i.e.,

$$U_j = (I_j/S_j) *100 \quad (5)$$

Wu *et al.* (2011) categorized the surface water quality, describing water with an EWQI<50 as excellent quality, between 50 and 100 as good, between 100 and 150 as average, between 150 and 200 as being poor, and EWQI>200 as extremely poor quality (Sajil, 2014; Shweta *et al.* 2013).

Hence, Fuzzy-TOPSIS is a multicriteria decision-making (MCDM) technique as a result of ranking the options. Based on information entropy, it seeks to identify an alternative or scenario that is both the furthest away from NIS and the closest to PIS. It is a suitable tool for making decisions between a variety of options by calculating their Euclidean distances. It is a useful tool for decision-making processes and can be used in the ways listed below, per the advice of Hwang and Yoon (1981). It stated the alternatives (sampling sites) and criteria (parameters for salinity and infiltration hazards) to which the ranking has to be applied based on its contaminated status. Then, criteria Weights were determined, based on information entropy methodology, that is referred as,

$$q_{ij} = x_{ij}/ (x_{ij} + \dots\dots\dots + x_{mj}); \text{ for all } j \in \{1\dots, c\} \text{ and,} \quad (6)$$

$$E_j = [-1/\ln (m)] \sum q_{ij} * \ln q_{ij}; \text{ for all } j \in \{1\dots, c\} \quad (7)$$

where, $0 \leq E_j \leq 1$ (where the fluctuation in an index with a higher entropy is also found greater). Therefore, the criteria's weight can be calculated. as:

$$W_j = d/ (d_1 + \dots\dots. + d_j) \text{ and,} \quad (8)$$

$$d_j = 1-E_j \quad (9)$$

After continuing this process, the final proximity or closeness coefficients (C.C.) of every alternative were calculated as:

$$\text{Performance score (PS)} = d_i^- / (d_i^- + d_i^+) \quad (10)$$

Finally, the possibilities were ordered by their closeness coefficients.

Additionally, irrigation water quality is a good indicator of its suitability for agricultural use. However, the highest agricultural output can be supported by good water quality (good soil and water management methods). Understanding the quality of irrigation water is important for deliberate management methods or other modifications that are necessary for long-term productivity. In light of this, the irrigation assessment parameters SAR, %Na, RSC, PI, KR, MH, RSBC, and PS were calculated, with all ions expressed in meq/l. The SAR index measures the percentage of Na^+ to Ca^{2+} and Mg^{2+} in a sample of ions. Sodium hazard can be easily comprehended by knowing SAR and is computed utilizing the formula:

$$SAR = Na^+ / 2\{(Ca^{2+} + Mg^{2+})/2\}^{0.5} \quad (11)$$

A greater quantity results in the creation of an alkaline soil, which in turn causes an excess of sodium in the water to have unfavorable impacts on the soil's qualities (creating a crust, causing water to pool, reducing soil aeration, reducing infiltration, and decreasing soil permeability, among others) (Manae *et al.* 2019). The index classifies/divides the irrigation water into four groups *viz*, value less than 10, represents ‘excellent’, between 10 and 18, highlights ‘good’ class, value varied among 18 to 26, indicates ‘doubtful’ and finally, more than 26, belongs to ‘not suitable’ category. Sodium percentage, in other words, soluble sodium content, is also another sign of the quality of irrigation water. Salinity danger, a TDS measurement stated in terms of EC, lowers plant osmotic activity and subsequently interferes with soil nutrient and water uptake (Edo Harka *et al.* 2021). Na^+ interacts with the soil and causes particle blockage, which lowers permeability. It can be determined using the relationship as given by:

$$Na\% = [Na^+ / (Ca^{2+} + Mg^{2+} + Na^+)] *100 \quad (12)$$

Fipps (2003) revealed that irrigation with water with a sodium content greater than 60% might cause sodium buildup in the soil, which will impair the soil's physical qualities. RSC is a combination of CO_3^{2-}, HCO_3^-, Ca^{2+} and Mg^{2+} ions. To determine the suitability of surface water irrigation through RSC, it is an important parameter and is expressed as:

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (13)$$

High RSC values have the potential to cause agricultural soil salinization and solidification. Irrigation should not be done with water that has an RSC index of more than 2.5 meq/l. It is moderately appropriate with an RSC between 1.25 and 2.5 meq/l and safe for irrigation with an RSC index less than 1.25 meq/l. Due to the deposition of sodium carbonate, fields irrigated by water with a high RSC have a high pH and become infertile (Namara *et al.* 2022). PI is a crucial factor to consider while evaluating the irrigation water's quality in relation to the soil for advancement in agriculture and it is expressed in meq/l. This value is determined through the formula:

$$PI = [Na^+ + (HCO_3^-)^{0.5} / (Ca^{2+} + Mg^{2+} + Na^+)] * 100 \quad (14)$$

Irrigated water influenced by Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- content changes the soil's permeability after prolonged use (Wali *et al.* 2020). Doneen (1965) separated the agricultural water into three categories by employing the permeability index (PI): Class I refers to 100%, which highlights 'maximum permeability', indicating 'suitable' for irrigation use, Class II represents 75% 'maximum permeability', that shows 'slightly appropriate' in nature and Class III signifies 25% 'maximum permeability', that represents 'unsuitable' for irrigation use. According to Keley's (1951) theory, the Na^+ problem in irrigation water may be easily resolved using the KI ratio values. This is a synthesis of Na^+ against Ca^{2+} and Mg^{2+} ions. This is calculated *via*,

$$KI = Na^+ / (Ca^{2+} + Mg^{2+}) \quad (15)$$

where, ions are characterized by meq/l. When KR is less than 1, water is suitable for irrigation, and when KR is greater than 1, it is not appropriate for cultivation. In irrigated soils, an overabundance of Mg^{2+} can typically exchange the Na^+ content. The soil structure is typically harmed by greater Mg^{2+} concentrations, which causes the water to absorb more Na^+ and salts and reduce crop yields (Hatfield and Prueger, 2015). The magnesium hazard (MH) is the harmful result of the excessive amount of Mg^{2+} in the water utilized for irrigation. Paliwal (1972) created an index for generating the index, which is shown in the following equation:

$$MH = [Mg^{2+} / (Ca^{2+} + Mg^{2+})] * 100 \quad (16)$$

Water with an MHR of less than 50 is regarded as appropriate, whereas surface water with an MH of above fifty is not acceptable for irrigation. Due to the precipitation of HCO_3, continuous irrigation decreases soil permeability. Since there is increased HCO_3 in irrigation water, sodium carbonate deposition will inhibit plant growth and slow the pace at which water permeates the soil (Angello *et al.* 2021). Since bicarbonate ions do not precipitate magnesium as an ion and the majority of natural waters do not contain significant amounts of carbonate ions, a measure known as residual sodium bicarbonate (RSBC) will be used to assess the alkalinity risk. An equation is utilized to calculate it and it is given as:

$$RSBC = HCO_3^- - Ca^{2+} \quad (17)$$

where, the unit of measurement for ion concentrations is meq/l. The index values of 5 meq/l were deemed satisfactory by Ravikumar *et al.* (2013). Plant growth may be impacted by concentrations higher than 10 meq/l. In the case of PS, the plants are at risk from salinity due to the overly salinized water. This higher number may have detrimental effects on the soil's structure and permeability (Neina, 2019). The salinity of the river is steadily rising each year and is now acknowledged as a significant issue for water users downstream. It is defined as the Cl^- concentration multiplied by 50% of the sulphate concentration. This is represented or calculated using an equation i.e., $PS = Cl^- + (½ * SO_4^{2-})$. Low salt-containing water is suitable for agricultural uses (Mekonnen *et al.* 2020). The Corrosivity Ratio (CR), which is defined as the ratio of alkaline earth metals to saline salts in surface water (Ryner, 1944), is used to indicate how susceptible surface water is to corrosion. Corrosion has an impact on the hydraulic capacity of pipes. It serves as a crucial indicator of whether water supply via metal pipe is possible. Its equation is given by,

$$CR = [(Cl^-/35) + \{2*(SO_4^{2-}/96)\}] / (CO_3^{2-} + \{HCO_3^-/100\}) \quad (18)$$

as suggested by Balasubramanian (1986).

The quantity of Cl- is related to the Chloroalkaline index (CA-I). The Cl^- ion regulates the balance of the soil and aids in plant photosynthesis; however, their excessive concentrations change the chemical makeup of the soil and make plants poisonous. The presence of ion exchange between the rock and water is also determined by CAI-1 and CAI-2. These indices help us comprehend the chemical processes in which ion exchange occurs. According to Schoeller (1977), it is calculated by,

$$CAI1 = (Cl^- - \{Na^+ + K^+\}) / Cl^- \text{ and,} \quad (19)$$

$$CAI2 = (Cl^- - \{Na^+ + K^+\}) / (SO_4^{2-} + CO_3^{2-} + NO_3^-) \quad (20)$$

After that, the Cl^-/HCO_3^- ratio can be used to categorize the level of salinization in the surface water. According to Revelle's (1941) classification, a zone with a score of 0.5 is referred to as 'not affected' zone, one with a score of 0.5 to 6.6 as 'slightly to moderately' affected, and a score of >6.6 as 'severely affected'.

In the case of Osmotic pressure (OP) analysis, it alludes to a variable that is concerned with the conductivity of irrigation water. It suggests that osmotic pressures of 15-20 atm cause plants to wilt permanently. The concentration of salt hinders plant water uptake due to osmotic effects, which have an impact on plant growth (Tiwari and Manzoor, 1988). As per classification, an OP value less than 10 is suitable for agricultural activity, promoting "no wilting of plants", while a value greater than 10 deems the plants unsuitable and indicates that "plants will wilt permanently".

Moreover, water bodies are categorized depending on their salt index (SI). Total Na^+, total Ca^{2+} and Ca^{2+} as $CaCO_3$ of irrigated water were taken into account to assess salt index. If SI has a negative value, irrigation is safe; if it has a positive value, irrigation is inappropriate. Hence, Piper (1944) developed a modified trilinear diagram to comprehend the hydrogeochemical regime of the research area. It has three unique fields—two triangular and one diamond-shaped—and it describes the variation or dominance of cation and anion concentrations in a way that is easy to understand. The character of the water is indicated by the relationship between the ions namely, Na^++K^+, $Ca^{2+}+Mg^{2+}$, $CO_3^-+HCO_3^-$ and Cl^-, and SO_4^2, which is projected from each point on the diagram into the upper field along a line parallel to the upper field edge. As per Gibb's diagram, despite the fact that it did not properly reflect the effects of human activity on hydro-chemical mechanisms, it is frequently used to analyze changes in hydrochemistry in river water (Gibbs, 1970). By plotting the weight ratios, this graphic was used to evaluate hydro-chemical processes such as the dominance of atmospheric precipitation, the dominance of rock weathering, and the dominance of evaporation-crystallization by $(Na^++K^+)/(Na^++Ca^{2+})$ and $(Cl^-/Cl^-+HCO_3^-)$ and it is shown as a component of the TDS. This graph offers excellent genetic details on the make-up, provenance, and distribution of the dissolved components in surface water.

For suitability for industrial use, water is needed by businesses for several reasons, including processing, cooling, boiler feeding, and hygienic functions (Langelier, 1944). However, the water quality needed for various sectors differs depending on the type of industry. While some companies, such as those in the dairy, brewing, and carbonated beverage industries, require drinking water requirements, some require water quality that can prevent pipe corrosion and scale development (Langelier, 1936). In this regard, the suitability of water for industrial uses has been determined using the Langelier saturation index (LSI), aggressive index (AI), Larson-Skold index (LS), Puckorius scaling index (PSI) and Ryznar stability index (RSI). In 1936, Langelier developed the LSI to analyze how well different water conditions can support scale growth. Additionally, it forecasts whether calcium carbonate will dissolve, precipitate, or be in equilibrium with water. The LSI is determined as the difference between the water's actual pH and the pH at which $CaCO_3$ is saturated and it is given by,

$$LH = pH_{measured} - pH_s \tag{21}$$

where, $pH_s = A+B-C-D$ (22)

Following this, the Langelier method is used to compute pHs A, B, C, and D. Further, Langelier also, invented the water corrosivity measurement tool known as the aggressive index (AI). However, the AI is easier to use and more convenient than the LSI because it does not consider the impact of temperature. This was estimated by,

$$AI=pH_{actual} +C+D \tag{23}$$

where, by utilizing the LSI approach, the values C and D are calculated. Ryznar developed a Stability Index, which is typically thought of as non-corrosive or scale-forming, to reduce or avoid the misconception of a positive saturation index. It is defined by $RSI = 2pH_s - pH$, where pH refers to the 'measured pH of the solution' and the pH_s signifies 'pH at the saturation point', and it is estimated by the LSI approach (Haritash *et al.* 2016). For all waterways, their stability score is always positive. Afterwards, two important indices *viz*, PSI and LS are also used to overcome the serious challenge of scaling and corrosion (Galib *et al.* 2017). The equation for PSI is represented as

$$PSI = 2\,(pH_{equivalent}) - pH_s \tag{24}$$

and for LS, it was estimated by,

$$LS = (Cl^- + SO_4^{2-}) \,/\, (HCO_3^- + CO_3^{2-}) \tag{25}$$

Hence, concerning water corrosivity or scaling, these methods greatly aid in evaluating the surface water buffer's capacity.

5. RESULTS AND DISCUSSION

Generalized Quality of Surface Water

Surface water chemistry is crucial since it is used to assess the quality of water for household, commercial and industrial uses. The proportions of hydrogen ions (pH) in water are quite significant. This helps to identify the nature of surface water, either acidic or alkaline. The value of pH varied from 7.3-9.7 mg/l, indicating alkaline conditions and nurtures phytoplankton growth. It is noticed that in accordance with the WHO's recommendation, the pH range will be taken as 6.5-8.5 for potable water. Besides, the high pH of irrigation water (>8.5) in St. 8 and 9, which harms vegetation, may be brought on by excessive levels of HCO_3^- and CO_3^{2-}. The clarity of water decreases due to the presence of these suspended particles that get deposited in the water termed as turbidity. Turbidity is permitted up to 5 NTU, according to the WHO. The values in the present study lie between 8.2 and 25.2. The value was discovered to be high in all-weather circumstances due to the presence of organic and inorganic debris from home wastewater disposal and fertilizer waste (Rawat *et al.* 2018). The expression for the entire amount of salt mixed with water is described as TDS (total dissolved solids). It is made up of significant ions dispersed in surface water, including calcium, magnesium, sodium, potassium, chloride, sulphate, nitrate, carbonate, and bicarbonate. Major health concerns like kidney stones, heart disease, and stomach difficulties could be brought on by a high TDS value. In the investigation, apart from ST-9, the recorded values ranged from 74-13200, indicating well within the limits (500 mg/l). The high amount of TSS (total suspended solids) may be due to the suspension of clay and soil particles. Due to excessive TSS, less light enters the water and photosynthesis proceeds more slowly. These effects lower the DO level and lessen the clarity of the water. The concentration varies from 30-121. However, the score was significantly below the cutoff of 500 mg/l as per WHO (2017), indicated for drinking and agricultural purposes.

