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Evaluation of Spatial Variations in Surface Water Quality of Mahanadi River Basin by Geospatial-FUCOM based Prediction Utilising Fuzzy-TOPSIS Approach

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ABSTRACT

This study highlights an evaluation of surface water quality for drinking purposes in Mahanadi River Basin, Odisha using Full Consistency Method (FUCOM) based WQI (F_U-WQI), with reliability-based MCDMs (Multiple-criteria decision making) such as Fuzzy-TOPSIS (F-TOP). Water samples from 19 locations were taken during the period 2018-2023 to test 20 physicochemical parameters. Further, the F_U-WQI revealed that 36.84% (n=7 sites) and 5.26% (n=1) of samples belong to poor/unsuitable water quality while 47.37% of sites come under the zone of excellent water (n=9 locations). However, 10.53% of samples indicated a medium water quality. The analysis primarily revealed that at 8 samples, deterioration of domestic water, illegally dumped municipal solid waste, and agricultural runoff were the leading sources causing adulteration of the river's water quality. As a result, a renowned MCDM model, such as F-TOP, was implemented to resolve conflicts regarding the WQI index. Hence, this innovative technique showed that SP-(9) was the most polluted in comparison with other locations, followed by SP-(8), (19), and (2). This was also accompanied by high values of nine crucial parameters, which were also higher than their desirable concentration and highest among all the locations. Following this, the analytic findings also suggest the same from the F_U-WQI values 423, 198, 182 and 184 at these locations. However, it was pertinent that the pollution level at these stations was associated more with increasing and diverse anthropogenic activities. So, it is found that river water is convenient for household usage and, after disinfection, fit for human consumption.

Keywords: Mahanadi River; FUCOM; Fuzzy-TOPSIS; Solid waste; Drinking water.

1. INTRODUCTION

Surface water, a naturally occurring vital resource, is more a pure form of water than ground water, since it is consistently clear, colourless, and odourless, and it keeps its temperature reasonably steady (Feng *et al.* 2023). In recent years, the world has faced a scarcity of surface water resources due to the population increase and urban sprawl, which exposed water resources to deterioration in both quality and quantity (Uddin *et al.* 2023). Due to inadequate hygiene, poor sanitation, and polluted water, drinking untreated contaminated water can lead to waterborne illnesses and has been linked to the daily death rate from diarrheal diseases. Regrettably, unchecked use of fertilisers and agrochemicals that seep into the aquifer system, along with overexploitation without a balanced recharge, are causing surface water degradation to worsen quickly in India (Nawaz *et al.* 2023). Also, surface water is especially susceptible to microbiological contamination from both natural and man-made sources, such as rainfall runoff, animal excreta leaching, leaking septic tanks, wastewater used for irrigation, and raw sewage discharge (Ding *et al.* 2023). Besides this, recent anthropogenic activities greatly increase the amount of nitrogen cycling between the living world, the soil and the water and the atmosphere. In fact, the abundance of synthetic fertilisers, aquaculture wastes, sewage disposal, and animal wastes also cause worry on a global scale (Gani *et al.* 2023). To lessen the detrimental impacts on drinking water, it is necessary to investigate the quality of agricultural water. The sustainable development of humankind may be in jeopardy due to the current imbalance in availability and increase in demand for water resources. Thus, water management measures have been established, mostly dependent on surface water and regular runoff. Therefore, water quality should be regularly analysed, particularly in places where there is a greater chance of sewage contamination and where there are less sophisticated or effective water treatment systems. To inspect water quality, numerous scholars have employed techniques including time-series numerical analysis of measured data, correlation analysis, and categorization (Gupta *et al.* 2023). However, a laborious and time-consuming data arrangement procedure is necessary for the time-series numerical analysis method of water quality monitoring on long-term observed data. Ultimately, one benefit of these approaches is that they do not call for specialised understanding of the environment or water quality (Anang *et al.* 2023).

Therefore, the water quality index (WQI) is regarded as a mathematical instrument that greatly reduces those data sets and yields a single classification value that characterises the level of pollution or the water quality condition of water bodies. These metrics have been developed and enhanced in various ways to depict water quality more precisely and successfully. Thus, utilising WQI, the index's specific end use, which could be for irrigation, drinking, or recreation, determines the selection of parameters and weighting. As a result, water quality is transformed into a single score for a thorough evaluation, assisting the general public and decision-makers in understanding the quality of the water (Ahsan *et al.* 2023). In the starting phase, the weights are assigned by professionals based on their real-world experiences. Additionally, they used to have diverse preferences, which led to multiple uncertainties in the results of the water quality evaluation. Regarding WQI issues, like ambiguity and obscureness, can be countered by combining geometric and additive techniques (Saqib *et al.* 2023). To resolve this arbitrary problem, Full Consistency Method (FUCOM)-based weights have become a popular method for weighting water quality measures using information entropy. This mechanism is applied to assess the importance of each response without taking the decision maker's option into account (Majumder, 2023). The basic idea is to use the two fundamental ideas to establish the indicators' objective weight namely, contrast intensity, that shows the variation in value between the various techniques for evaluating the same index, which is then shown as a standard deviation and secondly, the conflict among the evaluation indicators, which primarily depends on the relationship between indications. Nevertheless, the randomness, complexity, and non-linearity of environmental challenges, as well as the geographical and temporal fluctuations of surface water components, are not taken into account by such methods (Sadeghi *et al.* 2023). In comparison to those subjective assessment techniques, information based on FUCOM has more and stronger objectivity and accuracy, which helps to explain the outcomes. This method starts with defining the goals, then computes the normalised choice matrix and establishes the index weight based on the degree of variance of each index value. This helps to prevent deviations brought about by human factors (Khan *et al.* 2022). However, it presents itself as a group of correlation-based techniques that rely on analytical testing of the decision matrix to ascertain the data present in the standards that govern how criteria weights are assessed (Nemati *et al.* 2023). As opposed to fuzzy synthetic evaluation techniques, which concentrate on the spatial qualities of surface water, the FUCOM method can handle surface water quality data that is both temporally and spatially distributed (Debnath *et al.* 2023). In relation to spatial mapping, Geographical Information System (GIS) technology is used to create several spatial maps with themes for analysing variations in surface water quality. Thus, during the past few years, GIS provides a cutting-edge workspace for spatiotemporal data that allows digital geographic data from several sources to be integrated, visualised, analysed, and managed (Ahmed *et al.* 2023). In order to predict values for each site in the landscape, these analyses use sample points obtained from diffident locations to generate and interpolate a continuous parameter through the value from the observed parameters (Zafar *et al.* 2022). It is observed that the integration of GIS with remote sensing results in a versatile and easy-to-use tool that facilitates surface water management planning and decision-making by means of spatial analysis, manipulation, and visualisation (Simsek *et al.* 2023). The authors that followed used GIS tools to study the potential for surface water worldwide. Ernest and Isaac (2021) utilised the GIS to digitise the maps based on different chemical parameters and, in the end, to combine all of the maps to determine whether water zones are suitable for human consumption. Afterwards, Islam (2023) implemented GIS in conjunction with the limited irrigation WQI, to determine whether surface water is suitable for irrigation in case of West Pampa Plain, Argentina. Additionally, Mahammad *et al.* (2023) made use of an analytic hierarchy (AH) technology, that cooperatively linked to the use of GIS, to analyse WQ in Central Anatolia, Turkey. Badr *et al.* (2023) evaluated the irrigation water and made use of GIS in the Sivas Province, Turkey, and discovered that the majority of the water samples are in the appropriate irrigation zone. In this inquiry, the spatial variation maps were captured out by Inverse Distance Weighted (IDW) interpolation tools. It speaks of an interpolation method, which is employed to make the point data continuous by forecasting the elements that are unknown inside the study region (Pandey *et al.* 2023). Further, this innovative IDW technology was applied, because the variation between the surrounding points can be linearly weighted to forecast the value at the unsampled site, that also originates from variogram analysis (Azhari *et al.* 2022). During this procedure, weight is attributed to the unidentified point, which depends on the close-by recognised points. However, incorporating Multi-Criteria Decision-Making (MCDM) analysis with GIS encourages the use of an economical and useful method for managing geographic data (Nguyen *et al.* 2023). Researchers have been calculating susceptible zones for numerous decades by weighing various thematic layers using these methodologies. Therefore, when figuring out the specific relationships between the quality metrics and the measurement sites, the water quality assessment is required to be improved with Fuzzy (F)-TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) analysis (Dehghan *et al.* 2024). In earlier decades, several authors have used this approach for a variety of goals in the management of water resources to address environmental, power and economy, health and risk, and technology and data management issues (Wang *et al.* 2023). Consequently, using this programme to analyse the quality of the water, it yields amazing outcomes. Y Singh *et al.* (2022) created this concept, which is built on a hybrid of the weighting factor and exponentially weighted product techniques. Making use of this, it suggests possibilities for collaboration and the development of an integrated or combined strategy that, on the one hand, makes sense and is within the purview of the MCDM framework, and, on the other, receives good feedback (Nabizadeh *et al.* 2022). Moreover, due to this, a mechanism for providing an overall ranking of the sites must be used, by giving judgments on the highest priority during emergency situations and considering both the physiochemical properties (Ghorbani *et al.* 2023). Especially, its primary focus is on a single strategy to problem solving in any given location, leaving a research gap that needs to be filled by creating a novel integrated approach. This study demonstrates the value of this novel integrated approach. Hence, this creative study offers one of the earliest attempts at an integrated assessment method for analysing the surface water quality. Keeping this in mind, this study is to identify the surface water quality sensitive zones for drinking purposes and assess the annual and spatial variations of physicochemical factors impacting the water quality using F_U-WQI, GIS and F-TOP. However, not much research has been done on the hydrochemical and quality assessment of drinking water in the Mahanadi River Basin (MRB), Odisha. Here, FUCOM are employed to locate the criterion weight, whereas F-TOP selects the best option after ranking the possibilities. Finally, in the current project, the author selects a few standard indicators that are prominent on maps of the spatial variation of water quality parameters, after taking into account general environmental characteristics and using a decision matrix in conjunction with FUCOM and MCDM. This will contribute to the development of a conceptual knowledge of how the hydrochemical processes in the river basin are impacted by climate change. As a result, this will also assist local stakeholders, governmental organisations, and managers of water resources in putting into practise sustainable surface water resource management methods or updating strategies from the previous ten years for efficient management.

