Utilization of Geospatial Interpolation Technique for Evaluation of Groundwater Pollution Index (GPI): A Case Study in Coastal Odisha, India

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Abstract. The groundwater quality in coastal regions is significantly threatened by changing climate conditions. The purpose of this investigation is to quantify the pollution level of groundwater quality by analysing physicochemical characteristics of twenty water samples along the coastal tract of Odisha. Considering the seriousness of the problem and the concerns voiced by civil society, a conventional numerical model is used in conjunction with geospatial approaches to evaluate the water quality. Water quality parameters are examined through the application of the Groundwater Pollution Index (GPI), along with integrated interpolation and geographical information systems (GIS) for spatial mapping of pollution zones. The results demonstrate that the waters in the study area exhibit salinity and possess medium to high concentrations of major ions that exceed the defined limits for drinking water quality. Anions are dominated by Cl^-, which is followed by SO_4^{2-}, HCO_3^-, and NO_3, while cations are dominated by $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. The pollution index of the research area varies from 0.42 to 7.18. Based on the GPI values, 40% of the water samples are categorized as highly polluted, 15% are classified as moderately polluted, while the remaining 45% are free from pollution. This finding highlights the influence of natural factors on the groundwater quality of the study area and the subsequent changes that result from ongoing human activities. The GPI numerical model and geospatial interpolation of pollution zones serve as valuable tools for developing and implementing effective strategies for the sustainable management of groundwater resources.

Keywords: Geospatial interpolation, Groundwater pollution index, GIS, water quality

1 Introduction

Water is the dominant natural resource that constitutes the foundation of the ecological system. The decline in water quality represents a significant global challenge with profound consequences. Pollution associated with residential development, crop residue, emissions from industry, saltwater intrusion, and poor disposal of garbage contaminates vital groundwater sources [11]. Evaluating groundwater quality is critical to ensuring its safety and long-term use for drinking, farming, and industry [8, 13]. A substantial portion of the groundwater in many areas comes from coastal aquifers. Coastal water quality is declining for many reasons, such as increased urbanization and industrialization, improved agriculture methods, less forest cover, changing weather patterns, different ways of using land, and saltwater intrusion. Community members in coastal areas should be concerned about water quality and whether it is suitable for both household and industrial uses [14]. The low quality of the groundwater has already begun to impact the soil qualities in several regions of India. The complete water system has been negatively impacted by fertilizer made from chemicals, as the soil continues to use 90% of it without any benefit [17]. Anthropogenic activities and land use changes have major impact on quality and recharge of water [22].

Polluted groundwater significantly affects human health, leading to diseases and enduring health challenges [4]. One of the most crucial parts of our modern food system is safe drinking water, since polluted water can harm our peripheral nervous system, hearts, kidneys, and even cause hypertension [15]. In order to protect and maintain the purity of groundwater, it is crucial to establish stringent regulations, embrace sustainable practices, ensure effective waste management, and promote public awareness. The estimation of groundwater pollution index (GPI) serves as an essential method in the management of water resources, offering

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a comprehensive evaluation of water quality by integrating physical, chemical, and biological components into a unified index [1, 19]. This index organizes extensive data, enabling decision-makers, stakeholders, and the public to gain a clearer insight into the overall condition of groundwater resources. Many researchers have tried this water pollution indicators, which convert data into numerical ratings [8, 16, 20]. In order to prioritize pollution prevention, mitigation, and sustainable water use, the GPI assists in locating problem areas and water quality trends [5]. In recent years, the evaluation of drinking water quality has transitioned from laboratory tests to the application of remote sensing and geospatial technologies, facilitating the creation of diverse databases for water quality assessment. Presently, diverse geospatial methodologies, including Kriging as well as Cokriging techniques, and inverse distance weighting (IDW), are employed to estimate the spatial distribution of water quality indicators worldwide [7, 12].