EC (electrical conductivity) is a gauge for the water's salinity or dissolved ionic content. Elevated EC value measures the overall dissolved solids, aquifer type, interactions between rocks and water, and human activity (Saha *et al.* 2019). The quantity of mineral salt soluble in water increases with increasing EC and TDS values. It was in the range of 96-7770, which is well satisfying the WHO criteria of 2250 µS/cm except at Site 9. DO (dissolved oxygen) is an essential parameter for the assessment of surface water quality because it influences the organisms living within the water body. It is mostly used as an indicator of a river’s health. For the aquatic environment to function properly, there must be enough DO present. The DO values for this investigation were found to be 4.78-8.01. Hence, DO levels are healthy in the entire study area.

Alkalinity is brought on by the water's carbonate, alkali, and hydroxyl ions. Higher alkalinity in water, and vice versa, increases its ability to neutralize acids. A large amount gives off a harsh flavor and is bad for irrigation since it harms the soil and lowers crop yields (Sylus and Ramesh, 2018). It should not exceed 120 mg/l as per WHO (2017). The values fall between 43-99. In all the sampling seasons, the value was found within the permissible limit. BOD (biochemical oxygen demand) is the amount of oxygen used by microorganisms to decompose the organic matter. Improper greywater, foliage and other woody debris, dead animals, and animal manure were the main causes, according to the report. In the estimated study, the BOD values contributed in the range of 0.86-4.23. It is observed that the value was within the WHO standard limit (5 mg/l). Total hardness (TH) is made up of Ca^{2+}, Mg^{2+}, CO_3^{2-} and HCO_3^-; dilution in water is caused by weathering of silicate, calcite and dolomite as well as by mass bathing, detergent use and the discharge of domestic sewage and industrial effluents. It is an influence of Ca^{2+} and Mg^{2+} ions, within a river and had a frequency of 64-2170 Hz and was visible at Site 9, which was higher. This parameter is associated with natural rock weathering and runoff. Most of the values in the present study were below the permissible limit of 300 mg/l. Additionally, the bicarbonate (HCO_3^-) content was linked to physical weathering and interactions between rocks and water. Also, Ca^{2+} content on soil exchange sites decreases as HCO_3^- concentration increases. In the present investigation, the values ranged from 41.92-87.55.

The results indicated that at all of the chosen stations, concentrations during the wet season were greater than the levels during the dry season. Sulphate (SO_4^{2-}) is produced naturally in water as a result of gypsum being leached. The observed values ranged from 2.4 to 370. The quantity in the river was at a level that did not provide a health risk, and the current readings in the study region were below the WHO standard of 250 mg/l. If the measurement at Site 9 is higher than 250 mg/l, the soil becomes acidic. The main causes were people's trash disposal in open spaces, sewage treatment and chemical fertilizer that initiates nitrate (NO_3) contamination in surface water. The prolonged drinking of water containing this characteristic may cause serious illnesses like cardiac issues and blue baby syndrome. The NO_3^- content was found to be in a range of 0.81-4.86. The recommended limit for drinking water is 45 mg/l. However, all observations were within the prescribed limits for all sampling locations. Phosphate (PO_4^{3-}) parameter enters water systems via a variety of sources, such as sewage, manure, and various synthetic fertilizers used in farm areas. During the study area, its value ranged from 0.25 to1.04.

The findings showed that all of the water samples were within the WHO recommended limits of 1.2 mg/l and could be consumed directly without further treatment. Important sources of Cl^- (Chloride) in surface water include leaks, septic tanks, residential waste, dry climate, and irrigation return flows. The ingestion of water containing a higher dose of Cl^- can cause hypertension, osteoporosis, rental stones and asthma. The level of Cl^- in the study area is found to be ranged for 7.87-4900, which is included within the permissible range of 250 mg/l, except at ST-9. Ca^{2+} (Calcium) is an important element in developing proper bone growth, fluid balance in the body, muscle contraction as well as the descent of the testes. As per WHO guidelines, this parameter holds a permissible limit of Ca^{2+} as 75 mg/l. Excess of it can cause gastric disorders, kidney problems, bladder stones and urinary obstruction in humans. In the study area, it ranged from 14.83 to 28.72.

Water with Ca^{2+} levels in all the locations was within the WHO limits. In addition, a shortage of Ca^{2+} or K^{+} in plant tissues is caused by the greater concentration of Mg^{2+} (magnesium) in the irrigated water. Its overuse may result in serious health problems for people who utilize water for drinking and agriculture. The permissible limit of Mg^{2+} is 30 mg/l as per WHO standards. In the present study, the Mg^{2+} concentration ranged from 1.58 to 4.63 and these scores remained below the maximum allowable level at all sampling locations. Na^{+} (Sodium) is the most important element and is present in natural water. Elevated levels are associated with increased risks of cardiac disease, weathering of rock-forming minerals and dissolution of soil salts present therein due to evaporation. The limit set for drinking water is 200 mg/l as per WHO. The recorded values observed from 2-10.10. Low Na^{+} in river water could be brought on by the physical makeup of the soil and rocks, as well as the local climate's humidity and temperature. With the application of potassium (K^{+}), long-term cropping will reduce soil fertility. As a result, this is a crucial component for improving irrigation. This is referred to as a vital component of plant and human nutrition. In the present investigation, the values recorded between 0.7-3.20 and were less than the 12 mg/l as per WHO standard. The increase in coliform suggests that the balance of the aquatic ecosystem is disturbed, so the diversity of aquatic species could have decreased. In the study area, the value ranged between 970 and 42000 in the case of TC (total coliform). Higher levels have been reported in the waters at ST-8 and 9, which are near to factories, municipal sewers, or hospitals. The concentration of Fe^{2+} in the river was 0.19-1.08 in the present study. Although iron (Fe^{2+}) is a crucial component needed for the blood to pick up more oxygen, in high concentrations, it can destroy DNA and result in haemolytic anaemia. The concentration in all the water samples is below the permitted threshold of 1.0 mg/l except for Site 9. In addition to raising the Fe^{2+} content of the river water, the rainwater that came into contact with the soil also raised the iron concentration of the surface water. The degree to which Cr^{2+} is oxidized determines how it affects human health. Although it is a necessary component for human health, excessive intake can have negative effects on the liver and kidneys.

Drinking water with chromium (Cr^{2+}) lowers fatty acid and cholesterol levels and controls blood sugar and insulin levels. Cr^{2+} content readings vary from 0.05 to 0.17 at all sampling sites of the research area, which is under the threshold of drinking water restrictions (0.2 mg/l).

The quantity of soluble ions in the irrigation water has an impact on the physical and chemical characteristics of agricultural soil as well as plant growth (Ameen, 2019). Some significant indices are used to assess the quality of river water used for irrigation, including RSBC, SAR, MH, RSC, KI, PI, % Na, and PS. To determine whether river water is suitable for agricultural use, all factors are taken into account. SAR is a method for analyzing irrigation water's propensity to trigger a cation exchange process in soil and calculating the ratio of Na^{+} to Ca^{2+} and Mg^{2+} ions in water. Applying this index to the samples in the existing study indicates the magnitude of the SAR value, which fluctuates between 0.09 and 16.59, which signifies that water samples belong to the excellent category (Fig. 2a). It indicates that no alkali hazard is expected to the crops in all locations except Site 9.

USSL diagram points to a significant relationship between SAR of irrigation water and the extent of sodium adsorption by soil. The high presence of Na^{+} salts in soil affects its physical condition and the texture of soil makes it tough to plough. This helps to categorize irrigation water quality through a plot between SAR and EC (Fig. 2b). It was discovered that the majority of the samples belong to the C1-S1 zone, which denotes a low salinity and low alkalinity hazard area. One sample (Site 9) comes under C4-S3, which belongs to high salinity and very high alkalinity region. The main cause behind this is excessive solutes in irrigation water is a common problem in semi-arid areas where water loss through evaporation is maximum. Water grading based on Na^{+} concentration might be utilized to effectively irrigate the basin area since the permeability of soil is impacted by the Na^{+} concentration (Tadessa *et al.* 2018). The calculated results of % Na varied from 22.95% to 91% during the sampling duration. However, most of the samples fell under good to unsuitable quality. It is noticed that higher Na% (>10) is exhibited in most of the locations indicating that redox reactions and rock degradation from rock strata are dominant processes (Fig. 3).

RSC is thought to be a useful technique for determining if water is suitable for irrigation based on the carbonate-to-bicarbonate ratio (Edokpayi *et al.* 2017). This work displays a range from -0.138-0.78, and all reported values at all sites were under the class of good water quality (RSC<1.25). Thus, demonstrating that for all seasons river water may be used for irrigation (Fig. 4). Additionally, the fact that most sites have negative RSC indicates that Ca^{2+} and Mg^{2+} have not precipitated completely. A high MH ratio in water can interfere with the overall balanced Ca^{2+} and Mg^{2+} ratio. The MH values range from 18.34-85.55 (Fig. 5). The findings show that 94.73 % of the specimens were appropriate for irrigation i.e., (MH<50). The surface water samples were used to compute the KI, which ranged from 0.32 to 8.5. It shows that 84.2 % of the study region's samples, which is less than unity, indicate that these samples are acceptable for irrigation, whereas only about 15.7% of the samples are unsuitable for farming activities (Fig. 6).

On account of PI, it is a helpful tool for determining whether water samples are appropriate for irrigation (Aliyu *et al.* 2020). Based on the PI values observed in Fig. 7, its values ranged from 65 to 107.51%. It suggests that most of the locations fall into Class II. Based on RSBC, values ranged from 0.20 to 7.0, in the ongoing work. The values in the present investigation (Fig. 8) are significantly below the satisfactory value (<5) except Site 9 and it can be considered safe for irrigational purposes. As per the study area, in the context of PS values (Fig. 9), it ranged between 0.13 to 10% and is considered fair low at most of the places, with an exception at sites 8, 19 and 9. It is observed that the PS is extremely important in the estuary region because of the high concentration of salt in sea water (Nguyen *et al.* 2020).

Further, the current investigation demonstrated that the CR level at all sampling sites was found to be 0.120-2.0 mg/l. The increase in CR value at sites 9, 10 and 19 (Fig. 10) was caused by the irrigation water's higher Cl^- and SO_4^{2-} concentrations. This result supports the complaints of many farmers who have noticed damage to the irrigation pipe channel at these locations in the research region. In this investigation, the values of CAI1 (Fig. 11) and CAI2 (Fig. 12) fluctuated in a range of -0.33 to 0.37 and -1.48 to 2.34 meq/l, respectively. So, these data points show a direct interaction between Ca^{2+} and Mg^{2+} from rock and Na^+ and K^+ from water. Some samples contain negative values, exhibiting the exchange between Ca^{2+} or Mg^{2+} in the surface water with Na^+ or K^+. So, negative value-containing sites observe normal ion exchange. It was estimated in the present study, in the case of $Cl^-/HCO_3^{-\ \mathrm{ratio}}$, that for all surface water samples, the value varied from 0.13-0.38, which signifies all samples are safe and come under not affected zone category. However, it can be seen from the outcomes that 100% of the samples from the research area possess values less than 0.5 Cl^-/HCO_3^- ratios, which highlights that they are not affected by salinization. In the case of Piper analysis, the triangular cationic field shows that the majority of the samples fit within Ca^{2+}-Mg^{2+} type. In regards to the anionic triangle, samples fall into Cl^- group. However, all samples fall in the diamond-shaped field which indicates the predominance of Ca^{2+}-Mg^{2+}-Cl^- type (Fig. 13). This might indicate hardness and the chemical properties were dominated by alkaline earths and weak acids. It was noticed from (Gibb's diagram (Fig. 14) that most of the samples have a plot in the rock-water interaction field. TDS, Ca^{2+}, Mg^{2+}, Na^+, Cl^- and HCO_3^- ions in river water were derived through the rock-water interaction, which caused the weathering of minerals present in the water of the semi-arid region.

Along with reactions to home, industrial and agricultural activities, the hydrosphere, atmosphere, and biosphere also had an impact on the chemical composition of the nearby rocks and the variations in river water chemistry. From the reported results (Fig. 15) of OP, it is varied in a range of 4-20 atm. It shows that the water is suitable for irrigation at 16 sites, while in three samples (Sites 8, 9 and 19), it indicates unsuitable and plants will wilt permanently, if not controlled. Following this, the presence of sodium in the surface runoff from the basin area may be a contributing factor. SI was also assessed for all of the water samples because higher salt concentrations in the water will negatively impact the quality of the soil and crop productivity (Fig. 16). The reported readings span in a range of -92 to 10, during the chosen period. All the SI values of this study were below zero, indicating 'safe' for irrigational activity. Only one sample (ST-9) was above zero, making it unsuitable for irrigation. The presence of high sodium and magnesium, which are sourced from marine sources, is what causes these high amounts in this estuary environment. Therefore, regardless of the season, estuary water samples have a significantly high salt index when compared to freshwater systems; this can be attributed to the high levels of salt from seawater. As a result, fresh zone waters are suitable for irrigation while estuary stations are not at all suitable, according to SI.

For industrial purposes, Mahanadi River was examined to determine its suitability, based on a few well-known indices, namely, LSI, AI, RSI, PSI and LS. The calculated values of LSI/LI varied from -3 to 0.10, indicating the "highly aggressive to non-aggressive" in nature (Fig. 17). Usually, non-aggressive water is favored in businesses due to its applications. The AI scores fluctuate in the range of 8-11.90, in the ongoing research. Almost all tested water samples were in a class of 'highly to moderately aggressive' for industrial use (Fig. 18). The RSI values (Fig. 19) at all sampling sites were greater than 9, indicating the river water was 'highly aggressive and corrosion is intolerable'.