2. METHODOLOGY

2.1. Study Area

Mahanadi River System (MRS), the principal river in the State of Odisha, provides domestic water to the major towns and has a long history of being used for agriculture and fishing. It is divided into three sub-basins, namely the Upper (21.34%), Middle (37.16%), and Lower Mahanadi (41.5%). The basin's entire live storage capacity is expected to be 14.244 BCM (billion cubic meters). Out of the total, 12.799 BCM is found to be completed, and the remaining 1.465 BCM is currently in the building phase. This amounts to 28.4% of the 75% reliable useable water and 21.32 % of the average annual flow. The basin falls under the sub-tropical zone, with a recorded average annual rainfall in the range 1200–1400 mm and in relation to the Bay of Bengal, the catchment's geographic location mostly affects the climate (Kurwadkar *et al.* 2022). The lower basin, generally, covers an area of about 57960 Km^2. The total length of the river is around 851 Km, that extends over an area of about 141,600 Km^2. This research basin which is displayed in Fig. 1, is signified as the 3rd largest river in the Peninsula of India and it is located in between the geographical coordinates comprised of 80°30'-86°50'E and 19°20'-23°35'N. Here, the two primary land uses in the basin are agriculture and forestry, which are aided by extensive irrigation infrastructure made possible by major and medium-sized project (Kumar and Bassi, 2021). Additionally, it suggests that the core portions of Odisha within the basin have smaller-scale rainfed farming systems and are heavily wooded. It is also primarily an agricultural region, with a variety of commercial and sustainable farming practises that are dominated by the production of rice (Sajina *et al.* 2022). It is exhibited that around 90% of the total precipitation falls during the monsoon season, which starts in June and lasts until October, even if there are spells of rainfall with different intensities and durations. Every year, from January to May, this river contributes to the buildup of pollutants in the area since it is constantly flooded with raw sewage. The basin's observed average temperature ranges from 24°Cto 27°C, while in the basin, pulses are the second most common crop after rice in the cereal crop group. This basin shows red, yellow as well as mixed red-black soils (Paul *et al.* 2023). These are usually the most prevalent kinds of soil, that are typically found. It is important to note that the effluents from industries such as, aluminium, iron ore, chrome, cotton, polyethylene, polymer, paper, and pharmaceuticals, which mostly contain harmful materials such heavy metals, have contaminated the water in the river basin above. Nevertheless, these sectors typically hold annual sustainability clearance (Pati *et al.* 2023). It is discovered that the contaminants create a variety of bio-molecular pressures on the local population, which includes a large variety of fish.

2.2. Sampling and Chemical Analysis

An early survey has been performed in the Mahanadi River Basin (MRB), and 19 stations were chosen to sample surface water. Furthermore, from 2018 to 2023, about 25 samples were obtained from the State Pollution Control Board (SPCB), Odisha. To keep the model simple, 20 variables were used: pH, BOD (biochemical oxygen demand), DO (dissolved oxygen), TC (total coliform), TDS (total dissolved solids), TH (total hardness), Alkalinity, Chloride (Cl^-), Sulphate (SO_4^{2-}), Iron (Fe^{2+}), Fluoride (F^-), Boron (B^+), TSS (total suspended solids), electrical conductivity (EC), COD (chemical oxygen demand), NH_3-N (ammoniacal nitrogen), free ammonia (Free NH_3), TKN (total Kjeldahl nitrogen), SAR (sodium adsorption ratio), and TH (total hardness). The locations of the stations were identified with a handheld Global Positioning System (GPS). Chemical analysis was also conducted by using standard analytical procedures. The sampling bottles were cleaned and let to soak in HCl prior to gathering the samples. The bottles were carefully sealed after being collected and stored in the refrigerator at 4°C. The parameters EC, pH, DO, and TDS were measured in situ by a potable multi meter, while the Cl^-, SO_4^{2-}, F^- and NO_3^- were measured using Spectrophotometric technique. Alkalinity and TH were analysed by titration methods. Two metals in total, namely iron (Fe^{2+}) and boron (B^+) were examined by ion chromatograph (IC). The remaining tests were carried out in compliance with the Bureau of Indian standards (BIS, 2015). Moreover, observations that included no data were eliminated. During quality control, deionized water (Blank samples) was evaluated in parallel, with two repetitions of each analysis (Ravindra *et al.* 2023). The recommended Standard reference materials (SRM) method was applied for precision and quality management. The factors of water quality were double-checked, using Ion Balance Error (IBE) for their precision in the examination of chemical data, which is described in milliequivalent per litre (meq/L). The observed IBE falls within the permissible value of less than ± 5%.

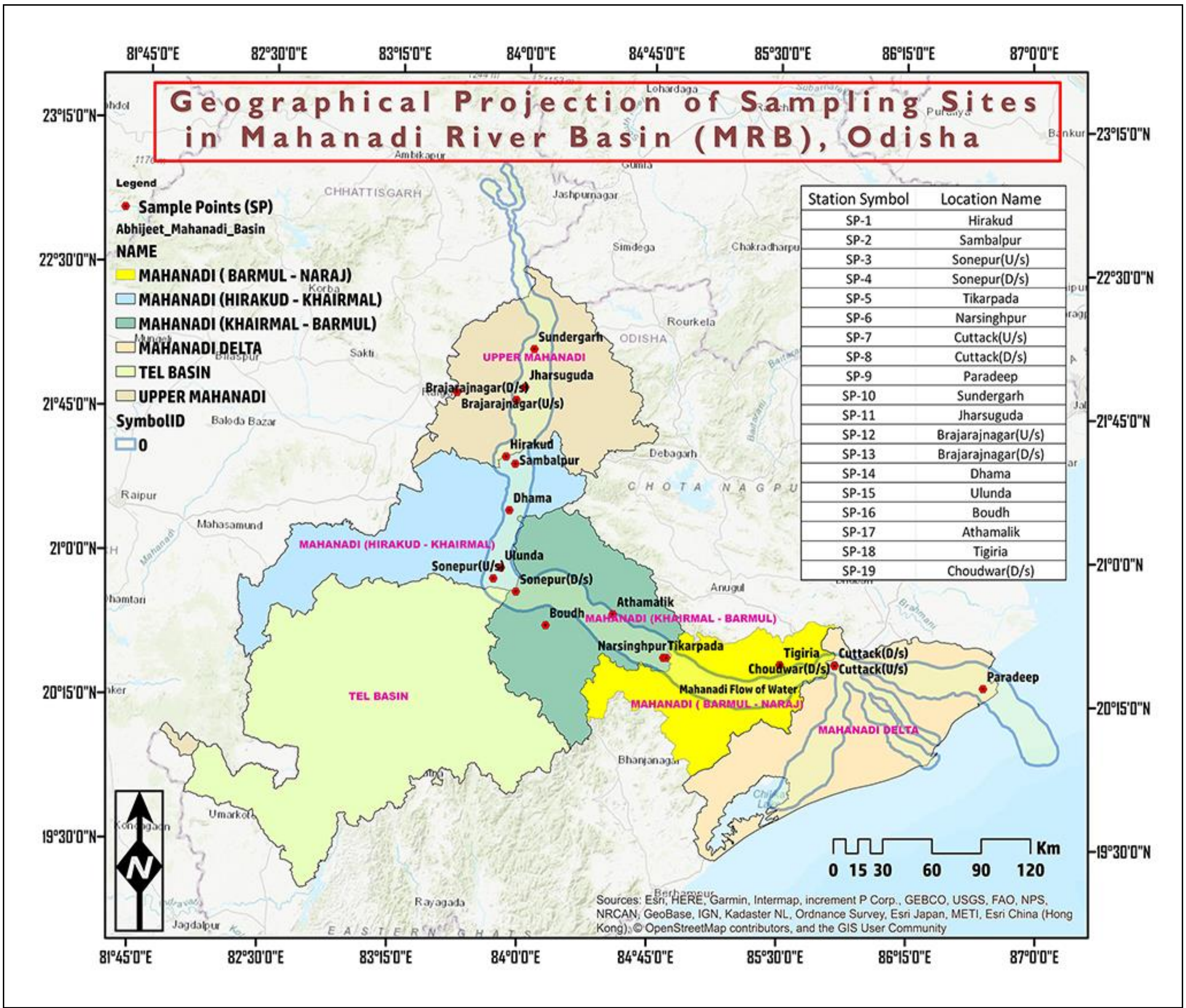


Fig. 1: Sample and study area location map

A reliable assessment of the dataset of numerous variables was scrutinized at different sampling sites using water quality index development. Therefore, to look into if the variations of sampling sites in water quality metrics are similar to one another, FUCOM weighing was included in this creative research (Majumder, 2023). The main goal of this review was to develop a simple WQI calculation process based on MCDM techniques for the evaluation of surface and subsurface water quality. This approach also involves reviewing the spatial heterogeneity of the quality of water of a watercourse with less effort and better accuracy (Gao *et al.* 2020). The stages involved in computing the results include identifying and prioritising the criteria for making decisions, estimating the coefficients for each criterion, determining the relative relevance of each criterion, and recalculating the weight, and finally, estimation of the relative weight (W_i) as endorsed by Sadeghi *et al.* (2023). Furthermore, it proposes a grading system that offers the combined impact of every chosen water quality measure on the total water quality.

