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HYDROGEOCHEMICAL CHARACTERIZATION AND SEASONAL SUITABILITY ASSESSMENT OF GROUNDWATER FOR AQUACULTURE IN PEDAVADLAPUDI, ANDHRA PRADESH, INDIA

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ABSTRACT
Groundwater plays a crucial role in sustaining rural livelihoods in the Pedavadlapudi village, Mangalagiri Mandal, Guntur District, Andhra Pradesh. In the present study, we evaluated the seasonal variations in groundwater quality and its suitability for drinking and aquaculture purposes. Groundwater samples were collected from three locations during the summer (May 2025), rainy (September 2025), and winter (January 2026) seasons. Physicochemical parameters, such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), alkalinity, total hardness, calcium, sodium, bicarbonate, ammonia, and copper, were analysed following the procedures outlined in the Bureau of Indian Standards (IS) 3025. The results were compared with drinking water standards prescribed by the Bureau of Indian Standards (IS) 10500 and World Health Organization guidelines.
The study revealed significant seasonal variations in terms of TDS, hardness, sodium, ammonia, and alkalinity. Although most samples exceeded the permissible limits for TDS and hardness, they were found to be moderately suitable for aquaculture owing to adequate alkalinity and acceptable pH levels. Elevated ammonia levels during the rainy season may indicate the possible effects of agricultural runoff. The study concludes that although groundwater in Pedavadlapudi is unsuitable for drinking without treatment, it can support aquaculture with appropriate management practices.

Keyword: Groundwater Quality, Seasonal Variation, Physico-chemical Parameters, Aquaculture Suitability, Drinking Water Standards

CHAPTER 1: INTRODUCTION

Groundwater is a critical natural resource that underpins domestic, agricultural, and aquaculture activities, particularly in rural regions of India. In locales where surface water resources are either limited or seasonal, groundwater is the principal source of water for drinking, irrigation, and sustaining livelihoods. Nevertheless, the quality of groundwater is dynamic and is significantly affected by seasonal variations, geological formations, and anthropogenic activities, including agricultural and aquaculture practices.
Seasonal fluctuations, particularly in monsoon-affected regions influenced by monsoons, play a pivotal role in modifying groundwater chemistry. During the rainy season, precipitation recharge often results in the dilution of certain ions while simultaneously introducing contaminants through surface runoff, such as fertilizers and organic waste. Conversely, the summer season is typically marked by elevated evaporation rates, leading to increased concentrations of dissolved solids and hardness in groundwater. These seasonal dynamics directly impact the suitability of groundwater for various applications, including drinking water and aquaculture.
Water quality assessment is generally based on physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), alkalinity, hardness, and the presence of specific ions such as calcium, sodium, bicarbonate, ammonia, and trace metals. These parameters provide essential insights into the hydrogeochemical processes that govern groundwater systems. Standard guidelines, such as those prescribed by the Bureau of Indian Standards (IS 10500) and the World Health Organization (WHO), are extensively used to evaluate the suitability of groundwater for drinking.
In recent years, concerns regarding groundwater quality degradation have intensified due to intensive agricultural practices, excessive application of chemical fertilizers, and improper waste disposal. These factors contribute to elevated levels of nutrients and dissolved solids, potentially rendering groundwater unsuitable for human consumption without adequate treatment. Nevertheless, certain water quality characteristics, such as moderate alkalinity and appropriate pH levels, may still support aquaculture activities, making groundwater a valuable resource for fish and shrimp farming when properly managed.

Pedavadlapudi village, situated in the Mangalagiri Mandal of Guntur District, Andhra Pradesh, is an agrarian region where groundwater is extensively utilized for both domestic and aquaculture purposes. Despite its significance, few studies have focused on the seasonal variability of groundwater quality in this region and its implications for various uses. Understanding these variations is essential for sustainable water resource management and ensuring safe utilization of water resources.

Therefore, this study aimed to evaluate the seasonal variations in groundwater quality at selected locations in Pedavadlapudi and assess its suitability for drinking and aquaculture applications. This study also sought to identify potential sources of contamination and provide recommendations for effective groundwater management practices.

1.1 Importance of Groundwater

Groundwater is a vital freshwater resource in India, especially in rural areas, where surface water availability is limited. In the Pedavadlapudi village of Andhra Pradesh, groundwater extracted through bore wells and hand pumps supports domestic consumption, irrigation, and aquaculture. Its perennial availability makes it a dependable resource for fish farming activities.

1.2 Drinking Water vs Aquaculture Water Requirements

Consuming water requires strict control of salinity, total dissolved solids (TDS), hardness, ammonia, and heavy metals to safeguard human health. According to the Bureau of Indian Standards (IS) 10500 and World Health Organization (WHO) guidelines,

a. TDS should be below 500 mg/L (desirable limit)

b. Hardness should not exceed 200 mg/L (desirable limit)

c. Ammonia should be minimal

In contrast, aquaculture systems can tolerate moderate hardness, alkalinity (100–300 mg/L), and mineral content, provided that toxic substances remain low. Hence, water unsuitable for drinking may sustain fish culture.

1.3 Groundwater Quality Issues in Rural Areas

Groundwater quality in rural areas is often affected by both natural and human-induced factors. Agricultural activities play a major role in groundwater deterioration, as excessive use of fertilizers, pesticides, and irrigation practices leads to the leaching of nutrients and chemicals into the subsurface. During the rainy season, agricultural runoff carries dissolved salts, nitrates, and ammonia into groundwater systems. In addition, leakage from septic tanks and improper sanitation facilities contributes organic matter, ammonia, and microbial contaminants to shallow aquifers.

Natural geological processes, such as soil mineral dissolution, further increase the concentration of dissolved ions, including calcium, magnesium, sodium, and bicarbonates, in groundwater. Transport corridors and small-scale industrial activities may also introduce pollutants through fuel leakage, oil spills, and surface contamination. Consequently, groundwater in rural regions commonly exhibits elevated levels of total dissolved solids (TDS), hardness, sodium, ammonia, and bicarbonates, which may reduce its suitability for drinking while still allowing potential use in aquaculture with appropriate management.

1.4 Study Area: Pedavadlapudi Village

Pedavadlapudi village is located in Mangalagiri Mandal, Guntur District, Andhra Pradesh. The area comprised agricultural lands, residential zones, transport corridors, and aquaculture ponds. Groundwater is extensively used for fish culture because of the limited number of surface water bodies.

1.5 Objectives:

a. To **analyse seasonal variations** in groundwater quality (summer, rainy, and winter seasons) in Pedavadlapudi.

b. To **assess the suitability of groundwater for drinking and aquaculture purposes** by comparing physicochemical parameters with standards prescribed by the Bureau of Indian Standards (IS 10500) and the World Health Organization.

c. To **identify possible sources of contamination and suggest sustainable groundwater management practices** for rural development and environmental sustainability.

1.6 Aim of the Study:

The primary aim of the study is to evaluate the seasonal variations in groundwater quality in Peddavadlapudi village and to assess its suitability for drinking and aquaculture purposes by comparing physicochemical parameters with the standards prescribed by the Bureau of Indian Standards (IS 10500) and the World Health Organization.

1.7 Scope of the Study

a. To examine the seasonal variations in groundwater quality in Peddavadlapudi during the summer, rainy, and winter seasons.

b. To evaluate the suitability of groundwater for drinking and aquaculture by comparing the results with standards prescribed by the Bureau of Indian Standards and the World Health Organization.

c. To provide baseline data and management recommendations for sustainable groundwater utilization in rural areas.

1.7 Literature Review:

A study on "Seasonal Variation of Groundwater Quality and Its Impact on Aquaculture at Pedavadlapudi, Guntur, India is being undertaken to encourage aquaculture farmers to support sustainable growth. This study evaluates the studies that are conducted in other places to compare and strengthen the present study.

A study was conducted on seasonal variation of groundwater quality of Taroda region in Nanded City by **S, Shillewar Vishal** in the year **2007.** The water quality test done to prove and strengthen the research study that the Physico-chemical parameters were found to be within the permissible limits in that area. The coliform bacteria were found to be more that the permissible limit. Consumption of such water may have the detrimental effects on human population. It is proposed to analyse the water samples to observe the growth of pathogenic bacteria in it. As the immediate precautionary measure, we recommended the water must be boiled before drinking or it must be chlorinated.

Ch. Maruthi Devi conducted the study on Assessment of ground water quality and its suitability for drinking and irrigation purposes of Prakasam district Andhra Pradesh, India 2013. In the study the analysis of pre and post monsoon data, and the average values obtained it has been inferred those certain parameters like Calcium, Magnesium, Total hardness, TDS have increased and remaining parameters like pH, Chlorides, Fluorides, Nitrates show decrease in concentration. The reason can be attributed to increase in concentration as a result of greater leaching and decrease in concentration as a result of dilution. The final output has been given in the spatial representation of groundwater quality in the study area of Prakasam District. The analysis indicates that the groundwater of the study area needs some degree of treatment before consumption. The study helps to understand the quality of water as well as to develop suitable management practices to protect the groundwater sources.

A study by **Sangeetha. S in 2018** analysed groundwater contamination by leachate near municipal waste dumps. Fresh water is crucial for all living beings, including humans, for food production, industry, and waste disposal purposes. Solid Waste Disposal is a major urban and industrial crisis worldwide. Industrialization, urbanization, and population growth have increased the amount of solid waste. In many cities, waste is dumped in open sites without proper lining, affecting the air, land, and water. Leachate pollutes groundwater, and waste incineration pollutes the air. Over the last century, groundwater contamination has increased due to human activities, leading to increased waterborne diseases and health hazards. Understanding the source, composition, reactions, and transport of water is essential. Water quality is vital for human health. Population growth depletes the water table along aquifers, and anthropogenic activities prevent the restoration of the original water quality. This study examined the impact of leachate migration on groundwater.

Lamma, Osama Asanousi Eshteiwi in 2018 conducted a study on Assessment of ground water quality in selected industrial areas of Guntur district A P India. The groundwater quality of Guntur District has a special significance and needs greater attention since it is the only major source for drinking, domestic and agricultural purposes. The known impacts of trace metals are in vogue in the area of Auton agar and an alternative supply of drinking water is being made by the 6 Government Authorities. Though the major use of ground water is for drinking but till date, no drinking water quality suitability study has been carried out in an organized manner. Hence, the main hypothesis of this study is a null hypothesis which can be put in the following form: The ground water in Guntur district, particularly in Industrial Development Area and other industrial areas is not polluted and is fit

In 2019, Jessy Mol studied "Assessment of seasonal variation in groundwater quality at coconut husk retting area Kanyakumari district." Groundwater quality management is challenging because monitoring pollutants is difficult and prone to errors. This study aimed to determine seasonal variations and model groundwater quality in Mondaikadu, Kanyakumari District. The physicochemical properties assessed groundwater quality and suitability for drinking. Parameters like TDS, EC, pH, Hardness, Mg, Ca, Mn, Na, K, HCO3, CO3, Cl, SO4, and NO3 were analyzed. Seasonal variations in quality were estimated for summer, winter, and the monsoon. The results showed higher concentrations in the monsoon, followed by winter, and the lowest in summer. Statistical analysis was performed to compare the results with the WHO and BIS standards. All parameters were within the limits, except for pH. Soda ash, sodium hydroxide, and aeration were used to neutralize pH, proving effective.

Vetri Selvi conducted research from 2017-2021 on groundwater quality in Mallipattinam's coastal area. This study highlights the need for regular monitoring of coastal regions, such as Mallipattinam, where aquaculture affects water resources. Despite these efforts, gaps remain in our understanding of hydrogeochemical interactions and the effectiveness of current methods in predicting salinity and contamination. Traditional methods may not capture variations in groundwater quality. This study used a novel approach that combined GIS, ion geochemistry, and machine learning, specifically ANNs, to assess groundwater quality. By analysing data from 15 locations, the relationship between electrical conductivity, chloride, sodium, magnesium, sulphate, and total examined, and the predictive accuracy of ANN models for sulphate, total dissolved solids, potassium, sodium, and chloride was evaluated. The findings show that 60% of the sampled water is non-potable, stressing the urgency of the situation. This study enhances the understanding of groundwater–saltwater interactions and demonstrates the potential of ANN models for improving coastal water quality monitoring.

Bushra (2024) characterized the water quality of some abandoned water bodies and their utilization for fish culture. Water is a vital resource for all living organisms on Earth, and its quality is critical for human health, aquatic ecosystems, and economic development. The chemical composition of water is influenced by a variety of factors, including natural geological processes, climate, and human activities. Water quality is determined by different physical, chemical, and biological parameters that can affect its suitability for different purposes, such as drinking, irrigation, and aquaculture.

In conclusion these topics collectively address groundwater quality assessment challenges, seasonal and spatial variations, the influence of human activities, and the application of both traditional and innovative methods for effective monitoring and management in diverse environmental contexts.

CHAPTER 2: MATERIALS AND METHODS

2.1 Sampling Locations

The following three locations were selected.

a. Pedavadlapudi Railway Gate Point
b. Pedavadlapudi Cultivation Land Point
c.Pedavadlapudi Railway Station Road

These patterns represent transport, agricultural, and residential land use.

2.2 Sample Collection

Samples were collected during the following periods.

- Summer – May 2025
- Rainy – September 2025
- Winter – January 2026

The hand pumps were flushed before sample collection. Clean, pre-rinsed polyethylene bottles were used.