Likewise, the PSI and LS were used to assess the degree of corrosion in the water tubes. The distinctions between water that is scaling or saturated have been identified, using the Puckorius index (Fig. 20), while the LS has been used to evaluate the water's corrosivity in low-carbon wrought iron and steel pipelines. From the results, water in this study was corrosive at ST-(2), (7), (8), (9), (10), (11), (12), (13) and (19), based on PSI and LS (Fig. 21). To overcome this effect, a protective coating made of chloride and sulphate will grow around the pipelines to counteract this damage. Similar results from other investigations have been published earlier (Mankikar, 2021; Egbueri, 2022); corrosion risks are predicted to be bigger than scaling risks. But significantly, the results of these five indices show that natural water supplies are more corrosive than encrustation-prone. This shows that without treatment, river water is unfit for industrial use.

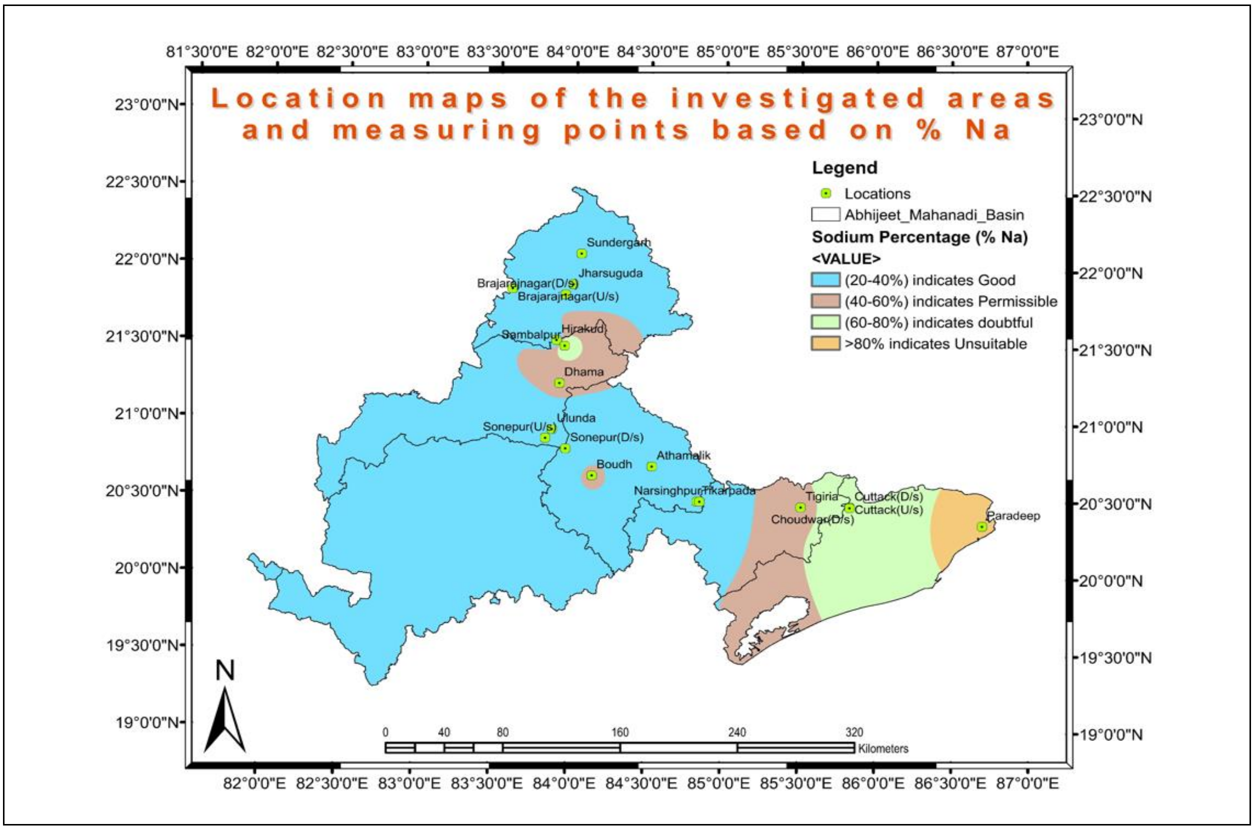

Fig. 3: Spatial map of Percent sodium (% Na)

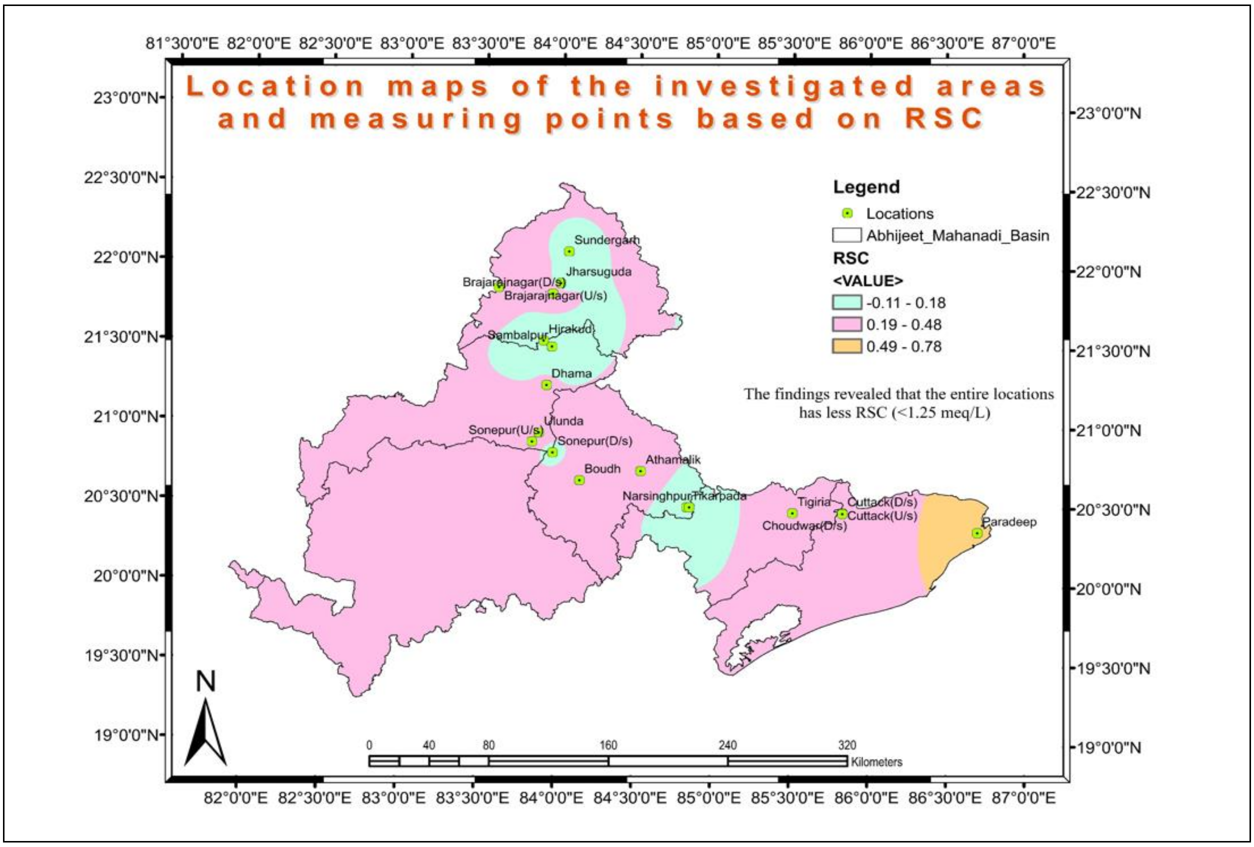

Fig. 4: Spatial map of Residual sodium carbonate (RSC)

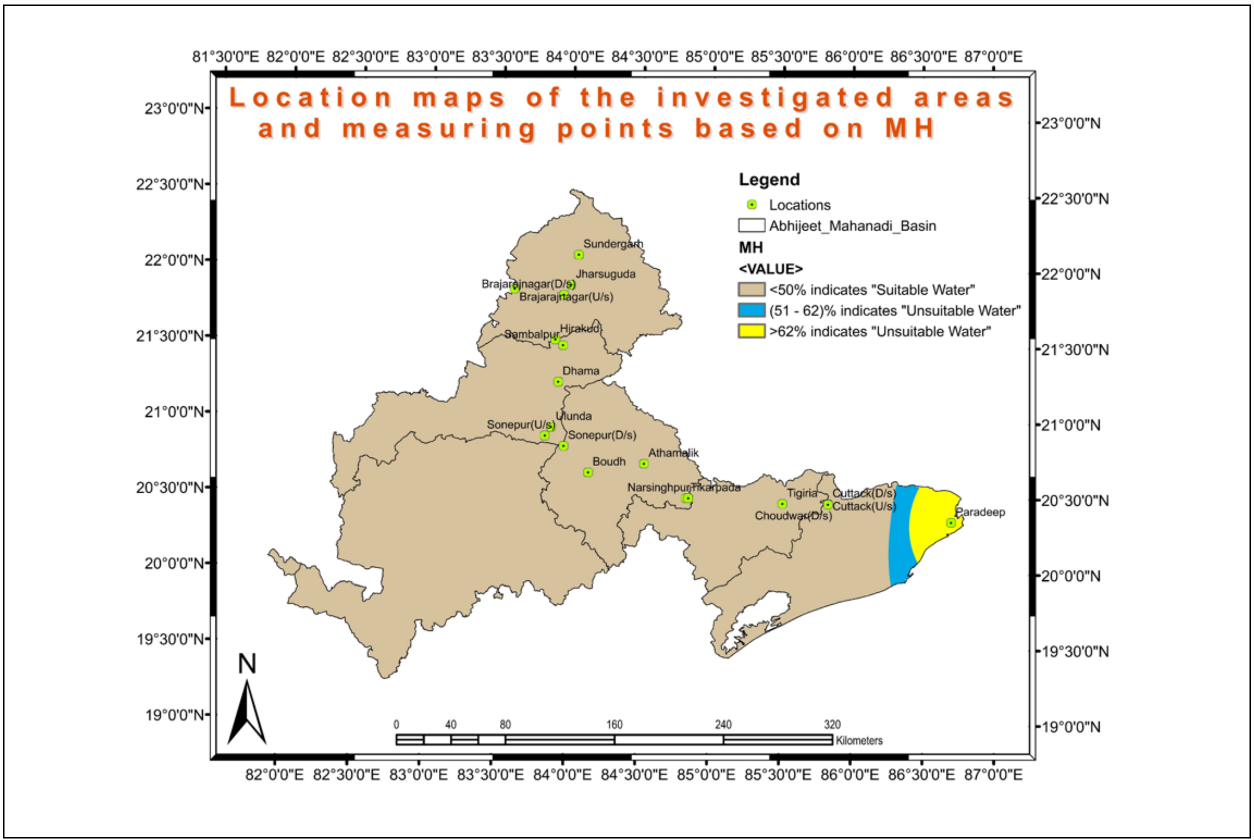

Fig. 5: Spatial map of Magnesium hazard (MH)

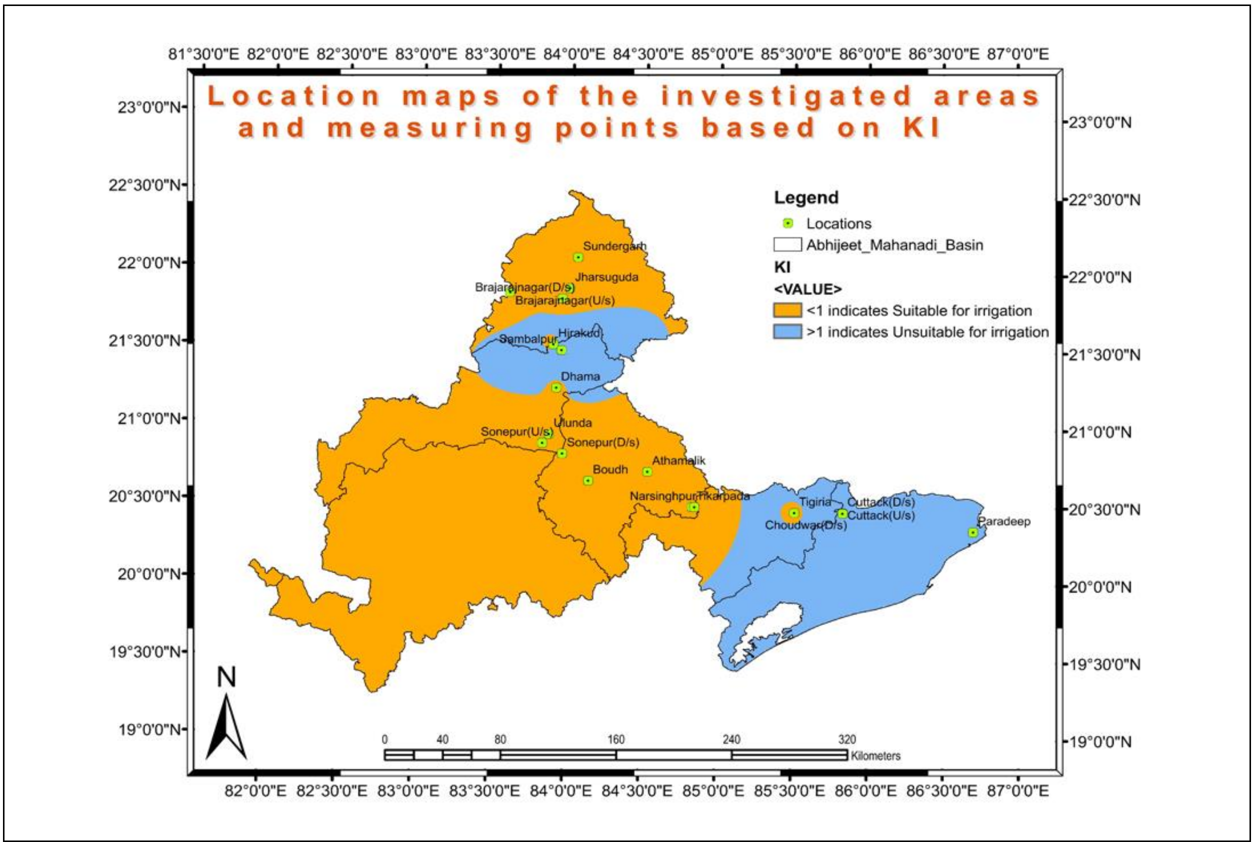

Fig. 6: Spatial map of Kelly's Index (KI)