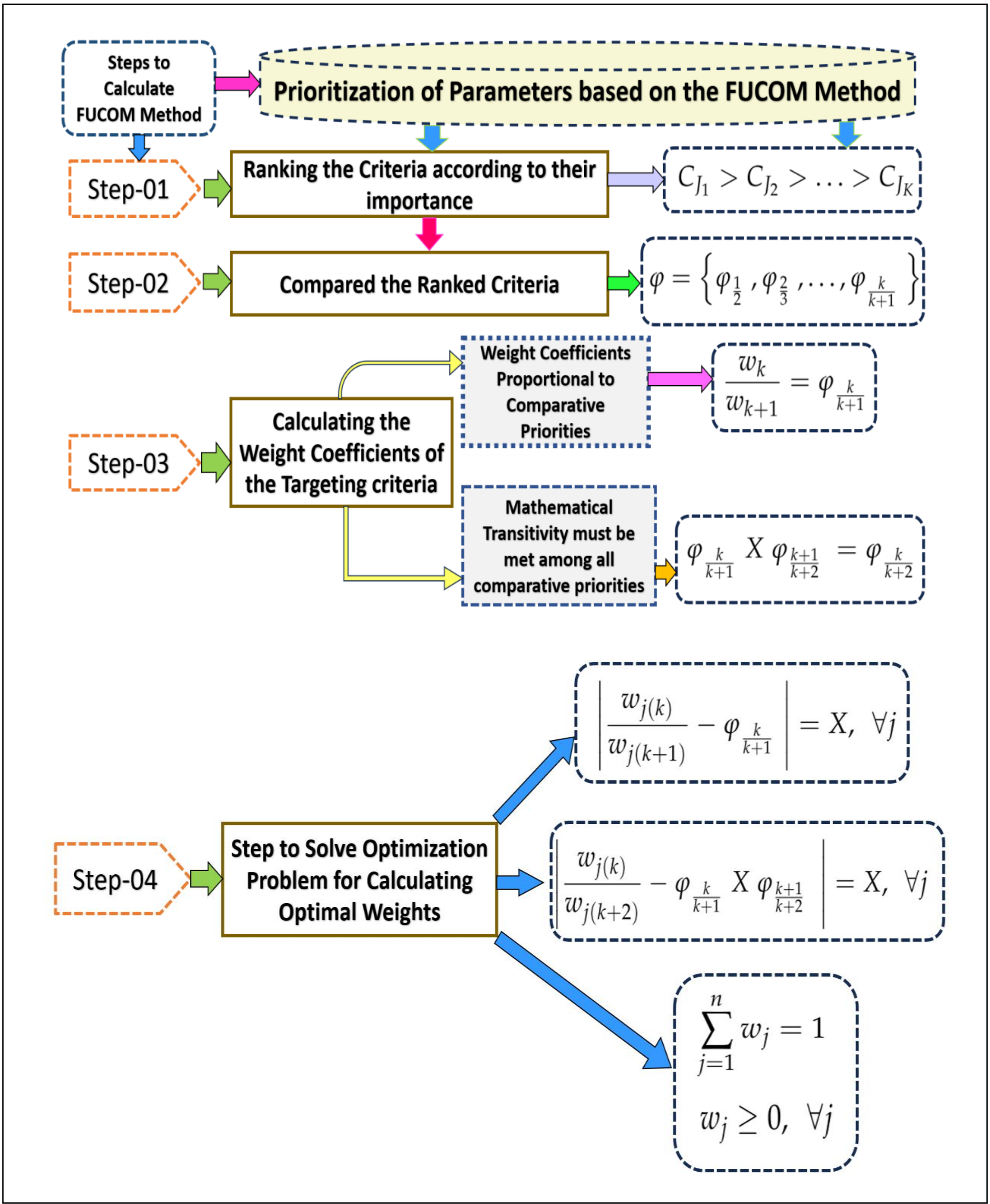


Fig. 2: Calculation principle and flow of water quality assessment based on the FUCOM approach

In general, a system's weighting on parameters tends to rise as it develops over time. This indicates that as time passes, the system gets increasingly erratic or unclear. As a result, this method computes the normalised choice matrix after attempting to determine objectives using a decision matrix and subsequently, provides a concise overview of the system domain to manage the stochastic component, which is in charge of ambiguity or unpredictable for a time-based study of time series information (Debnath *et al.* 2023). Second, using the two fundamental ideas, it establishes the objective weight of the indicators namely, contrast intensity, that is expressed as a standard deviation and shows the value difference between the various evaluation techniques of the same index. After performing this, in next phase, the disagreement among the assessment metrics were determined by the correlation between them (Nemati *et al.* 2023). The calculation of the index scores in F_U-WQI method was differentiated into following four categories and considered as excellent (<50), good (50-100), medium (100-150), poor (150-200) and >200 as unsuitable water class. Following this (Talal *et al.* 2023), the observed concentrations were put into assigned mathematical expression for individual parameter, given in Fig. 2 to find the index score. The final value was estimated, taking averages of twenty parameters for 19 sampling sites were evaluated.

The procedures for creating an F_U-WQI, are prone to complexity and subjectivity. Additionally, it is conceivable that MCDM techniques can lessen step uncertainty, such as in the ranking and variable selection procedures. But the recommended method, which addresses the advantages and disadvantages of constructing WQI for water quality evaluation, is predicated on an integrated, straightforward additive weighting and exponentially weighted product model that is readily simplified by Fuzzy (F)-TOPSIS (TOP), to measure each parameter's weight independently (Dehghan Rahimabadi *et al.* 2024). This suggested method aggregates the weights in two ways and employs a comparability sequence. Because of this, once the obtained data has been normalised, survey site ratings may yield reliable results. As a result, issues like obscureness, rigidity, and ambiguity will always arise while estimating a WQI score, but they can be resolved with this method (Nabizadeh *et al.* 2022). Additionally, it makes it simple to make decisions regarding the implications of uncertainty, which frequently characterise issues with water management. The weighted power of the distance from the comparability sequence is further described, along with the standard multiplication procedure (Ghorbani *et al.* 2023). So, the conceptual framework of assessment processes and the common language used to identify and address complex water concerns are therefore crucial to the effectiveness of the methods provided by this methodology (Wang *et al.* 2023). Moreover, it was established that this method's adaptability in measuring water quality was also confirmed through the joint use of the F-TOP method and integrated weight, in addition to using a preliminary set concept. Afterwards, its challenge originates from the Integrated WQI analysis, which is performed to analyse the criterion's weight and further, the innovative F-TOP technique should be used to rank the options in order of preference and determine which option is the best (Singh *et al.* 2022). Once the alternatives and relevant criteria have been established, the following processes are verified in order to solve a decision problem, as represented in Fig. 3.

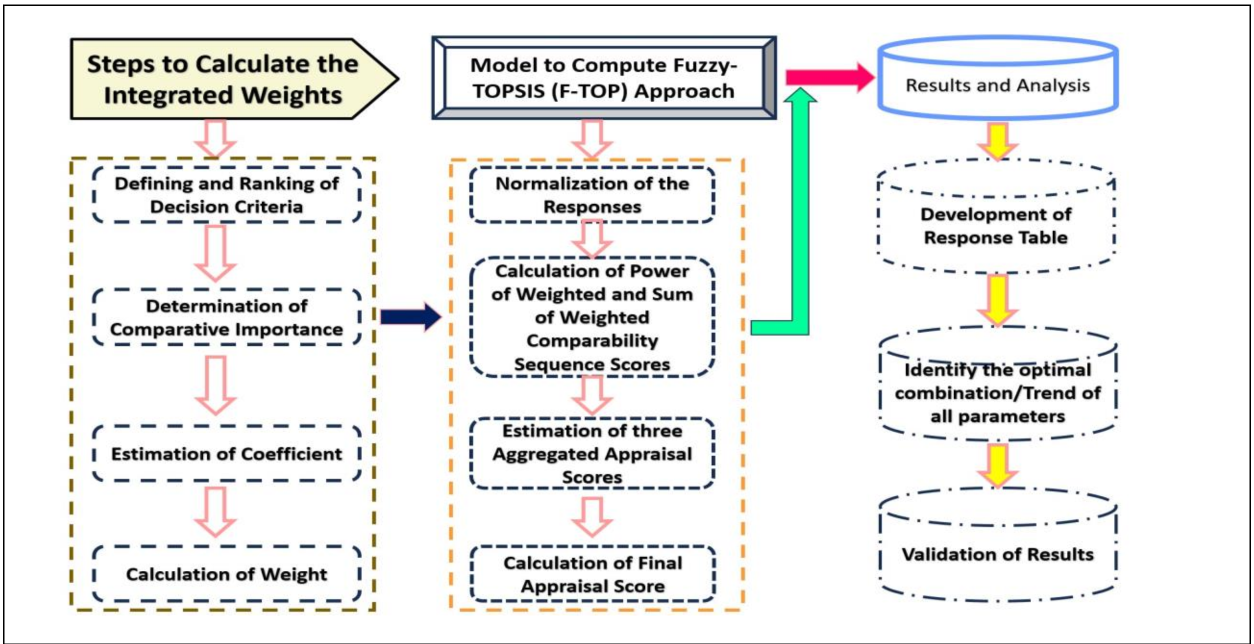
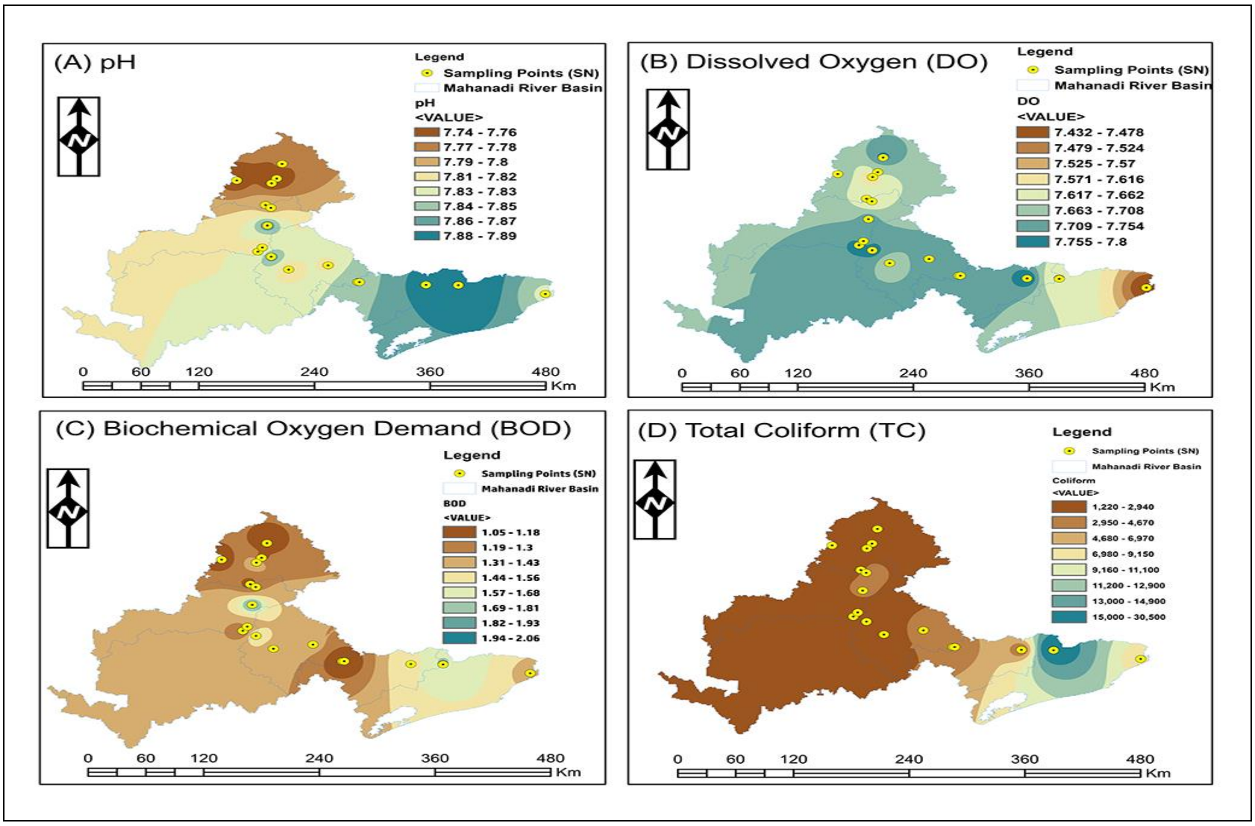