2.3 Parameters Analysed

- pH
- EC
- TDS
- Turbidity
- Dissolved Oxygen
- Alkalinity
- Hardness
- Calcium

- Sodium
- Bicarbonate
- Ammonia
- Copper

2.4 Analytical Methods

Analysis was conducted following the Bureau of Indian Standards (IS) 3025 standard procedures using:

- Digital pH meter
- Conductivity meter
- Titrimetric methods
- Spectrophotometric analysis

2.5 Standards Used

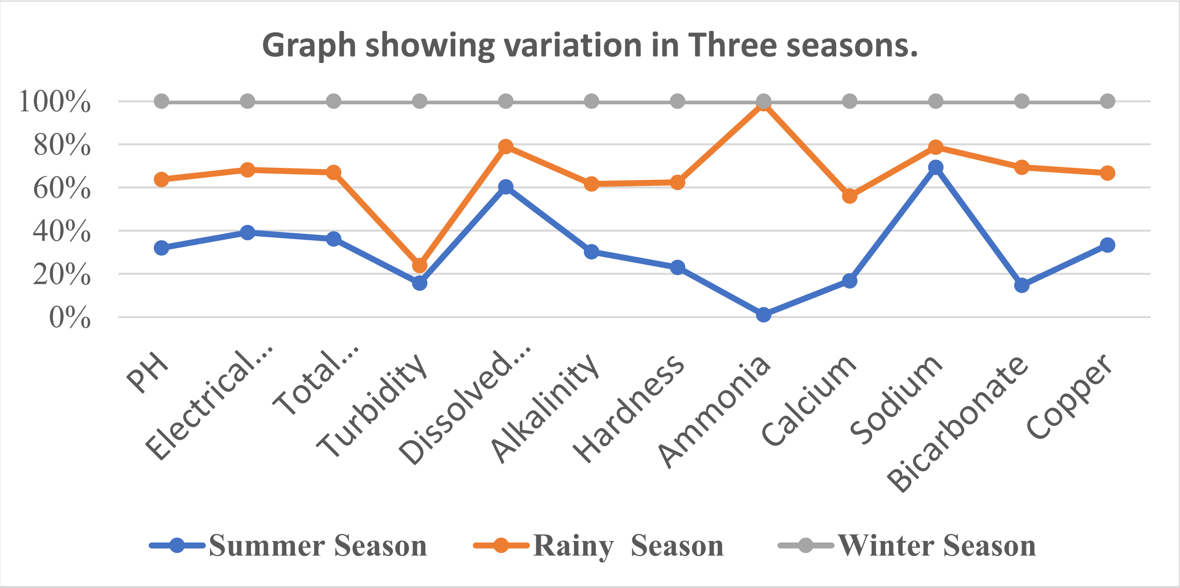
- Bureau of Indian Standards IS 10500 (Drinking water standards)
- World Health Organization Drinking Water Guidelines
- Aquaculture suitability criteria

CHAPTER 3: RESULTS

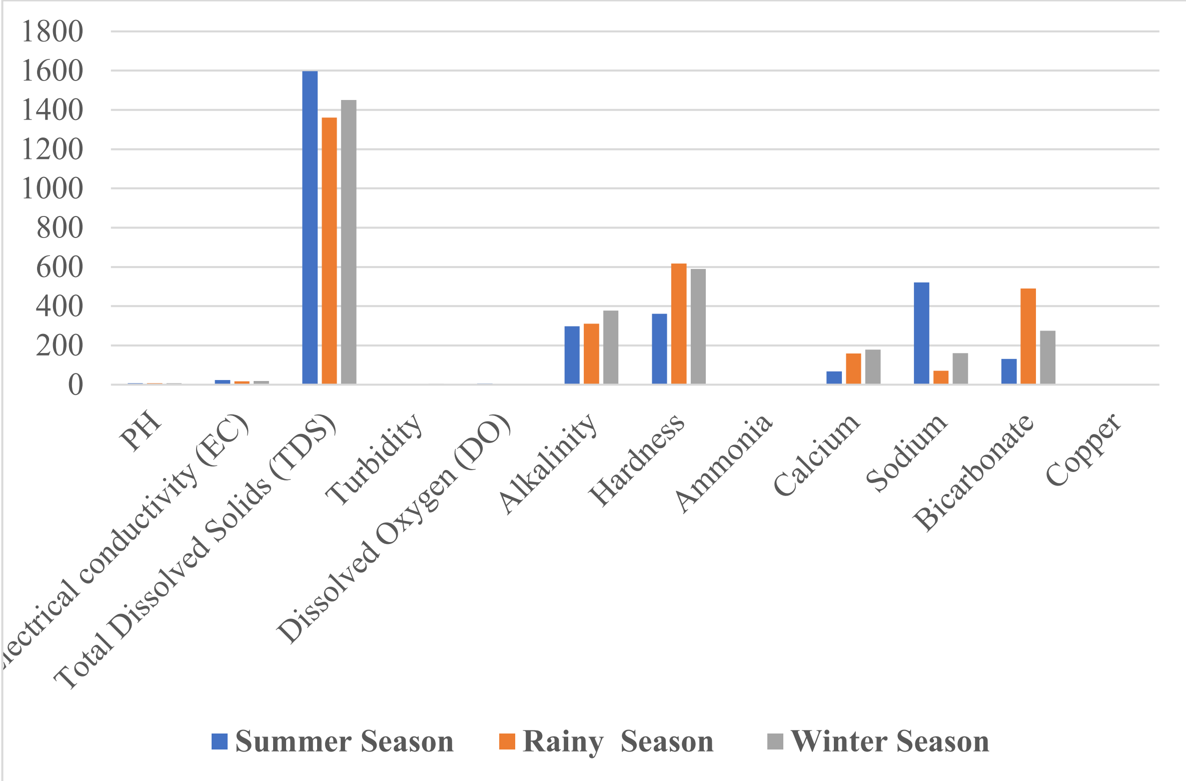
3.1 Seasonal Variation at Sampling Station 1

Sampling Station 1: Pedavadlapudi Railway Gate Point

S. No	Parameters	Summer Season	Rainy Season	Winter Season	Water Quality Standards	
					BIS 10500	WHO
1	P^H	7.19	7.1	8.12	6.5-8.5	6.5-8.5
2	Electrical conductivity (EC)	23.3	17.37	18.9	-	-
3	Total Dissolved Solids (TDS)	1597	1361	1451	500	500
4	Turbidity	0.77	0.40	3.71	1	5
5	Dissolved Oxygen (DO)	5.18	1.6	1.8	-	5
6	Alkalinity	298	310	378	200	-
7	Hardness	361.9	617.6	590	50-200	200
8	Ammonia	0.01	0.84	0.01	0.5	0.1-0.5
9	Calcium	68.3	159.3	178.3	75	-
10	Sodium	521.4	70.2	160	-	200
11	Bicarbonate	131.8	490	274	-	-
12	Copper	0.01	0.01	0.01	0.05	2



Graph showing variation in parameters of groundwater:



Groundwater quality at sampling station 1 showed noticeable seasonal variations in several physicochemical parameters. The pH ranged from 7.1 to 8.12, indicating neutral to slightly alkaline conditions throughout the year, which are generally suitable for aquaculture. Electrical conductivity (EC) values were relatively higher in summer (23.3) than in the rainy (17.37) and winter (18.9) seasons, suggesting increased ionic concentration due to evaporation during summer.

Total dissolved solids (TDS) were high in all seasons, with the maximum recorded during summer (1597 mg/L), followed by winter (1451 mg/L) and the rainy season (1361 mg/L). These values indicate high mineralization, rendering the water unsuitable for drinking without treatment. Turbidity remained low during the summer and rainy seasons but significantly increased in winter (3.71 NTU), possibly due to suspended particles or disturbances in groundwater recharge.

Dissolved oxygen (DO) levels showed a marked seasonal decline from 5.18 mg/L in summer to 1.6 mg/L during the rainy season and 1.8 mg/L in the winter, indicating reduced oxygen availability during the monsoon and post-monsoon periods. Alkalinity increased from 298 mg/L in summer to 378 mg/L in winter, which is beneficial for buffering capacity in aquaculture systems.

Total hardness exhibited a sharp increase during the rainy (617.6 mg/L) and winter (590 mg/L) seasons compared to summer (361.9 mg/L), suggesting leaching of calcium and magnesium from the soil during monsoon recharge. Ammonia concentration was significantly elevated during the rainy season (0.84 mg/L), indicating the influence of agricultural runoff. Sodium levels were extremely high in summer (521.4 mg/L) and decreased considerably during the rainy and winter seasons, possibly due to dilution effects. Bicarbonate peaked during the rainy season (490 mg/L), reflecting enhanced dissolution of carbonate minerals. Copper remained constant (0.01 mg/L) across all seasons, indicating no heavy metal contamination.

Overall, Station 1 exhibited a strong seasonal influence, particularly with respect to TDS, hardness, sodium, and ammonia.

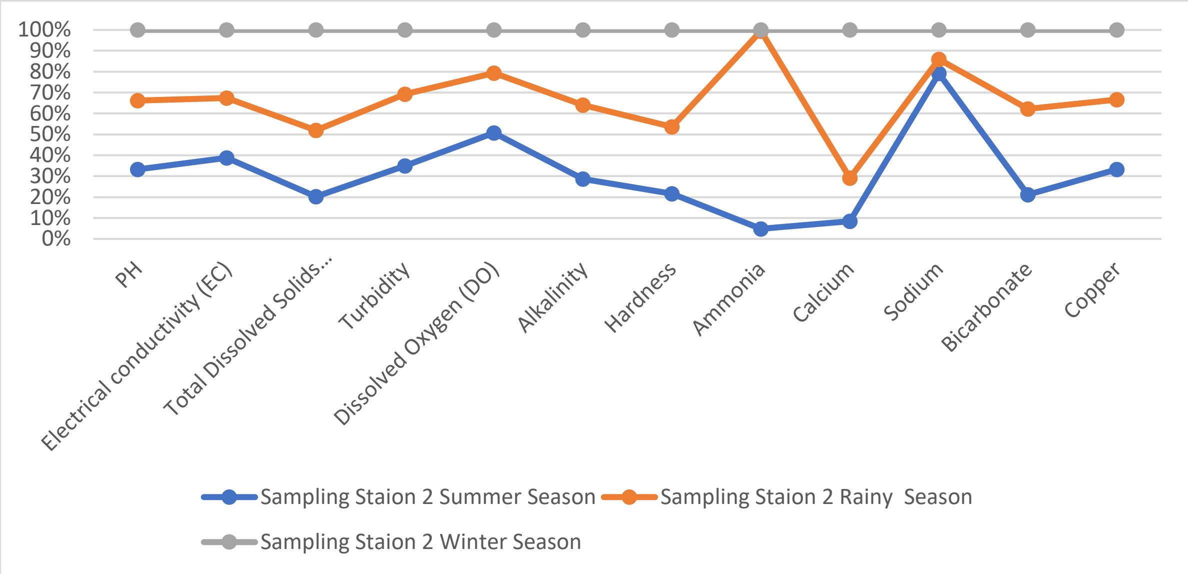
3.2 Seasonal Variation at Sampling Station 2

Sampling Station 2: Pedavadlapudi Cultivation Land Point

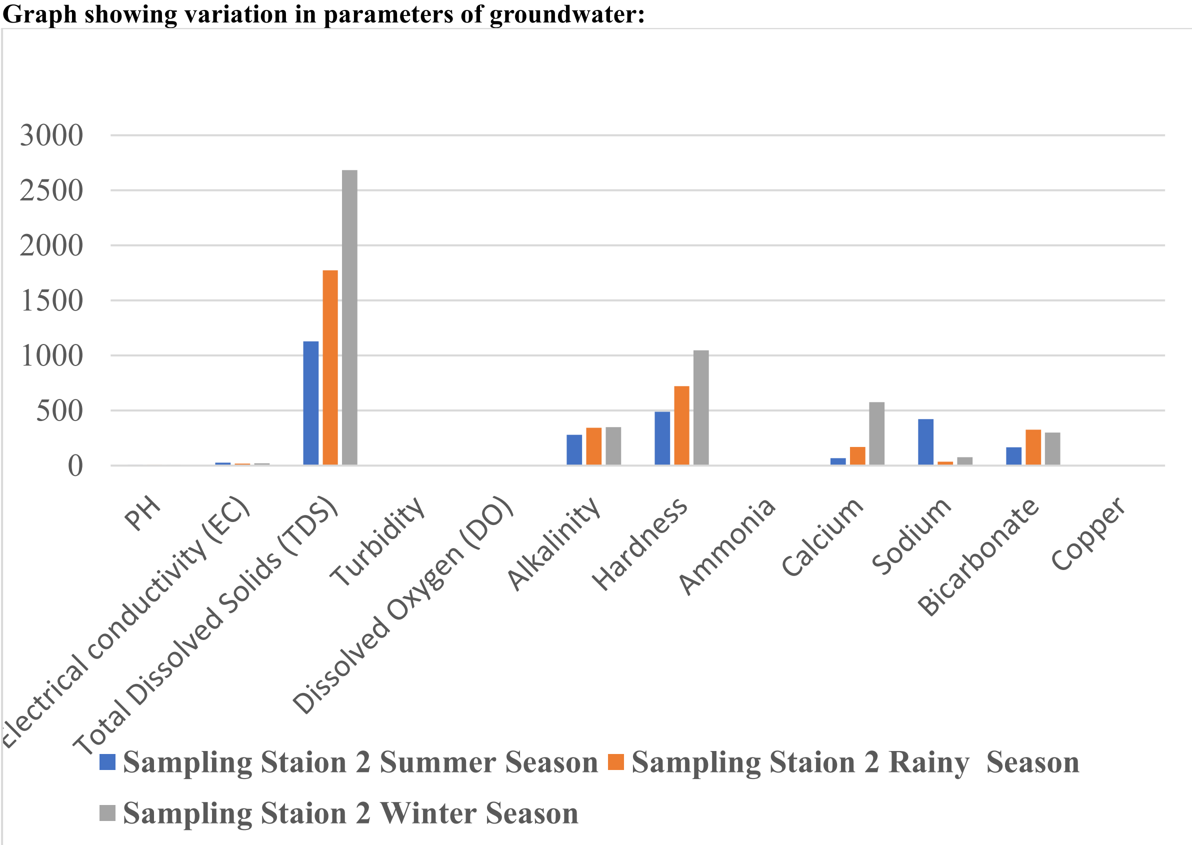
S. No	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**	**Water Quality Standards**	
					BIS 10500	**WHO**
1	P^H	7.15	7.1	7.29	6.5-8.5	6.5-8.5
2	Electrical conductivity (EC)	26.4	19.47	22.17	-	-
3	Total Dissolved Solids (TDS)	1128	1774	2684	500	500
4	Turbidity	0.50	0.49	0.44	1	5
5	Dissolved Oxygen (DO)	3.55	2.01	1.44	-	5
6	Alkalinity	280	345	350	200	-
7	Hardness	488.2	721.8	1046	50-200	200

8	Ammonia	0.086	1.68	0.01	0.5	0.1-0.5
9	Calcium	68.8	168.6	577	75	-
10	Sodium	421.5	36.2	75	-	200
11	Bicarbonate	167.2	325	299	-	-
12	Copper	0.01	0.01	0.01	0.05	2

Graph Sowing variation in sampling station:



Graph showing variation in parameters of groundwater:



Graph Showing variation of parameters in three seasons:

Sampling Station 2 recorded the most significant seasonal fluctuations among the three stations, likely because of its proximity to agricultural lands. The pH remained stable between 7.1 and 7.29, indicating neutral conditions suitable for aquaculture. EC values were highest in summer (26.4) and lower during the rainy and winter seasons, reflecting the concentration during dry periods.

