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Geospatial Assessment of Groundwater Hydrochemistry and Land Sustainability—A Case Study of Paderu Mandal, Andhra Pradesh, India

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ABSTRACT

This study rigorously investigates the hydrochemical characteristics of groundwater in Paderu Mandal, an enclave of tribal life in Andhra Pradesh, India, through a comprehensive GIS-based analysis of 83 water samples collected from open wells and bore wells. The study examines key parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), Turbidity, Chloride (Cl_2^-), Sulphate (SO_4^{2-}), Fluoride (F^-), Nitrate (NO_3^-), and Iron (Fe). Standardized methodologies are employed to evaluate these samples against the World Health Organization (WHO) and Bureau of Indian Standards (BIS) benchmarks, assessing water safety and suitability. Spatial distribution mapping reveals contamination hotspots and zones adhering to water quality norms, offering insights into potential contamination sources. The study further explores groundwater quality implications on land productivity, irrigation potential, and sustainable land use, linking contamination risks to

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soil degradation and agricultural viability. Correlation matrices, Hill-Piper diagrams, and irrigation suitability indices provide deeper insights into the intricate interactions between groundwater constituents and land resource management. The findings serve as a critical foundation for groundwater protection policies, land conservation strategies, and sustainable resource management in Paderu Mandal. The study underscores the need for targeted interventions to mitigate water quality deterioration and ensure long-term environmental and agricultural sustainability.

Keywords: Spatial Distribution; Groundwater Quality; Physiochemical Parameters; Geospatial Techniques

1. Introduction

India, home to the world's second-largest tribal population, faces critical challenges in providing safe drinking water, especially in tribal-dominant regions like Paderu, Andhra Pradesh, where 95% of the population belongs to tribal communities [1]. The pervasive issue of contaminated water serves as a root cause for numerous health ailments, impacting thousands annually. The urgency of addressing this challenge is underscored by the United Nations' guidelines, advocating a minimum of 50 liters of water daily for essential needs, including drinking, sanitation, culinary purposes, and hygiene [2]. The scarcity and contamination of water have become pivotal challenges in the 21st century [3].

This research aims to assess groundwater quality in the tribal expanse of Paderu Mandal, situated in the Visakhapatnam district of Andhra Pradesh, utilizing advanced geospatial methodologies. Several scholarly articles have delved into groundwater quality analysis within GIS frameworks, consistently emphasizing that water pollution primarily emanates from human activities [4]. While groundwater serves as a primary source of drinking water across most parts of the country, issues such as arsenic and fluoride contamination, stemming from both natural and human-induced factors, persist in several regions of India [5, 6]. The excessive utilization of nitrates in agricultural practices emerges as a pivotal contributor to groundwater pollution [7], as these nitrates permeate the soil and accumulate in groundwater, instigating chemical and biological transformations [8, 9].

Mineral ions naturally permeate groundwater, gradually dissolving from soil, sediments, and rocks during the water's passage through aquifers and unsaturated zones [10]. Geohydrological assessments of springs and stream water within the watershed have been scrutinized, facilitating the development of spatial distribution maps tailored for agricultural, livestock, and poultry requisites [11, 12]. The Hill-Piper trilinear plot has proven instrumental in formulating these maps alongside their corresponding areal statistics [13, 14]. The contamination of groundwater in rural regions often arises from agricultural pursuits, specifically the excessive application of nitrate-based fertilizers. Safeguarding potable water from pollution and biological impurities remains imperative. The quality of water bodies in the region displays substantial variations contingent upon their geographical placement and surrounding environmental influences [15]. It is noticed that, the health of numerous individuals within the study area suffers due to water-related challenges. In view of this, this study also focuses on find out the impact of land use practices on groundwater quality such as, unregulated agricultural practices, deforestation and urbanization, which can lead to contamination and depletion of groundwater resources. Incidentally, the research also endeavors to explore the interrelation between groundwater quality and land management policies, emphasizing the need for sustainable groundwater conservation measures, protection of recharge areas and informed land-use planning.

2. Study Area

The study area nestled within the confines of Paderu Mandal in Andhra Pradesh, India, forms a fragment of the Eastern Ghats. Spanning the coordinates of 18°04'39" in Northern Latitudes and 82°39'38" in Eastern Longitudes, this area encompasses 435 square kilometers of diverse terrain. Paderu Mandal, situated at an altitude exceeding 900 meters above sea level, boasts a captivating and lush valley landscape shown in **Figure 1** along with the sample locations.

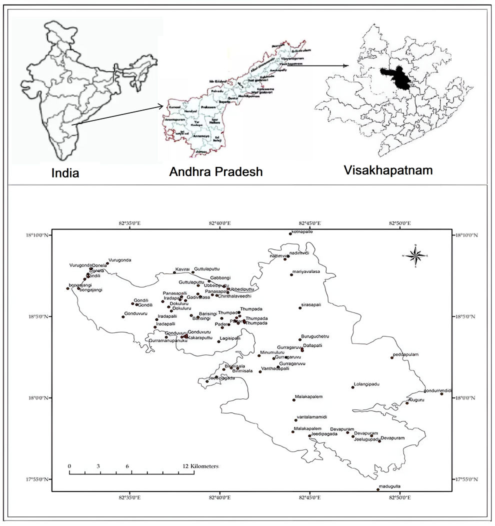

Figure 1. Location Map of the Study Area with sample locations.