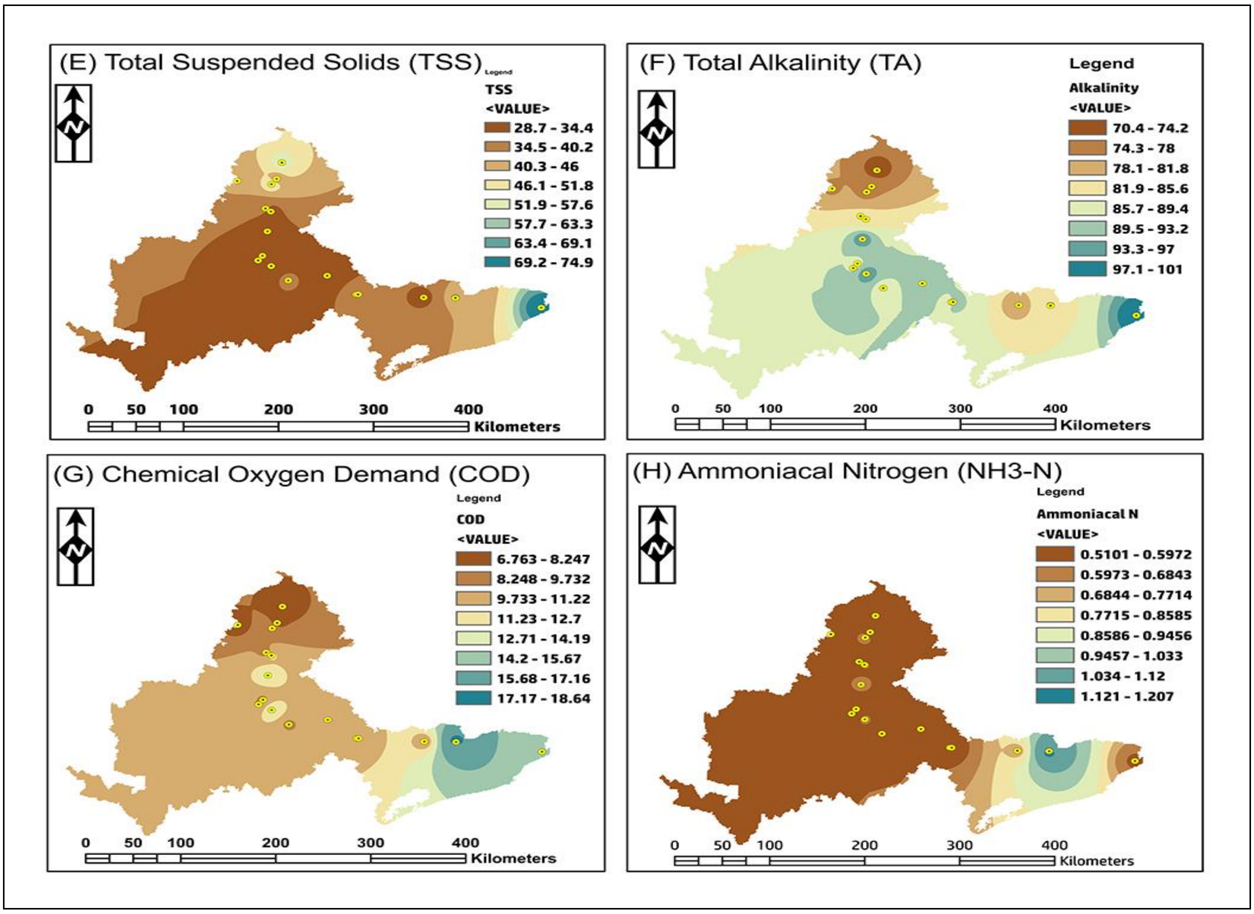
Fig. 3: Schematic representation of F-TOP Model

