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Hydrochemical Assessment of Groundwater Quality for Drinking and Irrigation in the Sudda Vagu Basin, Bhainsa Region, Telangana, India

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Abstract: Groundwater in the Sudda Vagu basin, located in the Bhainsa region of Nirmal District, Telangana, serves as a critical source of water for both drinking and irrigation. To evaluate its quality and suitability, 25 groundwater samples were systematically collected during the pre-monsoon (May 2022) and postmonsoon (November 2022) periods and analyzed for major cations and anions. The concentrations of sodium $\left(Na^{+}\right)$, potassium (K^{+}), carbonate $\left(CO_3^{2-}\right)$, bicarbonate $(HCO_3{}^{-})$, and sulfate $\left(SO_4{}^{2-}\right)$ were found to remain within the permissible limits recommended by the Bureau of Indian Standards (BIS), whereas elevated levels of calcium $\left(Ca^{2+}\right)$, magnesium $\left(Mg^{2+}\right)$, chloride $\left(Cl^{-}\right)$, nitrate $\left(NO_3^{-}\right)$, and fluoride (F^{-}) were detected in several samples, exceeding the prescribed thresholds. The pH of the groundwater ranged from 6.5 to 8.5 , indicating alkaline conditions, and was deemed generally acceptable for drinking based on BIS guidelines. Hydrochemical facies classification using the Piper trilinear diagram revealed the predominance of $Ca^{2+}-HCO_3^{-}$, $Na^{+}-Cl^{-}$, and mixed water types. Irrigation suitability was further assessed through indicators including the Sodium Adsorption Ratio (SAR), Kelly Ratio (KR), and Residual Sodium Carbonate (RSC), along with the Wilcox diagram. Pre-monsoon evaluation indicated that 12 samples were categorized under the S1C2 class (low sodium hazard-medium salinity hazard), while 13 samples were assigned to the S1C3 class (low sodium hazard-high salinity hazard). Postmonsoon analysis revealed that four samples remained in S1C2, whereas 21 shifted into S1C3. The findings indicate that the majority of samples are suitable for drinking and irrigation. Continuous monitoring and the implementation of sustainable groundwater management strategies are therefore essential to ensure water security in this region.

Keywords: Groundwater quality; Hydrochemical facies; Irrigation suitability; Piper diagram; Sodium adsorption ratio; Kelly Ratio; Residual sodium carbonate; Sudda Vagu basin

1 Introduction

Water is the foundation of all living things, and everyone requires access to safe drinking water. It is crucial to human health, yet many people do not have enough of it to maintain basic hygiene. Numerous studies [1–5] have identified contaminated drinking water as a major cause of infant mortality. Poor hygiene is also linked to respiratory illnesses. Groundwater quality is influenced by its ability to dissolve minerals while moving through the saturated zone. Both natural processes and anthropogenic activities such as urbanization, agricultural runoff, and industrial discharge play significant roles in altering groundwater chemistry [6–9]. Identifying contamination patterns both laterally and vertically, as well as understanding the water's chemical composition, is critical for effective groundwater management. In India, groundwater contamination is a growing concern due to increasing industrial effluents and excessive use of chemical fertilizers and pesticides in agriculture. Chemical characterization of groundwater is a crucial tool for detecting pollutants and determining suitability for consumption and irrigation. Particularly in rapidly urbanizing regions, changes in land use significantly affect groundwater dynamics. For example, surface water infiltration from lakes and rivers influences aquifer recharge patterns, especially in regions with complex geomorphology [10–13].

Trace elements introduced through water-rock interactions, agricultural inputs, and domestic wastewater are also key indicators of water quality. Although essential in small amounts, imbalances in these elements can pose serious health risks. Spatial and temporal variations in groundwater composition are therefore shaped by a combination of geogenic and anthropogenic factors. Although several regional studies have examined groundwater chemistry in Telangana, limited data exists for the Sudda Vagu basin, especially regarding seasonal hydrochemical variation and its implications for both domestic and agricultural uses. This gap is significant given the area's reliance on groundwater for daily consumption and irrigation.

To address this, the present study investigates the geochemical characteristics of groundwater in the Bhainsa region of the Sudda Vagu basin, located in the Nirmal District of Telangana. By examining samples from both pre- and post-monsoon seasons, this study provides insight into seasonal variability and the overall suitability of groundwater for drinking and irrigation purposes in the study area.

2 Study Area and Geology

The Sudda Vagu basin is situated in the Bhainsa region of the Nirmal District, Telangana State, extending between latitudes $18°59'00''$N and $19°17'00''$N and longitudes $77°47'00''$E and $78°02'00''$E, covering an area of approximately $323.8\ km^2$. The terrain is gently undulating with a gradual southeastward slope. A prominent hydrological feature of the region is the Sudda Vagu river, which flows from north-northwest (NNW) to south-southeast (SSE). This flow direction is significant for groundwater recharge, as it facilitates the transport of surface runoff from topographic highs in the north to discharge zones in the south. The river's passage through varied lithological zones supports localized infiltration, contributing to the hydrochemical variability observed in groundwater along its course.

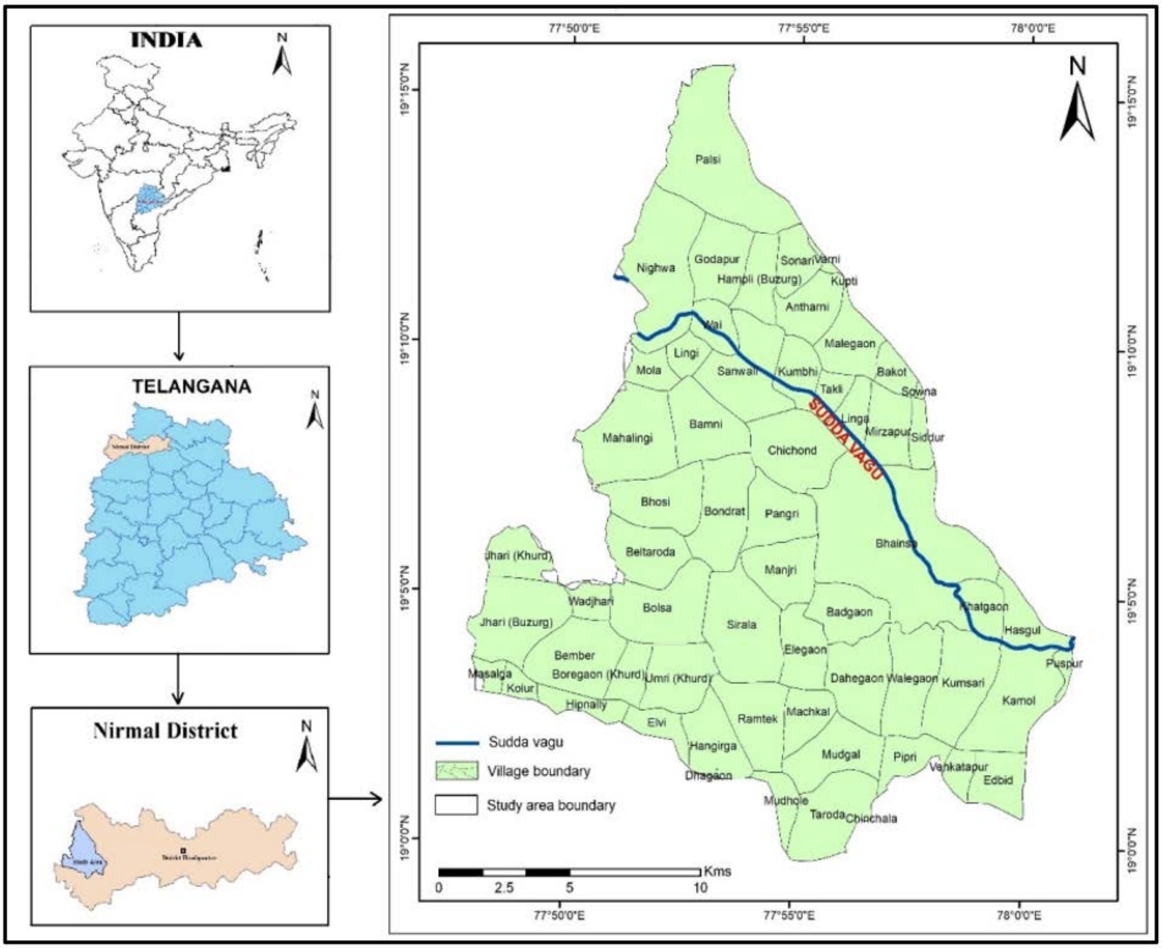

Figure 1. Location map of the Sudda Vagu basin, Bhainsa region of Nirmal District, Telangana State

Geologically, the basin is underlain by two principal lithological formations:

- The Deccan Trap basalts, dating to the Upper Cretaceous-Paleocene period, predominate in the central, northwestern, and southwestern regions. These volcanic rocks are formed from horizontal fissure-type lava flows and are typically massive, but weathering and jointing create secondary porosity, making them moderately productive aquifers. Basalts often contribute bicarbonate-rich, alkaline groundwater due to the weathering of silicate minerals.