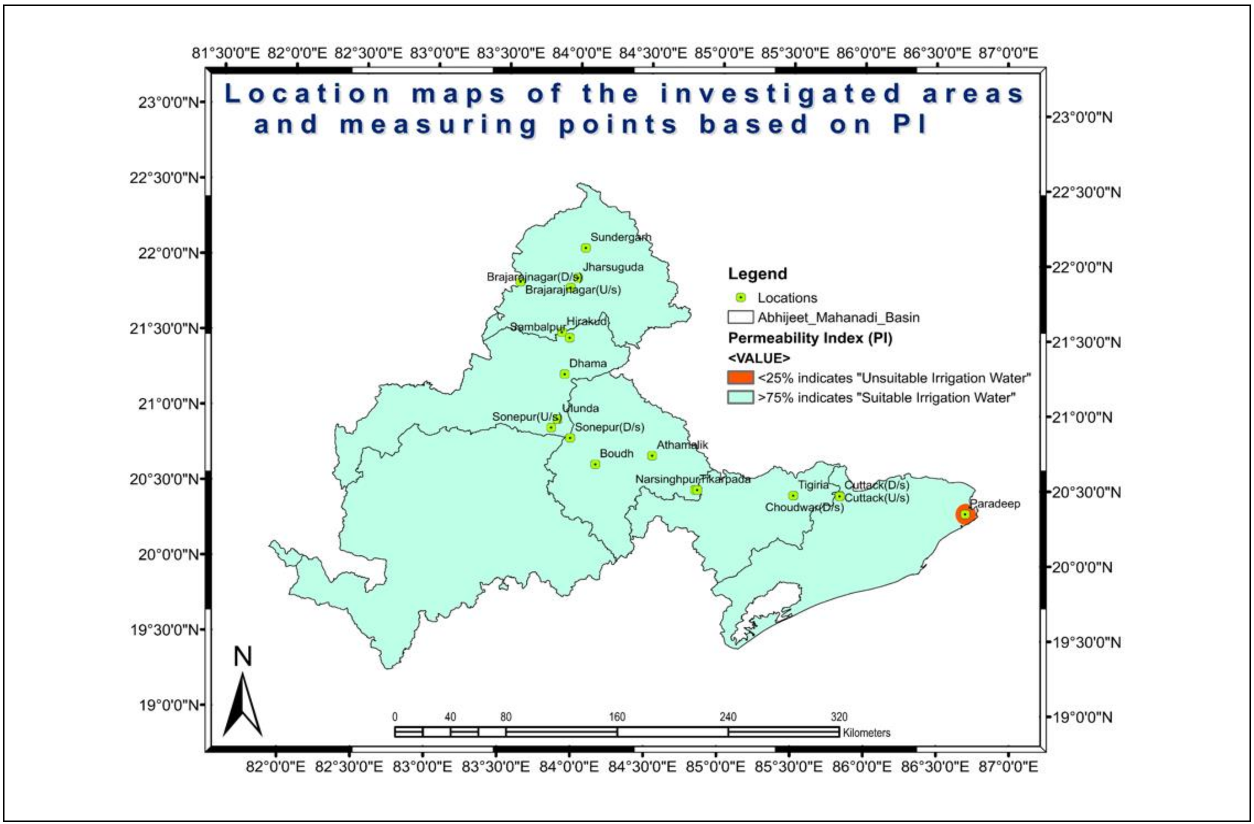

Fig. 7: Spatial map of Permeability Index (PI)

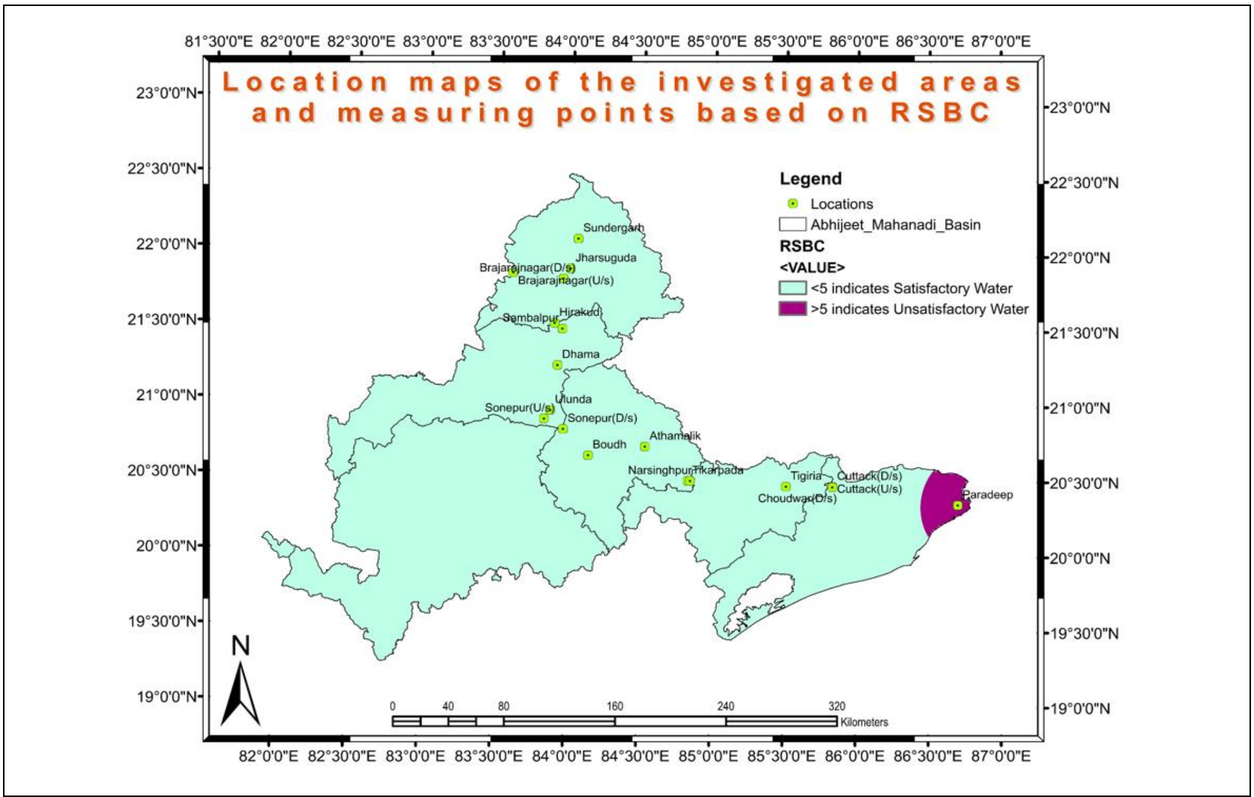

Fig. 8: Spatial map of Residual sodium bicarbonate (RSBC)

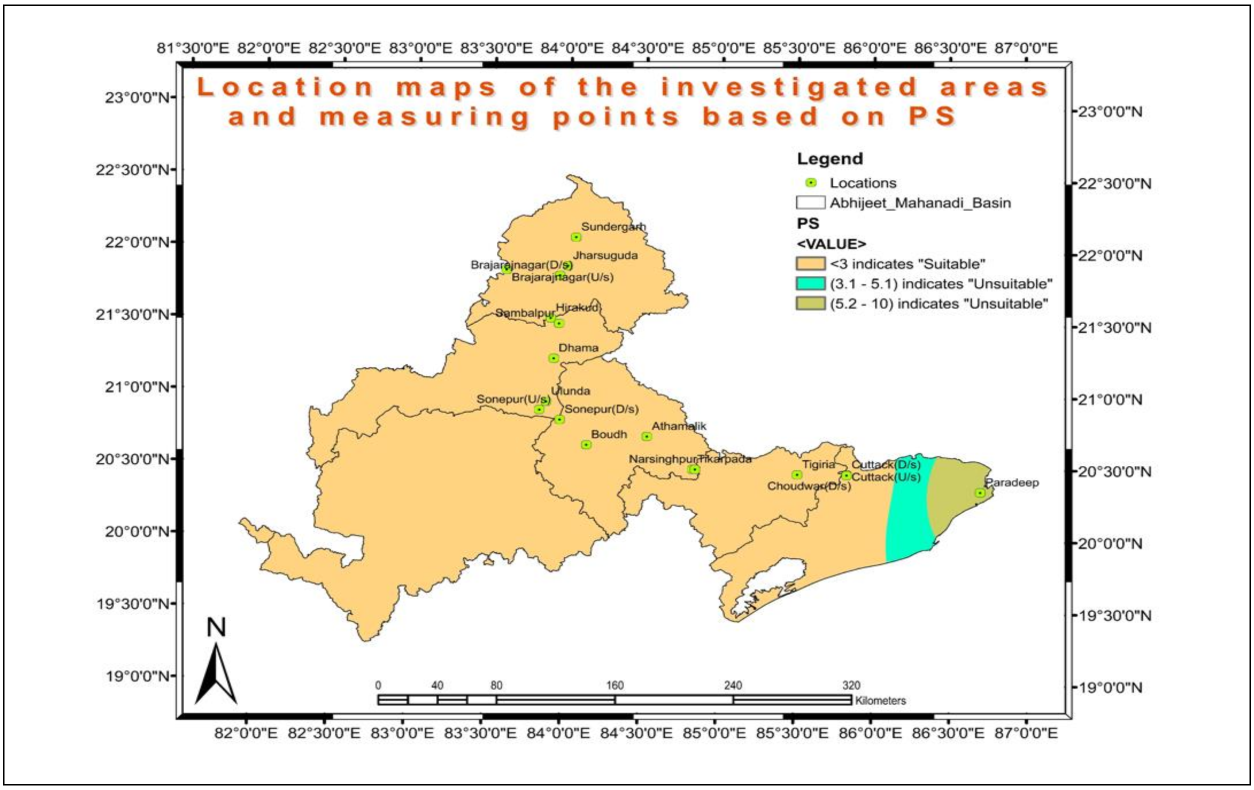

Fig. 9: Spatial map of Potential Salinity (PS)

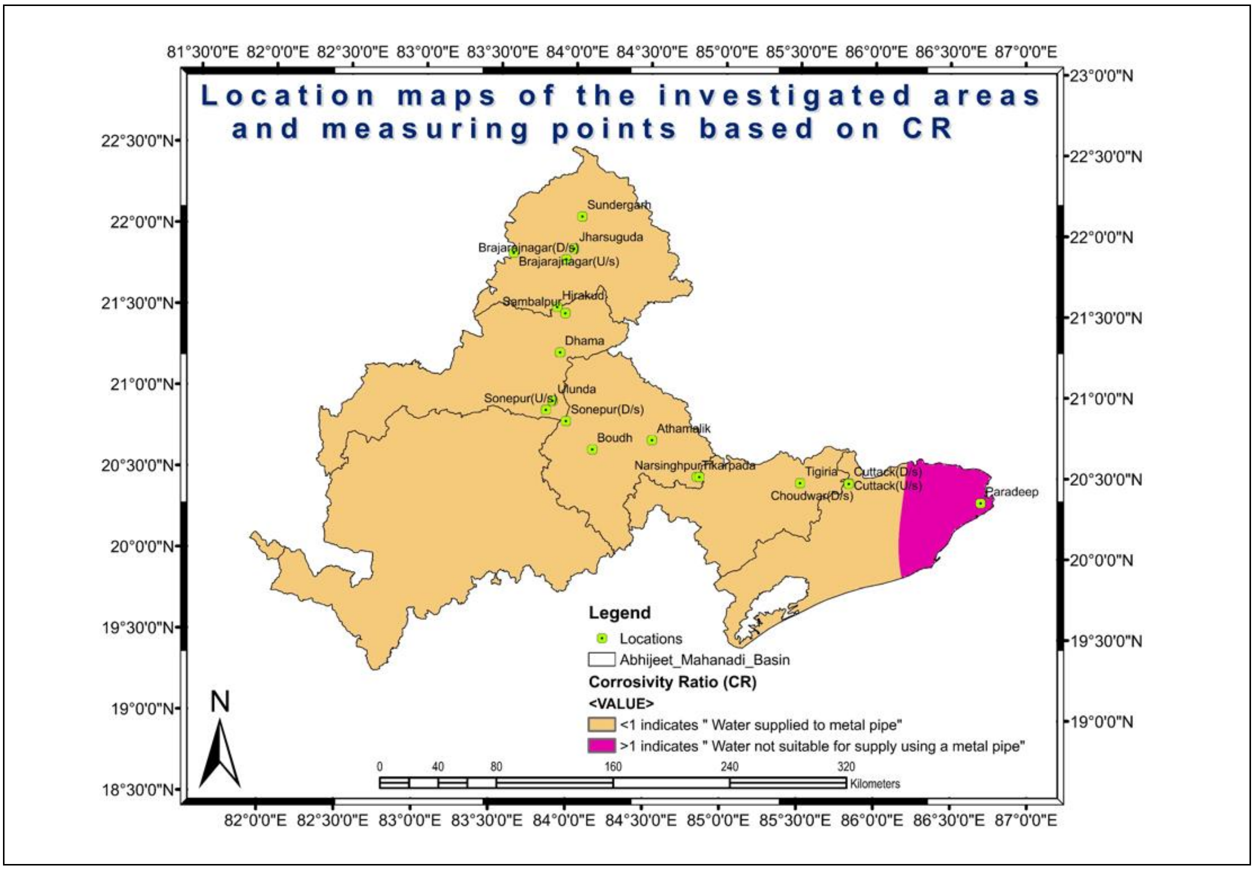

Fig. 10: Spatial map of Corrosivity Ratio (CR)