Inhabited entirely by scheduled tribes belonging to various sects, this region is encircled by an abundance of hill streams. Annual precipitation averages 1252 mm, benefiting from both the southwest and northeast monsoons, which results in the proliferation of numerous streams, open wells, and bore wells across the area.

The climate in these hills contrasts starkly with the plains, experiencing higher precipitation rates, leading to a cooler atmosphere. Mean annual temperatures fluctuate between 24 °C to 35 °C. May emerges as the hottest month, while January stands as the coldest in this picturesque enclave [16]. The region's unique topography and hydrological conditions significantly influence groundwater recharge and quality. The presence of lateritic and weathered rock formations impacts groundwater movement and storage, making it crucial to assess the hydrogeological dynamics for effective water resource management. On the other hand, land use in the study area is predominantly agricultural, with shifting cultivation practices affecting soil permeability and groundwater infiltration. Understanding these interrelations between geology, climate and human activities is essential for formulating sustainable groundwater management strategies suitable to the region's ecological and socio-economic background.

3. Methodology

About 83 water samples were collected for the study from open wells and bore wells from selected locations in the Paderu Mandal (**Figure 1**). Various physical and chemical parameters of water samples were analysed and the results were compared with the values of various water quality standards such as World Health Organization (WHO) and Bureau of Indian Standards (BIS) (**Table 1**). The parameters analyzed were pH, EC, TDS, TH, Turbidity, Chloride, Sulphate, Fluoride, Nitrate, and Iron. Standard methods were used for the determination of the chemistry of the water samples. The selection of these parameters for analysis in this study is guided by a comprehensive approach to water quality assessment, tailored to the address the explicit conditions of the Paderu Mandal region. These quality parameters were chosen based on their relevance to drinking water and irrigation suitability. These parameters align with global and national water quality standards, ensuring a comprehensive evaluation. The study aims to provide valuable insights into the unique challenges of the region, addressing both natural and anthropogenic sources of potential contaminants and offering a holistic understanding of groundwater quality for sustainable resource management and community welfare.

The collected water samples were subjected to laboratory analysis using spectrophotometry, titration, and ion-selective electrodes, ensuring precise quantification of each parameter. All the chemical constituents are expressed in mg/L (milligrams/liter) except pH, which is represented in standard pH units, which refers to the measurement of pH using the standard pH scale, which ranges from 0 to 14. On this scale, a pH value of 7 is considered neutral, values below 7 are acidic, and values above 7 are alkaline or basic. Standard pH units, provides a clear and consistent representation of the measurement units for pH throughout the water quality assessment.

Water quality limits and parameters mentioned in **Table 1** succinctly cover the various factors measured in water quality assessment, like pH, conductivity, TDS, and mineral concentrations such as sodium, potassium, calcium, and others. It highlights the acceptable, permissible, and unacceptable limits for each parameter, de-

Table 1. Water Quality Parameters and Permissible Limits.

S#	Parameter	Not Acceptable Limit	Acceptable Limit	Permissible Limit	Not Permissible Limit	WHO	BIS 10500-2012	Methods of Determination
1	pH	<6.5	=6.5	6.5–8.5	>8.5	6.5–8.5	6.5–8.5	pH meter
2	EC (μS/cm)	<200	=200	200–300	>300	250	<1000	Conductivity
3	TDS (mg/L)	<500	=500	500–2000	>2000	1000	500–2000	Conductivity
4	Sodium-Na (mg/L)	<100	100	100	>100		100	Flame photometry
5	Potassium-K (mg/L)	<10	10	10	>10		10	Flame photometry
6	Total Hardness-TD (mg/L)	<200	=200	200–600	>600	500	300–600	EDTA-Titrimetry
7	Magnesium-Mg (mg/L)	<30	30	30–100	>100		30–100	EDTA-Titrimetry
8	Calcium-Ca (mg/L)	<75	75	75–200	>200	75	75–200	EDTA-Titrimetry
9	Iron-Fe (mg/L)	<0.3	=0.3	No relaxation		0.3	250–1000	ICPMS
10	Fluoride-F (mg/L)	<1	=1	1–1.5	>1.5	1.5	1–1.5	Spectrophotometry
11	Chloride-Cl (mg/L)	<250	=250	250–1000	>1000	250	250–1000	Titrimetry
12	Sulphate-SO_4 (mg/L)	<200	=200	200–400	>400	250	200–400	Turbidimetric
13	Bicarbonate-HCO_3 (mEq/L)	1.0	=1	1–1000	1000		1– 1000	Titrimetric
14	Carbonate Ion-CO_3 (g/mol)	0.1	=0.1	0.1–10	10		0.1– 10	Titrimetric
15	Nitrate-NO_3 (mg/L)	<45	=45	45–100	>100	50	45–100	Spectrophotometry
16	Alkalinity (mg/L)	<200	=200	200–600	>600		200–600	Titrimetric

tailing the methods used for measurement. This table serves as a comprehensive guide for evaluating water quality based on multiple parameters and their respective thresholds.