- The Peninsular Gneissic Complex (PGC), of Archean to Paleoproterozoic age, dominates the southeastern and eastern parts of the basin. It comprises pink and grey granites, granodiorites, and banded gneisses. The weathered PGC rocks host aquifers with variable yield and are rich in Na^+ and F^-, attributed to the breakdown of feldspars, biotite, and apatite minerals.

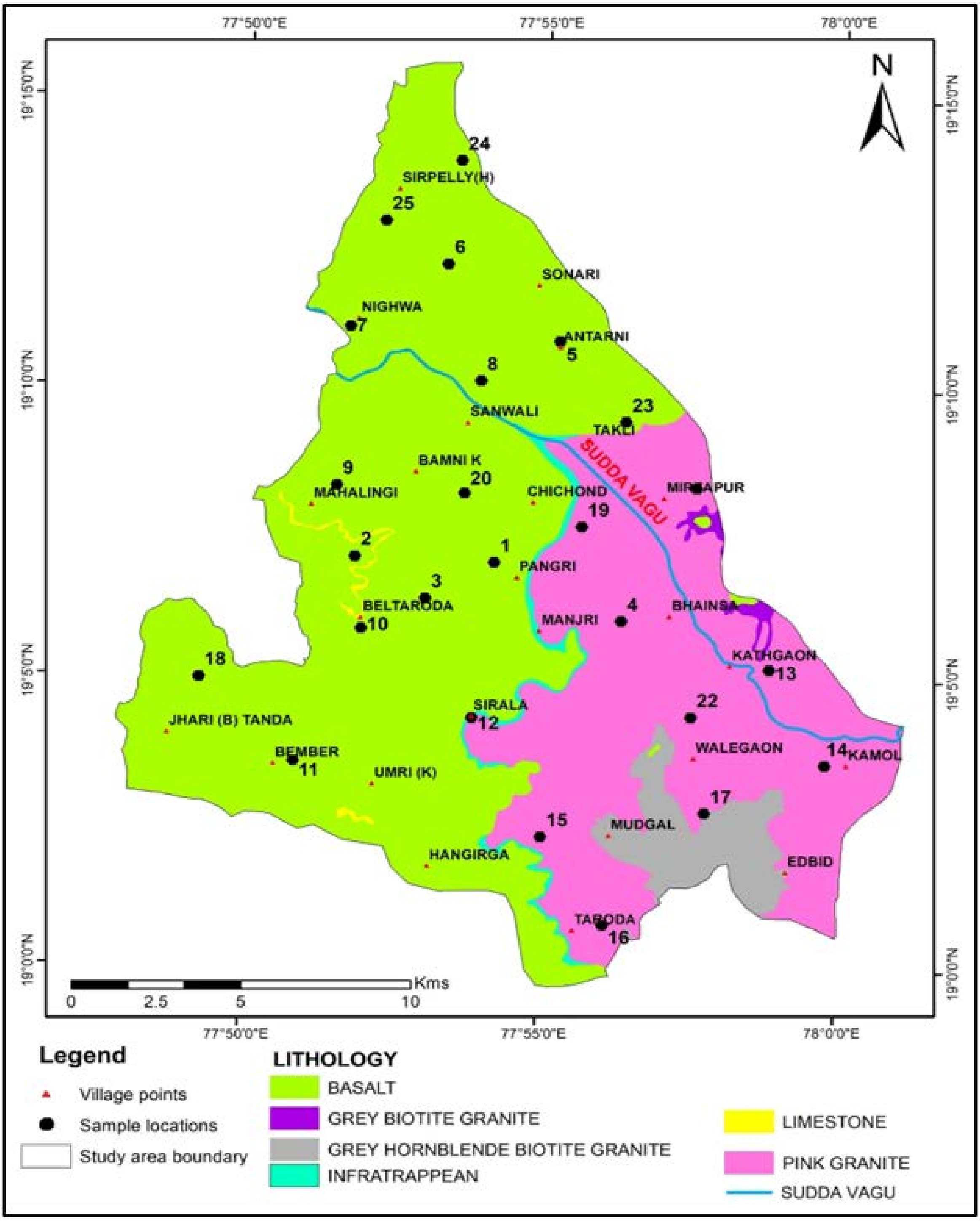

Figure 2. Geological map of the Sudda Vagu basin with groundwater sampling locations

The contact zone between the Deccan Traps and PGC forms a transitional hydrogeological interface. This zone exhibits contrasting mineralogy, porosity, and weathering behavior, which influence groundwater movement and storage capacity, ion exchange processes and mineral dissolution rates, and the release and mobility of trace elements, such as fluoride and nitrate. Additionally, the PGC zones are more susceptible to contamination due to their shallow water tables and relatively low permeability, which slows dilution and flushing of pollutants. The geological framework thus plays a fundamental role in shaping the groundwater quality across the basin. The interaction between lithology, topography, and hydrology determines the observed spatial and seasonal variations in hydrochemical facies, especially during pre- and post-monsoon periods.

Figure 1 presents the location map of the Sudda Vagu basin within the Bhainsa region of Nirmal District, highlighting major villages, drainage patterns, and topographical slope direction from NNW to SSE, which aligns with the flow of the Sudda Vagu river. Figure 2 illustrates the geological map of the study area overlaid with the sampling locations for groundwater analysis. It delineates the spatial distribution of key lithological formations—namely, Deccan Trap basalts, PGC, and patches of Penganga limestone—and their relation to sampling points. This figure aids in correlating geological variations with hydrochemical characteristics observed in groundwater samples.

3 Results and Discussion

3.1 Sampling of Groundwater

Groundwater samples were collected from 25 sites in the Bhainsa region of Nirmal District, Telangana State, using prewashed polypropylene narrow-mouth bottles. Samples were collected in the months preceding the monsoon (May 2022) and subsequent to it (November 2022) (Figure 2). A freshwater sample was obtained from the borewell or hand pumps after thoroughly rinsing the bottle with the same water multiple times to prevent contamination. The plastic container was then sealed and transported to the laboratory for chemical analysis. Care was taken to prevent hand contact during the filling of the container. Water samples from groundwater were collected in tagged containers, securely packaged, transported directly to the laboratory, and stored at 4°C for subsequent chemical analysis. Blanks and standards were analyzed at the outset of the procedures.

3.2 Site Selection Criteria

The selection of groundwater sampling sites in the Sudda Vagu basin was based on a combination of hydrogeolo gical, geographical, and anthropogenic criteria to ensure comprehensive spatial and seasonal representation. A total of 25 sampling locations were chosen across the Bhainsa region in the Nirmal District with the following considerations:

- Lithological variation: Sites were distributed across the two major geological formations-Deccan Trap basalts and PGC-to capture the influence of lithology on groundwater chemistry, particularly ion exchange and mineral dissolution patterns.
- Hydrological features: Sampling points were located both along and away from the Sudda Vagu river, which flows from NNW to SSE. This allowed for assessment of river-induced recharge zones versus non-influenced upland areas.
- Topography and drainage: The selection included topographic highs and lows, as lower areas are more prone to accumulation of runoff and potential contaminant loadings, affecting groundwater salinity and hardness levels.
- Land use and anthropogenic activity: Sites were chosen to represent areas under intensive agriculture (high fertilizer/pesticide input), village settlements with septic tanks, and open land. This helped assess human-induced impacts such as nitrate and fluoride contamination.
- Accessibility and consistency: Preference was given to existing borewells and hand pumps that were accessible in both pre- and post-monsoon seasons. Sites were tagged and georeferenced to maintain temporal consistency in sampling.
- Proximity to potential contaminant sources: Specific attention was given to areas near agricultural fields, domestic waste drains, and irrigation return flows, suspected to contribute to elevated concentrations of NO_3^-, Cl^-, and F^-.

This spatially distributed approach ensured that the groundwater samples reflected geochemical diversity, seasonal variation, and contamination vulnerability across the basin. Locations were mapped and overlaid on geological and topographical maps for interpretation (Figure 2).

3.3 Contamination Control Measures

To ensure the integrity of groundwater samples and avoid false positives due to external contamination, strict control measures were implemented throughout the sampling process. Potential sources of contamination in the Sudda Vagu basin were identified and recorded at each sampling site. These included:

- Agricultural runoff from fields using chemical fertilizers and pesticides.
- Septic tank leakage in densely populated village peripheries.
- Improper disposal of domestic waste and greywater near borewells.
- And return flows from irrigation canals, especially in low-lying cultivated areas.