TDS showed a progressive increase from summer (1128 mg/L) to rainy (1774 mg/L), reaching a maximum in winter (2684 mg/L). This indicates substantial mineral accumulation and possible fertilizer leaching. Turbidity remained consistently low across all seasons.

Low DO levels (3.55 mg/L) during summer and high DO levels (1.44 mg/L) during winter suggest oxygen depletion during colder months. High alkalinity (280 mg/L) during summer and around 350 mg/L during the rainy and winter seasons support the buffering capacity for fish culture.

High hardness, especially in winter (1046 mg/L), indicated strong mineral dissolution and groundwater recharge effects. Ammonia showed a sharp spike during the rainy season (1.68 mg/L), the highest among all stations, clearly reflecting the impact of agricultural runoff. Calcium also increased dramatically in winter (577 mg/L), contributing to high hardness.

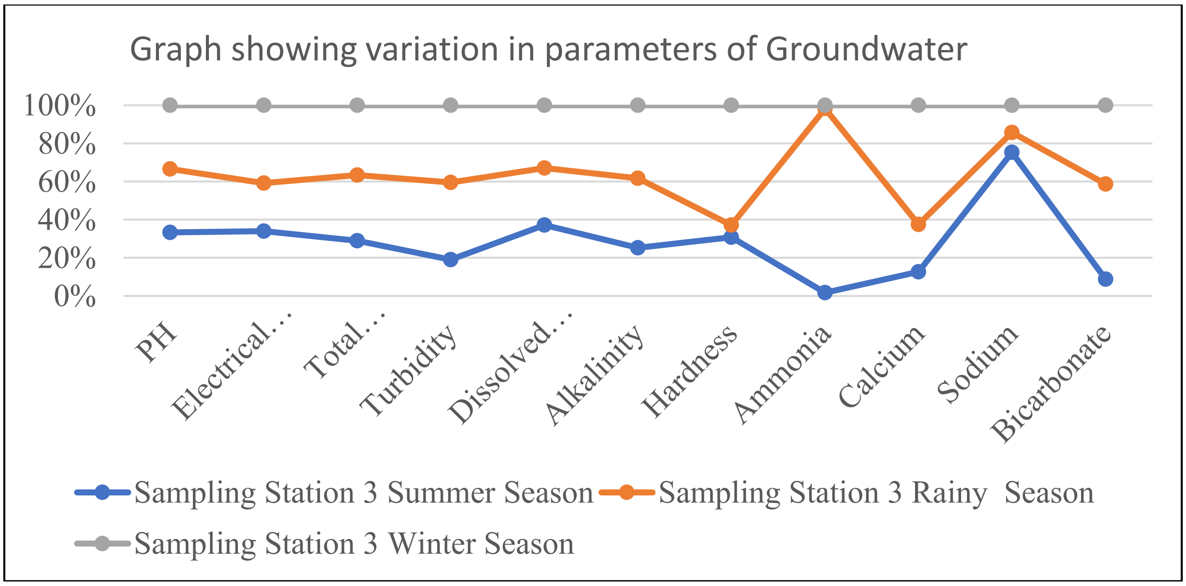
During summer, sodium levels were very high (421.5 mg/L) and decreased during the rainy and winter seasons. Bicarbonate concentrations increased during the rainy season (325 mg/L) and remained moderately high during winter. Copper levels remained constant and within safe limits.

At Station 2, agricultural activities significantly affect groundwater chemistry, particularly during the rainy and winter seasons.

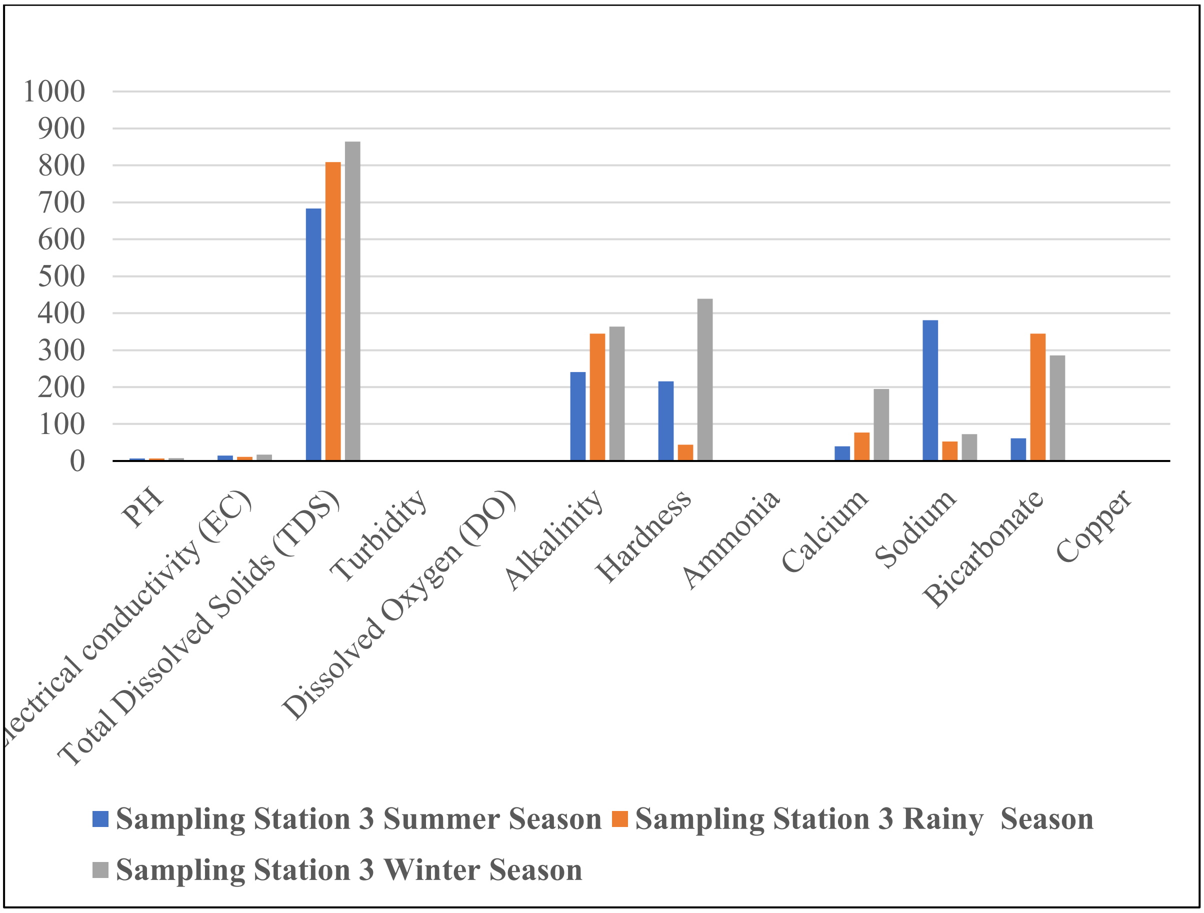
3.3 Seasonal Variation at Sampling Station 3 (Railway Station Road)

Sampling Station 3: Pedavadlapudi Railway Station Road

S. No	Parameters	Summer Season	Rainy Season	Winter Season	Water Quality Standards	
					BIS 10500	WHO
1	P^H	7.30	7.3	7.31	6.5-8.5	6.5-8.5
2	Electrical conductivity (EC)	14.70	10.89	17.6	-	-
3	Total Dissolved Solids (TDS)	683	809	864	500	500
4	Turbidity	0.15	0.32	0.32	1	5
5	Dissolved Oxygen (DO)	2.50	2.0	2.21	-	5
6	Alkalinity	240.5	345	364	200	-
7	Hardness	215.28	44.04	439.21	50-200	200
8	Ammonia	0.01	0.56	0.01	0.5	0.1-0.5
9	Calcium	39.6	77.3	194.5	75	-
10	Sodium	381.3	52.66	72.6	-	200
11	Bicarbonate	61.2	345	286	-	-
12	Copper	0.01	0.01	0.01	0.05	2



Graph showing variation in parameters of groundwater:



Sampling Station 3 recorded comparatively better water quality than Stations 1 and 2. The pH remained constant at 7.3 across all seasons, indicating stable neutral conditions. EC values were the lowest among the three stations, ranging from 10.8 to 17.6, suggesting lower ionic concentrations.

TDS ranged between 683 and 864 mg/L, which is lower than that at other stations but still above the desirable drinking-water limits during some seasons. Turbidity remained very low throughout the year, indicating clear water.

DO levels were moderate but slightly low (2–2.5 mg/L), showing minor seasonal variations. Alkalinity increased from 240.5 mg/L in summer to 364 mg/L in winter, reflecting seasonal recharge effects.

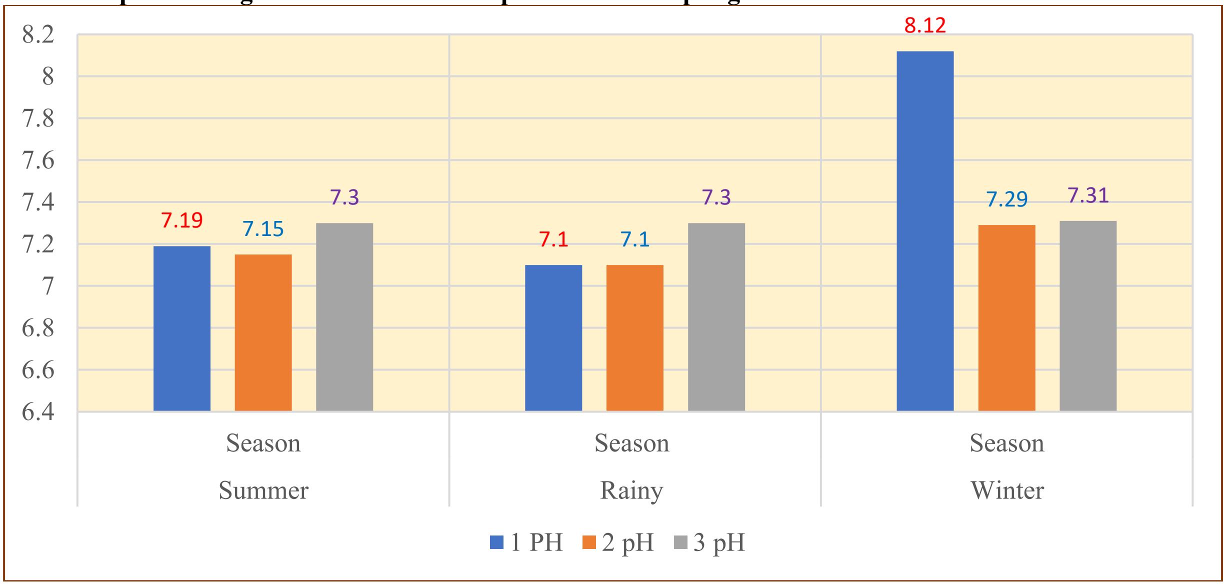
Hardness increased from 215.2 mg/L in summer to approximately 440 mg/L in the rainy and winter seasons, indicating moderate mineralization. Ammonia levels were elevated during the rainy season (0.56 mg/L), although lower than those at Station 2, suggesting a mild agricultural influence. Sodium levels were high in summer (381.3 mg/L) and decreased during other seasons. Bicarbonate levels increased sharply during the rainy season (345 mg/L). Copper levels remained constant and within safe limits.

Overall, Station 3 exhibited relatively moderate seasonal variations and comparatively better groundwater quality.

3.4: pH Analysis of Groundwater in three sampling stations (Seasonal Variation):

Sampling Stations	Parameters	Summer Season	Rainy Season	Winter Season
1	P^H	7.19	7.1	8.12
2	pH	7.15	7.1	7.29
3	pH	7.3	7.3	7.31

3.4.1: Graph Showing seasonal variation of pH in three sampling stations:



Introduction: The pH of groundwater serves as a crucial indicator of its chemical quality, affecting nutrient availability, biological activity, and suitability for aquaculture and domestic use. This study examined the pH values of groundwater from three sampling stations in Pedavadlapudi across the summer, rainy, and winter seasons. The findings showed that groundwater at all locations maintained a neutral to slightly alkaline range throughout the study period.

At sampling station 1 (Pedavadlapudi Railway Gate Point), pH values were 7.19 during summer, 7.1 during the rainy season, and 8.12 in winter. The decrease during the rainy season may be attributed to dilution from monsoon recharge, in which infiltrating rainwater reduces alkalinity. The increase in winter suggests reduced dilution and concentration of alkaline ions, such as bicarbonates and carbonates. The higher winter pH indicates enhanced mineral dissolution and limited groundwater recharge.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), pH values showed minor variations, with 7.15 in summer, 7.1 in the rainy season, and 7.29 in winter. Values remained consistently neutral, indicating stable hydro chemical conditions. The slight alkalinity during winter could be linked to agricultural runoff containing fertilizers and soil minerals, contributing to buffering capacity. The minimal variations suggest controlled anthropogenic influences at this site.