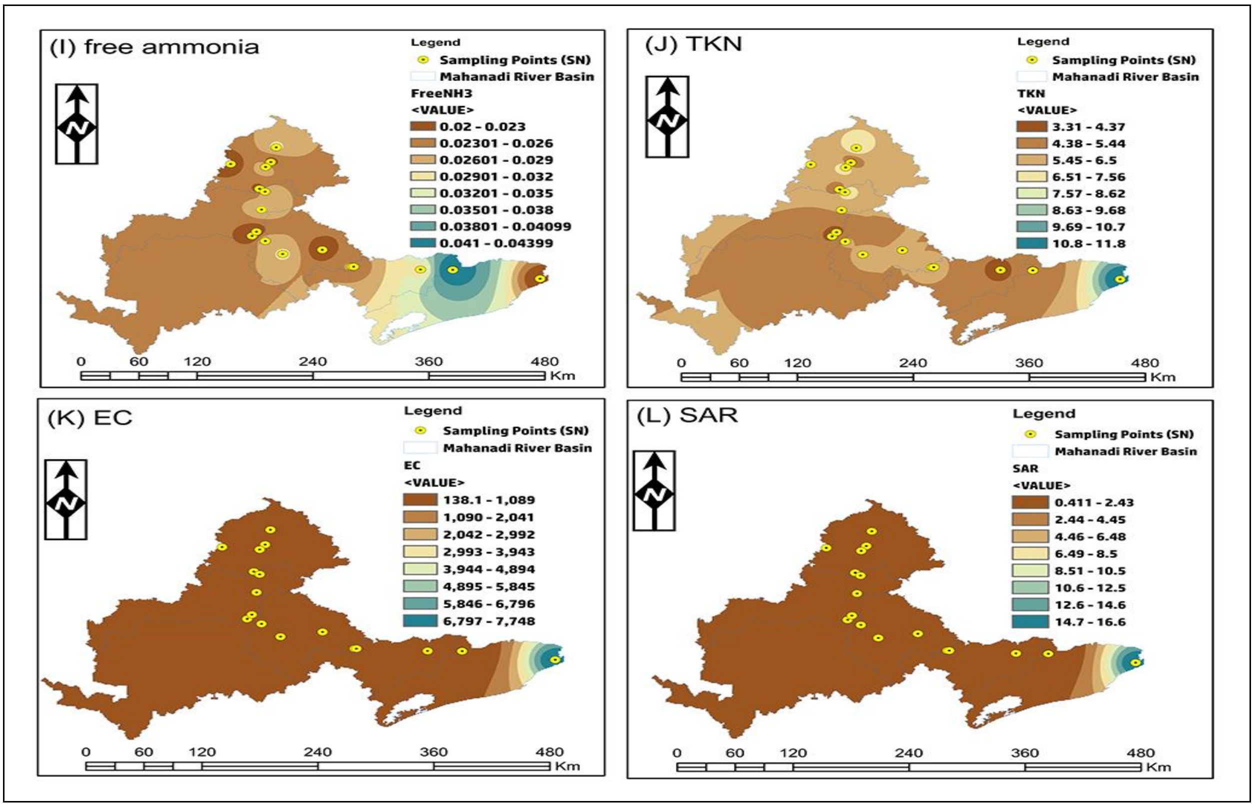
3. RESULTS AND DISCUSSION

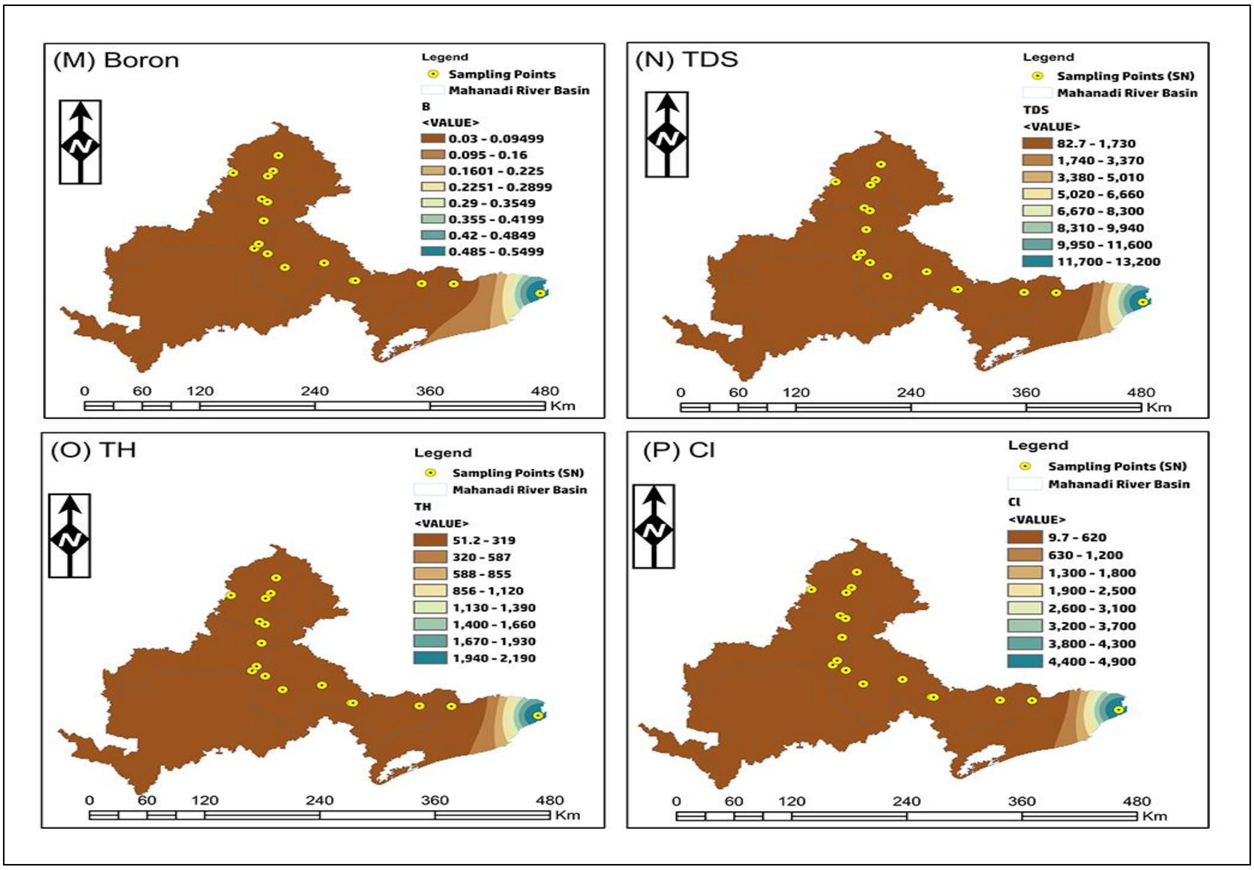
In this examination, as per chosen criteria listed below, the surface water quality maps were equipped with the aid of ArcGIS software 10.5. Descriptive statistics are frequently employed to identify the trend of variables and their correlation with one another. In other words, they are utilized to assess whether different chemical factors affect agricultural output and human health when surface water is consumed for irrigation and drinking. The World Health Organization (WHO, 2017) drinking water standards are indicated for differentiation. It has been established that pH can be used to determine whether surface water is acidic or alkaline. The water bodies' levels are impacted based on the elements found in soils and electrochemical properties, featuring SO_X and NO_X elements (Radha and Mahalingam 2024). In contrast, the photosynthesis process that algae and aquatic plants use in the river water uses hydrogen, which may possibly be a factor in the river's high pH. In the present work, the value ranged from 7.741-7.913 mg/L, indicating a perhaps alkaline state. In most of the sites, the pH was within the allowed drinking limit as given by WHO (6.6-8.5). In addition, the concentration of DO in water depends on numerous parameters, including pressure and temperature, chemical content, and biological activity. In this work, its value spanned from 7.257 to 7.812 mg/L. Nearly every station, DO surpasses the acceptable threshold of 6.0 mg/L for human consumption. Higher DO concentrations are linked to increased organic contaminants and sewage loads, unprocessed municipal sewage discharge, increased turbulent water flow, high atmospheric oxygen dissolution, and an increase in rain and water flows, as seen by other observers. However, the DO level in a water body is of great importance to all aerobic aquatic life; higher levels of DO will maintain biological diversity. The parameter BOD is required to assess the pollution of surface and ground water where contamination occurs due to the disposal of domestic and industrial effluents (Markad *et al.* 2023). In the current study, its measurements ranged from 1.095 to 2.389 mg/L, which is under the value of 5 mg/L, thus according WHO guidelines for every place, it is because of the dilution of the effluents and little to no organic compound mixing, which has helped to reduce the BOD concentration in this river water. Additionally, it is discovered that a low BOD level suggests that there is less organic matter for microbes to oxidise in the water sample. Therefore, in this study, the presence of coliform bacteria guarantees faecal contamination in the water body, indicating a higher risk of illness and an unfitness for drinking. During the study period, the TC count ranged from 1219 to 42530 MPN/100 ml, suggesting all stations are within the prescribed limits (>5000), with the exception of SP-(8), (9), and (19), which have readings higher than the threshold limits. Therefore, it is advised that the existence of larger coliform colonies at three locations suggest a high level of bacterial contamination, which caused a significant portion of the urban population to have cholera, diarrhoea, and gastroenteritis. Total suspended solids comprise all substances that float in the water, including clay, silt, and tiny particles of both organic and inorganic debris. A high score lowers the DO level and lowers the clarity of the water by slowing down photosynthesis and reducing the amount of light entering the water (Rout and Sahoo 2022). The concentration varies from 28.62-74.88 mg/L, in the current investigation. Therefore, the results showed that the reported readings of TSS in the river water were within the desirable limits of 100 mg/L. Mostly, water quality is very good in entire parts of the study area. Another important indicator namely, alkalinity, at every sampling site, was determined to be within the range 70.398-100.88 mg/L, which is observed falling within 200 mg/L. The presence of carbonate, bicarbonate, and hydroxide ions in the water causes this variable. Further, it suggests that water has a better capacity to neutralize acids when it has a higher alkalinity and vice versa. Because of this, the taste of water is affected further than this point (i.e., 200 mg/L). It is evident that water at SP-(9) was comparatively more alkaline as compared to other stations. This could be brought on by the extra salts present. However, the findings show that the river can counteract acidic contamination from waste water or rainfall. Chemical oxygen demand is a crucial marker for organic pollution originating from sources like partly or untreated urban residential and industrial wastewater (Nayak *et al.* 2024). It goes on to say that this indicator may be linked to the formation of organic acids as a result of anaerobic conditions developing from high dissolved organic matter, which lowers the pH value. The value obtained in the current work exhibits a range between 6.75 and 21.87 mg/L. As WHO (2017) prescribes, the maximum permissible limit is 30 mg/L in drinking water. When present in drinking water at the stated level, it may have a detectable flavour, and in certain users, very high concentrations can have a laxative effect. Ammoniacal Nitrogen (NH_3-N) and free ammonia (Free-NH_3) concentration are the most important surface water contaminants when taking agricultural and drinking uses into account. Within the research domain, the main causes of NH_3 contamination in surface water were chemical fertilisers, sewage disposal, and residents discarding waste in open areas. Furthermore, as nitrate is linked to the breakdown of organic matter from sewage, household wastes, animal dung, and nitrogen fertilisers, elevated levels of both markers are essentially a sign of anthropogenic activity. The main sources are animal, agricultural, and industrial wastes. The reported findings of NH_3-N and Free-NH_3 ranging from 0.511-1.928 and 0.021-0.059 mg/L, respectively. Hence, the recommended limit for drinking water should be 2 mg/L. However, all observations were within the prescribed limits for all sampling locations. Surface water is contaminated by TKN due to leaching from agricultural land, solid waste dumping sites, or ammonia oxidation. Therefore, greater nitrate values in the research region were linked to heightened values in untreated wastewater-irrigated areas, partially untreated wastewater-irrigated areas, and solid waste dumping sites. Additionally, the primary cause of the contamination of the potable water for human use was the overuse of plant nutrients and inorganic fertilisers. The levels in the current study region ranged between 3.279 and 11.791 mg/L. However, its readings should not exceed the threshold of 5 mg/L, as per WHO criteria. It is exhibited from the findings that, in most places, the values are higher. This results from the mixing of human and animal wastes, runoff from agricultural land, and anthropogenic contamination. The parameters EC and TDS often have a direct relationship in which the conductivity and TDS value increase with the quantity of ions present. This metric, called EC, is a useful indicator of salinity as well as the concentration of ionised chemicals in water. A low value means there are less ions in the water, making it safe to drink; a high EC shows that there is a lot of mineralization in the water as a result of anthropogenic and geogenic activity. In the surface water of the study area, concentrations of EC varied from 138.11 to 7779.342 mg/L. The findings showed that all of the locations' water samples were determined to be within the advised limits of 2250 mg/L, according to WHO (2017) and can be used without further treatment as drinking water, except at the site SP-(9). So, this location shows that the activity of geochemical processes vary widely. Thus, it is elucidated that the salinity factor is due to mineral dissolution. Numerous authors have noted that greater SAR values in drinking water may lower osmotic pressure, which in turn may limit plants' uptake of nutrients from the soil. This is termed as sodicity, which is the outcome of excessive Na^+ development in the soils. As a result, soil clays swell and disperse; recharge water infiltration is impeded by surface crusting and pore clogging. Additionally, inadequate drainage conditions are a source of Na^+ in water. In the period of the concerned study, the surface water shows a score of 0.412-16.589, which is comfortably within the permitted range of 10 mg/L, except at SP-(9). Elevated readings at SP-(9) in drinking water, frequently unsuitable for irrigation and drinking, degrades the soil's structural qualities and turns it alkaline. Also, higher values may be related to the cation exchange mechanism. Poor sanitation, chemical fertilizers, and residential waste dumps in open spaces were the primary causes of B^+ pollution in surface water. As a matter of fact, there are numerous ways that this indicator finds its way into water systems, including sewage, manure, and other synthetic fertilisers applied to areas of agriculture. Reduced oxygen in river water due to higher value has an impact on the material's consistency and nutrient cycle processes. Consequently, the study area's current levels fell short of the WHO's recommended of 2 mg/L, and there was no health risk associated with the concentration in the river. From the investigated work, it has been estimated that TDS concentration is high at SP-(9) & (19). It also highlights that at all sampling stations, TDS readings fell within the allowable range of WHO i.e., 100 mg/L. Significant precipitation is to blame for the extra TDS, which could surpass its conveyance capabilities. This pattern lowers the TDS concentration in the river and supports the diluting effect. Additionally, the discharge of industrial effluent, agricultural runoff, and household sewage into the river causes increased readings. In addition, water with high dissolved solids is known to cause impairment of physiological processes in the human body and may lead to gastrointestinal irritation, especially for people suffering from kidney problems. In general, water hardness is caused by various dissolved polyvalent metallic ions, mainly Ca^{2+} and Mg^{2+}. Ca^{2+} is one among the ions that temporarily causes surface water to become hard, and drinking too much of it can have a negative impact on one's health. Also, Mg^{2+} acts for the proper functioning of cells in enzyme activation, but at higher concentrations, leads to a laxative effect. Consequently, it may result in limited potential yield and nutritional benefits at higher soil levels. It is noticed that the observed values vary in the range 51.18-2194.90. As illustrated from WHO (2017), the recorded maximum allowable limit is taken as 300 mg/L. On the basis of its findings, the area is found to be within the TH limit, indicated for drinking purposes except SP-(9). The value at SP-(9) was observed to be higher as a result of weathering and carbonate minerals. Its value beyond permissible limits cause renal failure in humans. In the case of Cl^-, it is used in water treatment to kill bacteria, parasites, viruses, and microbes in water by neutralizing and oxidizing bacteria, parasites, viruses, and microbes. Higher Cl^- influences the river ecology and ecosystem services such as fisheries. Usually, Cl^- in drinking water comes from leachate, saline intrusion, fertilisers, sewage and industrial effluents, and natural sources. Also, excess Cl^- may make drinking water to taste salty. The unrestricted movement of Cl^- in the surface water environment was caused by a lack of natural sources in the research region as opposed to paleo salinity, which is not absorbed by the soil, or the breakdown of halite minerals. The permissible limit of Cl^- is 250 mg/L as per WHO standards. In the present study, its concentration ranged from 9.648-4904.88 mg/L, and its readings remained below the maximum allowable level at all sampling locations except at SP-(9). The reason for greater concentration at SP-(9) is because of the geological properties of the area, agricultural runoffs, wastewater from industries, and domestic sources. Sulphate (SO_4^{2-}) occurs spontaneously in surface water as a result of sedimentary and igneous rock weathering. Leachate from shuttered mines, air deposition from burning fossil fuels, and industrial waste water could be additional sources. Surface runoff from the contaminated areas and sewage discharge are two ways that this characteristic might get into water streams. Due to industrial and domestic waste, the concentration of sulphate in water increases. This parameter value also increases due to increased evaporation with increasing air temperature. In this regard, the value was considered to be in the range 4.97-376.07 mg/L in the present work. However, it is observed that the lowest SO_4^{2-} was recorded at SP-(13) and a higher value is exhibited at SP-9 (376.07 mg/L). Additionally, when its concentration above the WHO (2017) standard level (200 mg/L), it may have a laxative impact on people's health. It is found that an increase in concentration at SP-9. Given the study area's high level of farm-driven activity, it might be connected to runoff from agriculture. Higher doses also cause gastrointestinal distress and have a purgative impact on people. Surface water contains high levels of fluoride due to accelerated evaporation cycle caused by continuous water rock percolations of fluorite-bearing rocks in desert conditions with little precipitation and high temperatures. The weathering of primary rocks and the liquidation of fluoride-containing minerals, which are generally associated with low calcium levels and high bicarbonate ions, are the main causes of high fluoride rates in India. The primary source of this indication in drinking water is various geological processes. At low concentrations, it prevents and minimises risks that damage teeth, which has a significant impact on teeth. Human health benefits from drinking water with an allowed limit of 1 mg/L. High F^- levels are linked to the area's dental fluorosis. The current study's quantification of F^- concentration was discovered to be as 0.258-1.0 mg/L. After a disinfection procedure, the water could be utilised for drinking at all sites because the concentrations were within the WHO acceptable range. The principal source of nitrate (NO_3^-) in drinking water is a result of leaching from various agricultural and human activities that have caused water to infiltrate. Surface washing, phytoplankton absorption, and bacterial nitrate denitrification can all cause its levels to rise quickly, while increases in ground water nitrate levels usually happen gradually. Due to the oxidation of NH_3 and its similar sources, contamination from human or animal waste and excessive fertiliser use in agricultural land are the frequent sources of this characteristics. NH_3 penetrates the aquatic environment through indirect channels including nitrogen fixation, air deposition, and runoff from agricultural areas, as well as direct channels like animal excretion of nitrogenous waste and municipal effluent discharge. Furthermore, as a result of several agricultural and related activities, such as the excessive use of inorganic nitrogenous fertilisers and manures and the dumping of wastewater by particular enterprises, its concentration level can be seen in both surface water and groundwater. The Findings in the present area showed that its readings were in the range 1.289-2.689 mg/L. In all sites, the levels are within the criteria limit of 45 mg/L. Iron (Fe^{2+}) is a trace element that is vital to health and was obtained from industrial and natural waste water. Even though it encourages the blood's oxygen to be transported, at high concentrations, hemochromatosis, exhaustion, weight loss, joint discomfort, stomach issues, vomiting, and DNA damage are among the possible side effects. It also describes how rainwater that contacts the soil raises the river's Fe^{2+} content. Additionally, highly concentrated iron water can cause turbidity and turn a reddish-brown colour. During the research period, the iron varies between 0.59-2.609 mg/L, which is within the range, that is acceptable under 1 mg/L. Focused on the assessment above, it is detected that TC and TKN exhibit greater values, which exceeds the guidelines suggested by WHO standards, caused by the different sources from which geogenic and industrial origins are available. Thus, the controlling factor in the order of dominance of cations in the study area is $Fe^{2+} > B^+$, whereas the anions are $Cl^- > SO_4^{2-} > NO_3^- > F^-$. Hence, it is easy to observe the geospatial maps of the many water quality criteria throughout the river stretch, that is displayed in Fig. 4 (A)-(T).