Geospatial techniques were employed to visualize and interpret spatial distribution trends, highlighting contamination hotspots and safe zones within the study area. The methodology employs diverse analytical techniques which leverages spatial analysis tools like Inverse Distance Weightage (IDW) to map water quality distribution across the region. Specific statistical tests, such as Analysis of Variance (ANOVA) and Pearson correlation, were employed to identify trends and variations in the dataset. ANOVA was applied to assess differences in water quality parameters among various sample locations, helping discern spatial variations. Pearson correlation, on the other hand, was employed to explore relationships between different water quality variables, aiding in identifying potential interdependencies. These tests were intended to produce outcomes that enhance our understanding of spatial patterns in water quality across the Paderu Mandal region. ANOVA helps identify if there are significant differences in water quality metrics among various locations, contributing to spatial mapping accuracy. Pearson correlation, on the other hand, provides insights into potential associations between different parameters, aiding in the identification of complex relationships within the dataset. In addition to these tests, land-use patterns were examined to establish correlations between groundwater quality and human activities such as farming, deforestation, and settlement expansion.

Statistical methods such as correlation matrices and regression analysis were utilized to identify relationships among the water quality parameters, offering insights into potential contamination sources. The Hill Piper analysis, a key element in our methodology, plays a crucial role in evaluating water chemistry and its applicability for irrigation in the Paderu Mandal region. Utilizing a trilinear diagram, this analysis visually represents the proportions of major cations and anions in water samples, offering insights into the prevailing hydrochemical processes and the types of water present. By identifying potential sources of contamination and assessing groundwater quality dynamics, the Hill Piper analysis contributes significantly to our understanding of groundwater composition. Additionally, it aids in determining the suitability of groundwater for irrigation, guiding sustainable agricultural practices in the region. Irrigation suitability was assessed using key indices like the Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Permeability Index (PI), ensuring a comprehensive evaluation of water usability for agricultural practices. By integrating spatial mapping, statistical evaluation, and chemical analysis, this holistic approach provides a comprehensive assessment of both drinking water quality and irrigation potential, informing sustainable water management in the region.

4. Results and Discussion

This investigation uncovers a tapestry of insights and revelations stemming from the comprehensive analysis of collected data. This segment serves as the juncture where it delves into the implications, correlations, and significance of the results obtained through our meticulous study of the physical and chemical aspects of groundwater in Paderu Mandal in the state of Andhra Pradesh, India.

4.1. Spatial Distribution of Groundwater Quality

A comprehensive analysis of various physical and chemical parameters present in water samples was carried out to compare them against established water quality standards set forth by the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). Employing standardized procedures, we meticulously analyzed the collected samples for key parameters encompassing Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), Chloride (Cl_2^-), Fluoride (F), Nitrate (NO_3^-), Sulphate (SO_4^{2-}), Iron (Fe), and alkalinity. The measurements for these chemical constituents are reported in milligrams per liter (mg/L), except EC (measured in μS/cm).

pH stands as a pivotal parameter in evaluating water quality within an aquatic environment, signifying the acidity or alkalinity of a solution. Low pH levels can lead to gastrointestinal disorders such as hyperacidity, ulcers, stomach pain, and a burning sensation [17]. Additionally, climatological and vegetation factors exert influence on the pH levels within a system.

The results revealed that the groundwater pH values within the study area ranged from 6.37 to 8.27, with an average value of 7.46 and a standard deviation of 0.20. This signifies a moderate level of acidity or alkalinity across the sampled groundwater. Spatially, the distribution of groundwater pH fell within the permissible limit across 408.5 square kilometers and within the acceptable limit within 26.5 square kilometers, as illustrated in **Figure 2**. The observed spatial variability in pH within the Paderu region may be attributed to various factors. Potential causes include geological variations, land use practices, and anthropogenic activities in the vicinity.

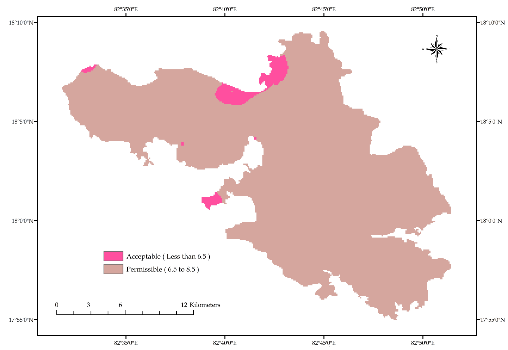

Figure 2. Spatial distribution of pH.

Electrical Conductivity (EC) serves as a metric for the water sample's ability to conduct electric current, reflecting the proportional ionic strength of the water. The conductivity is influenced by inorganic dissolved solids, including chloride, nitrate, sulfate, and phosphate ions, each carrying a positive charge. The actual relative concentrations of these substances and the temperature collectively determine water conductivity. Notably, the observed EC values exhibited significant variance across samples, ranging from 53 to 1864 μS/cm, with a mean value of 1382.3 μS/cm and a standard deviation of 622.017. This surpasses the WHO's recommended limit of 250 μS/cm, except for specific locations like Thumpada, which recorded the lowest EC level at 53 μS/cm.

The deviation from recommended EC values suggests a notable presence of Total Dissolved Solids (TDS) in the water (**Figure 3**), contributing significantly to elevated EC values. Inorganic ions such as chloride, nitrate, sulfate, and phosphate play a pivotal role in the overall conductivity of water, contributing to the observed disparities across different locations.

