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Research Paper

Hydrogeochemical characteristics of groundwater in the musi river basin during monsoon

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ABSTRACT

Groundwater samples were collected from a strategic monitoring grid to measure the levels of nine distinct dominant ionic species. The resulting data revealed a clear, continuous decline in overall water safety from one year to the next, demonstrating that the natural dilution typically expected from seasonal rains was heavily compromised. When these hydrogeochemical datasets were evaluated against the health-based drinking water safety thresholds established by the World Health Organization (WHO), the comparative analysis exposed a significant, escalating pollution load. This worsening contamination was directly linked to a substantial increase in hazardous chemical matter within the sub-surface water matrix. The primary driver of this environmental degradation was identified as rapidly increasing human interference, unmanaged urban development, and unregulated industrial wastewater dumping across the river basin. As human activities accelerated throughout the surrounding area, they introduced a large volume of artificial pollutants into the local water system. During the monsoon period, this problem was severely compounded as heavy rainfall washed these accumulated surface contaminants and agricultural chemicals directly down into the shallow, unconfined water table. The continuous expansion of the regional pollution index over the two-year study period provides undeniable evidence of this trend. Ultimately, these findings underscore an urgent need to transition away from unmonitored resource use toward strict watershed protection policies and real-time water safety monitoring to safeguard the remaining drinking water supplies.

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1. INTRODUCTION

Groundwater bodies provide huge volumes of water to both rural residential water distribution networks and urban municipal networks, besides being extensively used in agricultural irrigation schemes. Prior research reveals that groundwater provides about 65% of global household consumption, with irrigation taking 20% and industries 15% [1], [2]. Groundwater levels and underground geochemical composition constantly change, but while some changes originate from natural geochemical cycles and baseline mineral dissolution, an increasing part of these changes is caused by excessive human interference [1], [2].

The excessive extraction of groundwater from such vulnerable alluvial systems during drought and summer periods significantly affects both the quantity and quality of the water. It destroys the delicate balance between the surface streams and underground aquifers in alluvial command areas [3], [4].

In India, groundwater serves for providing 50-80% of agricultural irrigation and more than half of household water requirements. There is a number of problems associated with the over-extraction and pollution of water supplies, connected to the human activities [3], [5]. These problems include the depletion of aquifers, deterioration of water quality as a result of growth of industrial sector, urbanization, and agriculture, which is further aggravated by excessive extraction of the water resources [6]. Efficient management of these issues presupposes the knowledge of hydrogeochemical processes and mechanism of groundwater recharge, especially in semi-arid regions [7]. Consequently, hydrogeochemical characterization of the aquifer and mapping of the geological structure of the water body are crucial stages in protection of water resources [8]. The evaluation of hydrogeochemical processes gives important information about relative impact of human-induced pollution and natural rock-water interactions [9], [10].

2. RELATED WORK

Groundwater samples were obtained from the defined grid nodes during the active monsoon period. Monsoon period is chosen for sampling because of heavy rainfalls, which stimulate the aquifer recharge process, facilitate the leaching of elements from the soil zone, and cause the formation of sub-surface runoff. In order to preserve the initial purity of the samples taken from the field, all of them went through a two-stage processing immediately after their extraction. Water samples were first filtered with the help of membrane filters.

The analysis aspect largely concentrated on the assessment of the major alkaline earth cation groups, such as Calcium and Magnesium. On the other hand, laboratory analysis measured key dissolved anion groups, including sulfates, bicarbonates, chlorides, and nitrates. Such particular parameters serve as essential hydrochemical tracers of water-rock interaction, anthropogenic pollution, and saltwater intrusion lines. The quantification of those ionic species was conducted following standard analysis testing protocols and quality control procedures [11], [12], [13].

2.1 Study Area

In order to configure an ideal sampling network, the choice of the particular observation zones has been accomplished following a comprehensive geographic information system (GIS) approach. With the consideration of horizontal coordinates (latitude and longitude) along with vertical elevations above mean sea level, the sampling grid takes into account the three-dimensional displacement of the groundwater within localized aquifers. The high elevation sites mainly represent baseline conditions close to recharge zones while the low elevation sampling points stand for accumulation of discharge signals and possible downstream contamination with agricultural or industrial runoff. Such particular sampling configuration helps to take into consideration all the topographical and hydrological gradients of the river basin.