In the case of traditional WQIs methods, it prompts us to conclude that no surface water body's problematic situation is indicated by the analysis, monitoring, or index development alone. As a result, in further research, it will be simple to determine the sampling locations' relative pollution levels in relation to drinking water quality standards using the F_U-WQI approach. Consequently, another strategy of decision-making, namely, F-TOP, is suggested to use the following formulas covered in the methodology to compare their rating processes and averaged rating. These F_U-WQI values for every sample, according to the WHO's drinking water quality guidelines, are listed in Table 1. While conducting additional research in Fig. 5 (A & B), in the concerned area, the F_U-WQI varied from 25 to 423, which depicts excellent to unsuitable categories. Also, elevated values exhibited at SP-9 site because of 8 parameters namely, TH, SAR, TDS, Cl^-, TKN, EC, SO_4^{2-} and TC. In fact, the upstream areas close to the sample sites saw an improvement in the quality of the water. The outcome can be attributed to increased monsoon rainfall as well as groundwater infiltration that dilutes the surface water system (Pandey *et al.* 2023). This picture illustrates an example of both organic and inorganic contamination originating from human sources, including water treatment facilities, untreated municipal sewage discharge, and residential waste water. Approximately 47.37% of the testing locations, containing 9 sites showcase excellent water. Around 10.53% (n=2) signifies medium, 36.84% of the water samples (n=7) referred as poor conditions, and finally, 5.26% (n=1 location) suggests unsuitable category of drinking water. In addition, the places, namely SP-(2), (8), (9), (10), (11), (12), (13), and (19) showed poor/unsuitable water quality throughout the entire period. The river appears to pick up more pollution before emptying into the sea since it flows downstream past multiple towns and cities before entering the State of Odisha. Thus, with the exception of these eight stations, the majority of the study area's surface water quality falls into the excellent and good categories, making it ideal for both domestic and drinking purposes. The developed interpolated map has been illustrated in a GIS diagram displayed in Fig. 6.


(A) pH
Legend
Sampling Points (SN)
Mahanadi River Basin
pH
<VALUE>
7.74 - 7.76
7.77 - 7.78
7.79 - 7.8
7.81 - 7.82
7.83 - 7.83
7.84 - 7.85
7.86 - 7.87
7.88 - 7.89
N
0 60 120 240 360 480 Km
(B) Dissolved Oxygen (DO)
Legend
Sampling Points (SN)
Mahanadi River Basin
DO
<VALUE>
7.432 - 7.478
7.479 - 7.524
7.525 - 7.57
7.571 - 7.616
7.617 - 7.662
7.663 - 7.708
7.709 - 7.754
7.755 - 7.8
N
0 60 120 240 360 480 Km
(C) Biochemical Oxygen Demand (BOD)
Legend
Sampling Points (SN)
Mahanadi River Basin
BOD
<VALUE>
1.05 - 1.18
1.19 - 1.3
1.31 - 1.43
1.44 - 1.56
1.57 - 1.68
1.69 - 1.81
1.82 - 1.93
1.94 - 2.06
N
0 60 120 240 360 480 Km
(D) Total Coliform (TC)
Legend
Sampling Points (SN)
Mahanadi River Basin
Coliform
<VALUE>
1,220 - 2,940
2,950 - 4,670
4,680 - 6,970
6,980 - 9,150
9,160 - 11,100
11,200 - 12,900
13,000 - 14,900
15,000 - 30,500
N
0 60 120 240 360 480 Km


(E) Total Suspended Solids (TSS)
Legend
TSS
<VALUE>
28.7 - 34.4
34.5 - 40.2
40.3 - 46
46.1 - 51.8
51.9 - 57.6
57.7 - 63.3
63.4 - 69.1
69.2 - 74.9
N
0 50 100 200 300 400 Kilometers
(F) Total Alkalinity (TA)
Legend
Alkalinity
<VALUE>
70.4 - 74.2
74.3 - 78
78.1 - 81.8
81.9 - 85.6
85.7 - 89.4
89.5 - 93.2
93.3 - 97
97.1 - 101
N
0 50 100 200 300 400 Kilometers
(G) Chemical Oxygen Demand (COD)
Legend
COD
<VALUE>
6.763 - 8.247
8.248 - 9.732
9.733 - 11.22
11.23 - 12.7
12.71 - 14.19
14.2 - 15.67
15.68 - 17.16
17.17 - 18.64
N
0 50 100 200 300 400 Kilometers
(H) Ammoniacal Nitrogen (NH3-N)
Legend
Ammoniacal N
<VALUE>
0.5101 - 0.5972
0.5973 - 0.6843
0.6844 - 0.7714
0.7715 - 0.8585
0.8586 - 0.9456
0.9457 - 1.033
1.034 - 1.12
1.121 - 1.207
N
0 50 100 200 300 400 Kilometers


(I) free ammonia
Legend
Sampling Points (SN)
Mahanadi River Basin
FreeNH3
<VALUE>
0.02 - 0.023
0.02301 - 0.026
0.02601 - 0.029
0.02901 - 0.032
0.03201 - 0.035
0.03501 - 0.038
0.03801 - 0.04099
0.041 - 0.04399
0 60 120 240 360 480 Km
(J) TKN
Legend
Sampling Points (SN)
Mahanadi River Basin
TKN
<VALUE>
3.31 - 4.37
4.38 - 5.44
5.45 - 6.5
6.51 - 7.56
7.57 - 8.62
8.63 - 9.68
9.69 - 10.7
10.8 - 11.8
0 60 120 240 360 480 Km
(K) EC
Legend
Sampling Points (SN)
Mahanadi River Basin
EC
<VALUE>
138.1 - 1,089
1,090 - 2,041
2,042 - 2,992
2,993 - 3,943
3,944 - 4,894
4,895 - 5,845
5,846 - 6,796
6,797 - 7,748
0 60 120 240 360 480 Km
(L) SAR
Legend
Sampling Points (SN)
Mahanadi River Basin
SAR
<VALUE>
0.411 - 2.43
2.44 - 4.45
4.46 - 6.48
6.49 - 8.5
8.51 - 10.5
10.6 - 12.5
12.6 - 14.6
14.7 - 16.6
0 60 120 240 360 480 Km