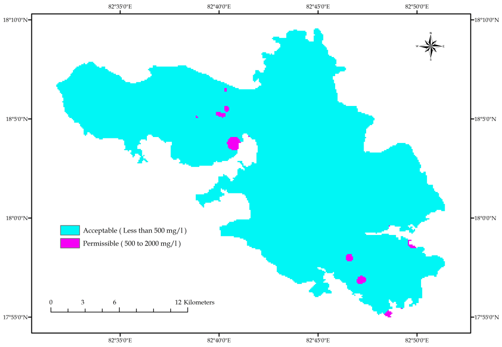

Figure 3. Spatial distribution of TDS.

Furthermore, variations in other parameters like Chloride, Nitrate, Sulphate, and Iron underscore the diverse composition and potential contamination sources within the groundwater across the study area. This highlights the necessity for further investigation and the implementation of remediation strategies to ensure the quality and safety of groundwater in these regions.

Total Dissolved Solids (TDS), encompassing mineral constituents dissolved in water, significantly impact water usability. Concentrations exceeding 500 mg/L are undesirable for drinking and many industrial purposes, while levels below 300 mg/L are preferable for specific manufacturing processes. In our study, TDS values in sampled groundwater ranged from 34 to 1211 mg/L, with an average of 968 mg/L and a standard deviation of 436.15. Notably, Thumpada and Dokuluru locations exhibited remarkably low concentrations of 34 mg/L.

Adhering to Bureau of Indian Standards (BIS) specifications, our study area's TDS values fall within the desirable limit of 500–2000 mg/L, as depicted in **Figure 3**, emphasizing the overall compliance and distribution pattern across different locations. This suggests that, despite variations in EC values, the TDS concentrations in the sampled groundwater generally meet established standards.

The Total Hardness of water denotes the cumulative concentration of alkaline earth metals within it. Predominantly attributed to calcium and magnesium in freshwater, the hardness can also be influenced by other metals like iron, strontium, and manganese, particularly in appreciable concentrations. The impact of hardness on health has been a subject of study, with reports suggesting a correlation between cardiovascular diseases and the water's hardness level, showing higher prevalence in areas with soft water [15].

In our study, Total Hardness (TH) values ranged from 20 to 310 mg/L within the sampled groundwater, with an average value of 329.29 mg/L and a standard deviation of 121.17. This variance in hardness reflects the geological composition of the areas from which the water samples were obtained. While the Bureau of Indian Standards (BIS) specifies a desirable limit for Total Hardness (TH) in drinking water at 300 mg/L and a maximum permissible limit of 600 mg/L, all samples from our study area adhere to the standard limits set by BIS, as depicted in **Figure 4**, showcasing the distribution pattern across various sampling locations. This suggests that the groundwater within the study area is within acceptable ranges of hardness as per regulatory guidelines, ensuring its suitability for drinking purposes. However, it is essential to note that despite meeting hardness standards, further investigations into the specific mineral composition are necessary to comprehensively assess potential health implications, particularly in relation to cardiovascular diseases, as studies have indicated that excessive hardness in water may contribute to an increased risk of such issues.

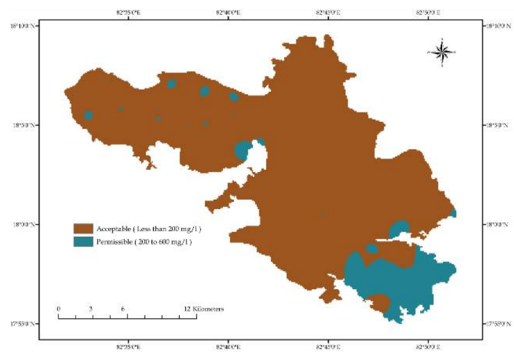

Figure 4. Spatial distribution of Total Hardness.

In addition to hardness, turbidity, indicating the cloudiness or haziness of a liquid due to numerous invisible particles, is crucial in assessing water quality. In the present study area, observations of turbidity ranged from 0.0 to 190 mg/bl, with an average value of 2.51 mg/bl and a standard deviation of 0.59. This variation signifies the presence of particles affecting water clarity. Specific locations like Arada, Relimamidi, and Vantaamamidi recorded turbidity levels exceeding the BIS specified standard limit. For instance, readings reached

140 mg/bl at Arada, 76 mg/bl at Relimamidi, and a significant 190 mg/bl at Vantaamamidi, among other areas. The spatial distribution of acceptable, permissible, and impermissible turbidity levels spans different areas. The distribution pattern shows an area of about 23 km^2 within acceptable limits, while the permissible limit covers 204 km^2, and the impermissible limit extends to 208 km^2, as depicted in **Figure 5**. This distribution highlights areas where turbidity levels comply with or exceed the specified standards, delineating zones where water clarity meets or falls short of regulatory thresholds. Considering the impact of turbidity on water quality, it is essential to acknowledge that elevated turbidity levels can potentially have health consequences, as the presence of suspended particles may facilitate the growth of harmful microorganisms and compromise the effectiveness of water treatment processes. Further research is warranted to comprehensively assess the potential health risks associated with turbidity in the studied areas.

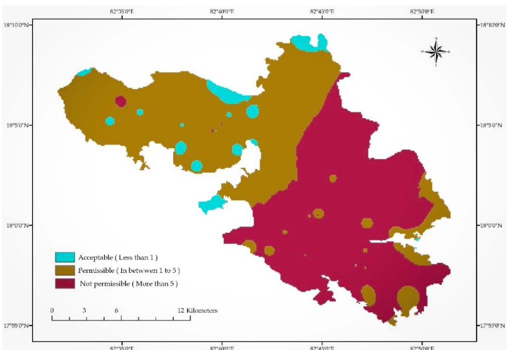

Figure 5. Spatial distribution of turbidity.