At each site, sample collectors wore disposable, powderless gloves, which were changed between each sampling point and every procedural step. Contact with surfaces such as coins, tools, or bare hands was strictly avoided during sampling. All sampling bottles and containers were made of inert, non-reactive materials (e.g., high-density polyethylene) and pre-cleaned according to American Public Health Association (APHA) protocols. Prior to sample collection, on-site rinsing with the same groundwater was carried out to minimize residual contamination. For parameters sensitive to environmental exposure—such as fluoride and nitrate—sample bottles were sealed immediately after filling and stored in insulated containers at 4°C. Field equipment, including electrical conductivity (EC) meters and pH meters, was cleaned and calibrated daily. Rinsing of equipment was limited or avoided entirely for certain parameters (e.g., organic or trace elements), following APHA guidelines. Blank and duplicate samples were collected at regular intervals to assess procedural accuracy. In field locations with high dust, organic debris, or exposure to runoff (e.g., sites near agricultural bunds or open drainage channels), sampling was delayed until water flow stabilized, and care was taken to draw water from the borewell only after sufficient flushing. All personnel involved in sampling underwent pre-field training to standardize the implementation of "Clean Hands/Dirty Hands" techniques and reduce inter-operator variability. Sampling followed a predefined sequence (north to south) to reduce cross-contamination and maintain consistency.

These field-specific adaptations ensured that the groundwater quality data obtained were reliable and reflective of in situ conditions, particularly given the varied anthropogenic pressures observed across the basin. In order to ensure the integrity of groundwater samples and eliminate potential contamination during collection and handling, both standard field protocols and study-specific procedures tailored to the environmental and anthropogenic conditions in the Sudda Vagu basin were followed. Following standard contamination control procedures, all groundwater samples were collected using pre-cleaned, narrow-mouth polyethylene bottles. Disposable, powder-free gloves were worn throughout the sampling process and changed between locations and tasks. Hand contact with sample water, inner surfaces of containers, and non-sterile equipment was strictly avoided. Field instruments (e.g., EC meters and pH meters) were cleaned and calibrated daily. Blanks and quality control duplicates were collected at consistent intervals to check for contamination and ensure accuracy. Samples were stored at 4°C immediately after collection to preserve chemical stability until analysis. Due to the unique mix of agricultural activity, shallow groundwater, and unregulated waste disposal in the Sudda Vagu basin, the following additional precautions were implemented:

- Site screening: At each borewell or hand pump, visible contamination risks were recorded, such as adjacent septic tanks, standing wastewater, agricultural runoff channels, and dumped domestic waste.

- Flushing protocol: Groundwater was collected only after running the borewell continuously for 510 minutes, especially in areas with recent irrigation or heavy sedimentation.

- Field positioning: In low-lying or downstream regions where irrigation return flow and stagnant surface water posed risks, sampling from up-gradient positions was ensured whenever possible.

- Surface protection: At locations exposed to dust or open defectation (e.g., near fields or rural peripheries), sample bottles were handled and capped within plastic sample enclosures to minimize airborne contamination.

- Labeling and tracking: Because some wells were unregistered and located on informal private lands, a GPS tagging system was used to reliably track site location, water use type (drinking/irrigation), and observed land use.

By differentiating general contamination protocols from these field-specific adaptations, the study ensured that groundwater chemistry data truly reflected in situ conditions across diverse geological and anthropogenic zones of the Sudda Vagu basin.

3.4 Equipment/Instruments

The study utilized various devices to analyze groundwater samples, including conductivity meters (Model 304, Systronics) for measuring EC and digital pH meters (Model 802, Systronics) for evaluating pH levels. A numerical method was employed to estimate the Total Dissolved Solids (TDS). A Systronics Model 130 flame photometer was employed to measure the concentrations of Na^+ and K^+. The volumetric analysis of total hardness (TH) and Ca^{2+} was conducted using conventional ethylenediaminetetraacetic acid (EDTA) methods. Methyl orange and phenolphthalein were used as acid-base indicators in the titration with standard hydrochloric acid (HCl) to determine the Mg^{2+} content. This concentration was ascertained by determining the difference between TH and the concentrations of Ca^{2+}, $CO_3{}^{2-}$, and $HCO_3{}^-$. The quantity of Cl^- was determined through the titration of standard silver nitrate ($AgNO_3$). $NO_3{}^-$ and $SO_4{}^{2-}$ measurements were conducted using the Spectronics-21 (Model BAUSCH & LOMB). An Orion ion analyzer and a fluoride ion-selective electrode were employed to determine the concentration of F^-. Other chemical variables, excluding pH , were quantified in milligrams per liter (mg/L), whereas EC was assessed in microsiemens per centimeter (μS/cm) at 25°C. Table 1 and Table 2 present the analytical results for the pre- and post-monsoon seasons comprehensively.

Table 1. Summary of groundwater quality parameters (pre- and post-monsoon)

Parameter	Pre-monsoon (Range and Mean)	Post-monsoon (Range and Mean)	BIS Limit	% Samples Exceeding Limit
pH	7.45-8.31 (8.01)	7.54-8.31 (7.87)	6.5-8.5	0%
EC (μS/cm)	336-1365	424-2065	2000	Some
TDS (mg/L)	215-874 (557.2)	271-1322 (704.4)	500	44% pre and 68% post
TH (mg/L)	100-500 (283.2)	140-600 (346.4)	200	68% pre and 80% post
Ca^{2+}(mg/L)	16-88	16-96	75	Some
Mg^{2+} (mg/L)	14.5-102.1	24.3-102.1	30	Many
Na^{+}(mg/L)	23-147	38-204	200	A few
K^{+}(mg/L)	1-7	1-22	10	Some
Cl^{-}(mg/L)	30-260	40-390	250	32%
$NO_3{}^{-}$ (mg/L)	4.03-191.4 (60.5)	6.24-196.8 (64.6)	45	52% pre and 40% post
F^{-}(mg/L)	0.15-2.91 (0.78)	0.13-3.30 (0.75)	1.2	24%

Table 2. Summary of the physical and chemical variables and ions in the groundwater samples of the Sudda Vagu basin

Variables	Pre-monsoon Season				Post-monsoon Season				BIS (2012) Acceptable Limit
	Min	Max	Mean	% of Samples Exceeded the Limits	Min	Max	Mean	% of Samples Exceeded the Limits	
pH	7.45	8.26	8.010	-	7.54	8.31	7.87	-	6.5-8.5
EC (μS/cm)	336	1365	870.72	-	424	2065	1100	-	-
TDS (mg/L $^{-1}$)	215	874	557.2	44	271	1322	704.4	68	500
TH as calcium carbonate $(CaCO_3)$ (mg/L^{-1})	100	500	283.2	68	140	600	346.4	80	200
Na^{+} (mg/L^{-1})	23	147	74.52	-	38	204	107	-	100
K^{+} (mg/L^{-1})	1	7	3.2	-	1	22	4.08	-	10
Ca^{2+} (mg/L^{-1})	16	88	32.32	-	16	96	53.12	-	75-100
Mg^{2+} (mg/L^{-1})	14.5	102.1	49.20	72	24.3	102.1	51.92	60	30-100
$CO_3{}^{-}$ (mg/L^{-1})	0	20	0.8	-	0	30	1.2	-	-
$HCO_3{}^{-}$ (mg/L^{-1})	120	350	205.2	-	140	460	276.4	-	300
Cl^{-} (mg/L^{-1})	30	260	113.2	28	40	390	150.4	36	250
$SO_4{}^{2-}$ (mg/L^{-1})	0	125	23.28	0	7	125	29.04	0	200
$NO_3{}^{-}$ (mg/L^{-1})	4.03	191.4	60.53	52	6.24	196.8	64.61	40	45
F^{-} (mg/L^{-1})	0.15	2.91	0.784	24	0.13	3.3	0.756	24	0.6-1.20

3.5 Analytical Chemical Procedures

The groundwater samples were analyzed for various physicochemical parameters, including pH, EC, TDS, TH, $Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}$, and F^{-}, employing standard methods established by APHA [14]. The results obtained were utilized to create graphical representations of the concentrations of various ions in a groundwater sample, employing both the Piper diagram and the Wilcox diagram. The evaluation of groundwater quality for irrigation suitability was performed utilizing KR, SAR, and RSC .

4 Results and Discussion

Table 1 and Table 2 present various physicochemical parameters obtained through the examination of water samples from the Bhainsa area.

4.1 Chemical Characteristics of Groundwater

pH: A quantitative assessment of the acidity or alkalinity of a solution. The pH of a fluid quantifies its hydrogen ion (H+) concentration in comparison to a standard solution. The pH scale spans from 0 to 14, with 0 indicating acidity, 14 representing basicity, and 7 denoting neutrality. The pre-monsoon pH of water samples ranged from 7.45 to 8.26, with a mean value of 8.01. The pH values of the post-monsoon samples ranged from 7.54 to 8.31, with a mean of 7.87 (Table 1 and Table 2). BIS [15, 16] specifies that the pH range for drinking water is 6.5 to 8.5 (Table 2). The groundwater samples analyzed are alkaline, and the results from both pre- and post-monsoon seasons indicate their suitability for drinking purposes.