Through the determination of the exact elevation and positioning of the sampling wells, the study helps to separate localized geogenic weathering processes like rock-water interaction and mineral dissolution from more wide-spread pollution induced by humans.

Geographic positions, including exact coordinates and regional elevations, were identified in order to provide a basis for spatial grid for temporal sampling as specified in Table 1.

Table 1. Monitoring Grid Coordinates and Spatial Reference Points

CODE	Sampling Points	Latitude (N)	Longitude (E)	Alt. (M)
LO1	River Musi at Osmansagar lake	17° 22’ 51"	78° 18’ 59"	595
LO2	River Esi at Himayatsagar Lake	17° 19’ 55"	78° 21’ 49"	569
RO1	River Musi at Moosarambagh Bridge	17° 22’ 46"	78° 31’ 00"	581
RO2	River Musi at Nagole Bridge	17° 22’58"	78° 33’ 29"	510

3. METHODOLOGY

The subsurface water sample collection process was carefully planned and performed within the framework of the specified grid nodes during active monsoonal season. Execution of the field activities during that specific stage of the hydrological cycle was essential. Collection of the samples during the time of maximum activity of monsoons allows obtaining information about the current hydrochemical regime under maximum dilution and terrestrial runoff conditions.

The collected water samples underwent immediate processing with high purity membrane filters in order to filter out any suspended particulates, colloids, and microorganisms. It is important to get rid of these contaminants because otherwise there can be chemical reactions, precipitation of minerals or consumption by microbes that would bias lab results.

The filtered water samples were then divided into several aliquots with different preservative treatments. One part of the sample was immediately acidified with 1 mg/L of ultra-pure, trace-metal-grade nitric acid to preserve the cations in it. By lowering the sample pH below 2, one prevents the adsorption of the positive ions on the inner surface of the bottle and precipitation of metal hydroxides. Another fraction was stored securely in the same sealed bottles but without any acidification treatment and without any headspace. These untouched fractions were kept for further anion validation. Thus, there would not be any acid-mediated chemical alterations of the negative ions in the samples.

The second stage of quantitative characterization entailed identification and measurement of the chemical constituents of the hydrogeologic matrix. Lab analyses emphasized the measurement of major alkaline earth cation groups, namely calcium and magnesium. These ions are important for evaluation of the water hardness and the dissolution of carbonate bearing rocks. At the same time, the test protocol included evaluation of major dissolved anion groups like sulfates, bicarbonates, chlorides, and nitrates.

All of these ions have certain importance as environmental tracers: thus, chlorides and nitrates indicate anthropogenic pollution by agriculture fertilizers or sewage, and bicarbonates and sulfates indicate natural weathering of the rocks. All laboratory equipment used was calibrated on a daily basis, and testing methods followed strictly the standardized protocols [7], [14].

4. RESULTS AND DISCUSSION

For the interpretation of the seasonal field data standard statistical tests were utilized. The subterranean water quality profiles in the Musi basin were comprehensively analyzed by means of nine primary diagnostic parameters: Na+, Ca2+, K+, Mg2+, HCO3-, Cl-, SO42-, NO3-, and F-. According to the criteria outlined in Table 2, the first stage of data analysis involved comparison of the raw parameter levels with the basic drinking water guidelines established by the Bureau of Indian Standards (BIS) and WHO.

Table 2. Safe Drinking Water Limits Configuration

Parameters	BIS / WHO Standards (mg/L)
Na	200
Cl	600

Sulphates	250
Nitrate	45
Fluoride	1.5
Ca	200
HCO3	600
Mg	200
K	12

Parametric One-Way ANOVA was utilized to test for variances. The null hypothesis (H0) was rejected for parameters such as potassium, calcium, magnesium, bicarbonate, sulfates, and nitrates, hence developing unique gaps ($p < 0.05$) in time periods. On the other hand, parameters such as sodium, chloride, and fluoride levels retained their structure invariantly in both observation years due to consistent geogenic sources and permanent contamination by nearby industrial sites.