Considering chloride's impact on water quality, it is noteworthy that Chloride (Cl_2^-) primarily originates from sedimentary rock (Evaporates) as a major natural source, with minor contributions from igneous rocks. In natural water, chloride concentrations typically range below 10 mg/L in humid regions but can surge to 1,000 mg/L in arid areas. Seawater, rich in chloride, registers around 19,300 mg/L, escalating up to 200,000 mg/L in brines. Excessive chloride levels exceeding 100 mg/L can impart a salty taste, and concentrations significantly surpassing this mark may lead to physiological harm. Various industries, including food processing, textile, paper manufacturing, and synthetic rubber production, necessitate chloride concentrations lower than specific thresholds, typically below 250 mg/L or even 100 mg/L for select sectors. Chloride ion concentrations varied between 10 and 230 mg/L across the sampled groundwater. Importantly, none of the samples exceeded the permissible limits outlined by the Bureau of Indian Standards (BIS). A remarkably low concentration of 10 mg/L was observed at Thumpada (BW1), as depicted in **Figure 6**, highlighting an area with exceptionally low chloride levels, ensuring adherence to regulatory standards for water usability.

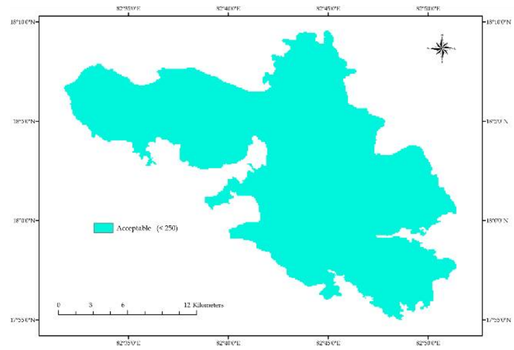

Figure 6. Spatial distribution of Chloride (Cl_2^-).

Sulphate (SO_4^{2-}) primarily originates from the oxidation of sulphide ores, gypsum and anhydrite. In natural water, sulphate concentrations commonly remain below 300 mg/L, except in wells affected by acid mine drainage, where higher levels might be present, sometimes reaching as much as 200,000 mg/L in brines. Its impact on water usability involves the formation of a heat-retarding scale when combined with calcium. Levels exceeding 250 mg/L can be objectionable in certain industries, and at around 500 mg/L, water might taste bitter, while concentrations around 1,000 mg/L could have a cathartic effect. Sulphate values in the Paderu region (**Figure 7**) ranged from 0 to 48 mg/L, all falling within the desirable limits prescribed by both the World Health Organization (WHO) and the Bureau of Indian Standards (BIS). This aligns with recommended standards, indicating that all samples maintain sulphate concentrations within the acceptable range, ensuring water suitability for various purposes as outlined by regulatory guidelines.

Fluoride finds its major natural sources in substances like amphiboles (hornblende), apatite, fluorite, and mica. Typically, concentrations in natural water remain below 10 mg/L, although in brines, levels might escalate to as high as 1,600 mg/L. The impact of fluoride on water usability manifests in its effects on dental health. Concentrations between 0.6 and 1.7 mg/L in drinking water are beneficial for the structure and decay resistance of children's teeth. However, in some areas, concentrations surpassing 1.5 mg/L can lead to "mottled enamel," and at levels exceeding 6.0 mg/L, pronounced mottling and disfiguration of teeth can occur. Fluoride concentrations were found (**Figure 8**) to range from 0.1 to 0.80 mg/L across the sampled groundwater. Notably, none of the samples exceeded the permissible limits outlined by regulatory standards. However, it's worth noting that potential factors like damp rubbish materials or sewer line conditions might contribute to local variations in fluoride levels, possibly leading to the formation of stagnant water.

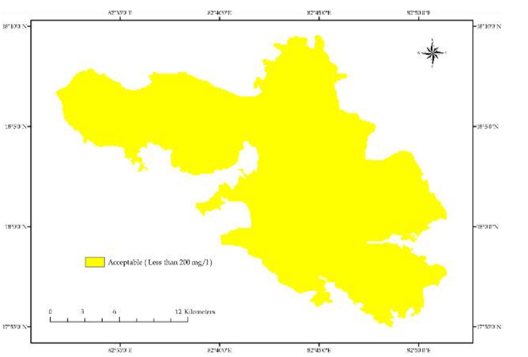

Figure 7. Spatial distribution of Sulphate ($SO_4{}^{2-}$).

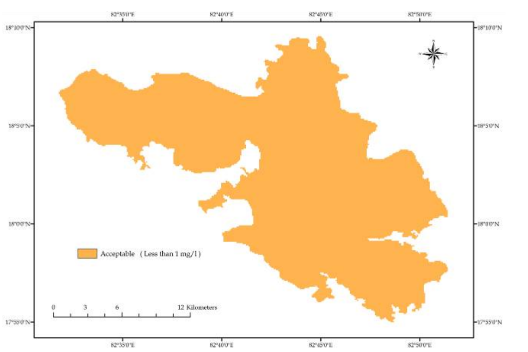

Figure 8. Spatial distributions of Fluoride (F^-).