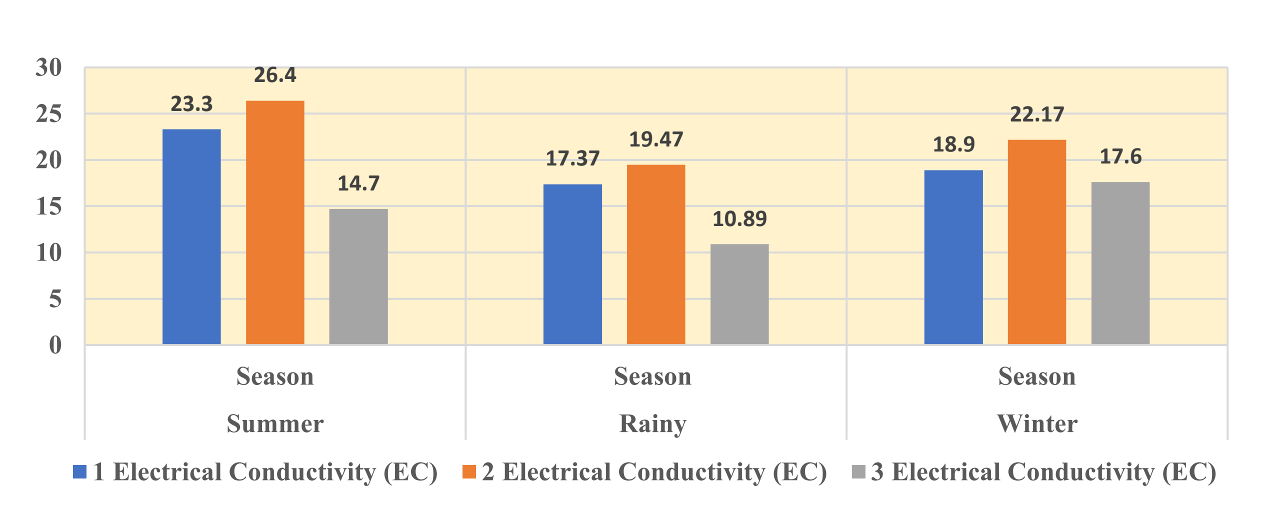
At sampling station 3 (Pedavadlapudi Railway Station Road), pH values were 7.3 in summer, 7.3 during the rainy season, and 7.31 in winter, showing minimal seasonal fluctuations. This stability indicates a well-buffered groundwater system controlled by consistent geological formations. The constant pH suggests that aquifer chemistry is not significantly affected by seasonal recharge or surface activities. The pH values across stations ranged from 7.1 to 8.12, indicating neutral to slightly alkaline conditions suitable for aquaculture and domestic purposes.

Seasonal trends showed decreased pH during the rainy season and increased pH in winter due to reduced recharge and mineral interactions. All values fell within the acceptable limits of water quality guidelines, suggesting chemically stable groundwater. The variations highlight the influence of natural processes, such as rainfall infiltration, mineral dissolution, and seasonal evaporation, with minor anthropogenic inputs. The groundwater maintained a favourable pH range, indicating good buffering capacity of the aquifer system.

3.5: Electrical Conductivity (EC) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Stations	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Electrical Conductivity (EC)	23.3	17.37	18.9
2	Electrical Conductivity (EC)	26.4	19.47	22.17
3	Electrical Conductivity (EC)	14.7	10.89	17.6

3.5.1: Graph Showing seasonal variation of EC in three sampling stations:



Electrical conductivity (EC) is a crucial parameter for evaluating the ionic concentration and mineralization of groundwater. It reflects the presence of dissolved salts, including chlorides, sulphates, bicarbonates, and other inorganic ions, thereby indicating the suitability of water for consumption and aquaculture. This study examined EC values at three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons, highlighting seasonal variations influenced by hydrogeochemical and environmental factors. At sampling station 1 (Pedavadlapudi Railway Gate Point), EC values were 23.3, 17.37, and 18.9 in summer, the rainy season, and winter, respectively. The elevated EC value in summer can be attributed to increased evaporation, which concentrates dissolved salts. During the rainy season, EC decreased due to dilution from monsoon recharge. In winter, EC exhibited a moderate increase, suggesting reduced dilution and gradual ion accumulation.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), EC values were higher than those at other stations, with 26.4, 19.47, and 22.17 in summer, the rainy season, and winter, respectively. The elevated EC levels may be linked to agricultural activities, in which fertilizers contribute additional dissolved ions. Similar to that at station 1, EC decreased during the rainy season due to dilution, followed by an increase in winter as recharge diminished. Higher EC values indicate stronger anthropogenic inputs.

At sampling station 3 (Pedavadlapudi Railway Station Road), EC values were lower, at 14.7, 10.89, and 17.6 in summer, the rainy season, and winter, respectively. The lower EC values suggest reduced mineralization and limited contamination. The seasonal trend remained consistent, showing a decline during the rainy season and an increase in winter. The lower EC values indicate better groundwater quality at this location.

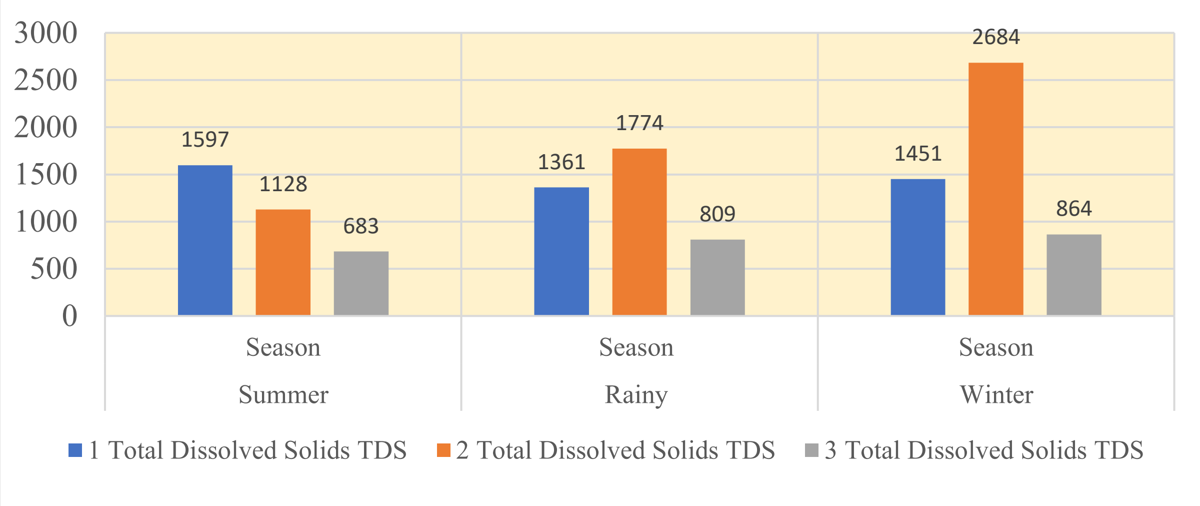
The EC values across all stations followed a clear seasonal pattern: highest in summer, lowest during the rainy season, and increasing in winter. This trend demonstrates the influence of evaporation, monsoon recharge, and land use activities on groundwater chemistry. Higher EC values at the cultivation point emphasize the role of agricultural runoff, while lower values at the roadside station indicate minimal anthropogenic impact.

In conclusion, EC variation reflects the dynamic nature of groundwater systems. Although seasonal fluctuations exist, EC levels remain within a manageable range, suggesting moderately mineralized groundwater suitable for aquaculture and other uses, with caution needed in agricultural areas.

3.6: Total Dissolved Solids (TDS) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Stations	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Total Dissolved Solids TDS	1597	1361	1451
2	Total Dissolved Solids TDS	1128	1774	2684
3	Total Dissolved Solids TDS	683	809	864

3.6.1: Graph Showing seasonal variation of TDS in three sampling stations:



Total dissolved solids (TDS) denote the concentration of dissolved inorganic and organic substances in groundwater, including minerals, salts, and ions, such as calcium, magnesium, sodium, chlorides, and sulphates. TDS is crucial for assessing water quality, as high levels affect taste, potability, and aquaculture suitability. In this study, TDS values were measured at three sampling stations in Pedavadlapudi across the summer, rainy, and winter seasons, revealing significant spatial and seasonal variations.

At sampling station 1 (Pedavadlapudi Railway Gate Point), TDS values were 1597 mg/L in summer, 1361 mg/L during the rainy season, and 1451 mg/L in winter. The highest value in summer indicates increased dissolved solids from evaporation and reduced groundwater recharge. During the rainy season, TDS decreases due to dilution by monsoon rainfall. In winter, TDS slightly increases, reflecting reduced dilution and interaction with mineral-rich formations. Values remained consistently high, indicating moderate to high mineralization.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), TDS values were 1128 mg/L in summer, 1774 mg/L in the rainy season, and 2684 mg/L in winter, showing an increasing trend. Unlike other stations, TDS was lowest in summer and increased during the rainy and winter seasons. This pattern suggests anthropogenic effects from agricultural activities. Rainy-season runoff from cultivated lands introduces fertilizers, pesticides, and dissolved salts into groundwater, increasing TDS. The winter rise indicates the accumulation of these substances in the aquifer. The high TDS value in winter (2684 mg/L) indicates poor water quality and high salinity.

At sampling station 3 on Pedavadlapudi Railway Station Road, total dissolved solids (TDS) values were lower, measuring 683 mg/L in summer, 809 mg/L during the rainy season, and 864 mg/L in winter. This increase from summer to winter suggests a steady accumulation of dissolved solids due to limited flushing and mineral dissolution. These values remained lower than those at other stations, indicating better groundwater quality and minimal contamination. The TDS values across the study area ranged from 683 to 2684 mg/L, reflecting moderate to high groundwater mineralization.

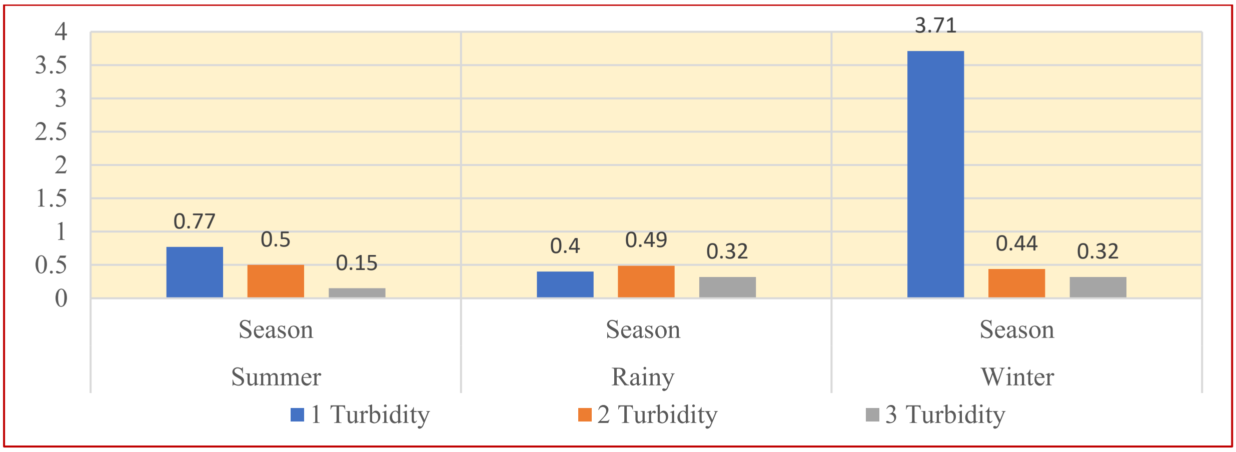
The seasonal trend varied: stations 1 and 3 showed a decrease during the rainy season due to dilution, while station 2 showed a significant increase from agricultural runoff. High TDS levels, particularly at cultivation land points, indicate that groundwater quality is influenced by geological processes and anthropogenic activities.

In conclusion, TDS analysis shows that groundwater in the study area has considerable seasonal fluctuations and localized contamination. While some locations maintain acceptable levels, others exceed recommended limits, making water less suitable for drinking and potentially harmful for aquaculture species. Proper management, including controlled fertilizer use and monitoring, is essential to maintain groundwater quality and ensure sustainable use.

3.7: Turbidity Analysis of Groundwater Samples (Seasonal Variation):

Sampling Stations	Parameters	Summer Season	Rainy Season	Winter Season
1	Turbidity	0.77	0.4	3.71
2	Turbidity	0.5	0.49	0.44
3	Turbidity	0.15	0.32	0.32

3.7.1: Graph Showing seasonal variation of Turbidity in three sampling stations:



Turbidity is a physical parameter that indicates the presence of suspended particles, such as silt, clay, organic matter, and microorganisms, in water. It affects water clarity and light penetration, which are significant factors in aquaculture systems. In groundwater, turbidity is generally low due to natural filtration; however, it may vary due to seasonal recharge, surface runoff, and anthropogenic activities. This study analysed turbidity levels at three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons.

At sampling station 1 (Pedavadlapudi Railway Gate Point), turbidity values were 0.77, 0.4, and 3.71 NTU during summer, the rainy season, and winter, respectively. The low turbidity during the summer and rainy seasons indicates clear groundwater with minimal suspended particles. However, a sharp increase in winter may be attributed to sediment disturbance, reduced water levels, or mixing of surface contaminants. The higher winter turbidity suggests suspended solids that could affect water quality if untreated.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), turbidity values were 0.5, 0.49, and 0.44 NTU during summer, the rainy season, and winter, respectively. These values show minimal seasonal variation and remain consistently low. The stable turbidity indicates effective natural filtration and minimal disturbance from agricultural runoff, suggesting well-controlled suspended particulate matter despite farming activities.

At sampling station 3 (Pedavadlapudi Railway Station Road), turbidity values were 0.15, 0.32, and 0.32 NTU during summer, the rainy season, and winter, respectively. These are the lowest values among all stations, indicating very clear groundwater. The slight increase during the rainy and winter seasons may be due to minor surface runoff infiltration, but turbidity remains within acceptable limits. Turbidity values across all sampling stations ranged from 0.15 to 3.71 NTU, indicating generally low turbidity and good groundwater clarity.