The Spearman's Rank Correlation Matrix shows similar co-dependencies [15], [16]. The highest correlated pattern is ($r = 0.99$) that denotes coherence between the ion groups and the two groups of anions across both rainy periods. Importantly, inter-group analysis between the cation and anion groups produced zero covariance ($r = 0$), which demonstrates that only the positive metallic matrices are under the influence of rock-water interaction processes while the anion profiles are separately fed into the ground waters by surface runoff and industrial effluents.

The synthesized classification using the Water Quality Index (WQI) showed deteriorating environment conditions [17]. It is evident from the correlation analysis in support of the seasonal species (ions) [18], [19]. The existence and movement of groundwater are dependent on the properties of aquifers such as porosity, permeability, and hydraulic conductivity. The index figures started with 'Poor Quality' category with 250.02 in 2019 but moved to a highly hazardous 'Class D & E' rating at 360.37 during 2020 period. This demonstrates total degradation of the layout and formation of the groundwater system as completely unusable by humans due to constant pollution and absence of monsoon washing effect. [20], [21].

The mean concentration values obtained through field surveys are presented in sequence in Table 3 and Table 4 for 2019 monsoon period and Table 5 and Table 6 for 2020 monsoon period.

Table 3. Statistical Analysis of Cation Parameters (Monsoon 2019)

Parameters	**Avg (mg/L)**
Na	62
K	4
Ca	23
Mg	12

Table 4. Statistical Analysis of Anion Parameters (Monsoon 2019)

Parameters	**Avg (mg/L)**
HCO3	85
Cl	72
So4	28
NO3	8.5
F	0.5

Table 5. Statistical Analysis of Cation Parameters (Monsoon 2020)

Parameters	**Avg (mg/L)**
Na	86
K	6
Ca	36

Mg	16

Table 6. Statistical Analysis of Anion Parameters (Monsoon 2020)

Parameters	Avg (mg/L)
HCO3	110
Cl	95
So4	38
NO3	15
F	1

The initial results show that chemical concentrations were within permissible safety boundaries. However, while analyzing the progress between the 2019 and 2020 rainy periods, it was found that there was an increasing trend in dissolved fluoride (F-) levels, moving much closer to the critical boundary limit of 1.5 mg/L as shown in Table 6. Such increase in the specific season shows that heavy monsoon rains act as flushing mechanism and dissolve fluoride-containing mineral structures into shallow water tables.

4.1 One Way ANOVA

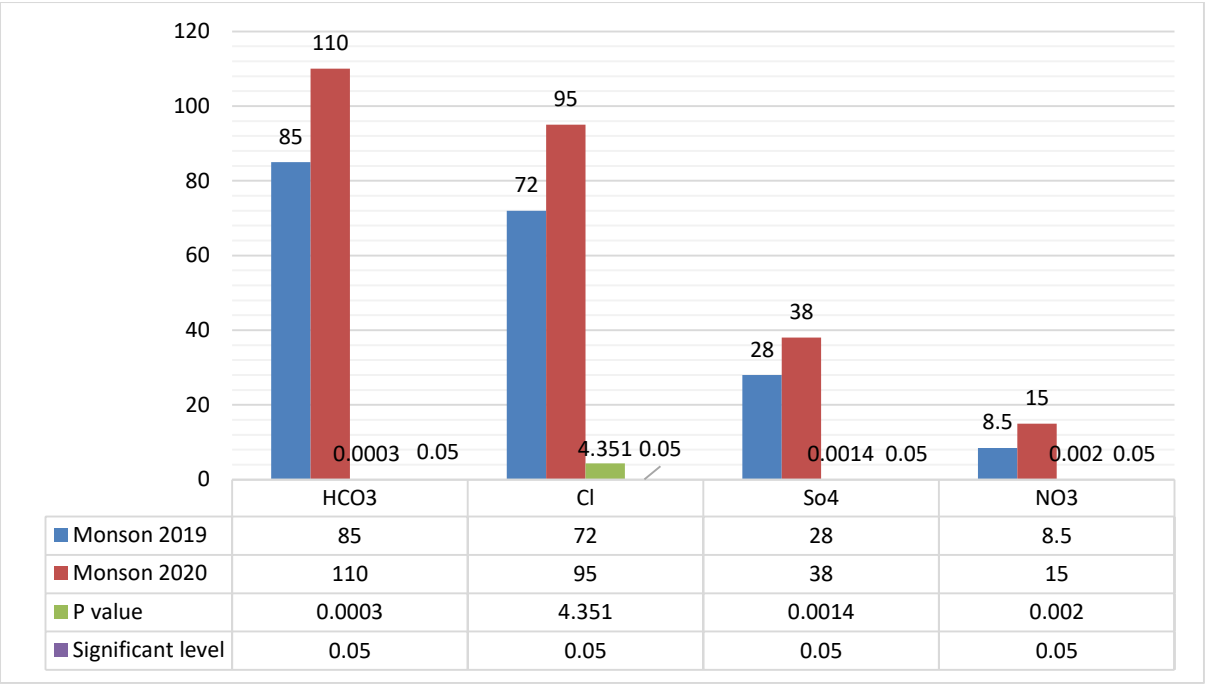
For systematic evaluation of whether monsoonal conditions resulted in any statistical significant changes in composition of groundwater, a parametric One-Way ANOVA test was utilized. This test compares variance of data samples against the variance within each sample. All results of the data processing are summarized in Table 7 for cations and Table 8 and Figure 2 for anions.