Nitrate ($NO_3{}^-$) derives primarily from natural sources such as the atmosphere, legumes, plant debris, and animal excrement, with concentrations in natural water typically remaining below 10 mg/L. The impact of nitrate on water usability manifests in its taste and potential physiological effects. Water with elevated nitrate levels, exceeding 100 mg/L, may taste bitter and cause physiological distress. In infants, water from shallow wells with more than 45 mg/L has been associated with methemoglobinemia. Interestingly, small nitrate amounts aid in reducing the cracking of high-pressure boiler steel. Nitrate concentrations found (**Figure 9**) spanned from 4.2 to 68.8 mg/L across the sampled groundwater, with an average of 24.905 mg/L and a standard deviation of 14.616 mg/L. Notably, only one sample at Vantalamamidi exceeded the permissible limits. This outlier could potentially be attributed to agricultural activities surrounding the well, possibly involving the use of nitrate fertilizers, leading to elevated nitrate levels in the water. This emphasizes the need for monitoring and managing fertilizer use in these areas to maintain safe nitrate levels in groundwater. The potential health consequences of elevated nitrate levels underscore the importance of continuous water quality monitoring to safeguard public health.

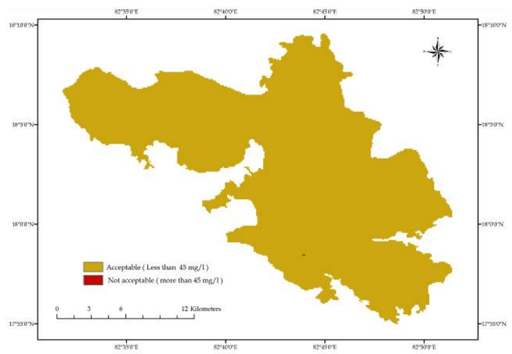

Figure 9. Spatial distribution of Nitrate ($NO_3{}^-$).

Iron (Fe) arises primarily from natural sources such as igneous rocks, amphiboles, ferromagnesian micas, iron sulphide compounds like FeS and FeS_2, and magnetite (Fe_3O_4), alongside various minerals in sandstone rocks and clay minerals rich in iron oxides, carbonates and sulphides. In fully aerated water, iron concentrations in natural water sources usually remain below 0.50 mg/L. Groundwater with a pH below 8.0 might occasionally contain up to 10 mg/L, and rarely as much as 50 mg/L. Acidic water from thermal springs, mine wastes, and industrial effluents might exhibit exceedingly high levels, surpassing 6,000 mg/L. The impact of iron on water usability becomes apparent when concen-

Table 2. Statistical analysis of the Groundwater Quality.

Observed Concentration	Groundwater Parameters														
	pH	Cond	TDS	Na^+	K^+	TH	Mg^{2+}	Ca^{2+}	Fe	F	Cl_2^-	SO_4^{2-}	HCO_3^{2-}	CO_3^{2-}	NO_3^-
Mean	7.1	497.4	319.1	42.1	21.1	140.4	8.5	43.7	0.2	0.1	69.0	18.3	128.6	38.8	13.2
Max.	8.3	987.0	641.6	145.0	108.0	320.3	18.5	104.7	0.9	0.8	230.0	48.0	300.0	300.0	60.5
Mini.	6.2	53.0	34.5	2.6	0.5	19.0	1.2	5.8	0.0	0.0	10.0	0.0	0.0	0.0	0.0
Range	2.1	934.0	607.1	142.4	107.5	301.3	17.3	98.9	0.9	0.8	220.0	48.0	300.0	300.0	60.5
Median	7.1	521.0	338.7	28.9	9.4	110.0	7.7	34.4	0.2	0.1	68.0	13.0	130.0	23.9	11.5
Mode	7.5	687.0	446.6	105.0	23.8	195.3	3.0	59.5	0.3	0.1	30.0	38.0	150.0	0.0	20.0
Std. Dev.	0.4	277.1	178.6	33.3	26.1	87.6	5.1	27.7	0.1	0.1	35.1	13.4	61.6	58.3	10.7
Skew	0.0	0.0	0.1	1.1	1.7	0.4	0.4	0.5	2.7	2.7	1.3	0.6	0.2	2.3	1.7
Kurtosis	0.5	−1.4	−1.3	0.1	2.0	−1.1	−1.2	−1.0	17.7	9.0	4.4	−1.1	−0.2	6.4	4.1
C.V.	5.7	55.7	56.0	79.1	123.8	62.4	60.1	63.5	54.1	113.5	50.9	73.3	47.9	150.3	81.2

and minerals. While some minerals are essential, elevated levels could imply contamination or water unsuitability for drinking, irrigation, or industrial use.

Metal Ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Fe): Presence of metal ions like Sodium, Potassium, Magnesium, Calcium and Iron beyond permissible limits can affect taste, health and the suitability of water for specific uses. For instance, high iron content may cause discoloration or affect taste.

Anions (Cl_2^-, SO_4^{2-}, F^-, NO_3^-): Chloride, Sulphate, Fluoride, and Nitrate concentrations beyond recommended levels can impact taste and health. High levels of nitrate and fluoride may pose health risks, particularly for vulnerable populations like infants or those with specific health conditions.

Turbidity: Elevated turbidity signifies suspended particles in water. While not directly harmful, it can indicate the presence of pathogens, affecting water aesthetics and potentially signalling contamination.