EC: EC quantifies a material's capacity to conduct electric current; thus, a higher EC signifies increased salt concentration in groundwater. EC is quantified in siemens per meter $(\mathrm{S/m})$, with the maximum permissible limit in groundwater set at 200 $\mu\,\mathrm{S/cm}$ [17]. The distribution of EC ranged from approximately 336 to 1365 $\mu\,\mathrm{S/cm}$ in the pre-monsoon period and from 424 to 2065 $\mu\,\mathrm{S/cm}$ in the postmonsoon period. EC can be categorized into three classifications: type I for low salt enrichments (EC <1500 $\mu\,\mathrm{S/cm}$), type II for medium salt enrichments (EC $=$ 1500 to 3000 $\mu\,\mathrm{S/cm}$), and type III for high salt enrichments (EC>3000 $\mu\,\mathrm{S/cm}$). EC in the study area varied from 336.3 $\mu\,\mathrm{S/cm}$ to 2065 $\mu\,\mathrm{S/cm}$, indicating that the salinity levels were classified as low to medium, as shown in Table 2. During the post-monsoon season, elevated EC concentrations (>2000 $\mu\,\mathrm{S/cm}$) were recorded in the eastern region, with these anomalous values attributed to a range of anthropogenic activities and geochemical processes occurring in the area.

TDS: The TDS values in pre-monsoon groundwater samples ranged from 215 to 874 $\mathrm{mg/L}$, while in post-monsoon samples, they ranged from 271 to 1322 $\mathrm{mg/L}$. The average TDS levels during the premonsoon period were 557 $\mathrm{mg/L}$, whereas the average TDS levels in the post-monsoon period increased to 704 $\mathrm{mg/L}$ (Table 2). While agriculture is the primary focus of this research area, TDS levels may also be affected by the loading of fertilizers and pesticides in water samples. The variations in TDS concentrations-low TDS (<1,000 $\mathrm{mg/L}$) in elevated areas and high TDS (>2,000 $\mathrm{mg/L}$) in lower regions-suggest that, depending on topographical features and water flow paths, anthropogenic and marine sources obscure the geogenic source.

TH as $\mathrm{CaCO_3}$: The combined presence of $\mathrm{Ca^{2+}}$ and $\mathrm{Mg^{2+}}$ ions determines overall hardness, expressed as $\mathrm{CaCO_3}$, and quantified in $\mathrm{mg/L}$ or parts per million (ppm). TH of water samples ranged from 100 to 500 $\mathrm{mg/L}$, with a mean of 283 $\mathrm{mg/L}$, and from 140 to 600 $\mathrm{mg/L}$, with a mean of 346 $\mathrm{mg/L}$, in the preand post-monsoon seasons, respectively (Table 1). The allowable hardness level is 200 $\mathrm{mg/L}$, with 72 % to 88% of samples surpassing this threshold. Water is typically classified as soft when its hardness is below 75 ppm and as very hard when it exceeds 300 ppm. Consequently, there is minimal variation of TH across both seasons (Table 2). The concentration of TH increased in the topographic low regions, particularly during the post-monsoon period. TH distribution generally aligns with trends observed in TDS. The study indicates that there are no 'soft' groundwaters in the Sudda Vagu basin, with hard to very hard groundwater being predominant in both seasons.

$\mathrm{Ca^{2+}}$ and $\mathrm{Mg^{2+}}$: BIS (2012) reports that the average concentration of $\mathrm{Ca^{2+}}$ in water samples collected before and after the monsoon season is 32 $\mathrm{mg/L}$ and 53 $\mathrm{mg/L}$, respectively. The upper limit for calcium consumption is 75 $\mathrm{mg/L.Mg^{2+}}$ concentrations in groundwater samples are higher during the premonsoon period, with a mean of $49\mathrm{mg/L}$, and lower during the post-monsoon period, with a mean of 52 $\mathrm{mg/L}$ (Table 2). According to the water quality specifications, the maximum allowable $\mathrm{Mg^{2+}}$ concentration is 30 $\mathrm{mg/L}$. The contribution of $\mathrm{Mg^{2+}}$ constitutes 72% to 80% of the total cations, respectively. The vagueness of the river environment, ion exchange between $\mathrm{Na^+}$ and $\mathrm{Ca^{2+}}$, precipitation of $\mathrm{CaCO_3}$, and the presence of ferromagnesium minerals all result in a greater contribution of $\mathrm{Mg^{2+}}$ compared to $\mathrm{Ca^{2+}}$.

$\mathrm{Na^+}$ and $\mathrm{K^+}$: $\mathrm{Na^+}$plays a crucial role in assessing whether water is suitable for irrigation. The primary source of $\mathrm{Na^+}$ in natural water is the dissolution of soluble materials caused by the weathering of sodic feldspars. Frequent use of irrigated water can raise the salinity of the soil, which can impair permeability and change the texture of the soil, rendering it unsuitable for farming. Table 1 and Table 2 show that the $\mathrm{Na^+}$ concentrations in the study area ranged from 23 to 147 $\mathrm{mg/L}$ in the pre-monsoon and from 38 to 204 $\mathrm{mg/L}$ in the post-monsoon. Samples from both the pre- and post-monsoon seasons are deemed safe for consumption, as $\mathrm{Na^+}$ levels do not exceed the recommended limit of 200 $\mathrm{mg/L}$. The $\mathrm{Na^+}$ concentration increased in the downstream area. Elevated $\mathrm{Na^+}$ concentrations in groundwater were observed on the eastern side of the downstream area. $\mathrm{K^+}$ was found in relatively low concentrations in groundwater, originating from the weathering of stable minerals such as orthoclase, microcline feldspars, and biotite present in the region's granites. During the pre- and post-monsoon seasons, $\mathrm{K^+}$ concentrations averaged 3.2 $\mathrm{mg/L}$ and 4.08 $\mathrm{mg/L}$, respectively (Table 1 and Table 2). The permissible limit for calcium is 10 $\mathrm{mg/L}$. The regions are primarily characterized by the weathering of orthoclase, microcline, and biotite minerals, which predominantly make up the granitic host rock in the study area.

$\mathrm{CO_3}^{2-}$ and $\mathrm{HCO_3}^-$: The solubility of carbon dioxide ($\mathrm{CO_2}$) in the hydrosphere, lithosphere, and atmosphere-stemming from sources such as the soil zone, dissolution of carbonate rocks, and organic matter degradation-results in the presence of dissolved carbonate species in various water types. During the pre- and post-monsoon seasons, $\mathrm{CO_3}^{2-}$ values ranged from 0 to 20 $\mathrm{mg/L}$, averaging 0.8 $\mathrm{mg/L}$, and from 0 to 30 $\mathrm{mg/L}$, averaging 1.2 $\mathrm{mg/L}$ (Table 1 and Table 2). During the post-monsoon season, the highest value was located east of Beltaroda village (Sample No. 3) and west of Sonari village (Sample No. 6) (Figure 2). The organic matter in the aquifer, upon oxidation, generates $\mathrm{CO_2}$ and facilitates mineral dissolution, representing a potential source of bicarbonate [18]. The $\mathrm{HCO_3}^-$ concentration in the groundwaters of the research region varied from 120 to 350 $\mathrm{mg/L}$, with an average of 205

mg/L, and from 140 to 460 mg/L, with an average of 276 mg/L during the pre- and post-monsoon seasons (Table 1 and Table 2). Ions of Ca^{2+}, Mg^{2+}, and HCO_3^- were found in groundwater. The weathering of silicate rocks can produce HCO_3^- ions [19]. According to the BIS regulations, 300 mg/L is the maximum amount of total alkalinity that can be present in drinking water.

Cl^-: The maximum allowable concentration of Cl^- is 250 mg/L. Pre-monsoon and post-monsoon groundwater samples obtained Cl^- concentrations between 30 and 260 mg/L and 40 and 390 mg/L, respectively (Table 1). During the pre-monsoon and post-monsoon seasons, elevated Cl^- concentrations were observed in approximately 4% and 12% of the samples, respectively (Table 2). The Vagu river environment significantly impacts the aquifer system, with the highest Cl^- concentrations recorded during the pre- and post-monsoon seasons at Nighwa village (Sample No. 7) and Kamol village (Sample No. 14), as illustrated in Figure 2. The distribution of TDS indicates that low concentrations of Cl^-($<$ 200 mg/L) were found in areas of topographic highs, while high concentrations (>400 mg/L) were observed in areas of topographic lows.