Monitoring of water quality is essential for environmental management, crucial for both human survival and ecosystem sustainability. An important aim of the Sustainable Development Goals (SDGs) is to guarantee that everyone has access to safe, affordable drinking water. It is crucial to conduct a thorough review of water quality measurements in order to ascertain the level of pollutants. Monitoring and identifying regional groundwater supplies is essential for sustainable use. Hence this research work aims to assess water quality and delineating the spatial variations of groundwater pollution zones in the part of eastern coastal tract of Odisha, employing established GPI models and geospatial methodologies to implement proper mitigation techniques at specific location.

2 Methodology

2. 1 Study area

The study area spans between the longitudes of 86° 12′ and 86°28′ and the latitudes of 20° 0′ and 20° 11′N, encompassing a portion of Eastern part of Peninsular India (Fig. 1). It is a coastal region of Odisha state characterized by the abundant appearance of its natural resources. The predominant lithological components in the study area consist of compact sand, sandstones, sandy clays, and silt [9]. Southern portion of the region is drained by the Devi rivers along the Bay of Bengal coast (Fig. 1b). The topography is slowly inclining toward the sea. The region is characterized by dendritic drainage patterns and the presence of active rivers. The region experiences tropical monsoon climate. Heat and aridity dominate the summer season (March-June), with temperatures reaching up to 40°C. After this, a rainy monsoon (mid-June–October) brings most of the 1500 mm of annual rainfall followed by a cold winter (November–February) with temperatures below 15°C. The current land use in the area is analyzed to identify the dominant human-induced sources of pollution and the spatial arrangement of different land uses (Fig. 1c).

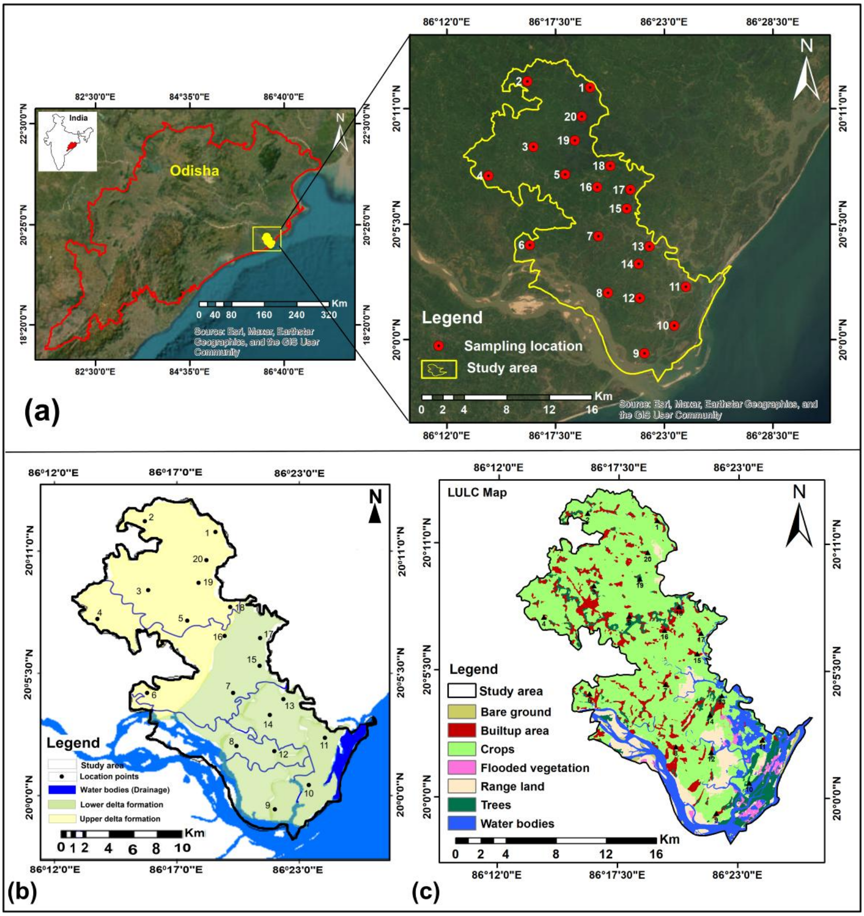

Fig. 1. Sampling sites along with (a) geographical location, (b) hydrological boundaries, (c) land use patterns