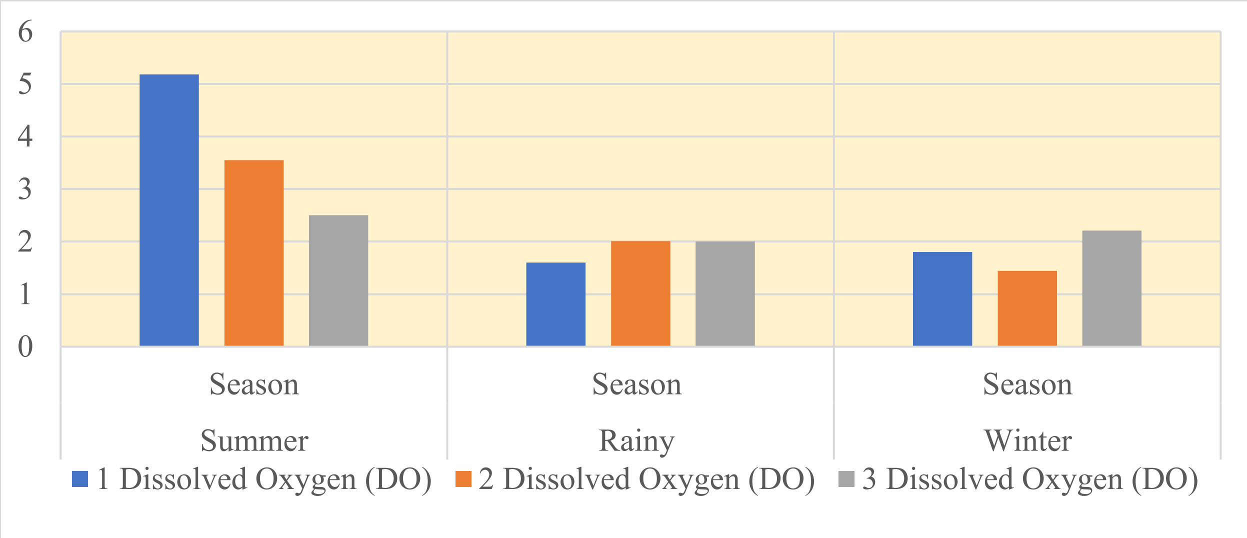
The seasonal pattern shows minimal variation, except at station 1, where winter increases suggest localized influences. The observed levels are within permissible limits for drinking water and aquaculture, indicating groundwater mostly free from excessive suspended matter. Variations can be attributed to seasonal recharge, sediment disturbance, and minor anthropogenic activities.

In conclusion, the turbidity analysis shows that Pedavadlapudi groundwater is generally clear and suitable for use, with occasional localized increases that require monitoring. Regular assessment is recommended to maintain groundwater clarity and quality in the study area.

3.8: Dissolved Oxygen (DO) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Stations	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Dissolved Oxygen (DO)	5.18	1.6	1.8
2	Dissolved Oxygen (DO)	3.55	2.01	1.44
3	Dissolved Oxygen (DO)	2.5	2	2.21

3.8.1: Graph Showing seasonal variation of DO in three sampling stations:



Dissolved oxygen (DO) indicates oxygen availability in water for biological processes. It influences the suitability of water for aquatic life and aquaculture. In groundwater systems, DO levels are lower than those in surface water due to limited atmospheric oxygen contact. Seasonal variations, recharge processes, organic matter decomposition, and anthropogenic influences affect DO concentrations. This study analysed DO levels at three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons.

At sampling station 1 (Pedavadlapudi Railway Gate Point), DO values were 5.18 mg/L in summer, 1.6 mg/L during the rainy season, and 1.8 mg/L in winter. The high DO level in summer suggests enhanced aeration or mixing with oxygen-rich sources. A sharp decline during the rainy season indicates the inflow of organic matter and microbial decomposition consuming oxygen. The slight improvement in winter may be due to reduced biological activity and stabilization of groundwater conditions, although levels remain low compared to those in summer.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), DO values were 3.55 mg/L in summer, 2.01 mg/L during the rainy season, and 1.44 mg/L in winter. Moderate DO levels in summer indicate limited oxygen availability, possibly from agricultural activities. The decline from the rainy to winter seasons suggests increased oxygen consumption from the decomposition of organic residues and reduced replenishment. The lowest DO in winter may be associated with stagnant conditions and higher microbial activity.

At sampling station 3 (Pedavadlapudi Railway Station Road), DO values were 2.5 mg/L in summer, 2.0 mg/L during the rainy season, and 2.21 mg/L in winter. These values show stable DO concentrations across seasons, indicating a balanced groundwater system with limited external disturbances. The increase in winter may be due to reduced temperatures enhancing oxygen solubility and lower biological oxygen demand. DO values across stations ranged from 1.44 to 5.18 mg/L, indicating low to moderate oxygen availability.

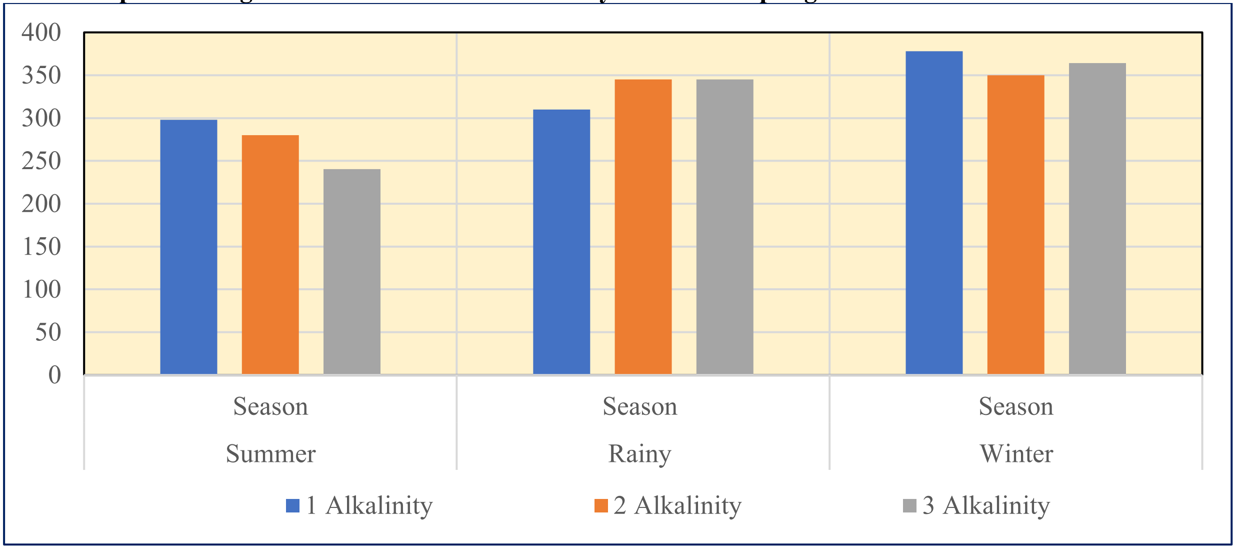
The seasonal trend shows higher DO in summer and lower values during the rainy and winter seasons, due to increased organic load, microbial activity, and reduced oxygen diffusion. The low DO levels at stations 1 and 2 during the rainy and winter seasons may not be suitable for certain aquaculture practices, as adequate oxygen is essential for aquatic organisms. These conditions may require aeration before use in aquaculture systems.

DO analysis shows the influence of seasonal recharge, organic matter decomposition, agricultural activities, and subsurface conditions on groundwater oxygen availability. Continuous monitoring and management strategies are recommended to maintain adequate DO levels, particularly where groundwater is used for aquaculture.

3.9: Alkalinity Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Alkalinity	298	310	378
2	Alkalinity	280	345	350
3	Alkalinity	240.5	345	364

3.9.1: Graph Showing seasonal variation of Alkalinity in three sampling stations:



Alkalinity reflects water's capacity to neutralize acids, primarily from bicarbonates, carbonates, and hydroxides. It maintains pH stability and supports buffering capacity and biological productivity. This study analyzed the alkalinity levels of groundwater samples from three locations in Pedavadlapudi across the summer, rainy, and winter seasons, revealing seasonal and spatial variations.

At sampling station 1 (Pedavadlapudi Railway Gate Point), alkalinity values were 298 mg/L in summer, 310 mg/L during the rainy season, and 378 mg/L in winter. The increase from summer to winter indicates enhanced accumulation of bicarbonates and carbonates. Lower summer values may be due to dilution from limited groundwater recharge, whereas increases during the rainy and winter seasons suggest increased leaching of soil minerals. High winter alkalinity reflects concentration effects from reduced dilution and evaporation.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), alkalinity values were 280 mg/L in summer, 345 mg/L during the rainy season, and 350 mg/L in winter. The rainy season increase may be due to the infiltration of agricultural runoff carrying dissolved salts into the groundwater. The winter increase indicates continued mineral dissolution and reduced recharge. Higher alkalinity values at this station suggest the influence of agricultural practices and soil chemistry.

At sampling station 3 on Pedavadlapudi Railway Station Road, alkalinity measurements were 240.5, 345, and 364 mg/L in the summer, rainy, and winter seasons, respectively. This station recorded an increase in alkalinity from the summer to the rainy season, similar to station 2, indicating the influence of monsoon recharge in mobilizing dissolved ions. The increase in winter suggests the accumulation of alkaline substances due to reduced flushing and geochemical interactions. The lower summer value and subsequent increase suggest seasonal enrichment. Alkalinity values across the study area ranged from 240.5 to 378 mg/L, indicating moderate to high alkalinity in groundwater.

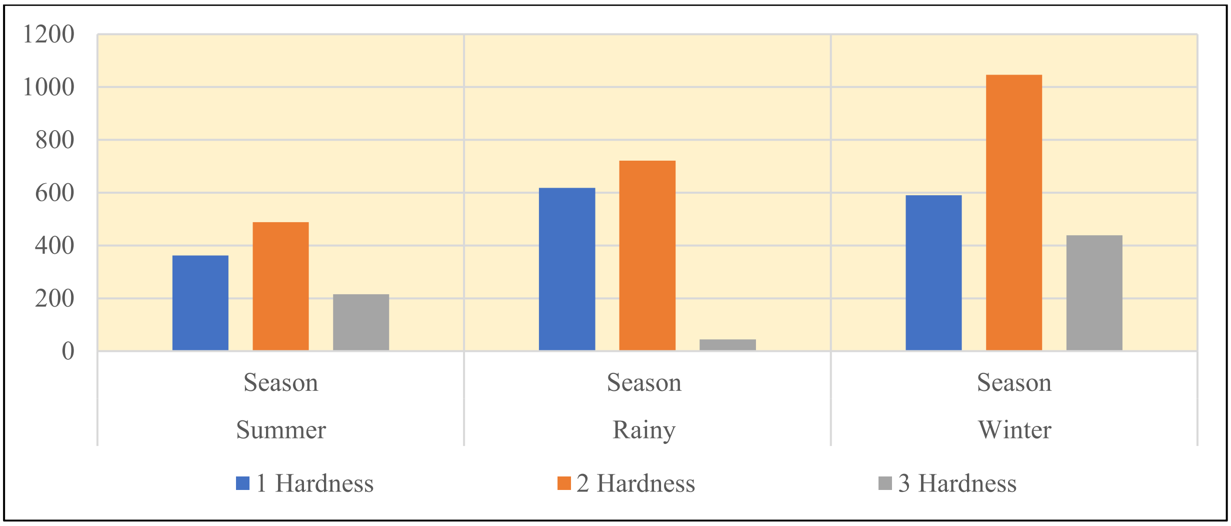
A seasonal trend existed at all stations, with lower values in summer and higher values in the rainy and winter seasons. This pattern shows the role of monsoon recharge, soil leaching, and water–rock interaction in regulating alkalinity. The observed alkalinity levels were high and may exceed drinking water standards in some cases. For aquaculture, moderate alkalinity improves buffering capacity and plankton growth, although high levels may require management.

In conclusion, alkalinity analysis shows that Pedavadlapudi groundwater is well-buffered but shows seasonal enrichment, particularly during and after the monsoon. These variations are influenced by natural geochemical processes and anthropogenic factors, such as agricultural activities. Regular monitoring is needed to ensure that alkalinity levels remain within acceptable limits for sustainable use.

3.10: Total Hardness Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Hardness	361.9	617.6	590
2	Hardness	488.2	721.8	1046
3	Hardness	215.28	44.04	439.21

3.10.1: Graph Showing seasonal variation of Hardness in three sampling stations:



Total hardness is a critical parameter for assessing water quality and reflects the concentrations of divalent metallic ions, primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}), in groundwater. It indicates the suitability of water for domestic use, irrigation, and aquaculture. High total hardness levels are linked to the dissolution of limestone, gypsum, and mineral-rich geological formations, along with anthropogenic contributions. This study evaluated the total hardness of groundwater at three Pedavadlapudi locations during the summer, rainy, and winter seasons, revealing seasonal and spatial variations.

At sampling station 1 (Pedavadlapudi Railway Gate Point), total hardness values were 361.9 mg/L in summer, 617.6 mg/L during the rainy season, and 590 mg/L in winter. The high total hardness during the rainy season may be attributed to the leaching of calcium and magnesium salts from soil and rock formations due to monsoon recharge. The lower winter value suggests stabilization, although it remains significantly high. The summer value indicates hard water conditions, likely due to mineral concentration through evaporation.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), hardness values were 488.2 mg/L in summer, 721.8 mg/L during the rainy season, and 1046 mg/L in winter. This station recorded the highest total hardness levels, particularly in winter. The increasing trend from summer to winter reflects the continuous accumulation of hardness-causing ions. High values are associated with agricultural activities, where fertilizers contribute to elevated calcium and magnesium levels. Reduced dilution and prolonged water–rock interaction during winter intensify hardness.

At sampling station 3 on Pedavadlapudi Railway Station Road, hardness values showed significant variations: 215.28 mg/L in summer, 44.04 mg/L during the rainy season, and 439.21 mg/L in winter. The low hardness during rains suggests dilution from monsoon recharge, decreasing dissolved mineral concentration. The increase in winter indicates rapid mineral dissolution under reduced recharge. The summer value reflects moderately hard water, showing mineral presence before seasonal changes.