The relationships observed in these parameters offer insights into potential water quality concerns. Elevated levels or significant deviations from standard values might indicate contamination, natural geological influences, or human activities affecting groundwater quality. Understanding these relationships helps in pinpointing potential sources of contamination, identifying water treatment needs and ensuring water meets acceptable quality standards for various purposes like drinking, agriculture and industrial use.

4.3. Correlation Matrix for Groundwater Quality

A correlation matrix was generated (**Table 3**) to illustrate the relationships between various parameters present in the water quality dataset. Many of the parameters demonstrate significant correlations, indicating substantial interactions among the chemical constituents within the water samples. Notably, there is a consistently strong positive correlation among most parameters with the measured cations and anions. However, Turbidity exhibits a consistent negative correlation with other parameters. This suggests that as the values of one parameter increase, the values of Turbidity tend to decrease, and vice versa. Moreover, a significant positive correlation is evident between Total Hardness (TH) and several other parameters, signifying a mutually influential relationship between Total Hardness and these specific chemical constituents. Overall, these correlations provide valuable insights into how different elements within the groundwater interact and influence each other. They offer a clearer understanding of the interdependencies among various chemical components, aiding in assessing water quality and potential relationships between different constituents.

4.4. Hill Piper Diagram for Groundwater Quality

In pursuit of comprehending the predominant groundwater anions and cations, the study integrates a Hill Piper diagram shown in **Figure 11**. This analytical tool helps delineate the composition and types of water present within the aquifers. Various factors, including lithological characteristics of aquifers, groundwater flow patterns, and retention time, alongside anthropogenic influences, collectively contribute to determining the water types within the aquifer system [18].

Table 3. Correlation Matrix for the groundwater quality data.

Parameters	pH	EC	TDS	TH	Tur	Cl	SO_4	F	NO_3	Fe
pH	**1.00**	0.15	0.16	0.17	−0.09	0.01	0.27	0.14	0.12	0.46
EC		**1.00**	0.98	0.95	−0.17	0.66	0.56	0.38	0.33	0.21
TDS			**1.00**	0.94	−0.17	0.64	0.57	0.40	0.35	0.21
TH				**1.00**	−0.18	0.63	0.59	0.44	0.36	0.25
Tur					**1.00**	−0.07	−0.02	−0.10	0.27	−0.08
Cl						**1.00**	0.27	0.16	0.24	0.19
SO_4							**1.00**	0.66	0.52	0.30
F								**1.00**	0.25	0.24
NO_3									**1.00**	0.16
Fe										**1.00**

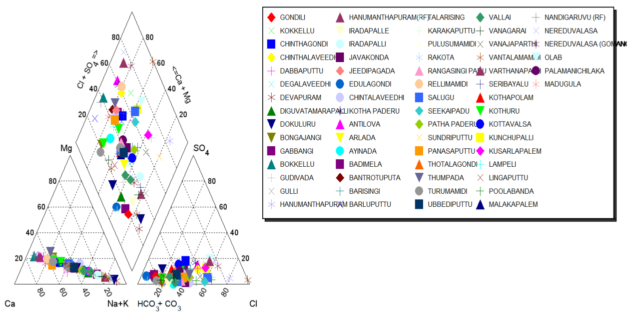

Figure 11. Hill Piper diagram.

Typically, sulfate and chloride serve as prominent anions, while no singular cation necessarily dominates the water composition. The Piper diagram illustrates a relatively even distribution of water types, encompassing Ca^{2+}-Mg^{+2}-Cl_2^-, Ca^{2+}+HCO_3^-, Ca^{2+}-Na^+-HCO_3^-, Ca^{2+}, Na^+/K^+, and HCO_3^- across all samples. This observation leads to a classification of the water type as SO_4^{2-}+ Cl_2^-/Na^++K^+, a classification uncommon in typical domestic groundwater scenarios [19].

The detection of calcium and magnesium ions might be attributed to water-rock interactions stemming from geogenic sources, aligning with the geological composition of the study area [20]. Conversely, the presence of Na^+, SO_4^{2-}, and Cl_2^- might indicate anthropogenic sources influencing the water composition.

This analysis aids in understanding the complex interplay between natural geological elements and human-induced factors, shedding light on the atypical classification of groundwater types within the study area, which diverges from conventional patterns found in domestic groundwater settings.

4.5. Irrigation Suitability and Land Resource Management

The US Salinity Laboratory's classification (**Figure 12**) categorizes the collected groundwater samples into salinity and alkalinity hazard classes: C3–S1 (15%), C2–S1 (60%), and C1–S1 (25%). This distribution suggests that a significant portion of the groundwater in Paderu Mandal exhibits moderate salinity with a low sodium hazard (C2–S1), making it suitable for irrigation with proper management.

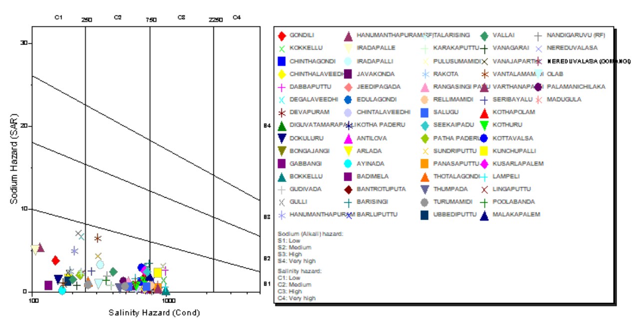

Figure 12. Sodium Hazard.