2.2 Sampling and Chemical analysis

During the pre-monsoon season, twenty water samples were carefully gathered from different locations within the study region. The samples were placed in 1L pre-washed plastic bottles and pumped for 10 minutes. Moving coolers were used to transport the samples to the laboratory, where they were kept at a constant 4°C. We used the standard techniques described in the APHA protocols to assess the chemical characteristics of the groundwater samples [3]. At the site of sampling, a portable meter was used to measure the electrical conductivity (EC) and pH. The collected ground water samples were analysed for significant cations such as Ca^{2+}, Mg^{2+}, Cl^{-}, and HCO_3 by Titration methods, and K^+ and Na^+ by Flame photometry. Anions such as SO_4, $N0_3$, and F^- are determined by UV spectrophotometer. The ionic balance error (IBE) is determined by calculating the difference between the cations and anions to ensure the precision of a comprehensive chemical analysis for each sample, utilizing the following Equation (1):

$$\text{IBE} = \frac{(\sum Cations - \sum Anions)}{(\sum Cations + \sum Anions)} \times 100 \qquad (1)$$

The ion balance is determined to be within ±5% before to data processing, suggesting good accuracy. A location map is created using the ARCGIS software, and the statistical data are examined using Excel 2021. The land use land cover (LULC) map (Fig.1c) for 2024 is generated using ArcGIS and data from Sentinel-2 (10m resolution) dataset of ESRI website. The Inverse Distance Weighted (IDW) interpolation method in ArcGIS 10.8.2 is used to map relevant parameters distribution and pollution contamination zones across the study area. The methodology flowchart utilized in this study is illustrated in Fig. 2.

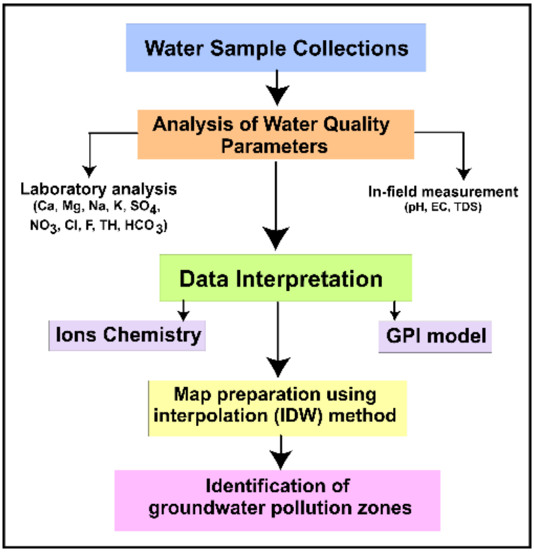

Fig. 2. Methodology flowchart

2.3 Calculation of Groundwater Pollution Index (GPI)

Groundwater suitability for domestic use is assessed by comparing various water quality indicators. In 2012, Subba Rao devised the Groundwater Pollution Index (GPI) model as a tool to assess groundwater purity. This evaluation generally measures the influence of specific chemical parameters, such as pH, Total Dissolved Solids (TDS), Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, $NO_3^{\ -}$, $SO_4^{\ 2-}$, and F^-, on the overall water quality intended for domestic use. The following five steps employed for the computation of GPI are elucidated as follows [19, 20, 21].

Step 1: The initial step entails the assignment of a relative weight (R_W) to each metric based on their importance for estimating groundwater quality and how it affects human health. The TDS, Na and Cl have been assigned the maximum value i.e. 5, whereas, pH, Ca, Mg, and HCO_3 are assigned the value of 3, SO_4 is assigned the value of 4 and F and K are assigned the least value i.e. 1 (Table 1). The highest value, which is 5, indicates the greatest influence of a parameter on the water quality of a region, whereas the lowest value, which is 1, represents the least contribution of a parameter to the entire water quality of that region.