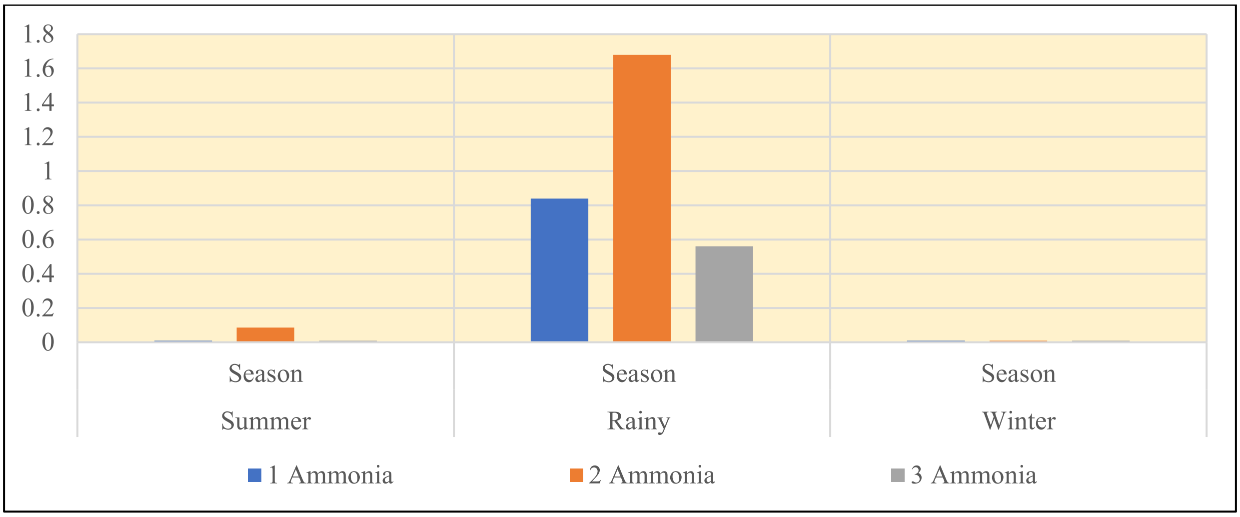
Total hardness values across the study area ranged from 44.04 to 1046 mg/L, indicating moderately hard to very hard groundwater. Hardness generally increased during the rainy and winter seasons, although station 3 showed a decrease during rains due to dilution effects. From a water quality perspective, hardness values exceeded drinking water limits at stations 1 and 2. Excessive hardness causes pipe scaling and may make water unsuitable for domestic use without treatment.

For aquaculture, moderate hardness provides essential minerals for aquatic organisms, although high levels may affect species sensitivity. The hardness analysis shows that groundwater in Pedavadlapudi is influenced by geological formations, seasonal recharge, and agricultural activities. Seasonal variations demonstrate the dynamic nature of groundwater chemistry. Monitoring and management strategies are necessary to control hardness and ensure sustainable groundwater use.

3.11: Ammonia Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Ammonia	0.01	0.84	0.01
2	Ammonia	0.086	1.68	0.01
3	Ammonia	0.01	0.56	0.01

3.11.1: Graph Showing seasonal variation of Ammonia in three sampling stations:



Ammonia (NH_3/NH_4^+) is a significant nitrogenous compound in aquatic environments, originating from organic matter decomposition, agricultural runoff, sewage contamination, and anthropogenic activities. It is crucial to evaluate water quality, particularly in aquaculture, as elevated ammonia levels can be toxic to aquatic organisms. In groundwater systems, ammonia concentrations are typically low due to natural filtration; however, seasonal variations and human activities can influence their levels. This study analysed ammonia concentrations across three sampling stations in Pedavadlapudi during summer, rainy, and winter seasons.

At Sampling Station 1 (Pedavadlapudi Railway Gate Point), ammonia levels were 0.01 mg/L in summer, 0.84 mg/L during the rainy season, and 0.01 mg/L in winter. The low concentrations in summer and winter indicate minimal contamination and effective natural filtration. However, the increase during the rainy season suggests influx of organic matter and nitrogenous compounds through surface runoff during monsoon rainfall. This spike indicates seasonal contamination linked to surrounding land-use activities.

At Sampling Station 2, located at Pedavadlapudi Cultivation Land Point, ammonia concentrations were 0.086 mg/L in summer, 1.68 mg/L during the rainy season, and 0.01 mg/L in winter. This station showed the highest ammonia levels, particularly during the rainy season. The elevated concentrations can be attributed to agricultural activities, where nitrogen-based fertilizers leach into groundwater during rainfall. The reduction in winter suggests dilution, nitrification, or decreased contaminant input following the monsoon period.

At Sampling Station 3, situated at Pedavadlapudi Railway Station Road, ammonia concentrations were recorded at 0.01 mg/L in the summer, 0.56 mg/L during the rainy season, and 0.01 mg/L in the winter. Similar to other stations, ammonia levels remained very low in summer and winter, indicating good groundwater quality. The moderate increase during the rainy season reflects minor contamination due to runoff, but the levels are comparatively lower than those at the cultivation land point, suggesting limited anthropogenic influence.

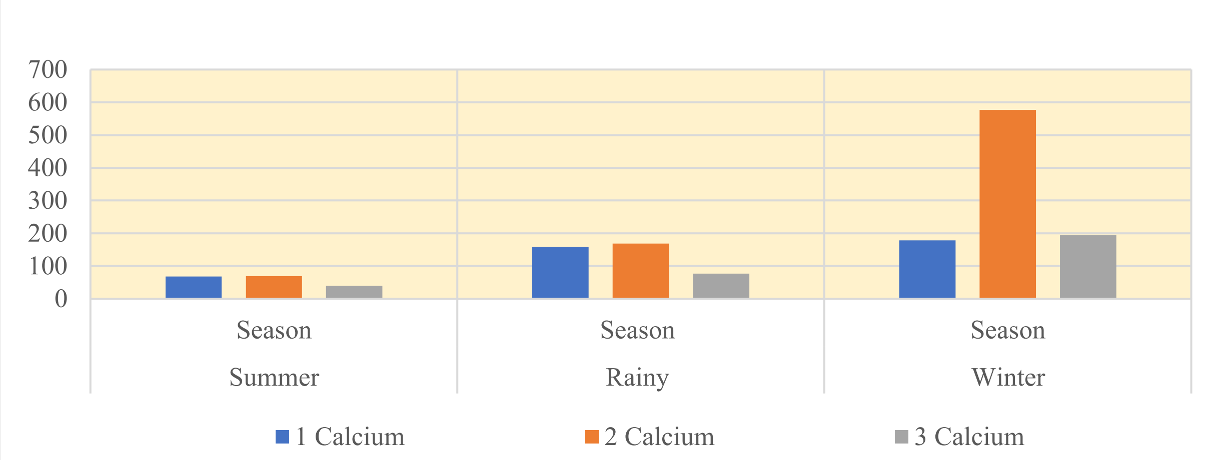
Overall, ammonia concentrations across the study area ranged from 0.01 mg/L to 1.68 mg/L, demonstrating a distinct seasonal pattern with very low levels in summer and winter and significant increases during the rainy season. This trend clearly indicates the impact of monsoon recharge, agricultural runoff, and organic matter decomposition on groundwater quality. From a water quality and aquaculture perspective, the elevated ammonia levels observed during the rainy season, particularly at Sampling Station 2, may pose a risk to aquatic organisms, as higher concentrations of ammonia can be toxic and may lead to stress or mortality in sensitive species. However, the rapid decline in ammonia levels after the rainy season suggests that the contamination is temporary and largely influenced by seasonal factors.

In conclusion, the ammonia analysis indicates that groundwater in Pedavadlapudi is generally of good quality with respect to ammonia during non-monsoon periods, but is temporarily impacted during the rainy season due to agricultural and environmental inputs. Continuous monitoring and controlled use of fertilizers are recommended to minimize ammonia contamination and ensure the sustainability of groundwater resources for aquaculture and other uses.

3.12: Calcium (Ca^{2+}) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	**Parameters**	**Summer Season**	**Rainy Season**	**Winter Season**
1	Calcium	68.3	159.3	178.3
2	Calcium	68.8	168.6	577
3	Calcium	39.6	77.3	194.5

3.12.1: Graph Showing seasonal variation of Calcium in three sampling stations:



Calcium is the principal divalent cation present in groundwater and significantly contributes to total hardness. It primarily originates from the dissolution of calcium-bearing minerals, such as limestone, dolomite, and gypsum. Calcium plays a crucial role in maintaining water quality, supporting aquatic life, and contributing to the buffering capacity of water. However, excessive concentrations may affect the suitability of water for drinking and certain aquaculture practices. In the present study, calcium concentrations were analyzed across three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons, revealing significant seasonal and spatial variations.

At sampling station 1 (Pedavadlapudi Railway Gate Point), calcium concentrations were 68.3 mg/L in summer, 159.3 mg/L during the rainy season, and 178.3 mg/L in winter. The relatively low concentration in summer suggests limited mineral dissolution under dry conditions. A substantial increase during the rainy season indicates enhanced leaching of calcium from the soil and rock formations owing to monsoon recharge. Further increases in winter suggest continued water–rock interaction and concentration of dissolved ions owing to the reduced dilution.

At sampling station 2 (Pedavadlapudi cultivation land point), calcium levels were 68.8 mg/L in summer, 168.6 mg/L during the rainy season, and 577 mg/L in winter. This station recorded the highest calcium concentration, particularly during winter. Elevated values can be strongly associated with agricultural activities, in which soil amendments, fertilizers, and irrigation return flows contribute to increased calcium levels in groundwater. The sharp increase in winter indicates significant accumulation and reduced flushing of dissolved minerals, along with prolonged contact between water and calcium-rich geological formations.

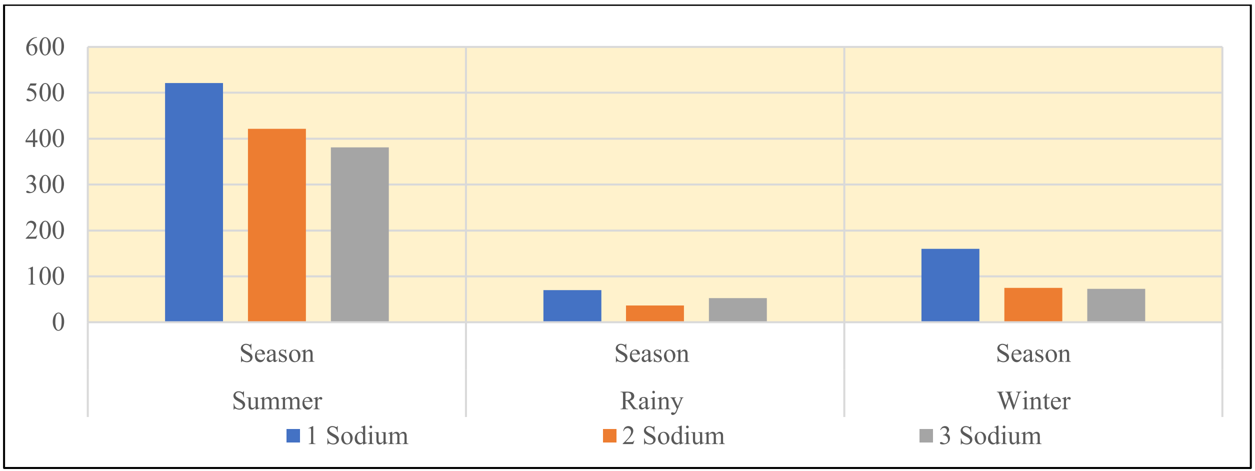
At sampling station 3, located on Pedavadlapudi Railway Station Road, calcium concentrations were measured at 39.6 mg/L during the summer, 77.3 mg/L during the rainy season, and 194.5 mg/L during the winter. The reduced concentration in summer indicates minimal mineralization, whereas the increase during the rainy season suggests moderate leaching due to monsoon infiltration. The substantial increase in winter signifies concentration effects and ongoing geochemical interactions, although these values remained lower than those recorded at the cultivation land point.

Overall, calcium concentrations throughout the study area ranged from 39.6 to 577 mg/L, indicating moderate to very high calcium content in groundwater. A consistent seasonal trend was evident, with lower concentrations in the summer and higher concentrations during the rainy and winter seasons, underscoring the influence of monsoon recharge, mineral dissolution, and evaporation. From the perspective of water quality, calcium positively contributes to aquaculture by supporting shell formation and physiological functions in aquatic organisms. However, excessively high concentrations, particularly at sampling station 2, may lead to increased hardness and scaling issues, rendering water less suitable for domestic use without treatment.

In conclusion, calcium analysis revealed that groundwater in Pedavadlapudi is significantly influenced by geological formations and agricultural practices, with pronounced seasonal enrichment during and after the monsoon. Continuous monitoring and appropriate management strategies are recommended to control excessive mineral accumulation and ensure sustainable groundwater quality for aquaculture and other applications.

3.13: Sodium (Na^+) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	Parameters	Summer Season	Rainy Season	Winter Season
1	Sodium	521.4	70.2	160
2	Sodium	421.5	36.2	75
3	Sodium	381.3	52.66	72.6



3.13.1: Graph Showing seasonal variation of Sodium in three sampling stations:

Sodium, an alkali metal ion prevalent in groundwater, plays a crucial role in assessing water quality for drinking, irrigation, and aquaculture. Its sources include weathering of sodium-bearing minerals, such as feldspars, and anthropogenic inputs from agricultural runoff, domestic waste, and irrigation flows. High sodium concentrations can affect soil permeability and pose risks to aquatic organisms and human health. This study analyzed sodium concentrations at three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons, revealing seasonal variations.

At sampling station 1 (Pedavadlapudi Railway Gate Point), sodium concentrations were 521.4 mg/L in summer, 70.2 mg/L during the rainy season, and 160 mg/L in winter. The high sodium level during summer resulted from intense evaporation, which concentrates dissolved salts. The decline in the rainy season occurred due to monsoon recharge dilution. The winter sodium levels increased, suggesting reduced dilution and gradual ion accumulation through water–rock interactions.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), sodium values were 421.5 mg/L in summer, 36.2 mg/L during the rainy season, and 75 mg/L in winter. Similar to station 1, high concentrations occurred in summer owing to evaporation effects. The lower rainy season value indicates dilution and leaching of salts from the aquifer. The winter increase reflects sodium enrichment due to reduced recharge and geochemical processes. Agricultural activities contribute sodium through fertilizers and irrigation.