Table 7. ANOVA Modeling Matrix for Groundwater Cations (2019 vs. 2020)

Parameters Cat Ions	Monsoon 2019 (MG/L)	Monsoon 2020 (MG/L)	P Value	Significance Level
Na	62	86	8.07	0.05
K	4	6	0.007	0.05
Ca	23	36	0.000117	0.05
Mg	12	16	0.0046	0.05

Table 8. ANOVA Modeling Matrix for Groundwater Anions (2019 vs. 2020)

Parameters An Ions	Monsoon 2019 (mg/L)	Monsoon 2020 (mg/L)	P value	Significance Level
HCO3	85	110	0.0003	0.05
Cl	72	95	4.351	0.05
So4	28	38	0.0014	0.05
NO3	8.5	15	0.002	0.05
F	0.5	1	0.08	0.05



	HCO3	Cl	So4	NO3
Monson 2019	85	72	28	8.5
Monson 2020	110	95	38	15
P value	0.0003	4.351	0.0014	0.002
Significant level	0.05	0.05	0.05	0.05

Figure 1. Comparison of Variability of Main Anions in the Musi River Basin during Monsoon Seasons (2019-2020): ANOVA Test Results

One-way ANOVA test is a parametric test used for testing hypotheses. It helps determine whether data obtained during monsoons are statistically different. The ANOVA test either supports or disproves null hypothesis (H0) or alternative hypothesis (H1).

The results of the ANOVA test (see Table 7, Table 8 and Figure 1) demonstrate significant differences ($p < 0.05$) between monsoon seasons regarding potassium (K), calcium (Ca), magnesium (Mg), bicarbonate (HCO_3^-), sulfates (SO_4^{2-}), and nitrates (NO_3^-). There were no significant differences found for sodium (Na), chloride (Cl) and fluoride (F) in 2019 and 2020 seasons.

Mathematical analysis of these data provided by ANOVA test is clearly illustrated in the Table 7 and Table 8 below.

A. Parameters with Significant Seasonal Disparities ($p < 0.05$)

A departure from the null hypothesis (H_0) was noted for K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, and NO_3^-. This was because the computed value of the p-test was very low when compared to the standard alpha value of 0.05.

The great level of variance indicates that these ions are very susceptible to seasonal changes. The difference in concentration from 2019 to 2020 is a direct reflection of the impact of:

- Rains washing through the agricultural soils.
- Variation in water table levels.
- Introduction of sudden pollutants due to seasonality

B. Parameters with Temporal Stability ($p \geq 0.05$)

In contrast, however, there was no statistically significant difference observed in the values of sodium (Na^+), chloride (Cl^-), and fluoride (F^-) ions between the 2019 and 2020 monsoons, thereby confirming the null hypothesis (H_0).

The consistent statistical results indicate that the origin and transportation of these particular ions were similar during both study periods. The stable baseline values of sodium and chloride ions prove that these ions originate from some continuous processes. Such processes might include the constant weathering of minerals within the rock matrix and constant wastewater discharges that remain unchanged despite rain.