Step 2: The Weight parameter (W_p) represents the ratio of the relative weight of each parameter to the total of the relative weights (R_w), as seen in Equation (2).

$$W_p = \frac{R_w}{\sum R_w} \tag{2}$$

Step 3: The Status of concentration (S_c) represents the ratio of the concentration (C_i) of each parameter in the water samples to its specific drinking water quality standards (D_c) as specified by [6] and [10]. The equation is presented below in Equation (3).

$$S_c = \frac{C_i}{D_c} \tag{3}$$

Step 4: The Overall water quality (O_w) is estimated by multiplying the S_c (status of concentration) of each parameter with its respective weight parameter (W_p), as illustrated in the equation below in Equation (4).

$$O_w = S_c \times W_p \tag{4}$$

Step 5: The GPI is calculated by summing all of the O_w values in order to ascertain the influence of contaminants on groundwater quality. Equation (5) illustrates below.

$$GPI = \sum O_w \tag{5}$$

The calculated value of GPI, when it remains within the limit of 1.0, indicates a pollution free metric. Conversely, if the value exceeds 1.0, it suggests that there are additional concentrations of parameters infiltrating the groundwater, attributed to pollution-induced entry of foreign substances into the aquifer. The GPI is classified into five groups based on its level of pollution: insignificant (GPI less than 1.0), low (GPI between 1.0 to 1.5), moderate (GPI ranges1.5 to 2.0), high (GPI ranges 2.0 to 2.5), and very high (GPI greater than 2.5) [1, 19].

Table 1 Assignment of weight of chemical parameter for the calculation of GPI and statistical result of ions concentration (Units are in mg/l except pH and GPI)

Sl. No.	Physico-chemical parameters of Water samples	Relative weight (R_w)	Weight parameter (W_p)	Water quality standard WHO (2011) and BIS (2012)	Minimum	Maximum	Average
1	pH	3	0.085	7.5	6.71	8.99	8.06
3	TDS	5	0.142	500	355	7132	2180
4	Sodium	5	0.142	200	45	2050	508
5	Potassium	1	0.028	12	5	80	21.4
6	Calcium	3	0.085	75	20	240	65.5
7	Magnesium	3	0.085	30	4	294	71.4
8	Sulphate	4	0.114	200	12	879	212.7
9	Nitrate	2	0.057	50	2	74	17.7
10	Chloride	5	0.142	250	56	3440	870.5
11	Fluoride	1	0.028	1.5	0.2	1.9	0.98
12	Bicarbonate	3	0.085	300	146	908	350.9
		$\sum R_w$ = 35	$\sum W_i$= 1				
13	GPI (Groundwater pollution index)				0.421	7.189	2.144