At sampling station 3 on Pedavadlapudi Railway Station Road, sodium concentrations were 381.3 mg/L in summer, 52.66 mg/L in the rainy season, and 72.6 mg/L in winter. The summer concentrations, although elevated, were lower than those at other stations, suggesting reduced mineralization or anthropogenic effects. The rainy season showed decreased sodium levels from dilution, followed by a moderate increase in winter, aligning with the seasonal trend across stations. Sodium concentrations in the study area ranged from 36.2 to 521.4 mg/L, indicating moderate to high sodium content in groundwater, particularly during summer.

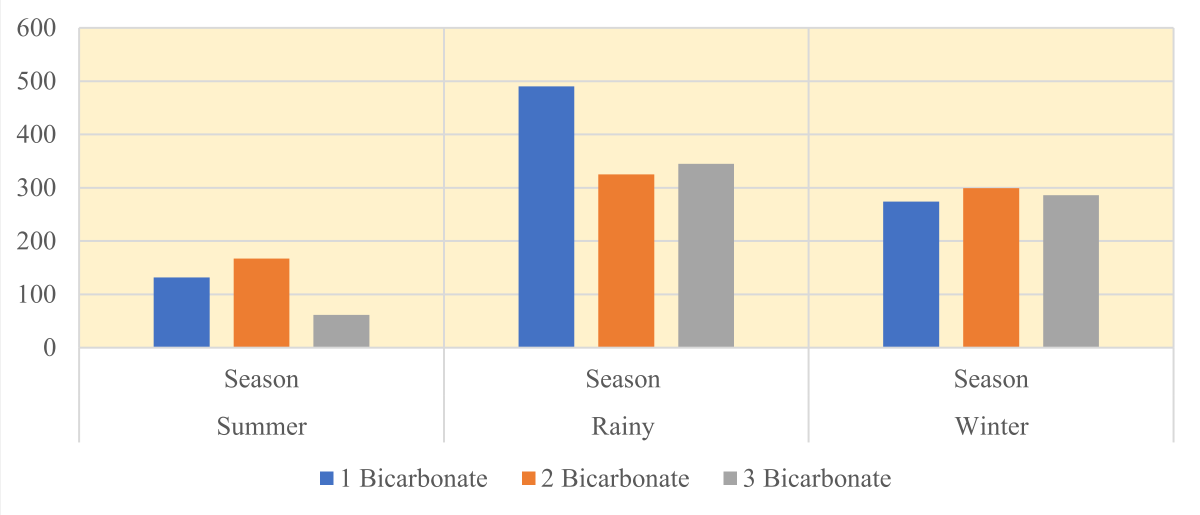
A seasonal pattern showed the highest concentrations in summer, the lowest in the rainy season, and moderate concentrations in winter. This trend reflects the impact of evaporation, monsoon recharge, and geological and anthropogenic factors. From a water quality perspective, high sodium levels in summer may affect drinking water and irrigation, as sodium can impact soil structure and crop productivity.

In aquaculture, excess sodium may disrupt the osmotic balance in aquatic organisms, affecting their growth and survival. Sodium analysis showed that groundwater in Pedavadlapudi was affected by seasonal conditions and land-use practices, with high concentrations during dry periods and dilution during the monsoon. Water management and monitoring are essential to control sodium levels for sustainable groundwater use for domestic, agricultural, and aquaculture purposes.

3.14: Bicarbonate (HCO_3^-) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	Parameters	Summer Season	Rainy Season	Winter Season
1	Bicarbonate	131.8	490	274
2	Bicarbonate	167.2	325	299
3	Bicarbonate	61.2	345	286

3.14.1: Graph Showing seasonal variation of Bicarbonate in three sampling stations:



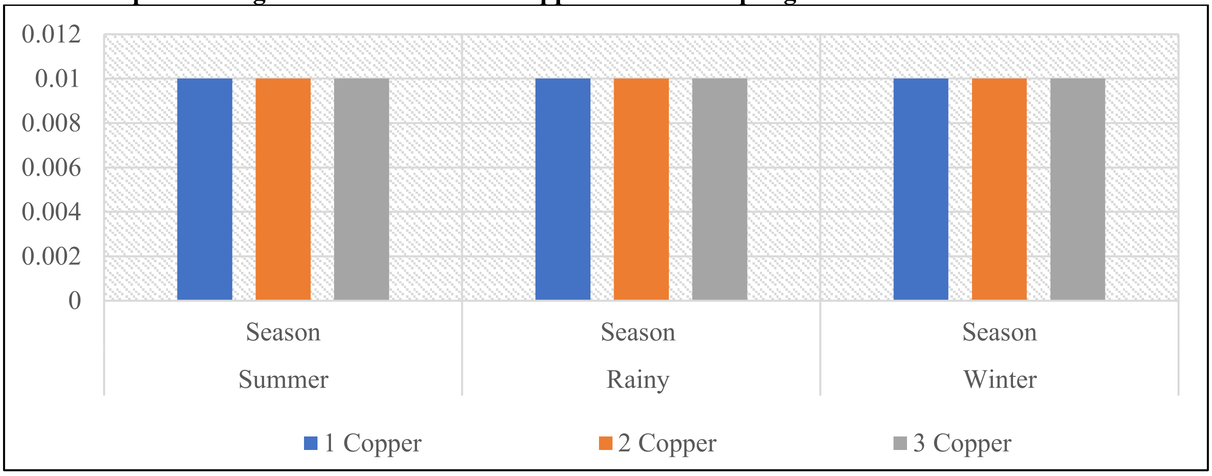
Bicarbonate (HCO_3^-) is the principal anion in groundwater, regulating alkalinity and buffering capacity. It originates from the dissolution of carbonate minerals like limestone and dolomite, and from carbon dioxide interaction with water and soil. Bicarbonate ions maintain pH stability and are vital for aquaculture systems, although excessive concentrations may indicate increased mineralization. In this study, bicarbonate levels were analyzed at three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons, revealing seasonal and spatial variations. At sampling station 1 (Pedavadlapudi Railway Gate Point), bicarbonate concentrations were 131.8 mg/L in summer, 490 mg/L during the rainy season, and 274 mg/L in winter. The low value in summer suggests limited dissolution of carbonate minerals under dry conditions. A sharp increase during the rainy season indicates intense leaching of bicarbonates from the soil and geological formations due to monsoon recharge. The winter decrease suggests partial stabilization as recharge diminishes. At sampling station 2 (Pedavadlapudi Cultivation Land Point), bicarbonate values were 167.2 mg/L in summer, 325 mg/L during the rainy season, and 299 mg/L in winter. The rainy season increase reflects enhanced dissolution of carbonate minerals and possible agricultural runoff contribution. The winter reduction indicates decreased recharge and gradual equilibrium. The higher values suggest moderate mineralization influenced by natural and anthropogenic factors.

At sampling station 3 on Pedavadlapudi Railway Station Road, bicarbonate concentrations were 61.2 mg/L in summer, 345 mg/L during the rainy season, and 286 mg/L in winter. The low concentration in summer suggests minimal carbonate dissolution and reduced mineral content. The substantial increase during the rainy season indicates strong monsoon infiltration, mobilizing bicarbonate ions from soil and rock strata. The elevated concentration in winter suggests the continued presence of dissolved bicarbonates due to reduced flushing and ongoing geochemical interactions. Bicarbonate concentrations throughout the study area ranged from 61.2 to 490 mg/L, reflecting low to high bicarbonate content in groundwater. A seasonal pattern was evident, with the lowest concentrations in summer, peak levels during the rainy season, and moderate levels in winter. This trend shows the role of monsoon recharge, soil leaching, and water–rock interaction in regulating bicarbonate levels. From a water quality perspective, bicarbonate contributes to alkalinity and buffering capacity, which benefits aquaculture by stabilizing pH and supporting biological productivity. However, high bicarbonate levels, particularly during the rainy season at station 1, may indicate increased mineralization and affect water taste and scaling properties. The analysis shows that groundwater in Pedavadlapudi is influenced by seasonal hydrological processes and geological formations, with enrichment during the monsoon period. Regular monitoring is recommended to manage bicarbonate levels for sustainable use in aquaculture and other applications.

3.15: Copper (Cu) Analysis of Groundwater Samples (Seasonal Variation):

Sampling Station	Parameters	Summer Season	Rainy Season	Winter Season
1	Copper	0.01	0.01	0.01
2	Copper	0.01	0.01	0.01
3	Copper	0.01	0.01	0.01

3.14.1: Graph Showing seasonal variation of copper in three sampling stations:



Copper is a trace element frequently detected in groundwater at minimal concentrations. Its presence is attributed to natural sources, such as weathering of copper-bearing minerals, as well as anthropogenic activities, including agricultural inputs, industrial discharge, and corrosion of plumbing materials. Although copper is an essential micronutrient for both aquatic organisms and humans, elevated concentrations can be toxic. Consequently, monitoring copper levels in groundwater is crucial for evaluating water quality and its suitability for aquaculture and domestic use.

In the present study, copper concentrations were assessed at three sampling stations in Pedavadlapudi during the summer, rainy, and winter seasons. The findings reveal a consistent concentration of 0.01 mg/L at all sampling stations and across all seasons, indicating no spatial or seasonal variations.

At sampling station 1 (Pedavadlapudi Railway Gate Point), the copper concentration remained constant at 0.01 mg/L throughout the summer, rainy, and winter seasons. This consistency suggests the absence of significant sources of copper contamination in this area and indicates that the groundwater system is stable with respect to trace metal content.

At sampling station 2 (Pedavadlapudi Cultivation Land Point), copper levels were similarly recorded at 0.01 mg/L across all three seasons. Despite the presence of agricultural activities, which can occasionally contribute trace metals through fertilizers and pesticides, no increase in copper concentration was observed. This implies that either copper inputs are minimal or that natural filtration processes effectively prevent its accumulation in groundwater.

At sampling station 3, located on Pedavadlapudi Railway Station Road, copper concentrations were consistently measured at 0.01 mg/L across all seasons. This consistency suggests minimal anthropogenic or geological effects on copper levels at this site.

Overall, copper concentrations at all sampling stations were uniformly 0.01 mg/L, indicating very low and stable levels of copper in groundwater. The lack of seasonal variations implies that copper concentrations are not significantly affected by factors such as monsoon recharge, evaporation, or land use practices in the study area.

From a water quality perspective, the observed Cu levels were well within the permissible limits set by drinking water standards and were deemed safe for aquaculture. At these low concentrations, Cu does not pose a toxic risk to aquatic organisms or human health and may even serve as a beneficial micronutrient.

In conclusion, the analysis of copper concentrations indicates that the groundwater in Pedavadlapudi is free from copper contamination and maintains excellent quality concerning trace metal content. The consistently low concentrations across all stations and seasons suggest a stable hydrogeochemical environment with minimal anthropogenic impact. Therefore, continuous monitoring is recommended to ensure the maintenance of these favourable conditions over time.

CHAPTER: 5: DISCUSSION

Groundwater quality is widely recognized as a dynamic system influenced by seasonal variations, hydrogeochemical processes, and anthropogenic activities. Several studies conducted in different parts of India support the findings of the present investigation.

The present investigation into the seasonal variations in groundwater quality at Pedavadlapudi revealed notable fluctuations in physicochemical parameters across the summer, rainy, and winter seasons. These variations are influenced by hydrogeochemical processes, monsoon recharge, agricultural runoff, evaporation, and anthropogenic activities. The findings were analysed for each parameter and compared with those of previous studies.

5.1. pH is a critical indicator of water quality because it affects chemical reactions, nutrient availability, and biological activities in aquatic environments. In the current study, pH values at all sampling stations ranged from

7.1 to 8.12, indicating neutral to slightly alkaline conditions. Such conditions are generally suitable for aquaculture, as most aquatic organisms thrive in waters with pH levels between 6.5 and 8.5. Station 1 exhibited slight seasonal variations, with values ranging from 7.1 in summer to 8.12 in winter, whereas Station 2 recorded values between 7.1 and 7.29, indicating relatively stable conditions. Station 3 demonstrated the most stable pH, maintaining a value of approximately 7.3 throughout the study period.

These findings align with those of Jessy Mol (2019), who reported seasonal variations in groundwater in coconut husk retting areas of the Kanyakumari District, but remained largely within acceptable limits, except for minor deviations. Similarly, Maruthi Devi (2013) reported moderate pH variations in the groundwater of the Prakasam District, influenced by seasonal dilution and leaching processes. The slightly alkaline nature of groundwater in the present study may be attributed to the presence of carbonate and bicarbonate minerals in the aquifer, which increase alkalinity during groundwater recharge.

5.2 Electrical Conductivity (EC)

Electrical conductivity (EC) serves as an indicator of the total ionic concentration in water, reflecting the presence of dissolved salts and minerals. In the present study, EC values were elevated during the summer at all sampling stations. At Station 1, EC values reached 23.3 in the summer and subsequently decreased during the rainy (17.37) and winter (18.9) seasons. A similar pattern was noted at Station 2, where EC peaked at 26.4 in the summer, suggesting an increased ionic concentration attributable to evaporation during dry periods. Station 3 exhibited comparatively lower EC values, ranging from 10.8 to 17.6, indicating reduced mineralization.

These findings align with those of Sangeetha (2018), who documented an increase in groundwater EC due to anthropogenic activities and leachate infiltration from solid waste dumpsites. Similarly, Vetri Selvi (2021) reported elevated EC levels in coastal groundwater resulting from interactions with dissolved salts and minerals. The heightened EC during the summer can thus be attributed to evaporation, the concentration of dissolved salts, and diminished groundwater recharge.

5.3 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) signify the aggregate concentration of dissolved minerals and salts in water and serve as a crucial indicator of water quality for both drinking and aquaculture purposes. In the present study, elevated TDS levels were recorded at all sampling stations. Station 1 recorded the highest TDS levels during the summer (1597 mg/L), followed by winter (1451 mg/L) and the rainy season (1361 mg/L). At Station 2, TDS values increased from 1128 mg/L in summer to 2684 mg/L in winter, suggesting significant mineral dissolution and potential agricultural contributions. Station 3 recorded relatively lower values (683–864 mg/L), although some measurements surpassed the recommended limits for drinking water.