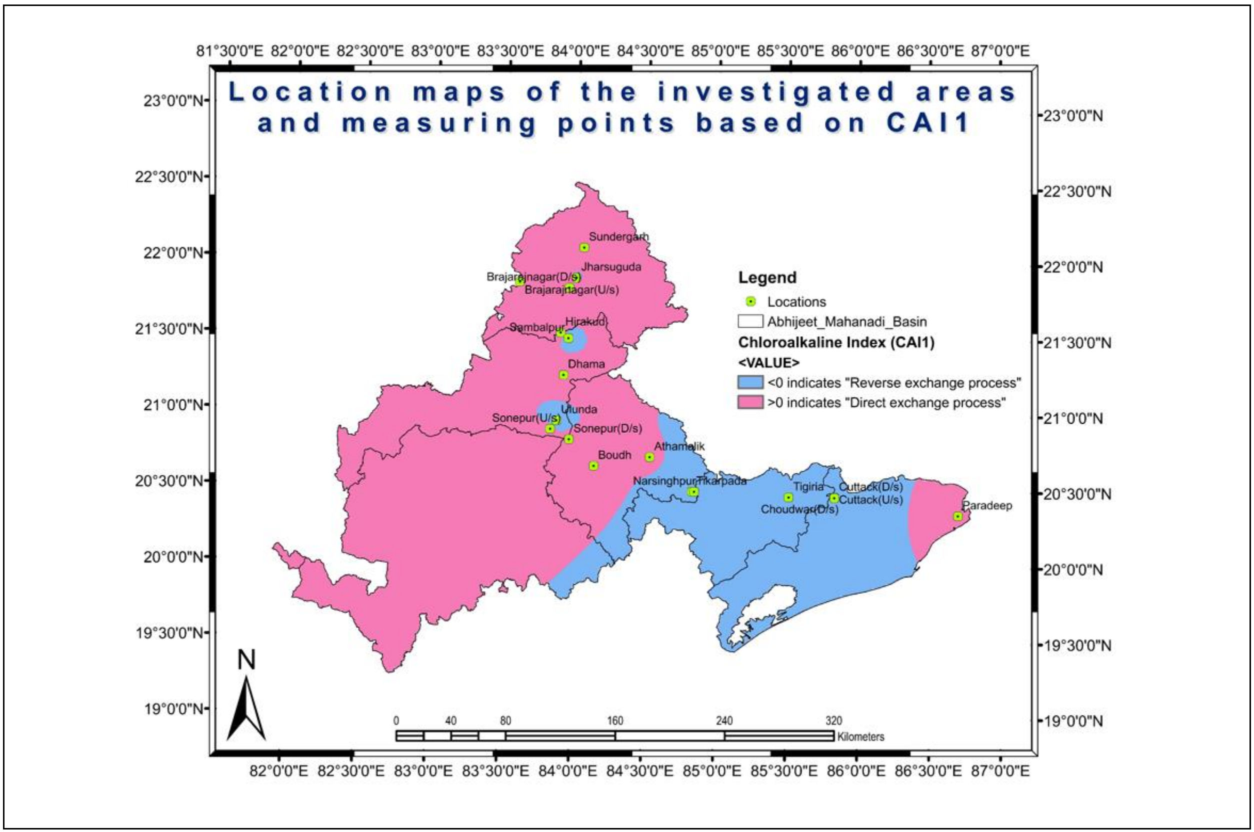

Fig. 11: Spatial map of Chloro-alkaline Index (CAI 1)

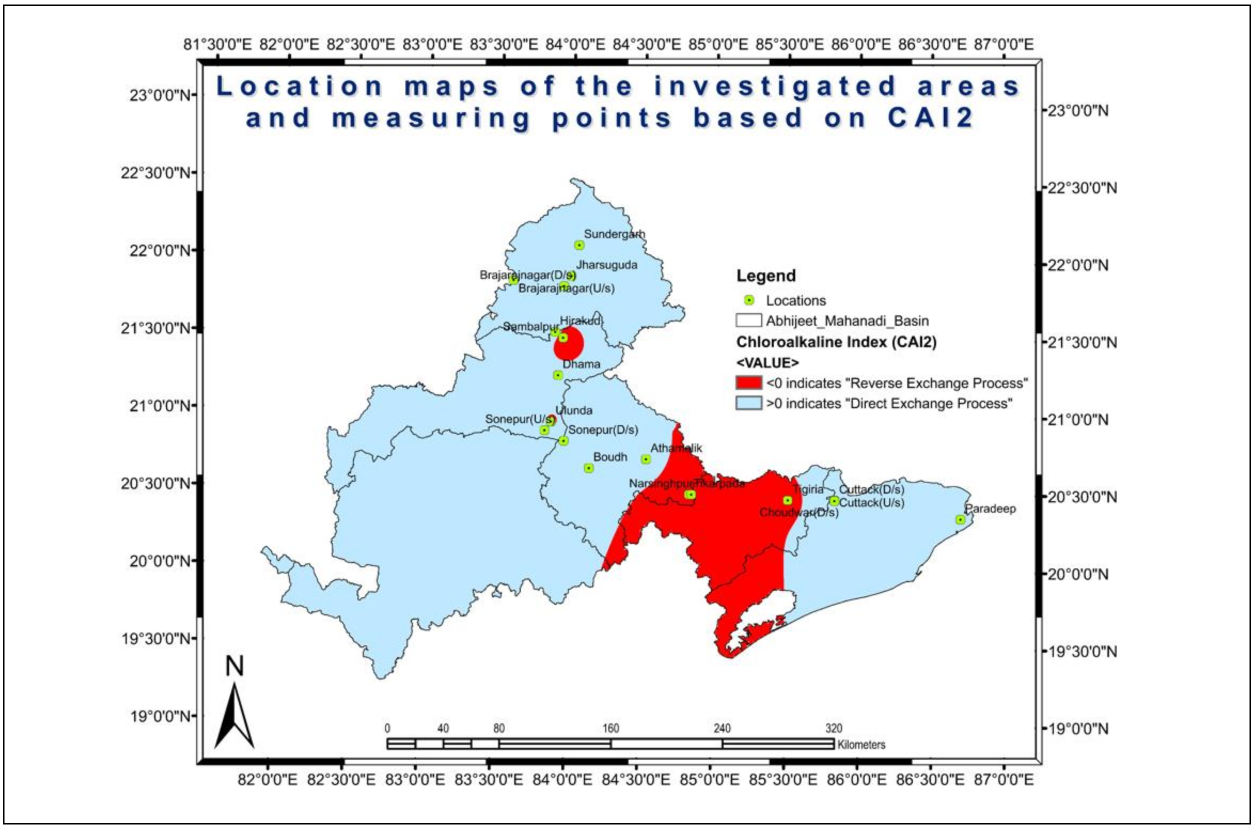

Fig. 12: Spatial map of Chloro-alkaline Index (CAI 2)

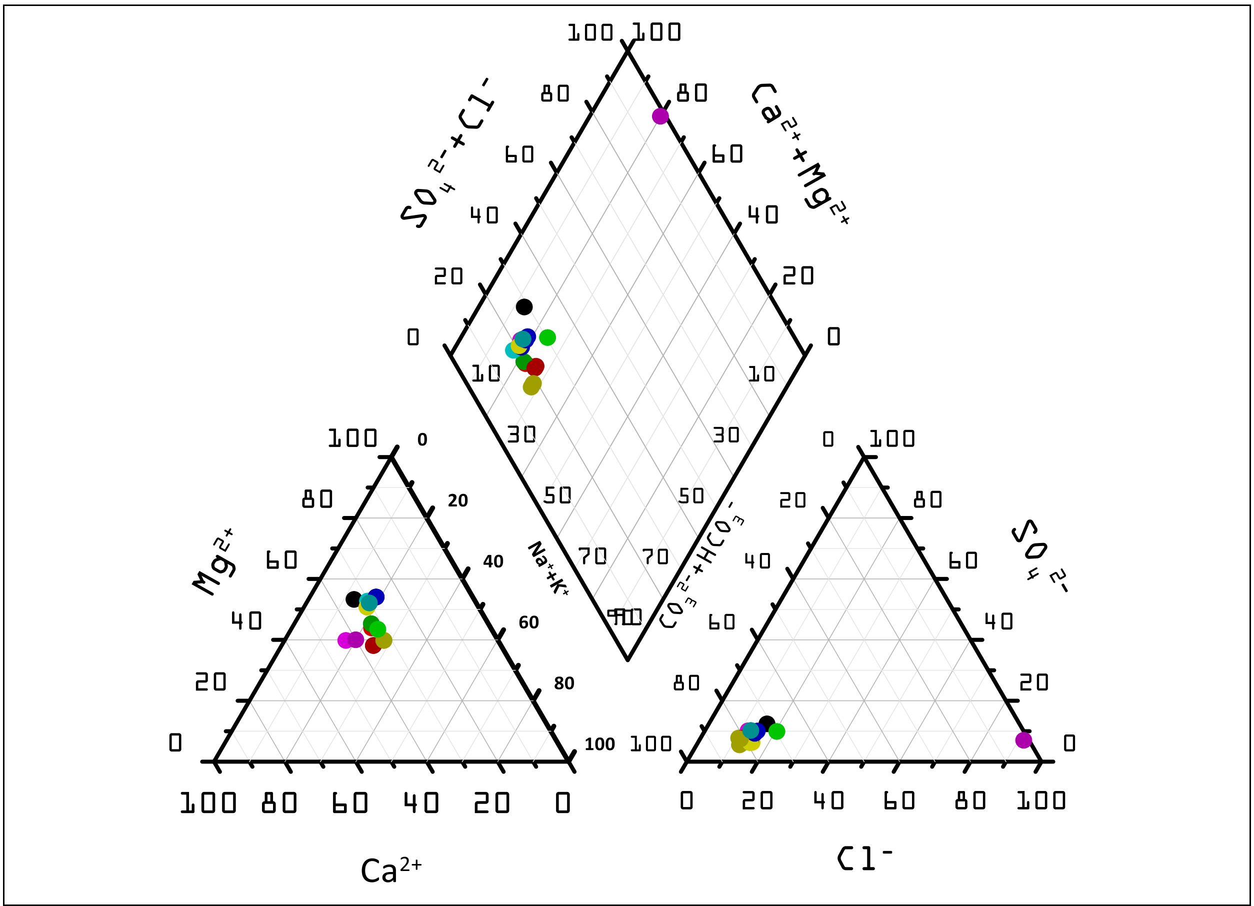

Fig. 13: Representation of Piper analysis for all sampling points

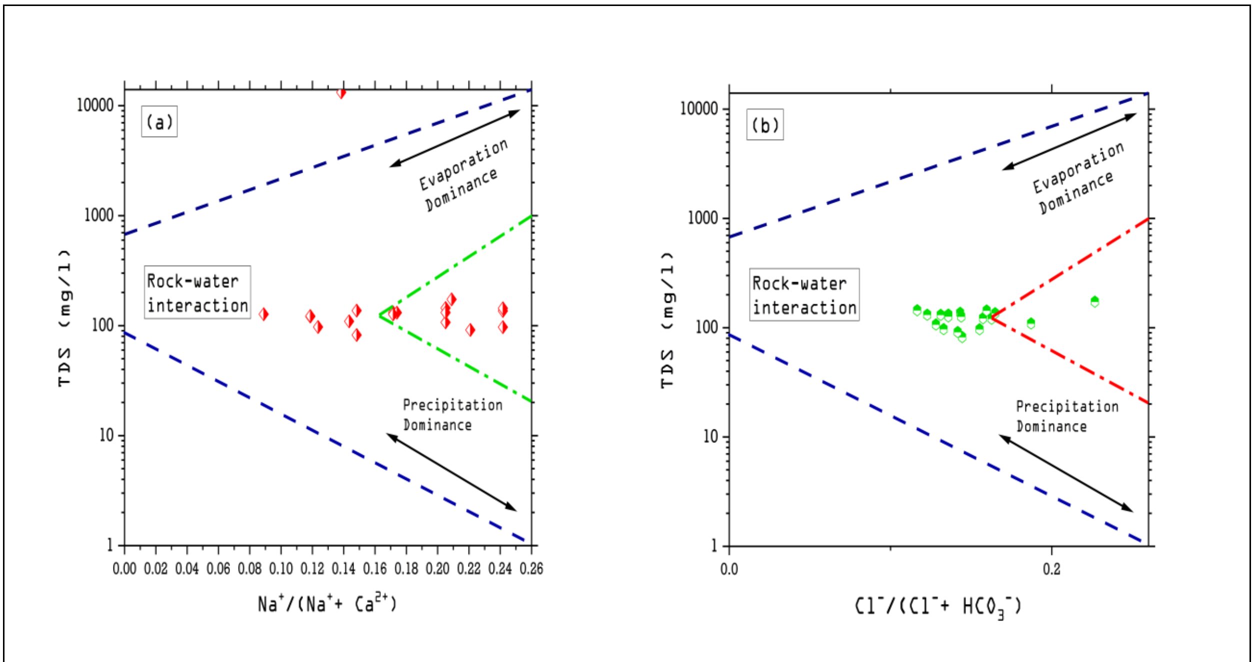

Fig. 14: Representation of Gibbs Diagram

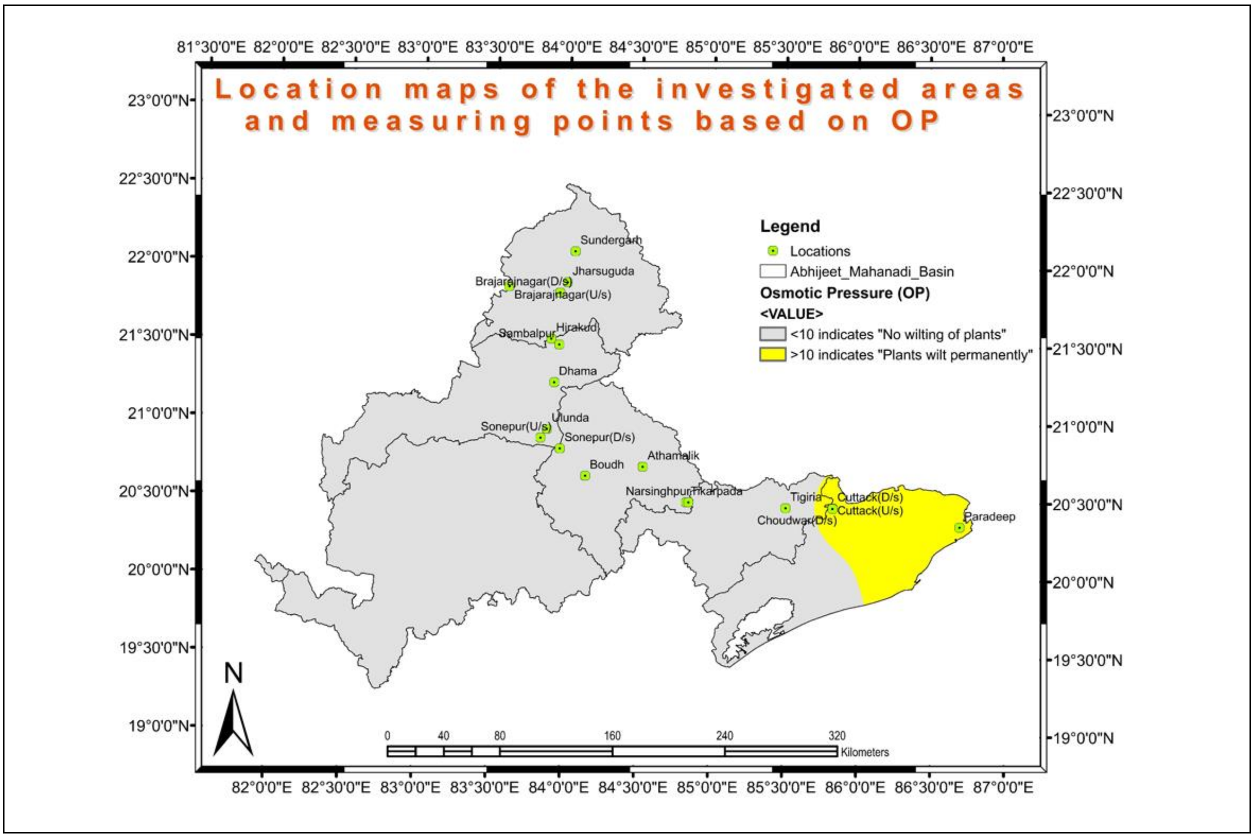

Fig. 15: Spatial Representation of all water samples based on Osmotic Pressure (OP)