(M) Boron
Legend
Sampling Points
Mahanadi River Basin
B
<VALUE>
0.03 - 0.09499
0.095 - 0.16
0.1601 - 0.225
0.2251 - 0.2899
0.29 - 0.3549
0.355 - 0.4199
0.42 - 0.4849
0.485 - 0.5499
0 60 120 240 360 480 Km
(N) TDS
Legend
Sampling Points (SN)
Mahanadi River Basin
TDS
<VALUE>
82.7 - 1,730
1,740 - 3,370
3,380 - 5,010
5,020 - 6,660
6,670 - 8,300
8,310 - 9,940
9,950 - 11,600
11,700 - 13,200
0 60 120 240 360 480 Km
(O) TH
Legend
Sampling Points (SN)
Mahanadi River Basin
TH
<VALUE>
51.2 - 319
320 - 587
588 - 855
856 - 1,120
1,130 - 1,390
1,400 - 1,660
1,670 - 1,930
1,940 - 2,190
0 60 120 240 360 480 Km
(P) Cl
Legend
Sampling Points (SN)
Mahanadi River Basin
Cl
<VALUE>
9.7 - 620
630 - 1,200
1,300 - 1,800
1,900 - 2,500
2,600 - 3,100
3,200 - 3,700
3,800 - 4,300
4,400 - 4,900
0 60 120 240 360 480 Km

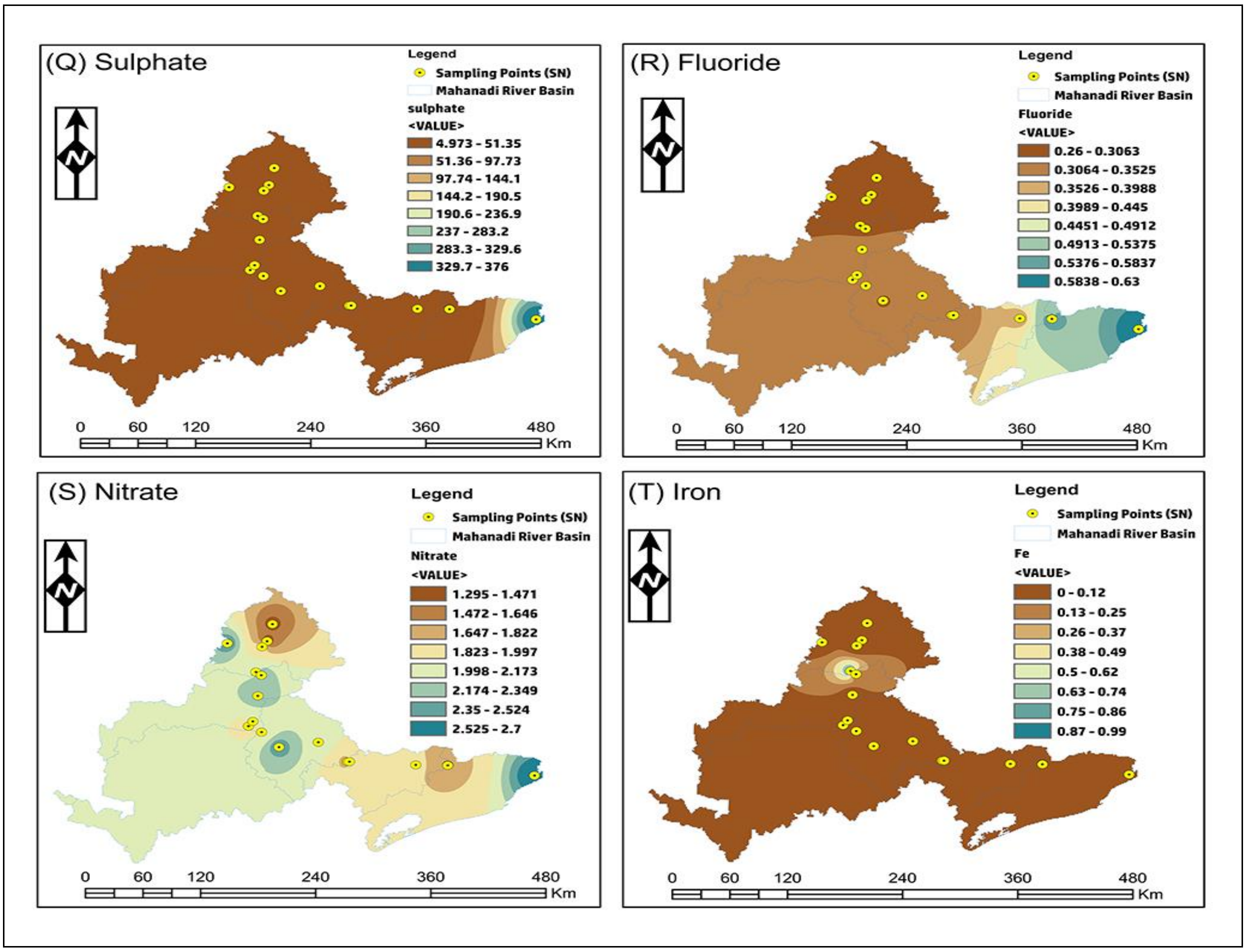


Fig. 4 (A)-(T): Spatial distribution maps of individual physiochemical parameters

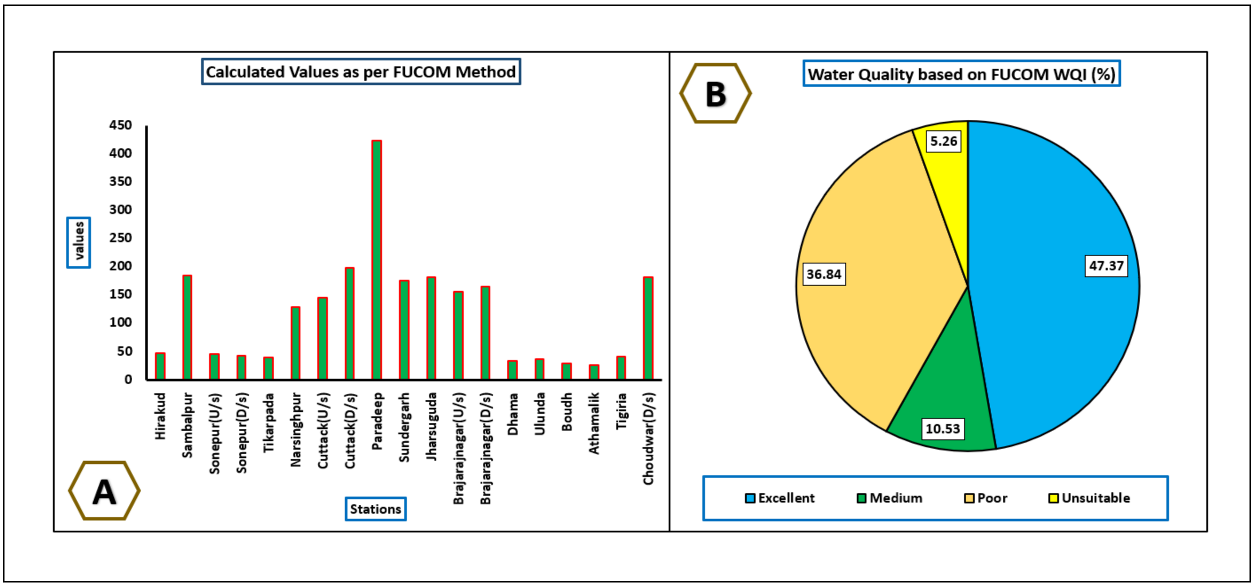


Fig. 5: F_U-WQI rating of various sampling sites (A) Concentration levels, (B) % of distribution