These findings are consistent with those of Maruthi Devi (2013), who documented increased TDS levels during the post-monsoon periods due to the leaching of minerals and agricultural chemicals. Similarly, Shillewar (2007) noted elevated mineral concentrations in groundwater, attributable to natural geological processes. The high TDS levels identified in this study indicate substantial mineralization of groundwater, rendering it unsuitable for drinking without treatment, although it may still be viable for aquaculture activities.

5.4 Turbidity

Turbidity is indicative of the presence of suspended particles, including clay, organic matter, and microorganisms, in water. In the present study, low turbidity levels were recorded across most seasons, suggesting relatively clear groundwater conditions. However, Station 1 recorded an increase during winter (3.71 NTU), potentially attributable to sediment disturbance or recharge processes introducing suspended materials. In contrast, Stations 2 and 3 consistently maintained low turbidity levels throughout the year.

These findings are consistent with those of Bushra (2024), who highlighted that turbidity variations in water bodies are frequently associated with seasonal runoff, suspended sediments, and anthropogenic disturbances. Overall, the turbidity levels in the study area remained within acceptable limits for aquaculture.

5.5 Dissolved Oxygen (DO)

Dissolved oxygen (DO) is crucial for sustaining aquatic life and serves as an indicator of the biological health of aquatic ecosystems. In the present study, DO levels were observed to be relatively low at all sampling stations. At Station 1, DO levels declined from 5.18 mg/L in the summer to 1.6 mg/L during the rainy season and 1.8 mg/L in the winter. Similarly, Station 2 recorded DO values ranging from 3.55 mg/L to 1.44 mg/L, while Station 3 exhibited slightly higher values, ranging between 2 and 2.5 mg/L. The observed reduction in DO levels during the rainy and winter seasons may be attributed to the decomposition of organic matter, increased microbial activity, and diminished water circulation.

These findings align with previous observations by Sangeetha (2018), who reported oxygen depletion in groundwater affected by organic contamination and anthropogenic activities. Although groundwater typically contains lower oxygen levels than surface water, maintaining adequate DO is essential for sustaining healthy aquaculture systems.

5.6 Alkalinity

Alkalinity denotes the buffering capacity of water and its ability to neutralize acids. In the present study, alkalinity values ranged from 240.5 to 378 mg/L. Station 1 exhibited an increase from 298 mg/L in summer to 378 mg/L in winter, whereas Station 2 recorded values between 280 and 350 mg/L. Station 3 also demonstrated a seasonal

increase from 240.5 mg/L in summer to 364 mg/L in winter. The elevated alkalinity observed during the rainy and winter seasons may be attributed to the dissolution of carbonate minerals during groundwater recharge.
These findings align with the results of Jessy Mol (2019), who reported seasonal fluctuations in alkalinity due to hydrogeochemical interactions between groundwater and surrounding geological formations. Moderate alkalinity is advantageous for aquaculture, as it stabilizes pH and enhances productivity in fish culture systems.

5.7 Total Hardness, Calcium, and Magnesium

Total hardness is primarily attributed to the presence of calcium and magnesium ions. The current study observed elevated hardness levels, particularly during the rainy and winter seasons. At Station 1, hardness increased from 361.9 mg/L in summer to 617.6 mg/L during the rainy season. Station 2 exhibited exceptionally high hardness levels, reaching 1046 mg/L in winter, while Station 3 recorded moderate hardness values of approximately 440 mg/L. The increase in hardness during the monsoon and post-monsoon periods may be attributed to the leaching of minerals from soil and rocks during groundwater recharge.
Similar findings were reported by Maruthi Devi (2013), who noted increased calcium and magnesium concentrations during the post-monsoon periods due to leaching processes. Vetri Selvi (2021) also emphasized the role of hydrogeochemical interactions in elevating hardness levels in coastal aquifers. Although high hardness may reduce water suitability for drinking, moderate hardness is advantageous for aquaculture, as calcium and magnesium support fish growth and shell formation.

5.8 Ammonia

Ammonia is a critical indicator of organic pollution and nutrient enrichment. In the present study, ammonia concentrations were notably elevated during the rainy season, particularly at Station 2 (1.68 mg/L), followed by Stations 1 (0.84 mg/L) and 3 (0.56 mg/L). The increased ammonia levels during the monsoon season can be attributed to agricultural runoff containing fertilizers, organic waste, and animal manure.
These findings are corroborated by Sangeetha (2018), who documented groundwater contamination resulting from anthropogenic activities and waste infiltration. Elevated ammonia concentrations can be toxic to aquatic organisms under excessive conditions, necessitating continuous monitoring in aquaculture areas.

5.9 Sodium

During the summer, sodium concentrations were the highest at all stations, with Station 1 recording 521.4 mg/L, Station 2 at 421.5 mg/L, and Station 3 at 381.3 mg/L. The decrease in sodium levels during the rainy and winter seasons can likely be attributed to dilution effects from rainfall and groundwater recharge.
Elevated sodium levels may result from weathering of sodium-bearing minerals, evaporation processes, and agricultural inputs. Similar findings were reported by Vetri Selvi (2021), who observed increased sodium concentrations in coastal groundwater due to mineral dissolution and saline interactions.

5.10 Bicarbonate

Bicarbonate concentrations reached their maximum during the rainy season at all stations, with Station 1 recording 490 mg/L, Station 2 at 325 mg/L, and Station 3 at 345 mg/L. The increase in bicarbonate levels during the monsoon season may be attributed to the enhanced dissolution of carbonate rocks and soil minerals during groundwater recharge. These observations are consistent with the hydrogeochemical processes outlined by Jessy Mol (2019) and Maruthi Devi (2013). Bicarbonates contribute to increased alkalinity and buffering capacity, which are beneficial for aquaculture systems.

5.11 Copper

The concentration of copper was consistently 0.01 mg/L across all seasons and sampling stations, indicating the absence of heavy metal contamination in the study area. This observation suggests that the groundwater in Pedavadlapudi is not affected by industrial metal pollution, unlike in certain industrial regions analysed by Lamma Osama Eshteiwi (2018) in parts of the Guntur district. The presence of copper within permissible limits signifies that the groundwater is chemically stable and suitable for aquaculture applications.

Overall Interpretation

The findings reveal that the groundwater quality in Pedavadlapudi is affected by seasonal climatic changes, agricultural activities, mineral dissolution, and groundwater recharge processes. Although most physicochemical parameters remained within acceptable limits for aquaculture, certain parameters, such as total dissolved solids (TDS), hardness, and sodium, exceeded drinking water standards at several stations.
Among the sampling stations, the highest seasonal fluctuations were observed at agricultural land locations, confirming the strong influence of land use patterns on groundwater quality. Agricultural activities contribute nutrients, salts, and chemical residues to subsurface water through leaching and infiltration. In contrast, comparatively stable parameter values at less disturbed stations indicate minimal anthropogenic interference and better groundwater quality.
Overall, the combined evidence from previous literature and the present investigation demonstrates that groundwater quality is governed by

- Seasonal recharge and rainfall patterns
- Evaporation and concentration effects
- Rock–water interaction and mineral weathering
- Agricultural and anthropogenic activities

Although groundwater in the study area may not be suitable for drinking without treatment, its hydro chemical characteristics—particularly alkalinity and pH—make it suitable for aquaculture with appropriate aeration and nutrient management strategies.

CHAPTER: 6: CONCLUSION

The study titled "Seasonal Variation of Groundwater Quality and Its Impact on Aquaculture at Pedavadlapudi, Guntur District" aimed to assess the physicochemical characteristics of groundwater and evaluate its suitability for aquaculture. Groundwater samples collected from various stations during the summer, rainy, and winter seasons revealed distinct seasonal variations in water quality parameters influenced by natural hydrogeochemical processes and human activities. The analysis of physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), alkalinity, total hardness, calcium, magnesium, ammonia, sodium, bicarbonate, and copper, provided a comprehensive understanding of groundwater quality in the study area. The pH values of groundwater across all sampling stations ranged from 7.1 to 8.12, indicating neutral to slightly alkaline conditions. These values are within the acceptable range for aquaculture and support the survival and growth of aquatic organisms. The slight alkalinity observed in the study area may be attributed to the dissolution of carbonate and bicarbonate minerals present in the aquifer system. Seasonal variations in pH were minimal, suggesting relatively stable chemical conditions in groundwater.

The electrical conductivity (EC) values were relatively higher during the summer season, indicating an increased concentration of dissolved ions and salts in the groundwater. This increase in EC during summer can be attributed to evaporation, reduced groundwater recharge, and the concentration of dissolved minerals. During the rainy season, EC values decreased slightly because of dilution effects caused by rainfall and groundwater recharge.

Similarly, total dissolved solids (TDS) showed elevated concentrations at several stations, particularly during the summer and winter seasons. High TDS levels reflect the presence of dissolved minerals, salts, and agricultural inputs. Although these values exceed desirable limits for drinking water in some locations, they do not necessarily pose serious constraints for aquaculture activities. However, the high mineral content indicates significant groundwater mineralization influenced by geological formations and anthropogenic inputs such as fertilizers and agricultural runoff.

Throughout the study, turbidity levels generally remained low across most sampling stations and seasons, indicating relatively clear groundwater conditions with minimal suspended particles. Slight increases in turbidity during certain seasons may be attributed to sediment disturbance or recharge processes introducing fine particles into groundwater systems.

The dissolved oxygen (DO) concentrations recorded during the study were relatively low compared to those in surface water systems. Groundwater naturally contains lower oxygen levels due to limited atmospheric interaction. However, the observed decrease in DO during the rainy and winter seasons may be associated with increased microbial decomposition of organic matter and reduced circulation of water within aquifers. Adequate aeration is therefore essential when groundwater is used in aquaculture systems to maintain optimal oxygen levels for aquatic organisms.

Alkalinity levels in the study area ranged from 240.5 to 378 mg/L, indicating a moderate to high buffering capacity of groundwater. The increase in alkalinity during the rainy and winter seasons can be linked to the dissolution of carbonate minerals during groundwater recharge. Moderate alkalinity is beneficial in aquaculture systems, as it helps stabilize pH and promotes biological productivity.

This study also revealed relatively high levels of total hardness, particularly during the rainy and winter seasons. The hardness values were primarily influenced by the presence of calcium and magnesium ions, which originated from the dissolution of limestone and other mineral-rich geological formations. Although excessive hardness may reduce the palatability of drinking water, moderate hardness is advantageous for aquaculture, because calcium and magnesium are essential for fish metabolism, bone development, and shell formation in aquatic organisms.

The concentration of ammonia increased during the rainy season, especially in areas close to agricultural land. This increase can be attributed to the leaching of fertilizers, organic waste, and animal manure into groundwater during rainfall events. Elevated ammonia levels may pose risks to aquatic organisms if concentrations become excessive, highlighting the importance of monitoring nutrient levels in aquaculture environments.

Sodium concentrations were highest during the summer season, which may be associated with evaporation processes and the weathering of sodium-bearing minerals in soil and rocks. Agricultural inputs may also contribute to increased sodium levels in groundwater. However, the decrease in sodium concentration during the rainy and winter seasons suggests dilution through groundwater recharge.

Bicarbonate concentrations reached their maximum during the rainy season, a phenomenon attributed to the increased dissolution of carbonate minerals during groundwater recharge. Bicarbonates play a critical role in maintaining alkalinity and buffering capacity in aquatic systems, thereby promoting stable environments conducive to aquaculture.

The analysis of copper concentrations consistently revealed low values (0.01 mg/L) across all sampling stations and seasons, indicating the absence of significant heavy metal contamination in the study area. The presence of copper within permissible limits confirms that the groundwater is not adversely affected by industrial pollution and remains chemically stable for aquaculture use.

Overall, the study demonstrates that seasonal climatic conditions, groundwater recharge, evaporation, rock–water interactions, and agricultural activities significantly influence groundwater quality in Pedavadlapudi. Among the sampling stations, those located near agricultural lands exhibited greater seasonal fluctuations in water quality parameters due to the infiltration of nutrients, salts, and agricultural chemicals.

Despite certain parameters, such as total dissolved solids (TDS), hardness, and sodium, exceeding the recommended limits for drinking water, most physicochemical characteristics fall within ranges suitable for aquaculture applications. Parameters, such as pH, alkalinity, calcium, and magnesium, provide favourable conditions for aquatic productivity and fish growth.

Based on the overall findings, it can be concluded that groundwater in Pedavadlapudi is generally unsuitable for direct consumption without treatment owing to high mineral content, but it is largely suitable for aquaculture practices when managed properly. The use of groundwater in aquaculture systems should be supported with appropriate aeration, periodic monitoring of water quality, and sustainable management practices to ensure healthy aquatic environments and long-term productivity.

In conclusion, this study underscores the importance of continuous monitoring and integrated groundwater management in aquaculture-dominated regions. Sustainable agricultural practices, controlled fertilizer use, and effective groundwater management strategies are essential to protect groundwater quality and support the long-term sustainability of aquaculture in the region.

Chapter 7: Future Scope of the Study

Based on the conclusions of the present investigation conducted in Pedavadlapudi, the following future research directions are recommended:

Long-term groundwater monitoring: Conduct multi-year monitoring of groundwater quality to understand long-term trends, climate variability impacts, and progressive changes due to intensive aquaculture and agriculture.

Advanced hydrogeochemical modelling and isotopic analysis should be conducted to identify the precise sources of mineralization, ammonia contamination, and seasonal recharge mechanisms.

Assessment of Heavy Metals and Emerging Pollutants: Expand the study to include heavy metals (e.g., lead, cadmium, and arsenic) and emerging contaminants, such as pesticides and antibiotic residues, commonly associated with aquaculture and farming activities.

Impact Assessment of Aquaculture Yield and Fish Health: Correlation of groundwater quality parameters with fish growth performance, disease incidence, and overall pond productivity to establish scientific water quality thresholds for sustainable aquaculture.

Development of Sustainable Water Management Strategies: Design and evaluation of cost-effective treatment methods (e.g., biofilters, constructed wetlands, and aeration systems) and promotion of integrated water resource management practices to reduce ammonia levels and maintain ecological balance.

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12. Self-Citations.