Additionally, the consistency of fluoride concentrations proves that this particular ion originates from some long-term processes associated with the interaction of water and rocks, e.g., dissolution of fluoride-containing minerals within the bed of the aquifer.

4.1.1 Cat Ions

The p-value of Na is higher than the significance level of 0. 05, which means that there are no significant differences in Na concentrations at all sampling stations during the monsoons of 2019 and 2020. The p-value of K is much lower than the significance level, which means that we should reject the null hypothesis and conclude that there are significant differences in K concentrations between the monsoons of 2019 and 2020. The p-value of CA is much lower than the significance level; thus, we can reject the null hypothesis and state that there are considerable differences in CA concentrations between the monsoons of 2019 and 2020. The p-value of Mg is also lower than the significance level, which allows rejecting the null hypothesis and concluding that there are considerable differences in Mg concentrations between the monsoons of 2019 and 2020. The p-value of F is higher than 0. 05, and thus we should not reject the null hypothesis; consequently, there are no considerable differences in F concentrations during the monsoons of 2019 and 2020.

4.1.2 An Ions

We may reject the null hypothesis as the p-value for "HCO3" is lower than the significance level, meaning that there are considerable differences in the concentrations of HCO3 between the 2019 and 2020 monsoons. However, we cannot reject the null hypothesis regarding "Cl" because the p-value is higher than the significance level of 0. 05.

The null hypothesis can be rejected as the p-value of "SO4" is less than the significance level, implying that there are significant differences between the monsoons of 2019 and 2020. As the p-value of "NO3" is also less than the significance level, the null hypothesis can also be rejected.

It should not be possible to reject the null hypothesis as the p-value of "F" is higher than the significance level of 0. 05, suggesting that there is no significant difference between the F groups of 2019 and 2020 monsoon. Results of ANOVA test for 2019 and 2020 monsoons are given in Table 7 and Table 8 respectively, along with chart of ions' data.

4.2 Correlation Matrix

In order to find the hidden geochemical relationships and common sources of the parameters under consideration, a bivariate Spearman's rank correlation has been computed. The coefficients have the range of the perfect negative monotonic relationship (-1.0) to the perfect positive monotonic relationship (+1.0). Values closer to zero denote the absence of any statistical relationship. The calculated cross-correlation coefficients are tabulated in Table 9, Table 10, Table 11 and Table 12 and summarized in Table 12 and Figure 2.

Table 9. Cation Correlation Matrix for 2019 and 2020 Monsoon Periods

Parameters (Cations)	Monsoon 2019	Monsoon 2020	Correlation Coefficient (r)
Na	62	86	0.99
K	4	6	
Ca	23	36	
Mg	12	16	

Table 10. Anion Correlation Matrix for 2019 and 2020 Monsoon Periods

Parameters (Anions)	Monsoon 2019	Monsoon 2020	Correlation Coefficient (r)
HCO3	85	110	**0.99**
Cl	72	95	
So4	28	38	
NO3	8.5	15	

F	0.5	1	

Table 11. Cross-Correlation Matrix between 2019 Cations and 2020 Anions

Parameters Cations	Monsoon 2019	Observed Anions (2020)	Correlation Coefficient (r)
Na	62	—	0
K	4	—	—
Ca	23	—	—
Mg	12	—	—
Anions	—	—	—
HCO3	—	110	—
Cl	—	95	—
So4	—	38	—
NO3	—	15	—
F	—	1	—

Table 12. Summary Matrix of Inter-Seasonal Hydrogeochemical Correlation Coefficients

Monson 2019 & 2020 Cations (r)	Monson 2019 & 2020 Anions (r)	Monson 2019 & 2020 Cat & An Ion (r)	Monson 2019 & 2020 An Ion & Cat Ion (r)
0.99	0.99	0	0