$SO_4{}^{2-}$: Groundwater $SO_4{}^{2-}$ levels ranged from 0 to 125 mg/L with a mean of 23 mg/L during the premonsoon season and from 7 to 125 mg/L with a mean of 29 mg/L during the post-monsoon season (Table 2). The impact of the Vagu river source is evidenced by the highest $SO_4{}^{2-}$ concentration of 105 to 120 mg/L in groundwater samples 1 and 2 (Figure 2). The breakdown of organic components in the topsoil and the water-leachable sulfate found in farmer-applied fertilizers cause $SO_4{}^{2-}$ concentrations.

$NO_3{}^-$: Table 1 indicates that $NO_3{}^-$ levels in pre-monsoon season samples varied from 4 to 191 mg/L, with an average of 60 mg/L, while post-monsoon season samples ranged from 6 to 196 mg/L, with an average of 64 mg/L. The maximum allowable concentration of $NO_3{}^-$ is 45 mg/L. In the study area, excess levels were observed in 52% of samples collected during the pre-monsoon season and 40% of samples collected during the post-monsoon season. The groundwater in the eastern section of the downstream Vagu area exhibited a significantly low concentration of $NO_3{}^-$, comprising less than 1% of the total anions when compared to other well water sources. The origin of $NO_3{}^-$ is not lithological. Significant increases in $NO_3{}^-$ concentrations were observed in the Beltaroda and Pangri regions (Samples No. 1, 2, and 3) (Figure 2). $NO_3{}^-$ concentrations in water typically do not exceed 10 mg/L; thus, any concentration above this threshold is likely attributable to human pollution. The primary causes are unhygienic conditions and the excessive application of fertilizers in the research area to enhance crop yields.

F^-: The pre-monsoon season exhibited a higher F^- concentration compared to the post-monsoon period. F^- concentrations ranged from 0.15 to 2.91 mg/L, with a pre-monsoon average of 0.78 mg/L and a postmonsoon average of 0.75 mg/L. During the pre- and post-monsoon seasons, approximately 24 % of the samples exhibited elevated Cl^- concentrations (Table 2). The maximum permissible concentration of F^-in groundwater is 1.0 mg/L. The topographic lows demonstrated elevated concentrations of F^-. The northern region of the Vagu riverside near Nighwa and Sanwali (Samples No. 6, 7, and 8) showed increased F^- concentrations during the pre-monsoon period, while the southern part of the Walegaon area (Sample No. 22) displayed similar trends in the post-monsoon season (Figure 2). The concentration of F^- in the study area is primarily influenced by geogenic sources such as apatite, biotite, and clays, as well as anthropogenic sources, including chemical fertilizers. Additionally, a higher evaporation rate and prolonged interaction of water with aquifer materials in an alkaline environment contribute to this concentration. Exceeding this amount leads to fluorosis. Fluoride leaching from parent minerals in rocks and soils is affected by several factors, including significant weathering, accessibility to circulating water from extensive irrigation, a semi-arid climate, and prolonged groundwater residence time in the aquifer. Fluoride release into groundwater during rock-water interaction was enhanced by elevated Na^+ levels and reduced Ca^{2+} concentrations [20].

4.2 Hydrogeochemical Facies

In order to evaluate differences in hydrochemical facies, this study classed groundwater samples hydrochemically by examining main cations and anions using the traditional Piper trilinear diagram [21]. Three separate fields make up the Piper trilinear diagram: one diamond-shaped field in the center and two bottom triangle fields. The primary cations, Ca^+, Mg^+, Na^+, and K^+, are depicted in percentage milliequivalents per liter (% meq /L) values within the triangle located in the lower left corner. The primary anions in the lower right triangle, including $CO_3, HCO_3{}^-, Cl^-$, and $SO_4{}^{2-}$, are presented in % meq/L. In the classification of groundwater types, the locations of the plots within two triangular fields were subsequently mapped onto a quadrilateral or diamond-shaped field. The groundwater in the study area was categorized into several types: $Ca^{2+} - HCO_3{}^-, Na^+ - Cl^-$, mixed $Ca^{2+} - Mg^{2+} - Cl^-$, mixed $Ca^{2+} - Na^+ - HCO_3^-, Na^+ - HCO_3^-$, and mixed $Ca^{2+} - Cl^-$ during both the pre-monsoon and post-monsoon seasons (Table 3). The distribution of groundwater samples across the sub-divisions of the Piper diagram's diamondshaped area illustrated the similarities and differences between pre- and post-monsoon periods (Figure 3).

Table 3. Classification of groundwater of the study area based on the Piper trilinear diagram

Classification	Pre-monsoon		Post-monsoon	
	Samples	Percentage	Samples	Percentage
$Ca^{2+} - HCO_3^-$	12	48	16	64
$Na^+ - Cl^-$	0	0	1	4
Mixed $Ca^{2+} - Na^+ - HCO_3^-$	3	12	0	0
Mixed $Ca^{2+} - Mg^{2+} - Cl^-$	9	36	8	32
$Ca^{2+} - Cl^-$	1	4	0	0
$Na^+ - HCO_3^-$	0	0	0	0

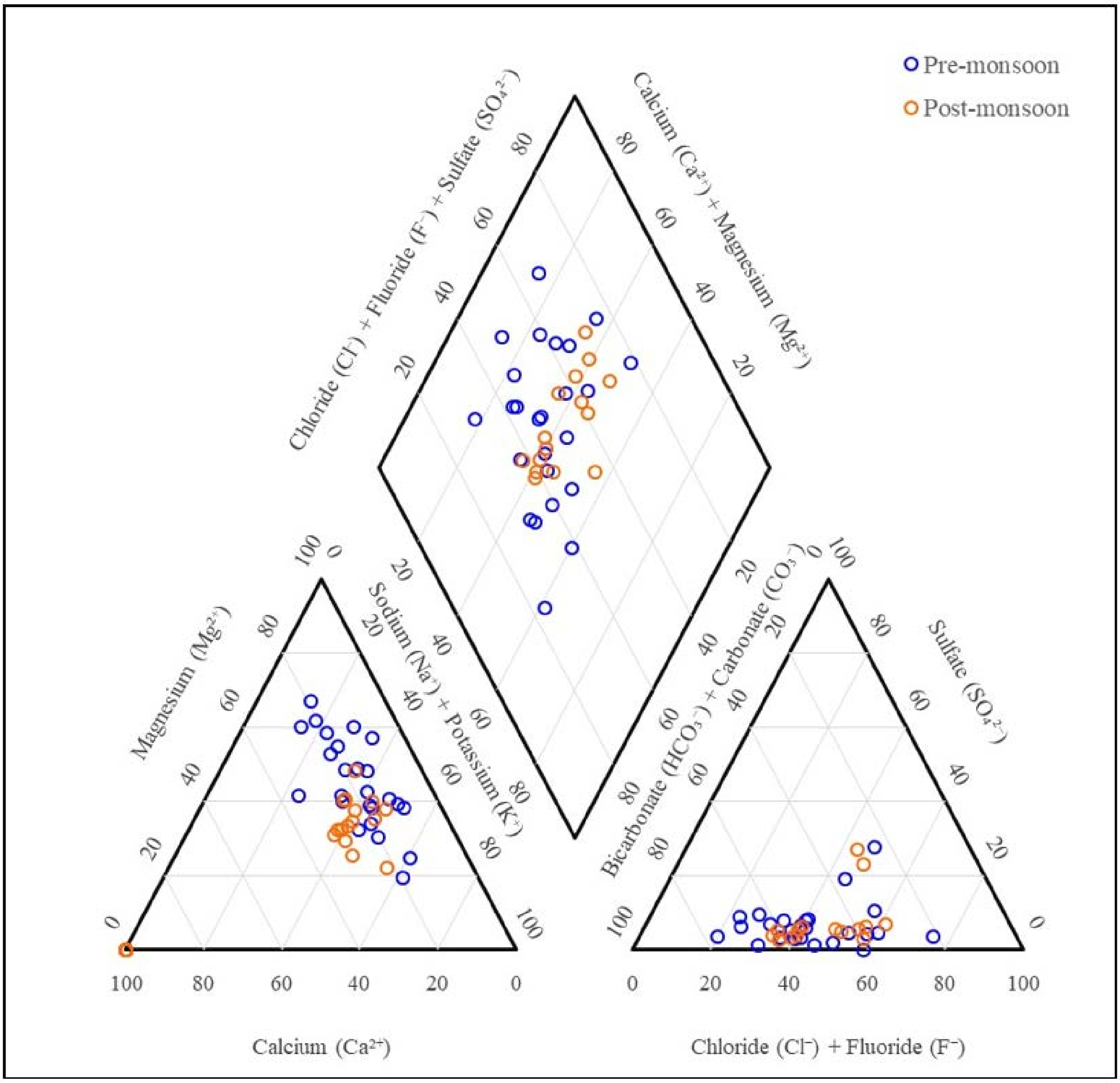

Figure 3. Comparison map of hydrochemical facies classification of groundwater in the pre- and post-monsoon seasons

4.3 Suitability of Groundwater Quality

4.3.1 Drinking purpose

pH determines the acidic or basic condition of water quality. Deviation of pH from the established range of 6.5 to 8.5 can result in damage to the mucous membranes of the eyes, nose, mouth, abdomen, and anus. The pH levels (ranging from 7 to 8.2) in all groundwater samples (100%) from the study area are within the acceptable limits (Table 1 and Table 2).

