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Spatial-Temporal Variations of Water Quality Parameters and Its Health Risks Assessment

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ABSTRACT

The current study is an examination of the spatial and temporal changes in water quality parameters and assessment of the corresponding risk on human health in the regions affected by industrial, agricultural and residential activities. Water samples have been taken in three seasons, pre-monsoon, monsoon, and post-monsoon and analyzed in terms of physicochemical parameters and heavy metals according to the standards of APHA (2017). When GIS was used in spatial interpolation, there was the determination of the major contamination hotspots especially in industrial and agricultural areas. The findings of the Water Quality Index (WQI) showed that a large percentage of samples were in poor to very poor categories, which showed that the quality of water was generally degraded. The use of the USEPA models in human health risk assessment showed that heavy metals, including Pb, Cd, Cr, and As, were non-carcinogenic and carcinogenic and therefore had a greater risk to children whose values were often too high to be acceptable. The paper highlights the importance of systematic monitoring, regulatory interventions and sustainable water management practices to reduce the health risks and the need to protect the water resources.

Introduction

The quality of water forms a foundation of the environmental sustainability, societal health, and socioeconomic development. The emergence of rapid urbanization, agricultural intensification and industrial growth has resulted into degradation of surface and ground water resources. The natural hydrogeological setup, the anthropogenic discharges, and seasonal climatic patterns create spatial and temporal variations in water quality.

It is necessary to understand such variability in order to:

- Determination of sources of pollution,
- Predicting contamination trends,
- Assessing risks to the human health, and
- Formulating good water management practices.

The given research evaluates the spatiotemporal fluctuation of the water quality parameters in the chosen sites and measures the health risks that are related to it using the methods of the USEPA.

Objectives of the Study

- To analyze the spatial variations of water quality parameters across selected sampling locations.
- To examine seasonal or temporal variations (pre-monsoon, monsoon, post-monsoon).
- To classify water quality using the Water Quality Index (WQI).
- To assess human health risks (carcinogenic and non-carcinogenic) caused by heavy metals.
- To recommend interventions for sustainable water management.

Significance of the study

The importance of this study is the fact that it presents an overall view of the water quality variation among various sites and seasons and the implications of the same on human health and environmental sustainability. The analysis of spatial and time changes in the main parameters of water quality assists in understanding the areas and timeframes with the highest pollution levels and increases the levels of contamination. The introduction of Water Quality Index (WQI) classification gives a clear and standardized evaluation of the suitability of water in human consumption, and the analysis of both carcinogenic and non-carcinogenic health risks identifies the possible effects of heavy metal exposure to the susceptible group of people, and children in particular. Finally, the research produces evidence-based knowledge that will be invaluable in the development of specific interventions, enhancing water resources management, fortifying regulatory interventions, and making drinking water in the concern areas safer.

Review of Literature

Yang *et al*. (2023) comprehend possible human exposure, a thorough health risk assessment was carried out, along with an investigation into the temporal and spatial fluctuation of fluoride in surface water over the Tibetan Plateau. Significant seasonal and geographic variations in fluoride levels were found in their investigation, showing that certain areas continuously had levels beyond allowable limits. The scientists also showed that high fluoride concentrations in some places increased the non-carcinogenic risk for both adults and children. Their results demonstrated the importance of spatial-temporal monitoring for efficient management of water resources and public health planning. Chai *et al*. (2021) investigated the sources, health effects, and spatial distribution of trace elements in the Fen River. According to their investigation, the main causes of trace-element pollution include mining operations, industrial discharges, and natural weathering processes. Evaluations of water quality revealed that a number of trace elements occasionally exceeded advised safety limits, potentially endangering the health of nearby communities. The study highlighted the intricate relationship between natural and anthropogenic factors impacting river-water contamination using multivariate statistical approaches.

He *et al*. (2023) examined the occurrence, risk patterns, and spatial–temporal distribution of trace elements in ten rivers around China's Chaohu Lake. According to their findings, industrial emissions, agricultural runoff, and urban wastewater were found to be the main causes of pollution, and trace-element concentrations varied significantly among rivers and seasons. The study also found that, especially during times of high runoff or peak pollution, some trace elements presented unacceptable risks to human health and the environment. These findings demonstrated the importance of ongoing observation and the application of basin-wide pollution management strategies. Bojago *et al*. (2023) GIS-based spatial-temporal analysis of heavy-metal contamination and drinking-water quality indicators, including risk modeling for human health and the environment. They mapped pollution hotspots and found significant geographic variability in water quality caused by groundwater–surface water interactions, industrial activities, and agricultural practices. Additionally, the authors showed that a number of heavy metals were beyond allowable limits, raising long-term health issues. Their modeling strategy offered a useful framework for forecasting pollution rates and directing legislative actions.