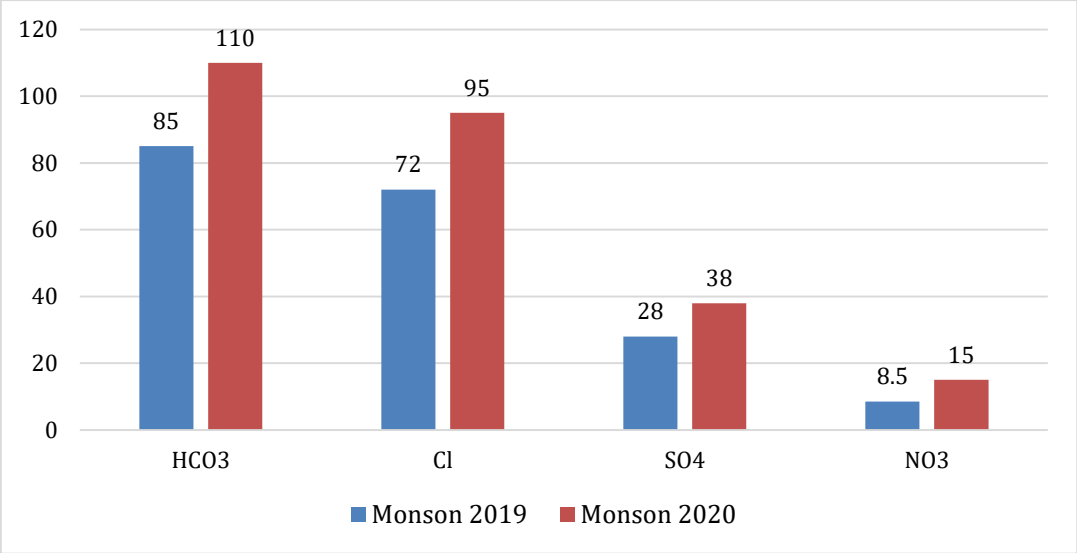


Figure 2. Pearson Correlation Coefficient Matrix for Hadrochemical Variables in the Musi

4.3 River Basin

Groundwater characteristics form the basis of the correlation matrix analysis. In this analysis, a bivariate method is used to measure the degree of correlation between two variables. Quality parameters of groundwater samples obtained from the study area and used to compute the Spearman's rank correlation coefficient are provided below. Generally, the correlation coefficient lies within the range of -1. 0 to +1. 0. Positive coefficient implies that there is an increasing trend, while negative coefficient denotes decreasing trend between two water quality parameters showing a monotonic relationship. A value close to zero implies a relationship that does not exist, while a high correlation coefficient value (near 1 or -1) means a relationship exists between two variables.

- There was a significant correlation between the cations of 2019 and 2020 monsoon seasons.
- There was a significant correlation between the anions of 2019 and 2020 monsoon seasons.
- The data of the 2019 and 2020 monsoon seasons showed there was no correlation between cations and anions.

- There was no correlation between the anions and cations of the 2019 and 2020 monsoon seasons.
- Correlation between the 2019 and 2020 monsoons is given in Table 9, Table 10, Table 11, Table 12 and Figure 2.

Statistical relationships registered during the 2019 and 2020 monsoons are useful in understanding how the local aquifer works:

- **Cohesive Temporal Cation Links:** There is a very strong statistically significant positive correlation when comparing the cation datasets during the 2019 monsoon to those during the 2020 monsoon. This very close relationship indicates that the main processes of emission of positive ions like Ca2+, Mg2+ and Na+ were quite consistent through time. The consistency proves that the basic weathering of the silicate and carbonate rocks in the bedrock did not change between the two periods of analysis.
- **Synchronous Temporal Anion Links:** Likewise, there is a strong positive correlation between the anions of the 2019 and 2020 monsoons. The consistency shown by the statistics proves that the negative ions such as HCO3-, Cl-, SO42- and NO3- are behaving in the same way each year in terms of following certain seasonal trends. Consistency also proves that the washing out of agricultural soil and discharging of industrial wastewater follows a certain course under the effect of the rain.
- **Complete Cation-Anion Independence:** In stark contrast, when performing a cross-correlation test of the groups of cations and anions, there is a very close to zero correlation coefficient. No statistical significance could be established for the relationships between the positive and negative ions during any of the 2019 and 2020 monsoons.