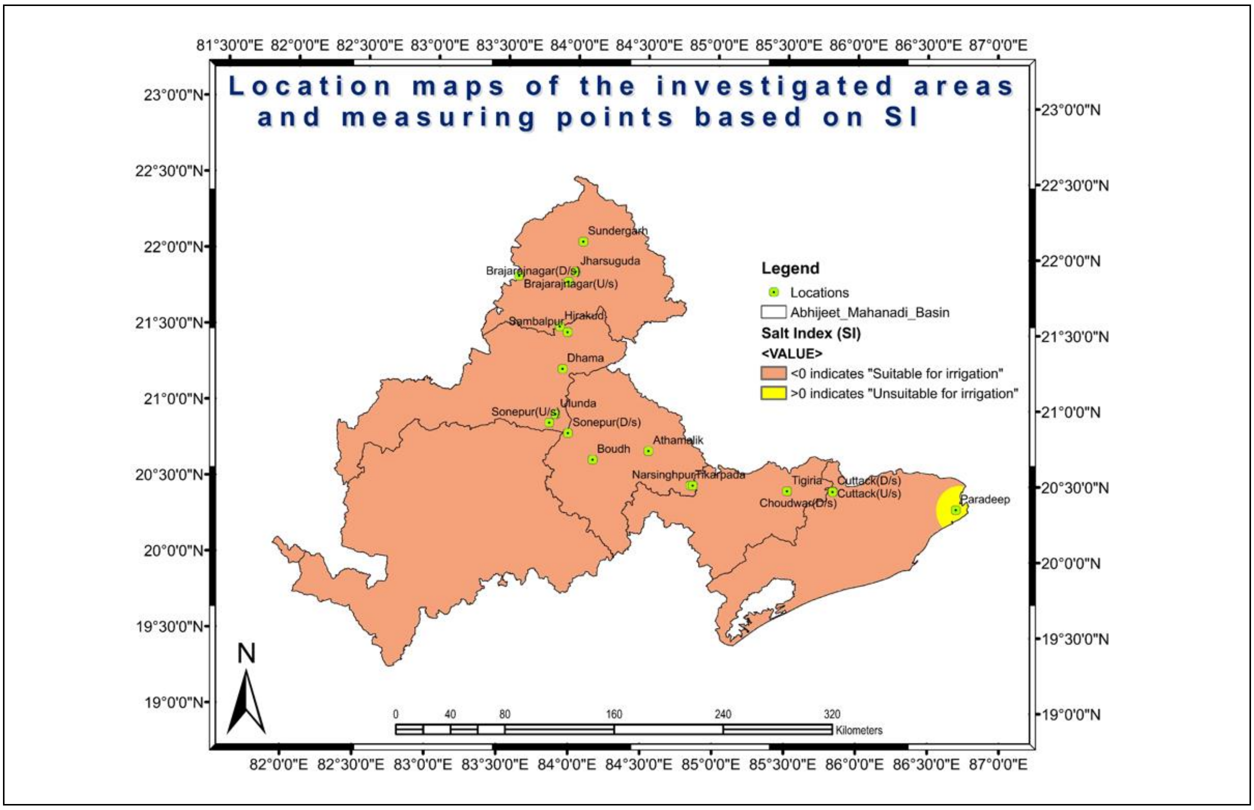

Fig. 16: Spatial Representation of all water samples based on Salt Index (SI)

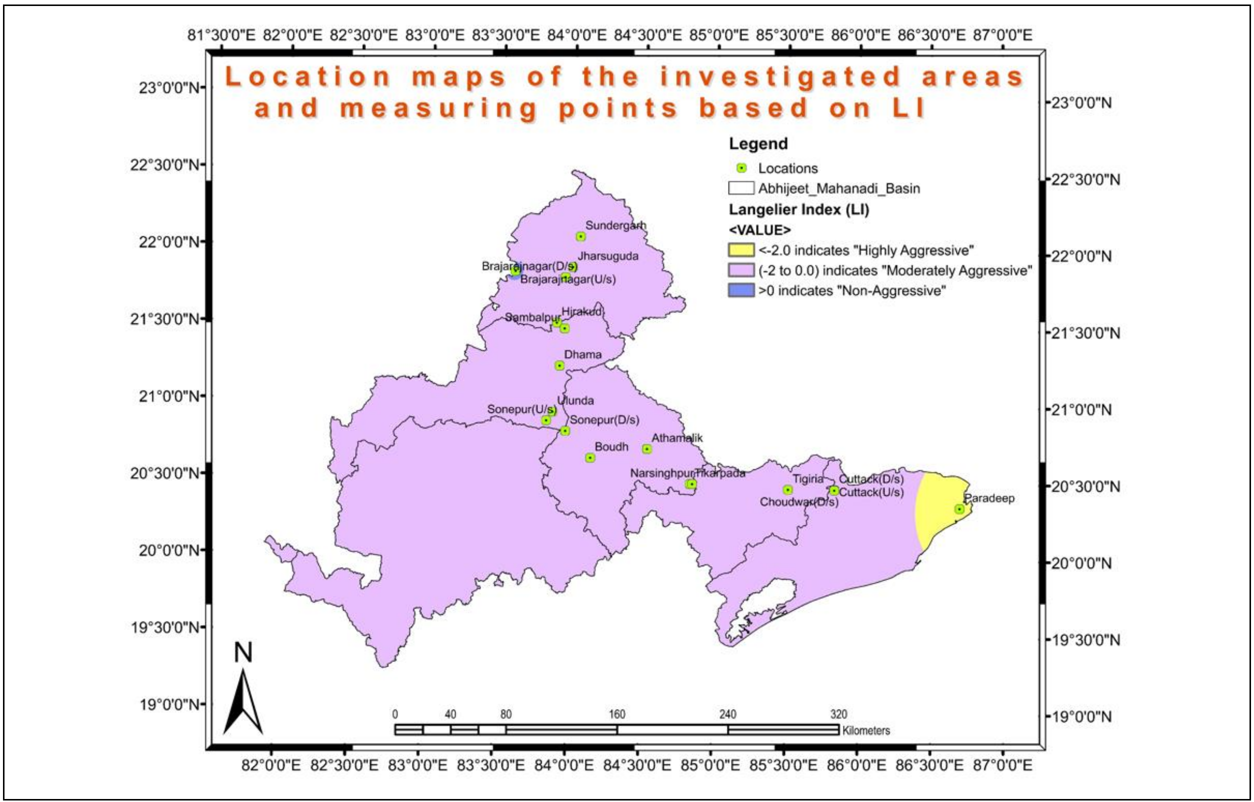

Fig. 17: Spatial Representation of all water samples based on Langelier Index (LSI/LI)

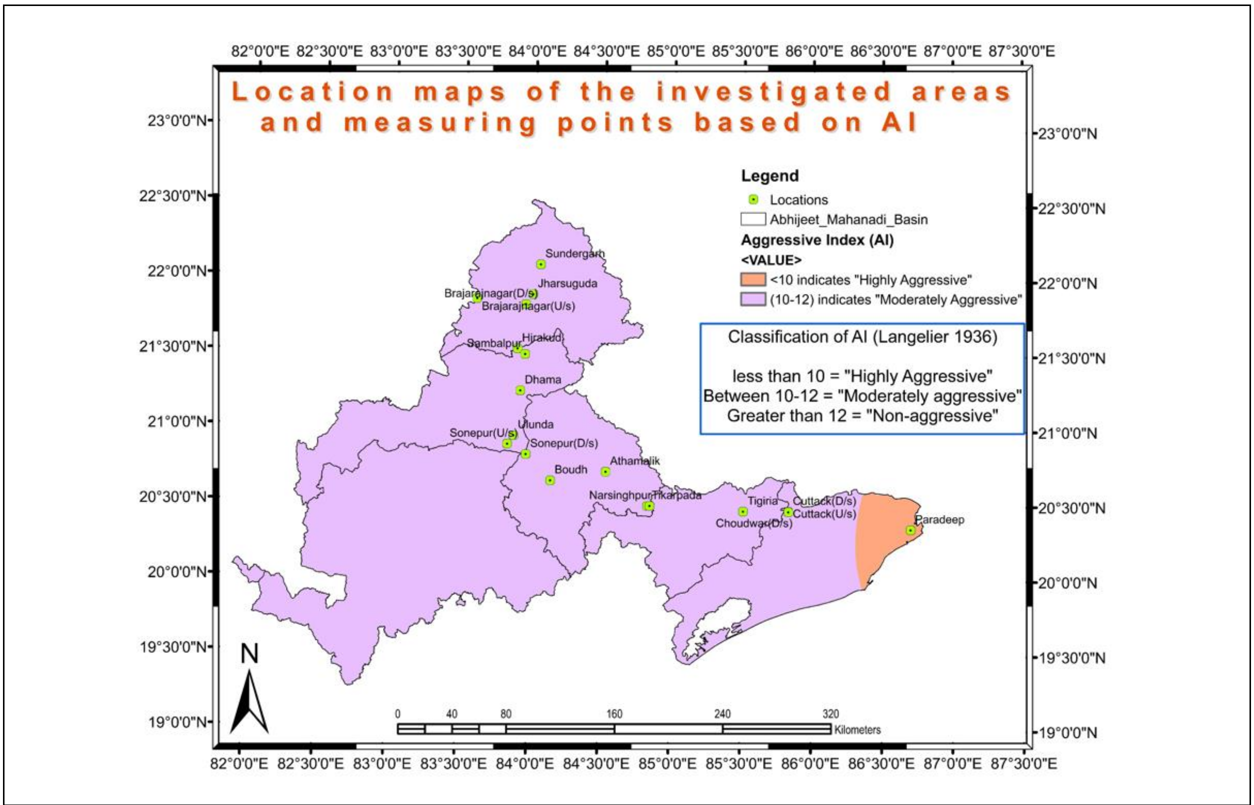

Fig. 18: Spatial Representation of all water samples based on Aggressive Index (AI)

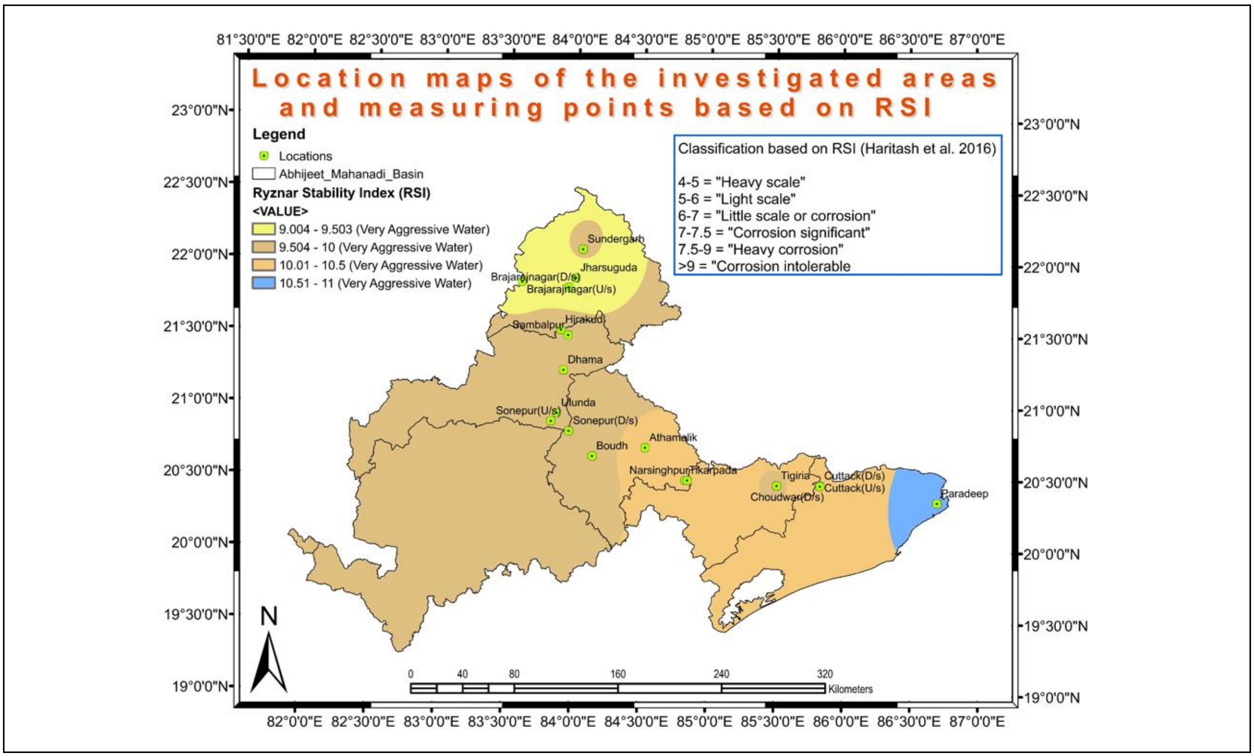

Fig. 19: Spatial Representation of all water samples based on Ryznar Stability Index (RSI)