Table 2 Overall water quality (O_w) of samples

Sampling Location No.	$O_w = W_p * S_c$											$\sum O_w$
	pH	**TDS**	**Na**	**K**	**Ca**	**Mg**	**SO_4**	**NO3**	**Cl**	**F**	**HCO_3**	**GPI**
1	0.0805	0.1008	0.0320	0.0187	0.0363	0.0482	0.0138	0.0035	0.0314	0.0056	0.0510	0.4216
2	0.0867	0.1517	0.0604	0.0350	0.0453	0.0623	0.0385	0.0127	0.0504	0.0093	0.0623	0.6146
3	0.0901	0.2082	0.0852	0.0210	0.0589	0.0793	0.0534	0.0213	0.0504	0.0149	0.1077	0.7904
4	0.0760	0.2144	0.0680	0.1869	0.0476	0.0680	0.0426	0.0154	0.0784	0.0037	0.0886	0.8897
5	0.0776	0.1639	0.0604	0.0593	0.0726	0.0137	0.0616	0.0117	0.0336	0.0112	0.0698	0.6354
6	0.0980	1.0999	0.8591	0.0663	0.0409	0.1813	0.1953	0.0027	1.1088	0.0355	0.0708	3.7586
7	0.0784	0.2252	0.0606	0.0217	0.0953	0.0897	0.0462	0.0354	0.0616	0.0131	0.1037	0.8309
8	0.0969	2.0539	1.4697	0.0807	0.2040	0.5666	0.4838	0.0142	1.9320	0.0299	0.2575	7.1891
9	0.0856	0.1534	0.0692	0.0210	0.0409	0.0552	0.0470	0.0298	0.0672	0.0075	0.0501	0.6267
10	0.0916	1.3854	0.6369	0.0273	0.2720	0.5327	0.2810	0.0025	1.0808	0.0355	0.0847	4.4302
11	0.0989	0.6404	0.3060	0.0219	0.0545	0.3173	0.0270	0.0749	0.4760	0.0187	0.1408	2.1765
12	0.1006	1.8284	1.2695	0.1507	0.0545	0.8330	0.3731	0.0346	1.8032	0.0317	0.1947	6.6740
13	0.1019	0.5936	0.4260	0.0530	0.0227	0.0793	0.0787	0.0038	0.4480	0.0317	0.0844	1.9230
14	0.0972	0.6183	0.3397	0.0453	0.0999	0.1795	0.1111	0.0050	0.5096	0.0243	0.0830	2.1127
15	0.0994	0.5921	0.3607	0.0362	0.0363	0.1520	0.0069	0.0096	0.5152	0.0168	0.0968	1.9220
16	0.0890	0.5393	0.2606	0.0282	0.1452	0.3107	0.2291	0.0022	0.3920	0.0224	0.0760	2.0948
17	0.0941	0.7324	0.2592	0.0513	0.0431	0.1247	0.1018	0.0064	0.4872	0.0168	0.0680	1.9849
18	0.0977	0.6688	0.3344	0.0243	0.0522	0.2731	0.0270	0.0855	0.4928	0.0168	0.1408	2.2134
19	0.1015	0.2900	0.1873	0.0119	0.0272	0.0345	0.0371	0.0067	0.1232	0.0093	0.1279	0.9566
20	0.0857	0.1497	0.0709	0.0413	0.0363	0.0483	0.0845	0.0276	0.0504	0.0112	0.0415	0.6474

3 Results and Discussion

3.1 Water chemistry and spatial mapping

Table 1 presents the statistical overview of various physicochemical parameters in the sampled groundwater. Water quality for human consumption, agricultural use, and manufacturing is mostly assessed using the TDS [18]. It is a mixture of inorganic ions and dissolved organic matter in water. A concentration of TDS exceeding 1000 mg/l negatively affects the suitability of drinking water for consumption. The analyzed water samples have the TDS concentrations ranging from 355 to 7132 mg/l, mean of 2180 mg/l. A total of 85 percent of the samples tested have TDS concentrations higher than 500 mg/L. Drinking water quality in the study area is adversely affected by the elevated levels. Figure 3a shows that the southern portion of the research region has a higher potential for contamination due to the high TDS values detected there.

The pH of water used for drinking should be between 6.5 and 8.5, per WHO (2011) recommendations. Groundwater samples taken in the study region have pH readings ranging from 6.71 to 8.9, on average 8.06. In the southeast part of the research area, the interpolated spatially distributed pH map (Fig. 3b) shows that the pH readings are greater above the permitted limit of 8.5. The concentration of SO_4 is between 12 mg/l to 879 mg/l and a mean of 212 mg/l. The interpolated spatially distributed map of SO_4 (Fig. 3c) demonstrate that the sulphate levels in the southern regions surpassed the safe limit of 200 mg/l. Chloride is the predominant anion in the research area. The concentration varies from 56 to 3450 mg/l. Figure 3d highlights the spatial distribution of chloride, making the southern region of the study area more contaminated due to elevated chloride levels. Samples of groundwater have sodium concentrations varying from 45 to 2050 mg/l, with a mean of 507 mg/l. Sixty percentage of samples exceed the BIS (2012) maximum allowed level of 200 mg/l in the southern part of the study area close to sea (Fig. 3e).