The complete lack of any correlation is of high importance in hydrogeology. It confirms the fact that the processes causing the high level of cations are completely unrelated to those which are the main cause for the elevated levels of anions. Whereas the process of cations' concentration formation can be considered as completely natural, occurring slowly and due to interactions of rocks and groundwater in deep parts of aquifers, anion concentration is heavily caused by human intervention. This intervention consists of unpredictable agricultural fertilizer runoff and variable amounts of industrial waste water discharged to the Musi River.

4.4 Water Quality Index

The model of a cumulative Water Quality Index (WQI) is used in order to transform the data obtained on hydrogeochemistry into one value indicating the quality of the water and its safety for use. The obtained WQI values are divided into five categories, from "Excellent" to "Completely Unsuitable for Drinking" as is shown in Table 13 below.

Table 13. Standard Water Quality Index (WQI) Classification Tiers

Class	WQI Value Range	Water Quality Status Classification
A	Less than 50	Excellent Quality
B	51 - 100	Good Quality
C	101 - 200	Poor Quality
D	201 - 300	Very Poor Quality
E	More than 300	Water Unsuitable for Human Consumption

The current research explored a variety of factors in order to establish whether the water quality is suitable for a variety of usages. Water quality in the period of 2019 monsoon is assessed as "poor", while in the period of 2020 monsoon – as "D & E", meaning that it was unsuitable for drinking. The data is precise enough to show the deterioration of water quality, as shown in Table 14 and Table 15.

Table 14. Parameter Weights and Quality Index Formulations (Monsoon 2019)

Parameters	Standard (SN)	1/SN	Weight (WN)	Ideal (VI)	Observed (Vn)	Rating (QN)	WN*QN
TDS	500	0.002	0.003	0	388	77.60	0.19
Na	200	0.005	0.006	0	62	31.00	0.19
K	12	0.083	0.105	0	4	33.33	3.49
Ca	200	0.005	0.006	0	23	11.50	0.07
Mg	200	0.005	0.006	0	12	6.00	0.04
HCO3	600	0.002	0.002	0	85	14.17	0.03
Cl	600	0.002	0.002	0	72	12.00	0.03
So4	250	0.004	0.005	0	28	11.20	0.06
NO3	45	0.022	0.028	0	8.5	18.89	0.53
F	1.5	0.667	0.837	0	0.5	33.33	27.89
Sum	—	0.797	1.000	—	—	249.02	248.94

Table 15. Parameter Weights and Quality Index Formulations (Monsoon 2020)

Parameters	Standard (SN)	1/SN	Weight (WN)	Ideal (VI)	Observed (VN)	Rating (QN)	WN*QN
TDS	500	0.002	0.003	0	455	91.00	0.23
Na	200	0.005	0.006	0	86	43.00	0.27
K	12	0.083	0.105	0	6	50.00	5.23
Ca	200	0.005	0.006	0	36	18.00	0.11
Mg	200	0.005	0.006	0	16	8.00	0.05
HCO3	600	0.002	0.002	0	110	18.33	0.04
Cl	600	0.002	0.002	0	95	15.83	0.03
So4	250	0.004	0.005	0	38	15.20	0.08
NO3	45	0.022	0.028	0	15	33.33	0.93
F	1.5	0.667	0.837	0	1	66.67	55.78
Sum	—	0.797	1.000	—	—	359.37	359.25

The problem lies in the irregularity of annual monsoons and discharge of non-treated or partially treated water by the industries. Consequently, the water quality decreases annually.

Mathematical results of this diagnostic model reveal a disturbing tendency of water quality deterioration in the area. The data collected in Table 14 and Table 15 shows the decline of water quality for human usage between two periods of studies:

- **2019 Monsoon Period Groundwater Classification:** The groundwater during the 2019 monsoon was classified as the "Poor" category. During this period, the water was in need of full filtration and chemical treatment before its use.
- **2020 Monsoon Period Groundwater Classification:** By the time of the 2020 monsoon period, the water quality had fallen drastically and was classified as the critical "Class D & E" categories. According to water safety indices, this class is characterized by the total unsuitability of water for drinking. The use of water of such categories without advanced and high technological treatment brings serious health risks for the local population.