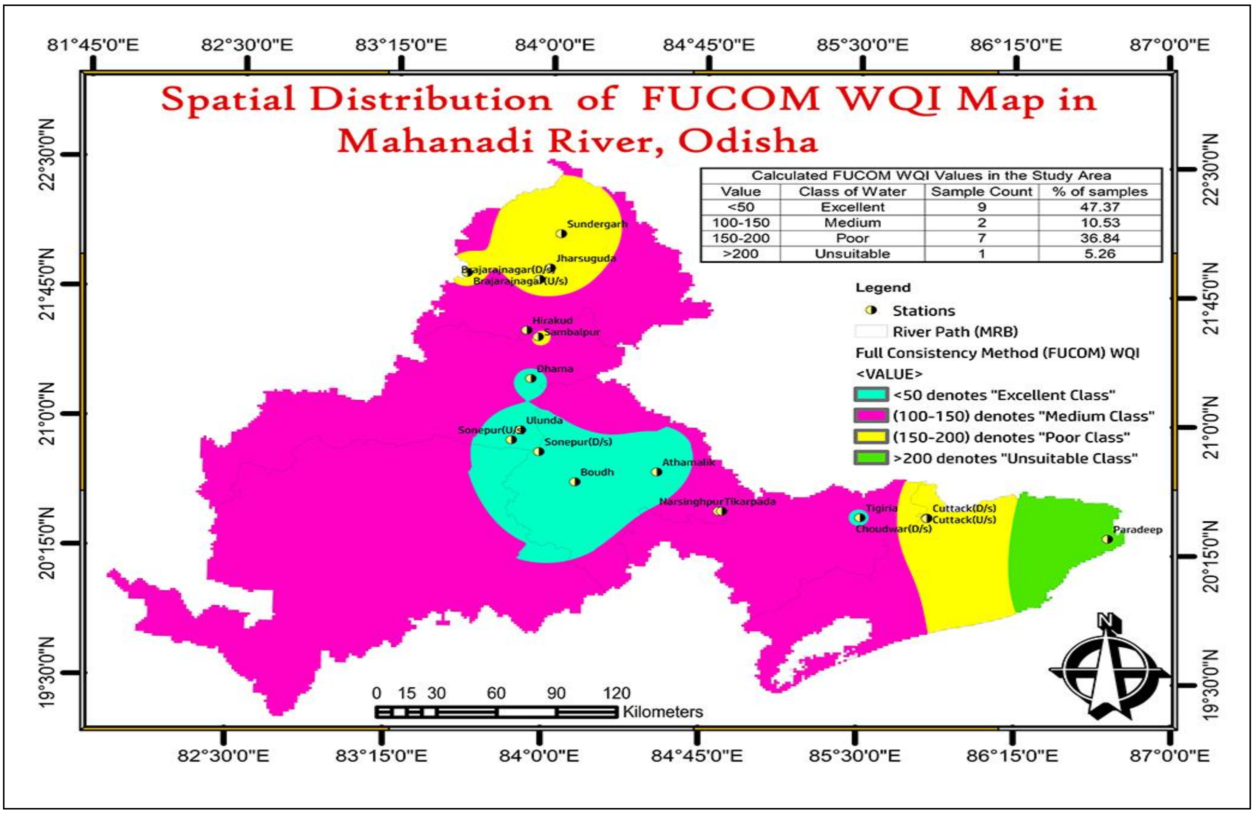


Fig. 6: Spatial variation of F_U-WQI in various stretches of River Mahanadi

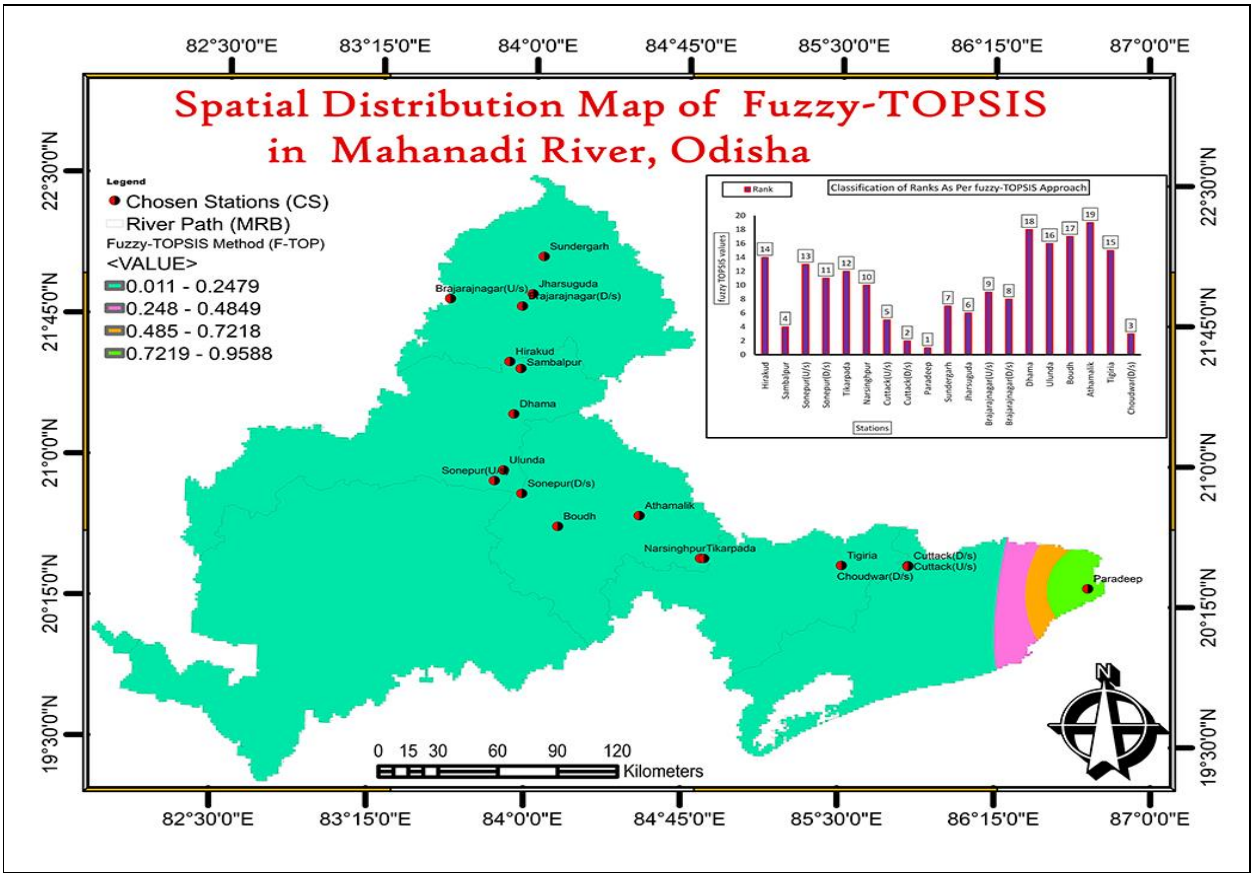


Fig. 7: Spatial variation of F-TOP, showing the performance values (P_i) along with rank

The index of water quality is a rating that reflects the cumulative effect of the parameters of water quality (Bilali *et al.* 2022). Therefore, employing each parameter's normalized value in the MCDM computation could result in a greater impact on F_U-WQI ranking. So, the F-TOP method also determined the relative pollution level and listed these places as the most contaminated, offering them an overall rank (P_i). Its rankings for each sampling location as well as its performance score are displayed in Fig. 7 and Table 1. Considering this, the outcomes in the studied region, observed that the location SP-(8) holds a score of $P_i = 0.074$ and site-(19) also holds a coefficient of $P_i = 0.046$, which possesses the second and third highest F_U-WQI indicating it as poor water class. In addition, a place like SP-9 ($P_i = 0.959$) is situated in the zone of heavily polluted location, with an overall rank of 1, on account of higher concentrations in four parameters namely, TKN, Cl^-, SO_4^{2-}, and TC, which were also higher than their desirable concentration and highest among all the locations. A higher value in four places namely, SP-(9), (8), (19) and (2) is noted, that follows the trend of higher TKN and TC. Regarding the lengthy discussion above, the total results show that "poor and unsuitable locations" indicate the presence of high levels of pollutants from sewage disposal, agricultural runoffs, textile industry, and related industrial effluents (Liu *et al.* 2021). They also show that the area cannot be used for drinking without treatment. Finally, locations with excellent and bad water characteristics were identified by contouring the retrieved values using geostatistical approaches.

Table 1. WQI at individual sampling location and its overall performance score (P_i), and its ranking for each site computed by the F-TOP approach

Sample No.	F_U-WQI		F-TOP	
	Value	Water Quality Status	Performance Score (P_i)	Rank
SP-1	47	Excellent	0.028	14
SP-2	184	Poor	0.041	4
SP-3	45	Excellent	0.028	13
SP-4	42	Excellent	0.029	11
SP-5	39	Excellent	0.029	12
SP-6	129	Medium	0.029	10
SP-7	145	Medium	0.031	5
SP-8	198	Poor	0.074	2
SP-9	423	Unsuitable	0.959	1
SP-10	176	Poor	0.031	7
SP-11	181	Poor	0.031	6
SP-12	156	Poor	0.030	9
SP-13	165	Poor	0.031	8
SP-14	34	Excellent	0.021	18
SP-15	37	Excellent	0.027	16
SP-16	28	Excellent	0.026	17
SP-17	25	Excellent	0.011	19
SP-18	41	Excellent	0.027	15
SP-19	182	Poor	0.046	3

4. CONCLUSION

The first steps in pollution control and mitigation are mapping the pollutants in surface water and locating their sources. These approaches must be combined in decision-making because there are numerous developing contaminants and a variety of mapping techniques are available. In this work, an effort has been made to comprehend the suitability for human consumption, considering 20 water quality (WQ) parameters collected yearly from nineteen water sources. The time frame taken into consideration is 5 years (2018-2023). The integrated-based FUCOM (F_U) water quality index (WQI) and MCDMs like the F-TOP method were applied to compute the results. The results in the study area illustrate that most of the parameters evaluated were found to fall within the allowable limits of the WHO standards except TC and TKN. Also, the river water is slightly alkaline and DO is quite healthy. Eight locations are used to display the variance in the water quality parameters using the IDW interpolation method of spatial distribution analysis. Approximately 57.89 % of samples are determined to be fit for drinking when the WQI for drinking is taken into account; these values fall between 25 and 423. However, the findings of F_U-WQI reveal that the water quality is polluted at eight sites and it is not fit for drinking purpose, even though the local people are drinking. The high WQI values at SP-9 (423) were prompted on by the elevated TC, TKN, EC, TDS, Cl^-, SO_4^{2-}, NO_3^- and Fe^{2+} values. Nine samples are deemed to have excellent drinking water quality, while just one sample is deemed unfit for human consumption. This could be ascribed to the sites that are located at the periphery of industrial area and it is mainly influenced by excessive concentrations of many parameters and also, due to the impact of industrial and intense human activities. In addition, the spatial assessment of the relative water quality with respect to physicochemical variables was carried out by MCDMs. The developed F-TOP model was applied to the dataset and ranked the site i.e., SP-9 ($P_i = 0.959$) as the most contaminated sampling point on the degree of performance score or closeness coefficients, followed by 2nd i.e., SP-8 ($P_i = 0.074$) and 3rd i.e., SP-19 ($P_i = 0.046$). The significant factors are industrial discharges, human waste, and fertilisers used in agriculture. Additionally, it was reported that seasonal fluctuations, agricultural practises, and other human-induced activities are the key factors affecting the water quality at these three locations. The nitrogen content and coliform in the river's water pose a serious risk to humans. The river water contains a significant concentration of organic contaminants. Therefore, it was clear from the water quality data set that it offered a more thorough understanding of how water quality was categorised in relation to physicochemical factors. Thus, this is the first study in the river basin to present findings that point to significant discrepancies between the indices at different sampling sites. For the sake of both human health and the wellbeing of the water body, certain water conservation and water body conservation techniques should be implemented. Using a variety of strategies, such as this study, will help you avoid making quick decisions. Ultimately, the investigation has verified the practicability and dependability of the previously mentioned techniques for deciphering and interpreting surface water quality analysis data.

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AUTHOR CONTRIBUTIONS

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

FUNDING

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DECLARATION OF COMPETING INTEREST

The author declares no conflict of interests.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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