The measured concentration of magnesium in the analysed water samples varies from 5 to 294 mg/l. Overall, magnesium concentrations in 45% of the water samples are below the permissible limit of 30 mg/l, while the remaining 55% exceed this threshold. Spatial mapping of magnesium is shown in Figure 3f. The elevated concentration of calcium and magnesium results in water hardness. Pipes would get scale buildup if the total hardness level in the water was more than 200 mg/l, and if it was less than 100 mg/l, the water may become corrosive because its pH would drop [18]. Groundwater samples show total hardness values between 90 to 1,470 mg/l, with the mean of 370 mg/l. Hardness ratings range from 25% to 40% in the investigated area, with 35% being moderately hard and 40% being very hard. The study area appears to be most affected by sodium and chloride ions, according to the ionic concentration. Coastal groundwater is unfit for human consumption due to an elevated concentration of chloride and sodium ions, which indicates a significant influence from saltwater intrusion.

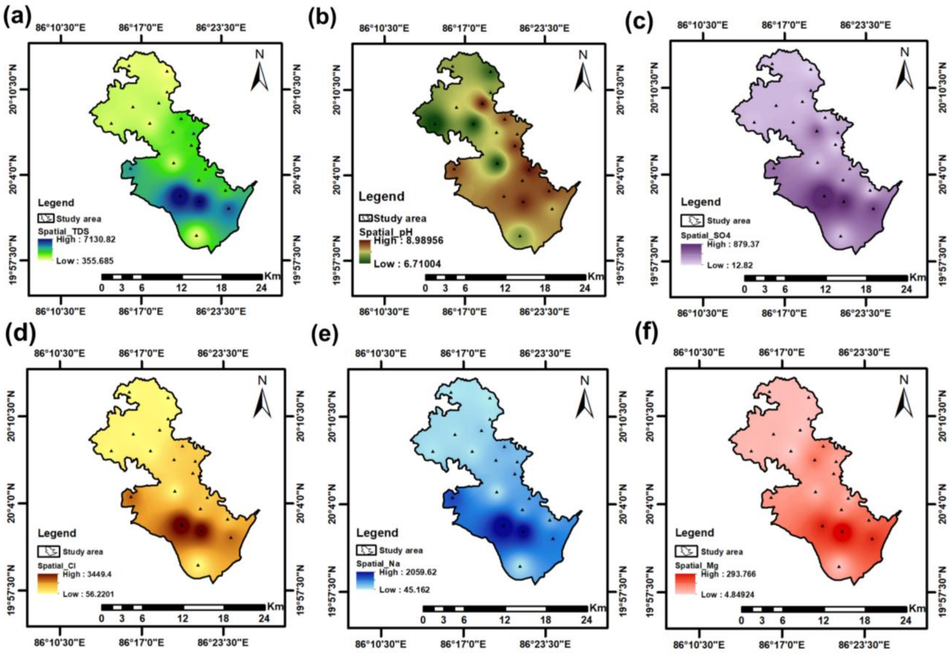

Fig. 3 Spatial mapping of the (a) Total Dissolved Solids, (b) pH, (c) Sulphate, (d) Chloride, (e) Sodium, (f) Magnesium

3.2 Evaluation of groundwater quality based on GPI model

The GPI is created to consolidate a vast amount of physico-chemical data into a single integer, thereby providing dependable details on the overall state of groundwater. In addition, groundwater categorization with the help of GPI value explains the chemical compatibility of water sample for human use [16]. The estimated GPI ranges from 0.42 to 7.18 (Table 2). Nine samples (45%) were considered acceptable for consumption due to "insignificant pollution" by the GPI value. As per the classification for GPI, 15% of the water samples signify moderate pollution zone, while the rest 40% of the samples represent high to very high pollution zone (Fig. 4). A total of 8 and 3 samples is identified as having high to moderate levels of pollution, rendering the water harmful for human use (Fig. 4). The water quality parameters, including Na, Mg, SO_4, and Cl, exhibit O_w values exceeding 0.1, signifying their significant influence on the overall water quality of the studied area. Elevated Na^+ and Cl^- ion concentrations in groundwater might result from mineral dissolution, ion exchange activities and saline water intrusion within the coastal aquifer [2]. The spatial map (Fig. 5) of the GPI indicates that the water quality in the northern and northeastern study area ranges from insignificant to low pollution water for human intake, while the remaining areas of the study area are not recommended for direct consumption.