The measured TDS in the study area ranged from 557 to 704 mg/L (Table 2). The concentration of TDS exceeds the permissible limit of 500 mg/L in approximately 56% of the groundwater samples (1, 2, 3, 4, 7, 10, 13, 14, 16, 17, 19, 20, 23, 25), as shown in Table 4. Elevated TDS frequently leads to gastrointestinal irritation in consumers and diminishes palatability. Furthermore, it exhibits a laxative effect, especially during transit. Kidney stones frequently arise as complications from prolonged consumption of water with elevated TDS. Hardness significantly impacts water quality, affecting taste and the efficacy of soap lathering, thereby serving as an essential criterion for assessing the suitability of water for drinking and household use. Approximately 74% of groundwater samples in the study area exhibited TH levels ranging from 283 to 346 mg/L, exceeding the recommended limit of 200 mg/L for drinking water (1, 2, 3, 4, 6, 7, 9, 10, 13, 14, 15, 16, 17, 18, 19, 20, 23, and 25) (Table 4). TH distribution generally aligns with trends in TDS.

Table 4. Criteria for groundwater quality for drinking in the Sudda Vagu basin

Chemical Parameter	BIS (2012)	Sample Numbers Exceeding the Safe Limit	% of Samples Exceeding the Limit	% of Safe Drinking Water
pH	6.5-8.5	-	-	100
TDS (mg/L)	500	1,2,3,4,7, 10,13,14,16, 17,19,20,23 and 25	56	60
TH as $CaCO_3$(mg/L)	200	1,2,3,4,6, 7,9,10,13,14,15, 16, 17, 18, 19, 20, 23, and 25	74	28
Na^+(mg/L)	100	-	-	100
K^+(mg/L)	10	-	-	100
Ca^{2+}(mg/L)	75-100	-	-	100
Mg^{2+}(mg/L)	30-100	1,2,3,6, 7,10,13,14, 15,16,17, 18, 19,20 and 25	66	56
$CO_3{}^-$(mg/L)	-	-	-	100
$HCO_3{}^-$(mg/L)	300	-	-	100
Cl^-(mg/L)	250	2, 3, 7, 10, 13, 14, 16, 19	32	48
$SO_4{}^{2-}$(mg/L)	200	-	-	100
$NO_3{}^-$(mg/L)	45	1, 2, 3, 4, 5, 6, 10, 13, 15, 19, 23 and 24	46	60
F^-(mg/L)	0.6-1.20	6, 7, 8, 11, 18 and 22	24	84

The findings indicate that there are no 'soft' groundwaters in the Sudda Vagu basin, with hard to very hard groundwater being predominant in both seasons. The observed concentration of Na^+in the groundwater ranged from 74 to 107 mg/L, with 100% of the total groundwater samples meeting the recommended limit of 100 mg/L for safe water. The concentration of $K^+$was $3.2 mg/L$ and 4.08 mg/L, both of which are below the 10 mg/L threshold in drinking water. It regulates fluid balance in the body, with K^+present in 100% of the safe total groundwater samples (Table 4). Ca^{2+} ions are necessary for the best possible bone growth. All groundwater samples (100%) had Ca^{2+} concentrations between 32 and 53 mg/L, which is below the standard limit of 75 mg/L. In around 66% of the total samples examined, the Mg^{2+} concentration in groundwater samples (ranging from 49 to 52 mg/L) surpassed the recommended limit of 30 mg/L for potable water $(1, 2, 3, 6, 7, 10, 13, 14, 15, 16, 17, 18, 19, 20,$ and 25). Although Mg^{2+} is a necessary ion for enzyme activation and cellular function, it is considered a laxative at high amounts. In the pre-monsoon season, the $CO_3{}^{2-}$ levels were 0.8 mg/L, whereas in the post-monsoon season, they were 1.2 mg/L. The $HCO_3{}^-$concentration in the research area's groundwaters varied between 205 and 276 mg/L during the pre- and post-monsoon seasons. According to the BIS regulations, 300 mg/L of total alkalinity is the maximum amount that can be present in safe drinking water.

$Cl^-$and $SO_4{}^{2-}$ are significant inorganic ions that substantially degrade drinking water quality. Cl^- is crucial for maintaining electrolyte balance in blood plasma; however, elevated levels may lead to hypertension, increased stroke risk, left ventricular hypertrophy, osteoporosis, renal stones, and asthma. Additionally, the consumption of water with $SO_4{}^{2-}$ may result in diarrhea, catharsis, dehydration, and gastrointestinal irritation. The acceptable concentrations of Cl^- and $SO_4{}^{2-}$ in drinking water are 250 mg/L and 200 mg/L, respectively (Table 2). The groundwater in the study area exhibited Cl^- concentrations ranging from 113 to 150 mg/L and $SO_4{}^{2-}$ concentrations from

23 to 29 mg/L, as presented in Table 2. The concentration of Cl^-exceeded the allowable limit of 250 mg/L in approximately 32% of the total groundwater samples $(2, 3, 7, 10, 13, 14, 16, 19)$. The concentration of $SO_4{}^{2-}$ in all safe groundwater samples (100%) was below the recommended limit of 200 mg/L (Table 4).

The advised threshold for NO_3^- in potable water is 45mg/L; however, the measured concentration of $NO_3{}^-$ in groundwater ranged from 60 to 64 mg/L (Table 2). A total of 24 groundwater samples exhibited concentrations of NO_3 - exceeding the acceptable limit by approximately 46% (Table 4). This condition can lead to methemoglobinemia, commonly referred to as "blue baby syndrome," a disorder that is often fatal in infants under four months of age. Women consuming water contaminated with $NO_3{}^-$ have been reported to experience spontaneous abortions [22, 23]. Dental health benefits from the acceptable range of F^- in drinking water, which is 0.60 to 1.20 mg/L. Dental decay is caused by F^- concentrations below 0.60mg/L, whereas dental fluorosis is caused by excessive F^-concentrations in water, surpassing 1.20 mg/L. According to Table 2, F^- concentrations in the research area's groundwater ranged from 0.78 to 0.75mg/L, surpassing the 1.20mg/L legal limit in roughly 24% of the total groundwater samples (6, 7 , 8, 11, 18, and 22) shown in Table 4. The metabolic processes of soft tissues, including the thyroid, reproductive organs, brain, liver, and kidney, may be altered by increased F^- consumption and the peripheral zone of women's placentas has a notable plasma F^- content [24–26].

4.4 Irrigation Purpose

By reducing the osmotic pressure in the structural cells of the plant, high amounts of dissolved ions in irrigation water have a physical and chemical impact on agricultural soil and plants. This lowers agricultural yield by keeping water from getting to the leaves and branches.

KR , which compares salt concentration to Ca^{2+} and Mg^{2+} levels, serves as an important metric for evaluating irrigation water quality. A high Na^+ concentration in water generally modifies soil permeability and other characteristics, indicating an alkali hazard. A reduced calcium content in water leads to soil dispersion, consequently decreasing the infiltration rate. The Kelly criterion can be represented by the following equation:

$$KR = Na^+/Ca^{2+} + Mg^{2+} \tag{1}$$

Irrigation is considered acceptable when KR is less than 1 , while a KR greater than 1 signifies an excess of salt in the water, rendering it unsuitable for irrigation. The Kelly factor value in pre- and postmonsoon season samples ranged from 0.16 to 1.54 milliequivalents per liter (mEq/L) and 0.16 to 2.16 mEq/L, respectively, with average values of 0.64 and 0.99 mEq/L (Table 5). Approximately 88% of samples were classified as suitable for irrigation, while 12% were deemed marginally suitable for irrigation during the pre-monsoon season. In the study area, 56% of samples were classified as suitable, while 36% were deemed marginally suitable for irrigation purposes (Table 6).