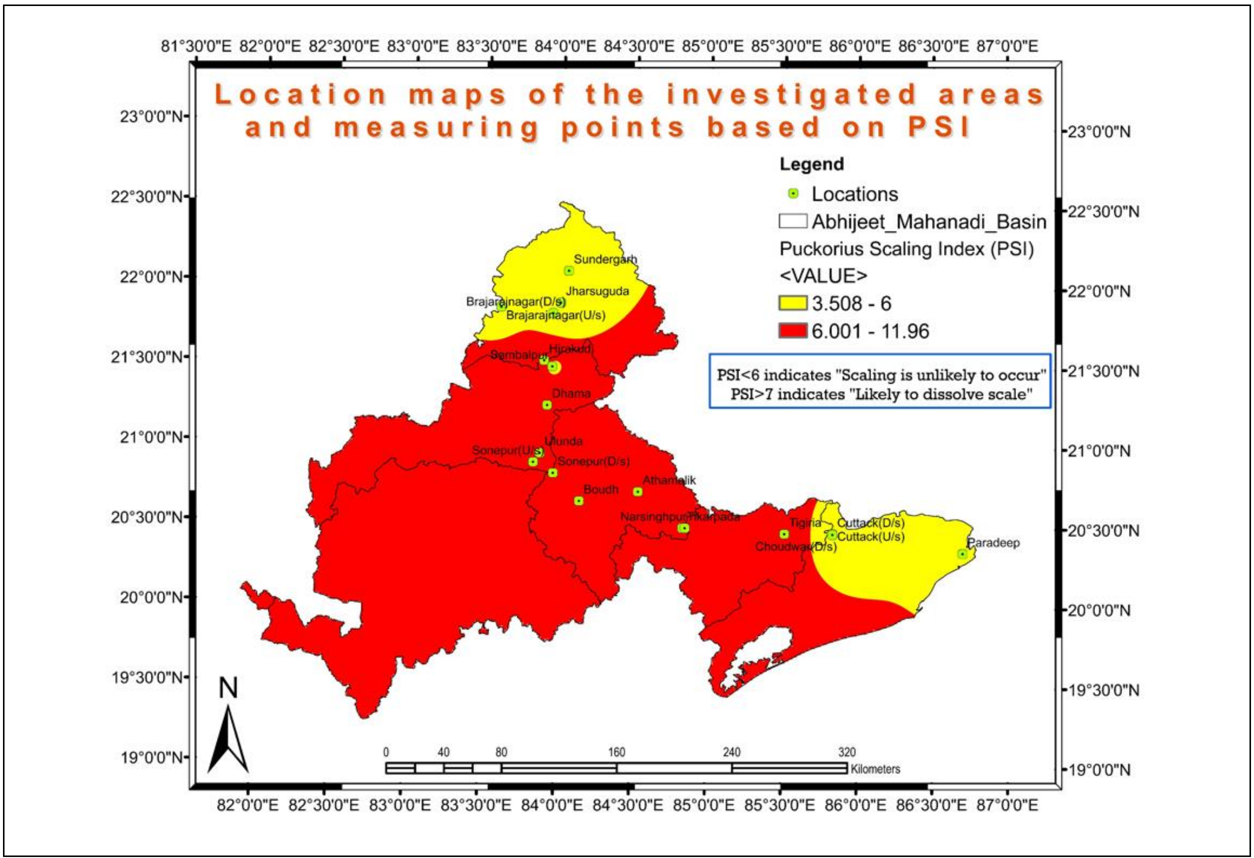

Fig. 20: Spatial Representation of all water samples based on Puckorius Scaling Index (PSI)

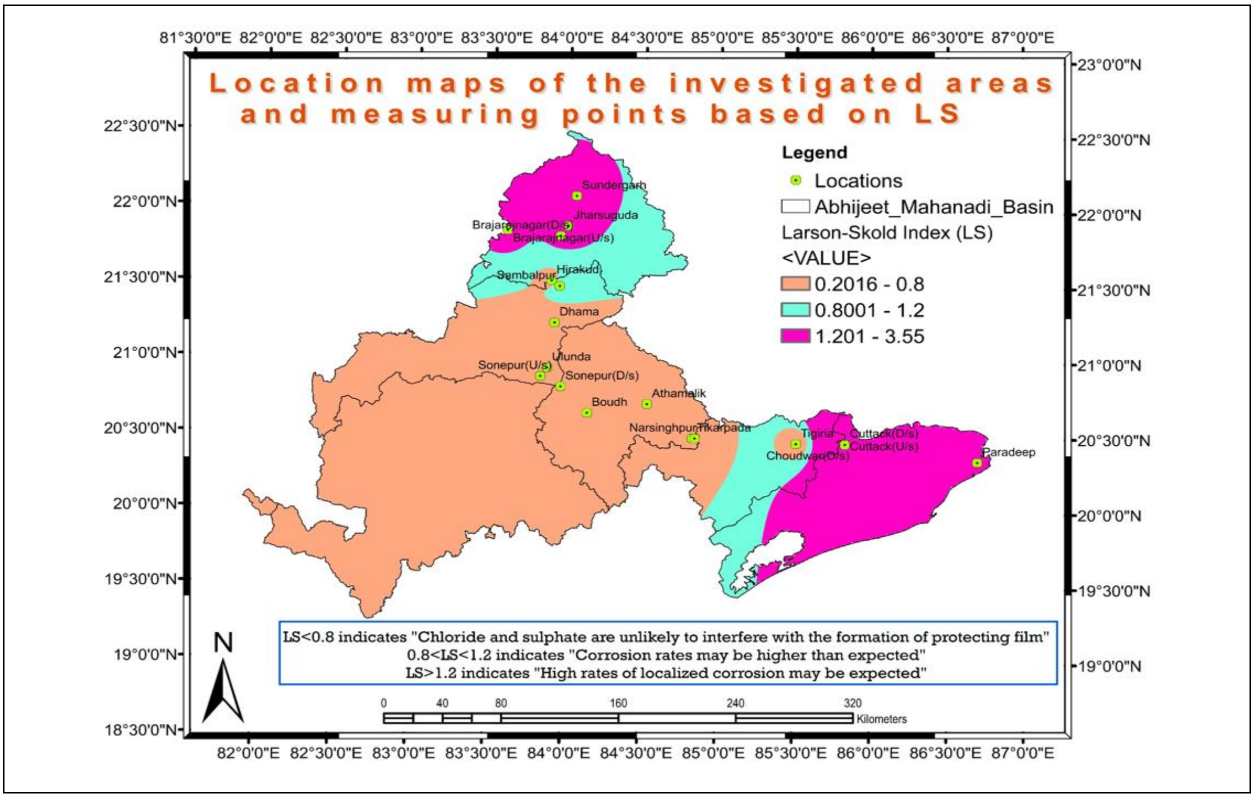

Fig. 21: Spatial Representation of all water samples based on Larson-Skold Index (LS)

Table 1. EWQI values of all chosen points

Locations	EWQI
St. 1	15.69
St. 2	18.4
St. 3	16.21
St. 4	19.88
St. 5	18.58
St. 6	19.47
St. 7	17.61
St. 8	196
St. 9	1066.2
St. 10	14.97
St. 11	15.08
St. 12	14.59
St. 13	16.93
St. 14	19.98
St. 15	16.32
St. 16	18.35
St. 17	19.45
St. 18	17.91
St. 19	152

Additionally, as recommended by Li *et al.* (2013), EWQI assessed the Mahanadi River's water quality as per the drinking water quality standard (Table 1). Water quality is most affected by the parameter with the highest entropy weight and the lowest information entropy value. It was found that TC (maximum entropy weight) had the greatest impact. The second most important factor was turbidity.

Table 2. Closeness coefficients (C.C.) and TOPSIS ranks of all the locations

St. No.	Pre-monsoon (PRM)	
	C.C.	Rank
St. 1	0.028	14
St. 2	0.041	4
St. 3	0.028	13
St. 4	0.029	11
St. 5	0.029	12
St. 6	0.029	10
St. 7	0.031	5
St. 8	0.074	2
St. 9	0.959	1
St. 10	0.031	7
St. 11	0.031	6
St. 12	0.030	9
St. 13	0.031	8
St. 14	0.021	18
St. 15	0.027	16
St. 16	0.026	17
St. 17	0.011	19
St. 18	0.027	15

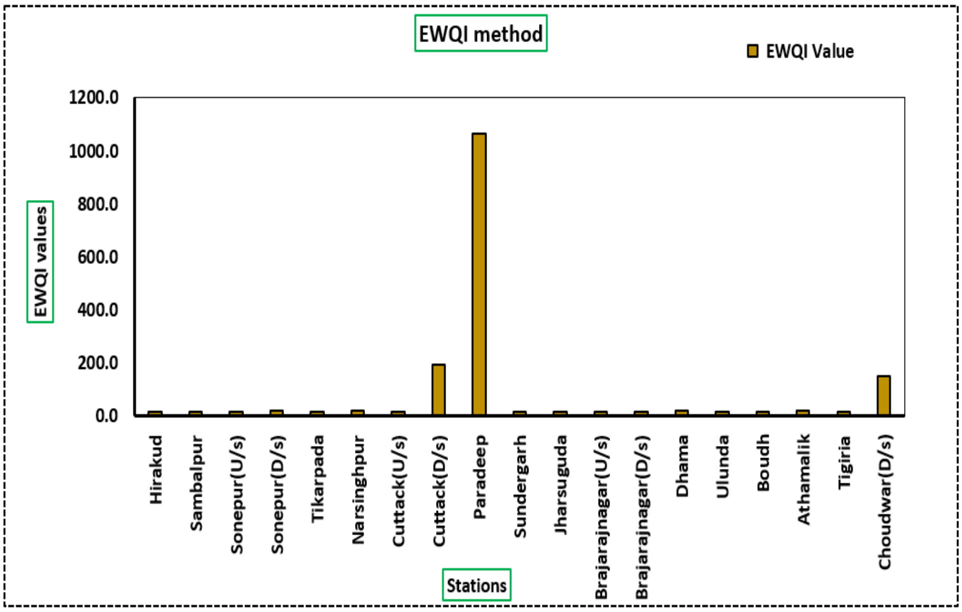

Fig. 22: Classification based on EWQI values

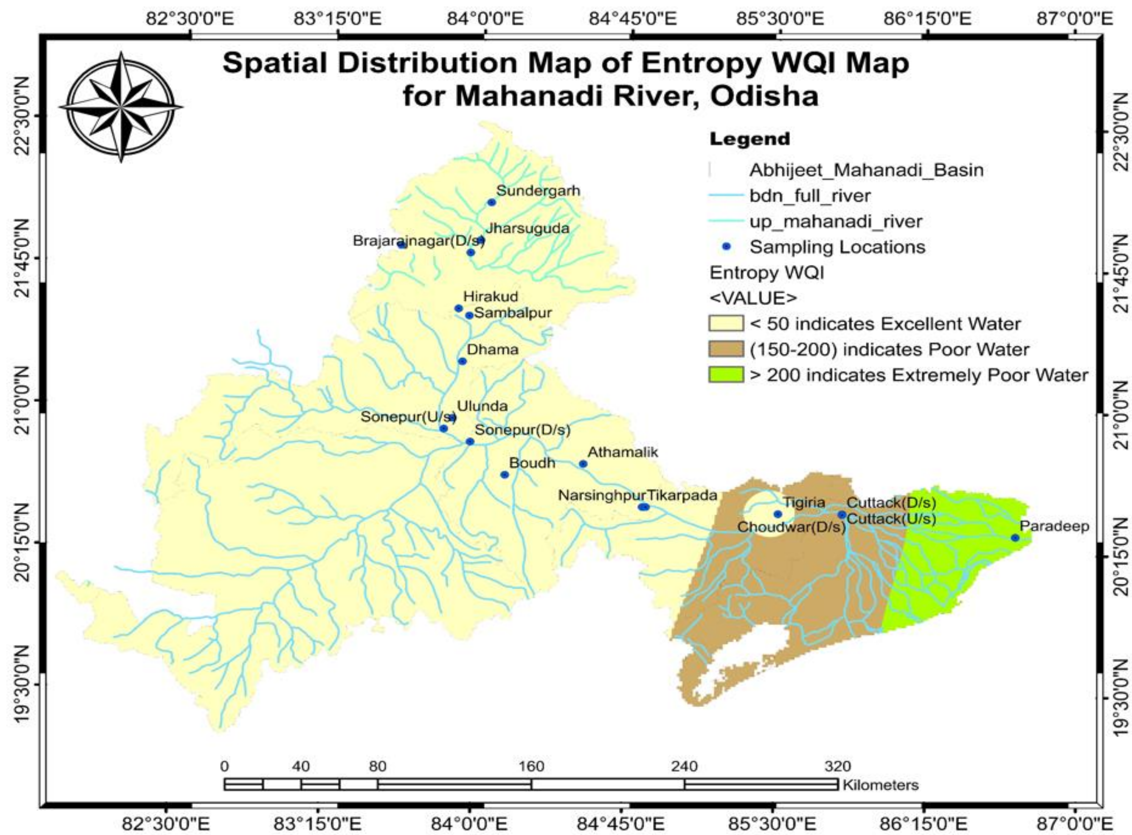

Fig. 23: Spatial distribution map of EWQI

The calculated EWQI was found to be in the range of 14.6 to 1066 and graded as excellent to extremely poor during the sampling period (Fig. 22). It was observed from the dataset that almost 16 testing locations promote excellent water, which holds a value of EWQI<50. Rural regions with low population densities and little human activity surrounding these locales; mostly agricultural activities were observed (Wu *et al.* 2015). It is noted that St. 9 received the highest EWQI evaluation, which possesses high concentrations of TC, TH, turbidity, SO_4^{2-}, NO_3^-, Fe^{2+}, Cl^-, SAR, EC and TDS. It was evident that from the analysis at St. 9, most of the parameters had high values relative to their permissible drinking water standards. Fig. 10 signifies the variation of EWQI throughout the study area. The allocation of the samples in percentage terms indicates that over the entire research, excellent water was present in 84.21% of samples, poor water was available in 10.53%, and extremely poor water was prevalent in 5.26%. The variables were extrapolated throughout the full study region to produce an index map in ArcGIS. Results (Fig. 23) show that sites 8, 9 and 19 had low water quality and were extremely susceptible to human activity. The effects of human activity on water quality outweighed the effects of natural forces (Aydin *et al.* 2020).