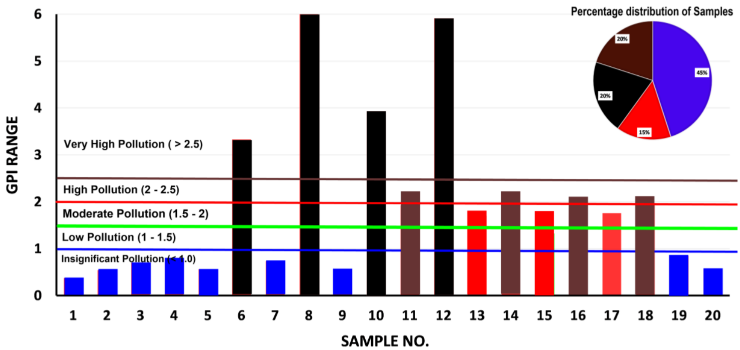

Fig. 4 Bar diagram showing percentage and GPI value distribution among water samples

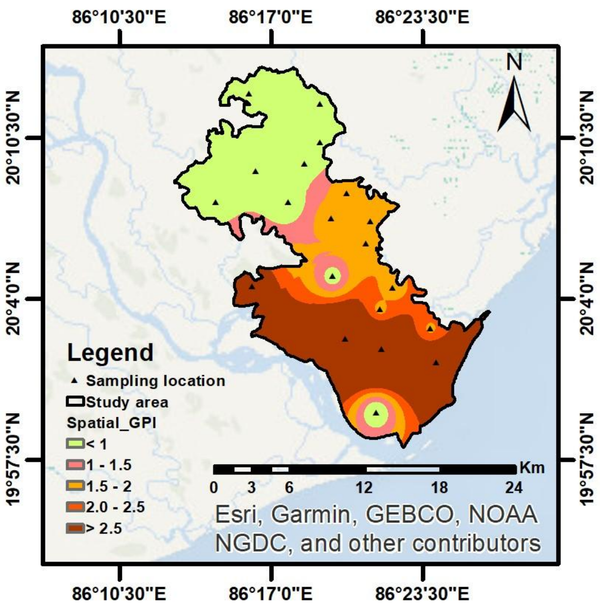

Fig. 5 Delineation of pollution zones based on GPI classification

4 Conclusion

Coastal Odisha relies on high-quality groundwater for both human consumption and agricultural purposes. The current study aimed to assess groundwater quality in relation to both naturally occurring and man-made pollution. The quantification of groundwater pollution in the coastal region of Odisha is conducted utilizing the GPI numerical model. With regard to drinking water quality standards, the GPI classifies and explains the contamination levels in water quality parameters. The elevated levels of TDS, Na^+ and Cl^- indicate salinity issues, make a substantial portion of the samples are unfit for domestic use. Saltwater intrusion could be a significant factor in the degradation of groundwater quality. Anthropogenic activities, including agricultural discharge, may be the cause of high nitrate contamination in certain water samples. The presence of hard to very hard water in 75% of the samples raises concerns for various applications, including industrial processes. Geospatial interpolation method is utilized to delineate the polluted zones. The spatial distribution of pollution index map indicates a decline towards the southern and southwestern regions; however, groundwater sources in the northern and northeastern inland areas remain suitable for human consumption. The analysis emphasizes the need of sustainable groundwater management in reducing the adverse impact of human and natural variables on coastal aquifer water quality to preserve this essential resource. Efforts should be directed towards addressing salinization issues and implementing appropriate treatment measures to safeguard both human use and agricultural practices in the studied region.

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