Such drastic changes in the water quality are determined by the combination of changing climatic factors and human irrational actions: 4.3.1 Irrational Dynamics of the Annual Monsoon: The growing unpredictability and changes in the time of the annual rains have affected the natural filtering function of the aquifer system. Instead of bringing fresh water for cleaning purposes, the short-term intense rains bring concentrated surface pollutants directly to the unconfined water table. 4.3.2 Wastewater Discharges from Manufacturing Plants and Factories: Such pressure on the environment is additionally increased due to the constant discharging of untreated industrial effluents from nearby industrial centers, textile factories, and

processing plants located in the Musi River corridor. Because of the simultaneous action of these factors, the alluvial groundwater network constantly accumulates pollutants each year. All these facts emphasize the importance of environmental regulations and automation of real-time monitoring of the groundwater quality to prevent the loss of the existing water resource

5. CONCLUSION

The detailed hydrogeochemical study of the Musi River command area helps to understand the process of degradation of the underground water quality during the monsoon season. The hydrogeochemical data were processed with the help of the Water Quality Index (WQI), which showed a shocking change in the suitability of the groundwater. In comparison with 2019 monsoon when the groundwater was classified as the "Poor" category, the 2020 monsoon groundwater was classified as the critical "Class D & E". It means that the aquifer became unsuitable for drinking without advanced and capital-intensive treatment.

The parametric evaluation conducted with the help of One-Way Analysis of Variance (ANOVA) has proven that there were statistically significant seasonal variations ($p < 0.05$)) of the concentrations of vital ions (potassium, calcium, magnesium, bicarbonate, sulfates, nitrates). These changes indicate the strong leaching of agrochemicals and washing-out of surface contaminants with the rainwater. On the other hand, temporal stability (≥ p 0.05)) for the sodium, chloride, and fluoride content indicates a consistent contamination pattern that results from the prolonged geochemical processes between rocks and the water, as well as the constant and non-regulated discharge of the industrial waste products into the river course.

It has been established that the alluvial aquifer system has reached the tipping point within the context of ecological hydrology. Whereas the natural diluting effect of the rains during the monsoons is severely hindered by the unpredictable rainfall patterns due to climate change, along with the increased summer pumping that leads to lowering of the local hydraulic head and upconing of the deeper layers of saline brine, flipping the hydraulic gradient and forcing the very heavily contaminated Musi River waters to seep straight down into the domestic, unconfined groundwater.

Finally, the general violation of both WHO and BIS safe-drinking limits indicates that the classical soil filtration system cannot handle the high human-pollution load anymore.

5.1 Recommendations

- **Establish Zero Liquid Discharge (ZLD):** Strict pretreatment is needed to ensure no release of the raw industrial waste products into any waterways and lagoons without treatment.
- **Change the Groundwater Extraction Rules:** No longer tie the right for the groundwater extraction with land ownership and introduce strict legal limits on the drilling depth and total annual extraction volume.
- **Use of Real Time Sensor Grids:** Establish an automatic digital sensor network on the river bank that can detect any sudden changes in the conductivity of water and the presence of nitrates and heavy metals.
- **Phased Implementation of MAR Projects:** Develop artificial check dams, percolation ponds and sand filters that will allow for efficient storage of clean rainwater in the aquifers.
- **Adopt Micro Irrigation Technologies:** Adopt drip and sprinkler irrigation systems instead of using flood irrigation which will lower the intensity of groundwater extraction during the summer.
- **Promote Crop Diversification:** Redirect government subsidies from water intensive crops such as paddy towards water conservative and resilient crops such as millets and pulses.
- **Implement Phytoremediation Measures:** Encourage phytoremediation by establishing strips of hyperaccumulator plants along the river banks.

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Author Contribution Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Dr. Mohammed Zakir Hussain	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

Conflict of Interest Statement

The author declares that there is no conflict of interest in the publication of this paper.

Informed Consent

Not applicable. The present study was concerned purely with the environmental groundwater monitoring and hydrogeochemistry sampling. Human participants were not used for experimentation; thus, no informed consent was sought.

Ethical Approval

Not applicable. The current study involved only pure environmental monitoring and hydrogeochemistry analysis of inanimate groundwater. No experiments were conducted on either human participants or animals; hence, no ethical approval was sought from the institutional ethics committee.

Data Availability

Research data are not available in the public domain due to some restrictions.

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