Salinity is a critical determinant of soil health and agricultural productivity, as high salt concentrations can impair plant growth through osmotic stress, nutrient imbalance, and ion toxicity [21]. The presence of elevated salinity in some samples suggests that long-term irrigation without appropriate mitigation strategies, such as leaching requirements or the adoption of salt-tolerant crops, could lead to soil degradation. If a sample falls under C4–S4, prolonged use can significantly impact land productivity by inducing salinity stress, altering soil texture, and reducing water infiltration capacity, ultimately threatening sustainable agricultural practices.

4.5.1. Land-Water Interactions and Implications for Sustainable Management

The analysis of groundwater samples in Paderu Mandal reveals that the majority exhibit moderate salinity (C2–S1) with a low sodium hazard, making them generally suitable for irrigation. However, localized elevations in Total Dissolved Solids (TDS) and nitrate concentrations—particularly in agricultural zones—indicate anthropogenic influences such as fertilizer and pesticide leaching. The spatial variability in these contaminants underscores the necessity for hydrogeochemical assessments to monitor water quality fluctuations and their impact on land productivity.

Salinity-induced soil degradation poses a significant challenge to sustainable agriculture in the region. Prolonged irrigation with high TDS water accelerates soil salinization, reducing crop yield and soil permeability. GIS analysis of soil moisture and salinity in the Paderu region provided critical insights for optimizing irrigation planning by identifying high-risk zones and facilitating the implementation of site-specific water management strategies, such as precision irrigation, controlled drainage, and adaptive cropping patterns to mitigate salinity-induced land degradation. Groundwater regulatory frameworks play a critical role in mitigating pollution risks. The enforcement of water quality thresholds in agricultural zones is essential to control nitrate leaching and excessive groundwater withdrawals. Moreover, the integration of spatiotemporal groundwater monitoring with land-use planning can optimize resource allocation, ensuring agricultural viability without compromising hydrological balance.

The study underscores the critical need for ecological restoration to mitigate groundwater depletion and land degradation in the Paderu region, where unregulated extraction has disrupted aquifer recharge dynamics, leading to progressive soil salinization and declining agricultural productivity. Hydrochemical analysis reveals elevated TDS concentrations in intensively irrigated zones, suggesting a direct link between excessive groundwater use and soil degradation. To counter these effects, precision irrigation techniques, informed by soil moisture analytics, can optimize water application and minimize salinity build-up. Additionally, the adoption of salt-tolerant crops, crop rotation strategies, and conservation tillage can enhance soil resilience and sustain long-term productivity. Implementing integrated land-use policies, including watershed management and agroforestry, is essential to balancing agricultural demands with ecological conservation. These measures are crucial for ensuring the long-term sustainability of groundwater and land resources in Paderu Mandal while mitigating the adverse impacts of intensive land use on regional hydrology and soil health.

4.5.2. Groundwater Quality and Sustainable Land Utilization

Heavy metal analysis indicates elevated iron and manganese concentrations in certain groundwater samples, primarily influenced by regional lithology and geogenic processes. These metals pose potential risks for both human consumption and agricultural irrigation, necessitating targeted water treatment strategies to ensure safe usage. Moreover, land-use alterations, including deforestation and unregulated urban expansion, may further impact groundwater recharge and quality by altering natural infiltration dynamics. To mitigate these risks, a sustainable land management framework that integrates groundwater conservation policies is imperative for maintaining agricultural viability and ecological stability in Paderu Mandal. This study establishes a scientific basis for land and water resource policy formulation, aligning with the broader goals of sustainable land utilization and environmental conservation.

5. Conclusions

The investigation of groundwater quality in Paderu Mandal, Andhra Pradesh, traversed a multitude of areas including Chintalaveedhi, Gondali, Vanagarai, Kothapalem, Jeedipagada, Kothuru, Bongajangi, Bontrotuputa, Thumpada, Dokuluru, Arada, Relimamidi, Vantaamamidi and in other areas. Unveiling substantial variations in pH, TDS, TH, Chloride, Sulfate, Fluoride, Nitrate and Iron across these locations, the study highlighted adherence to recommended WHO and BIS standards in most areas. However, specific regions such as Arada, Relimamidi, Vantaamamidi and other areas showcased deviations, hinting at potential contamination sources or geological influences. This emphasizes the continual need for monitoring, further investigations, and tailored remediation strategies to uphold water quality and safety across these diverse regions. Integrating techniques like GIS, spatial analysis, statistical analysis and Hill Piper analysis, the study mapped variations, discerned parameter relationships and identified potential contamination sources within these locations, forming the foundation for informed groundwater management decisions and targeted remediation efforts aimed at sustaining water quality in this diverse region. The study further emphasizes on implementing strategic land-water interaction policies and groundwater-related land-management regulations, so that stakeholders can ensure sustainable water resources while minimizing contamination risks.

Author Contributions

Conceptualization, R.N.D.; methodology, M.K.G.; validation, A.R.N.; formal analysis, R.N.D.; investigation, R.N.D.; data curation, R.N.D.; writing—original draft preparation, M.K.G.; writing—review and editing, A.R.N. and N.R.K.; supervision, M.K.G.; project administration, N.R.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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