Table 5. KR in the study area

KR (mEq/L)	Pre-monsoon	Post-monsoon
Minimum	0.16	0.16
Maximum	1.54	2.16
Average	0.64	0.99

Table 6. Suitability classification of Sudda Vagu basin groundwater for irrigation purposes (after Kelly)

KR	Class	% of Pre-monsoon	% of Post-monsoon
<1	Suitable	88%	56%
1-2	Marginally suitable	4%	36%
>2	Unsuitable	Nil	8%

In the pre-monsoon season, the samples' specific adsorption ratio ranged from 0.60 to 3.75 mEq/L, with an average of 1.98 mg/L; in the post-monsoon season, it ranged from 1.15 to 3.90 mEq/L, with an average of 2.47 mg/L (Table 7). Table 8 shows that all samples were suitable for irrigation during the pre-monsoon and post-monsoon seasons. The classification indicates that in the study area, 12 samples fell within the S1C2 class, representing low sodium (alkali) hazard and medium salinity hazard during the pre-monsoon season (Figure 4). In addition, 13 samples were categorized in the S1C3 class, indicating low sodium (alkali) hazard and high salinity hazard. In the post-monsoon season, four samples again fell within the S1C2 class, while 21 samples were classified in the S1C3 class (Figure 5) [27].

Table 7. SAR of the groundwater of the study area (mEq/L)

SAR	Pre-monsoon Season	Post-monsoon Season
Minimum	0.60	1.15
Maximum	3.75	3.90
Average	1.98	2.47

Table 8. Groundwater quality of the study area on the basis of SAR

Category	Range	% of Pre-monsoon Season	% of Post-monsoon Season
Excellent	<10	100	100
Good	10-18	Nil	Nil
Doubtful	18-26	Nil	Nil
Unsuitable	>26	Nil	Nil

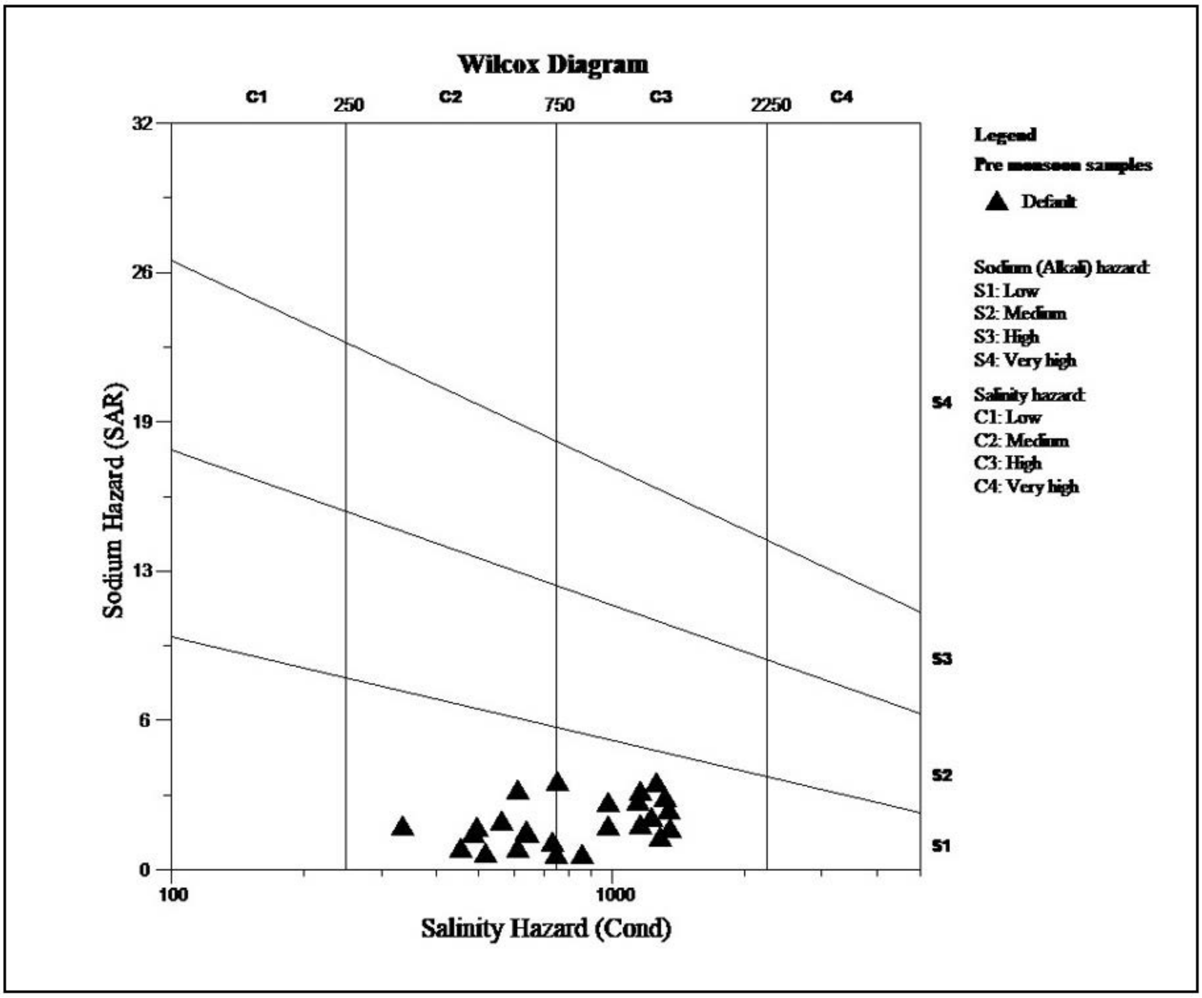

Figure 4. Wilcox diagram for the groundwater of Sudda Vagu basin in the pre-monsoon season

Too much precipitation or the breakdown of alkaline earth carbonates alters Ca^{2+} and Mg^{2+} concentrations, which in turn alters the SAR content of the soil. Carbonate deposition in groundwater occurs at a higher intensity. Groundwater with elevated $HCO_3{}^-$ levels and a partial pressure of CO_2 exists in equilibrium; however, upon extraction and exposure to the atmosphere, CO_2 is released, leading to the formation of calcium and magnesium carbonate deposits. Ca^{2+} and Mg^{2+} ions precipitate as carbonate during this process, and RSC can be calculated using the equation below. $\mathrm{mEq/L}$ was utilized to denote all concentrations.

$$\mathrm{RSC} = \left(\mathrm{CO}_3^{2-} + \mathrm{HCO}_3^{-}\right) + \left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right) \tag{2}$$

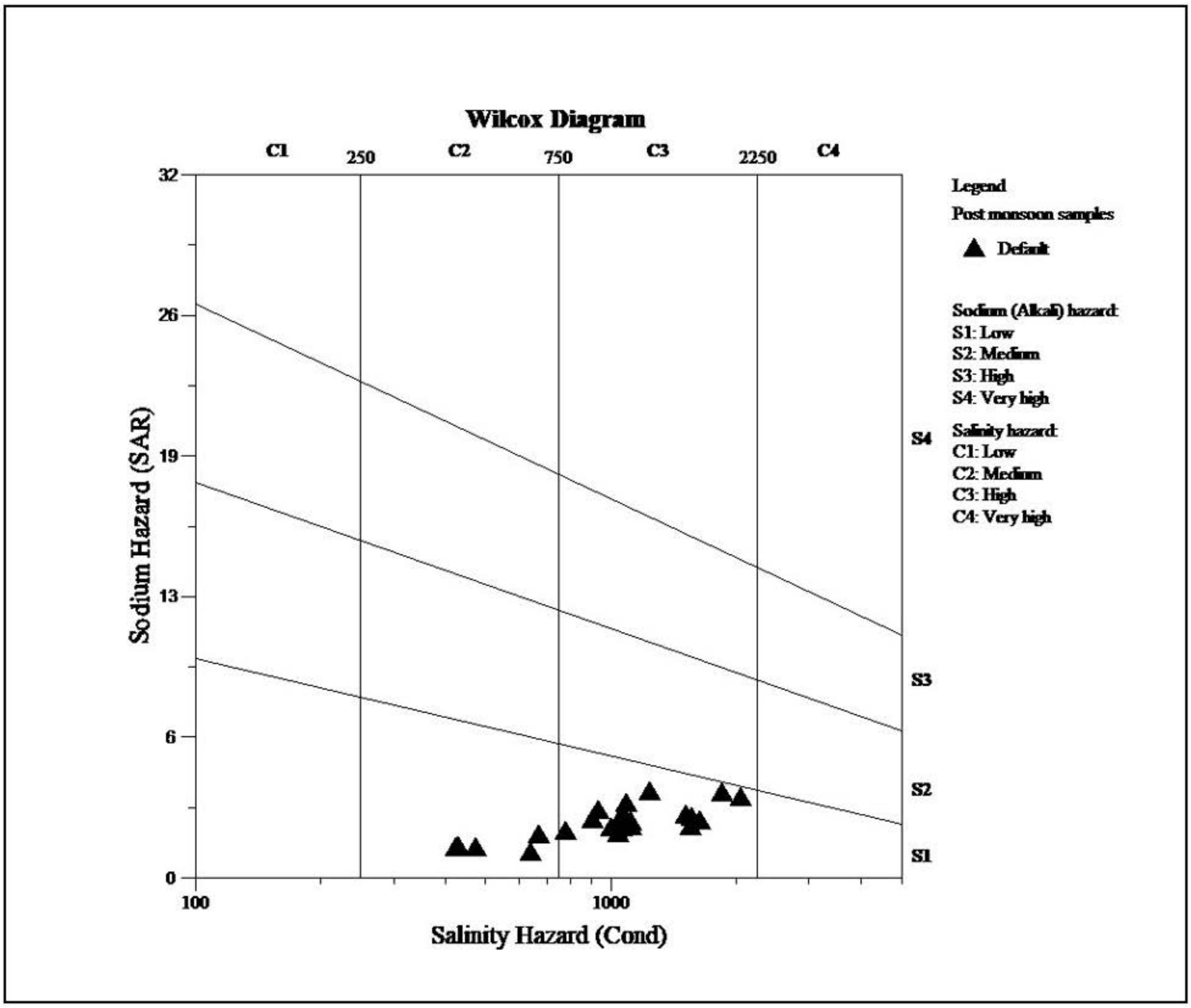

Figure 5. Wilcox diagram for the groundwater of Sudda Vagu basin in the post-monsoon season