However, Fuzzy-TOPSIS method gives the total rankings, which distinctly indicates the relative pollution level, on the principle of CC to PIS. Such a ranking is beneficial in assisting policymakers with both technical and non-technical backgrounds in reaching well-informed decisions (Omeka *et al.* 2022). In this study, the Fuzzy-TOPSIS approach of decision-making was used to discover the optimal places along the river stretch. All 21 parameters were taken into consideration. The rankings for CC and TOPSIS are shown in Table 2. From the results, it has been obtained that St. 9 was the most contaminated location throughout the test period compared to other places. Fig. 24 and Fig. 25 show the results of performance scores and rank in the selected study. Hence, Fuzzy-TOPSIS ranks were identified as being relatively better at obtaining water for irrigation and drinking. Thus, St. 9 was extremely inappropriate for irrigation and drinking since it had a lot of anthropogenic impacts (Mustapha *et al.* 2013). The spatial variation of output across the region can be seen in Fig. 26. However, this method has been successful in assessing the quality of water from the source to determine if it is suitable for the intended end use.

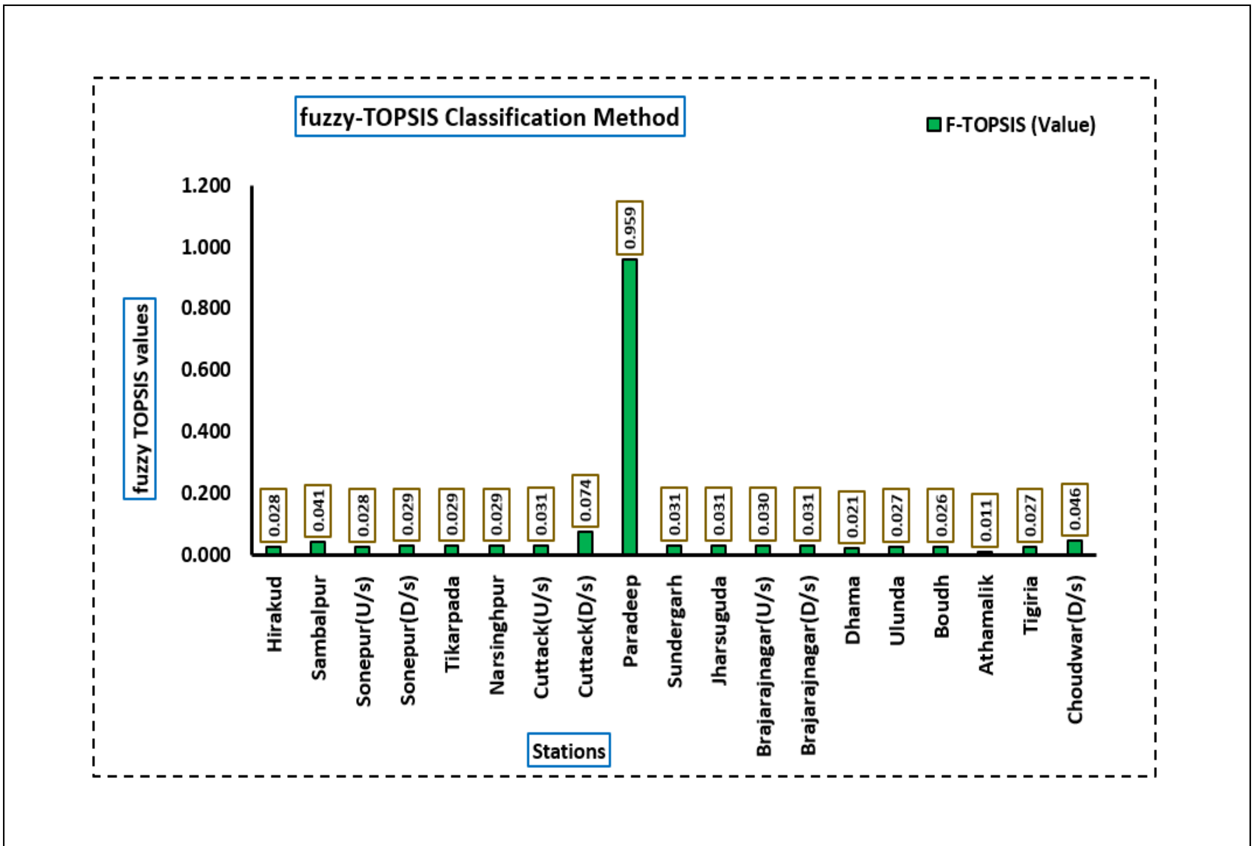

Fig. 24: Variability of Fuzzy-TOPSIS ranks of concerned locations

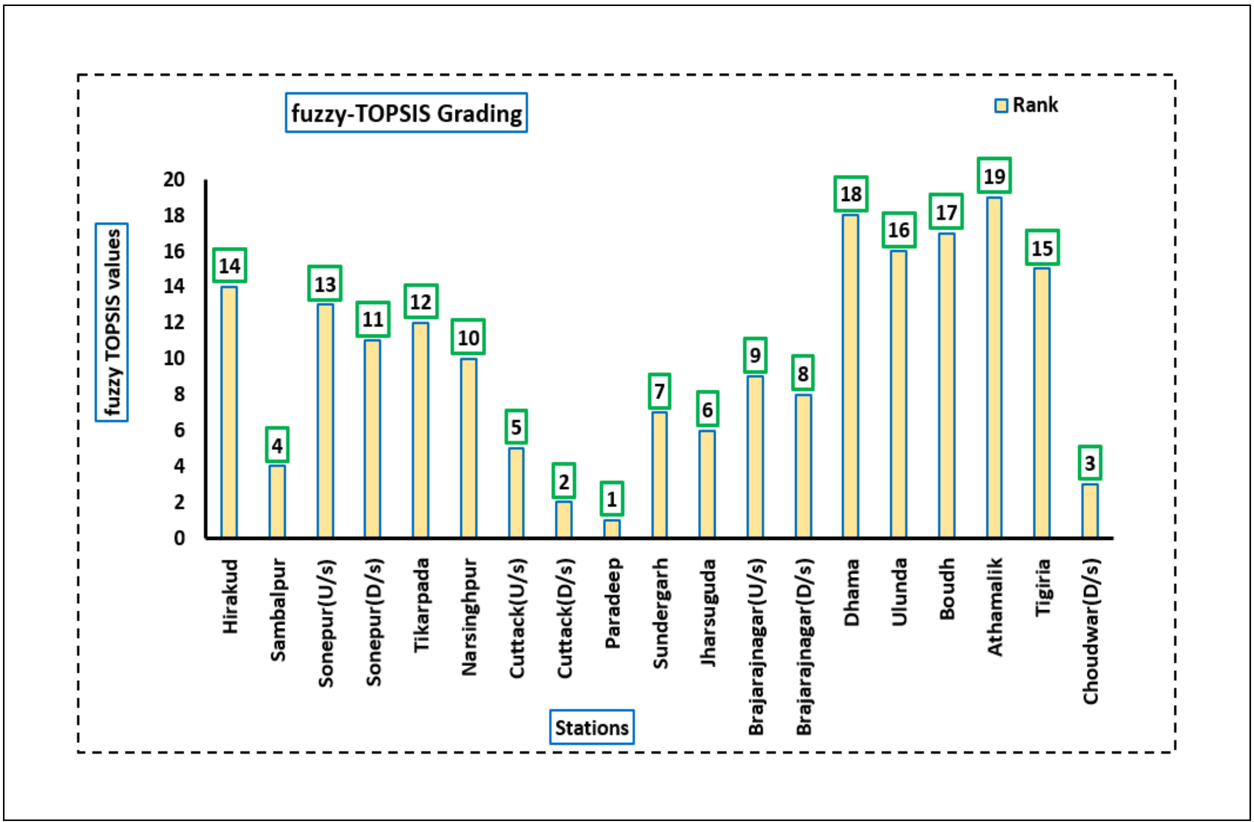

Fig. 25: Fuzzy-TOPSIS ranks of sampling sites

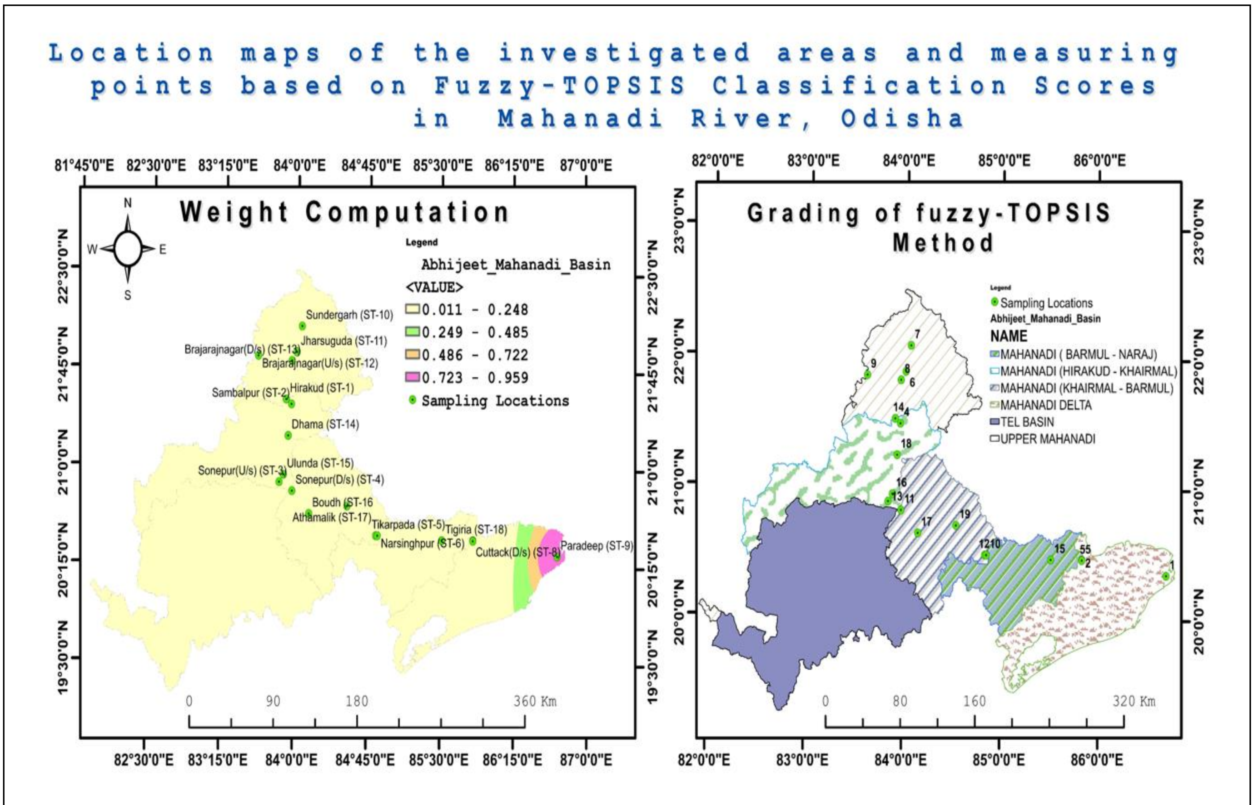

Fig. 26: Seasonal and spatial distribution of Closeness coefficients (C.C.) on account of Fuzzy-TOPSIS approach

6. CONCLUSION

In this study, a highly effective approach was used to capture water quality by employing the entropy-based weight determining method (EWQI), in combination with Fuzzy-TOPSIS method to provide information on the temporal along with spatial variations for determining the appropriateness of surface water for farming and domestic uses. Yearly samples for a period of 4 years (2019-2023) were gathered from 19 discharge points representing the stream's overall pollutant load to measure the quality of the water.

There was a finding that a relatively higher pH signifies an alkaline nature in both seasons. An adequate amount of DO is available in both periods which promotes the proper functioning of the aquatic ecosystem. All the investigated parameters are found within the threshold limits; however, the concentration of turbidity and TC, surpassed the water's optimum limit at all locations, in both seasons. High turbidity was due to the rainfall-runoff discharge in all seasons. In addition, SAR, % Na, RSC, MH, CR, SI, OP, CAI-1, CAI-2 and KI readings found that in all locations in the research region water was suitable for irrigation. However, PI of river water quality signifies doubt and should be restricted because irrigation may have dangerous consequences. This was done as part of the assessment of water quality for agricultural production.

As per the Piper trilinear classification, the dominant water type was classified as Ca^{2+}-Mg^{2+}-Cl^{-}. This was due to the water-rock interaction and anthropogenic contamination. Hence, the total hydrochemistry was dominated by alkalis mainly Na^{+}. Based on Wilcox model, most surface water samples showed relatively low alkalinity hazard (S1) and low salinity hazard (C1). Gibb's diagram suggested an increase in Na^{+} and Cl^{-} ions and consequent higher TDS due to water contamination, caused by the influences of poor sanitary conditions, agricultural fertilizers and irrigation return. In all locations, most of the water samples belonged to the category of rock-water type. The results based on SI demonstrated that the chosen period's estuary samples were extremely unsuitable, while the waters of some polluted stations (such as ST-8, 9 and 19) were unsuitable to some level. For instance, OP indicated 16 locations as safe for irrigation without promoting wilting of plants, while around 3 sites (15.7%) were deemed unsuitable for agriculture.

For industrial applications, LSI/LI analysis classified the water as 'non-aggressive to highly aggressive' in nature, limiting its usage for commercial endeavors. According to the results, the majority of the sources of water were moderate to highly corrosive according to AI and PSI, and corrosion was unacceptable according to RSI and LS. Most of the time, the water was found to be corrosive, necessitating filtering before industrial use. Based on EWQI scores, the reported value indicated excellent to extremely poor quality at all sampling sites. The toxicity of water at St. 9. 19 and 9 had high EWQI values, that penetrated the food chain actively or passively, which was the main reason for many health issues.

Further, Fuzzy-TOPSIS characterized sample locations using all measured metrics, and an overall rating of the sites based on their respective pollution levels. The ranking findings were consistent with the entropy method's results for calculating water quality, demonstrating its validity and application. According to the findings, St. 9 was the most contaminated location in both periods compared to other places. The main causes were the effects of climate change, population growth that is occurring at a rapid rate, urbanization, and agricultural practices, all of which having a significant impact on human activities, including the quantity and quality of surface water resources. Based on the study's findings, combining these two models with irrigational indices can be used to find and separate the sources of surface water contamination, unearthing new avenues for surface water protection and purification.

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AUTHOR CONTRIBUTION

The whole manuscript is being written, analyzed and prepared by Mr. Abhijeet Das.

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DECLARATION OF COMPETING INTEREST

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its supplementary information

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