Table 9 categorizes RSC as unsuitable if its value exceeds 2.50 $\mathrm{mEq/L}$, slightly suitable if it ranges from 1.25 to 2.50 $\mathrm{mEq/L}$, and marginally suitable if it is below 2.50 $\mathrm{mEq/L}$. The RSC values varied from -6.10 to 1.21 $\mathrm{mEq/L}$, yielding a mean of -2.27 $\mathrm{mEq/L}$, and from -8.30 to 2.60 $\mathrm{mEq/L}$, resulting in a mean of -0.46$\mathrm{mEq/L}$, during the pre- and post-monsoon seasons, respectively (Table 9). Table 10 indicates that all samples within the research area's RSC categorization levels were suitable for irrigation in both the pre- and post-monsoon seasons. Field studies examining the distribution of alkali white patches and soil penetrability offer substantial evidence for this phenomenon. Consequently, the application of high RSC waters affects crop productivity.

Table 9. RSC (mEq/L) in the investigated samples of the Sudda Vagu basin

RSC	Pre-monsoon Season	Post-monsoon Season
Minimum	-6.10	-8.30
Maximum	1.21	3.60
Average	-2.27	-0.46

Table 10. Classification of RSC (mEq/L)

Class	RSC Content	% of Pre-monsoon	% of Post-monsoon
Suitable	$<$1.25	96%	64%
Marginally suitable	1.25-2.5	4%	32%
Unsuitable	$>$2.5	Nil	4%

4.5 Limited Seasonal Exploration

By only comparing pre- and post-monsoon periods, the study may not capture the full range of natural variation in the environment throughout the entire year. Other seasonal factors (e.g., temperature fluctuations and dry season dynamics) could affect the study's outcomes but were not fully explored in analysis. Future research will aim to address this gap by incorporating data on extreme weather events and expanding the seasonal analysis to capture these impacts more comprehensively.

5 Water Quality Management

Managing water quality is associated with the broader concept of managing water resources for optimal and efficient human utilization. It is essential to manage and utilize water resources in a manner that safeguards their quality for current and future users. This is the basis of effective water management. The geography of the research area is characterized by undulations, with a southeast dip downstream, and it generally receives substantial rainfall. Implementing water management practices like rainwater harvesting can effectively reduce the concentrations of TDS, TH, Mg^{2+}, Cl^-, NO_3^-, and F^- for industrial, agricultural, and drinking purposes. The objective of rainwater harvesting is to gather runoff at suitable locations, taking into account the specific field conditions of topography, soil cover, drainage, geomorphology, geology, lineaments, and land use/cover. These factors facilitate the identification of appropriate locations to enhance groundwater conditions. Lowering the concentrations of F^- ions can improve water quality through processes such as water softening and defluoridation. Development of additional subsurface drainage conditions, deep farming techniques, reclamation, leaching, and the use of drip or sprinkler irrigation are significant agricultural practices that enhance soil texture and manage soil and water salinity, thereby facilitating more efficient irrigation. A campaign is necessary to inform the public about the negative effects of low water quality on industry, agriculture, and human health. Water quality management events are essential for achieving sustainable growth. To improve water quality, it is essential for policymakers, planners, and administrators to take responsibility for implementing suitable site-specific actions.

The importance of future water quality projections for informed decision-making in water management, policy development, and climate adaptation strategies is acknowledged. Their inclusion would enhance the strategic value of the study by providing long-term insights. While this study primarily focuses on current and short-term water quality data, future research will aim to incorporate long-term projections using climate models, land-use change scenarios, and pollution trends. By incorporating these projections, a more comprehensive understanding of potential water quality trends can be provided, offering valuable insights for future water management and policy decisions.

6 Conclusions

The mean pH values of groundwater in the Sudda Vagu basin, Bhainsa region of Nirmal District, Telangana, India, ranged from 8.01 during pre-monsoon seasons to 7.87 in post-monsoon seasons. BIS specifies that the pH of drinking water must range from 6.5 to 8.5. Groundwater samples exhibited alkaline characteristics, making them suitable for consumption according to findings from pre- and post-monsoon assessments. Groundwater facies, influenced by topographical and water flow-path conditions, exhibited $Ca^{2+} - HCO_3^-$, $Na^+ - Cl^-$, mixed $Ca^{2+} - Mg^{2+} - Cl^-$, mixed $Ca^{2+} - Na^+ - HCO_3^-$, $Na^+ - HCO_3^-$, and mixed $Ca^{2+} - Cl^-$ compositions. These variations resulted from geogenic factors (mineral dissolution, mineral solubility, ion exchange, and evaporation), anthropogenic influences (domestic wastes, septic tanks, chemical fertilizers, and irrigation return flows), and contributions from Vagu river sources (Vagu river clay). The hydrogeochemical signatures $\left(Na^+/Cl^- > 1\right.$ and $HCO_3^-/Cl^- < 1)$ and the sequential progression of genetic groundwater chemistry ($HCO_3{}^-$and $Cl^- - HCO_3{}^-$ types under a major group of $HCO_3{}^-$) indicate that the groundwater initially transitioned to a fresh quality before becoming saline due to anthropogenic influences and contributions from Vagu river sources. Statistical analysis supports the conclusions below. Concentrations of TDS, TH, Mg^{2+}, Cl^-, NO_3^-, and F^- in most locations surpassed recommended limits, rendering the groundwater unsuitable for drinking. In numerous locations, the salinity hazard was less significant than the sodium hazard, rendering the groundwater appropriate for irrigation based on RSC and KR. Groundwater quality in numerous locations was compromised, as indicated by concentrations of TDS, TH, Cl^-, and F^- exceeding permissible limits, leading to issues of incrustation and corrosion. Consequently, it is advisable to implement beneficial measures to enhance the inadequate water quality with the support of public and civic authorities.

Based on the findings of this study, several targeted measures are recommended to improve water quality in the region by addressing specific issues identified in the analysis with practical actions supported by public authorities and civic organizations. Upgrading wastewater treatment infrastructure is essential, as untreated wastewater in urban areas contributes to high contamination levels; this can be mitigated by enhancing existing facilities to meet stricter effluent standards, expanding plant capacity, and implementing advanced filtration technologies. To reduce nutrient pollution from agricultural runoff, particularly in rural areas, sustainable agricultural practices such as reduced pesticide use, crop rotation, and the establishment of vegetative buffer zones along watercourses are suggested. Public participation is vital for improving water quality, and launching comprehensive public awareness campaigns can educate local communities on water conservation and pollution prevention, with schools, local media, and community organizations serving as key partners. Additionally, establishing a robust water quality monitoring system through investments in real-time monitoring stations and strengthening data collection efforts will help identify pollution hotspots and enable timely interventions. These recommendations are not only grounded in the study's findings but are also feasible given the region's resources and infrastructure. With active involvement from local governments, Non-Governmental Organizations (NGOs), and community stakeholders, these actions can significantly improve water quality and ensure sustainable water resources for future generations.

Author Contribution

Conceptualization, T. Priyanka and B. Veeraiah; methodology, T. Priyanka and B. Veeraiah; validation, T. Priyanka, B. Veeraiah, and Linga Swamy Jogu; formal analysis, T. Priyanka; investigation, T. Priyanka; resources, B. Veeraiah; data curation, T. Priyanka; writing—original draft preparation, T. Priyanka and Linga Swamy Jogu; writing—review and editing, B. Veeraiah; visualization, supervision, B. Veeraiah; project administration, B. Veeraiah; assistance in research process, Naveen Kumar Gardas. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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