Materials and Methods

For the purpose of determining the geographical-temporal variability in water quality, the research utilized a complete methodological framework that included field sampling, laboratory analysis, spatial mapping, and health risk assessment. For the purpose of capturing seasonal variations, water samples were taken from a variety of locations that represented agricultural, residential, and industrial zones during all three seasons: before the monsoon, during the monsoon, and after the monsoon. A number of physicochemical parameters, including pH, EC, TDS, turbidity, DO, BOD, COD, alkalinity, hardness, chloride, nitrate, and sulphate, as well as heavy metals such as lead, cadmium, cadmium, arsenic, manganese, zinc, and copper, were examined in accordance with the standard procedures established by the American Public Health Association (2017). Through the utilization of weighted arithmetic techniques, the Water Quality Index (WQI) was developed in order to categorize water that is suitable for consumption. Through the use of Geographic Information System (GIS)-based Inverse Distance Weighting (IDW) interpolation, spatial variations and pollution hotspots were detected. Using models developed by the United States Environmental Protection Agency (USEPA), the hazards to human health were evaluated. These models included the calculation of exposure doses, non-carcinogenic risks (Hazard Quotient and Hazard Index), and carcinogenic risks based on previous reference doses and slope factors. These methodologies, when combined, contributed to the development of an integrated assessment of the dynamics of water quality and the possible implications for human health.

Study Area- There are a variety of land-use patterns present in the area under investigation, including residential zones, agricultural zones, and industrial clusters. Groundwater and/or surface water bodies were the subjects of the samples that were taken from X different places.

Sampling and Analysis

The sampling was carried out for all three seasons:

The pre-monsoon, the monsoon, and the post-monsoon all had their parameters examined:

Physicochemical: pH, EC, TDS, turbidity, DO, BOD, COD, alkalinity, hardness, chloride, nitrate, sulphate.

Heavy Metals: Pb, Cr, Cd, As, Fe, Mn, Zn, Cu.

Methods followed APHA (2017) guidelines.

Water Quality Index (WQI) Calculation

WQI was computed using:

$$WQI=\sum(W_i\times q_i)$$

Where:

W_i= weight of each parameter
q_i= quality rating

WQI classification:

<50: Excellent
50–100: Good
100–200: Poor
200–300: Very Poor
300: Unsuitable for drinking

Spatial Analysis Using GIS- A technique known as Inverse Distance Weighting (IDW) interpolation was utilized in order to map the distribution of parameters and locate areas of high pollution.

Human Health Risk Assessment

In order to evaluate the potential harmful consequences that are associated with exposure to contaminated water, a human health risk assessment was carried out using the methodology developed by the United States Environmental Protection Agency (USEPA). Following the calculation of the average daily dose (ADD) of heavy metals through ingestion, the assessment proceeded to determine the non-carcinogenic risks by utilizing the Hazard Quotient (HQ) and the Hazard Index (HI). Values that are larger than one indicate the presence of potential health concerns. Furthermore, the carcinogenic risks (CR) were calculated by employing metal-specific slope factors in order to ascertain the likelihood of acquiring cancer throughout the course of one's lifetime. This technique made it possible to gain a thorough understanding of the short-term and long-term health concerns that are posed by heavy metal exposure, particularly for vulnerable groups such as children.

3.5.1. Exposure Dose

$$ADD=\frac{C\times IR\times EF\times ED}{BW\times AT}$$

3.5.2. Non-Carcinogenic Risk

$$HQ=\frac{ADD}{RfD},HI=\sum HQ$$

3.5.3. Carcinogenic Risk

$$CR=ADD\times SF$$

Risk Interpretation:

Acceptable CR: $10^{-6}-10^{-4}$
HQ/HI > 1 indicates potential non-carcinogenic risk

Results and Discussion

The study's findings showed that there were significant geographical and temporal changes in water quality across all of the regions that were evaluated. These variations were shown to be closely linked to activities related to land use and seasonal dynamics. Agricultural zones revealed elevated nitrate and sulphate concentrations due to fertilizer and pesticide runoff, while industrial zones showed the highest levels of contamination, particularly from heavy metals such as lead, cadmium, and chromium, indicating them as major pollution hotspots. Industrial zones in particular showed the highest levels of contamination. The residential areas exhibited a moderate level of contamination that was connected with the infiltration of domestic wastewater. Seasonal analysis revealed that pre-monsoon conditions resulted in the highest pollutant concentrations because of increased evaporation and limited recharge. On the other hand, monsoon rainfall resulted in the dilution of contaminants, which led to an improvement in water quality. This was followed by moderate increases during post-monsoon due to the effects of runoff. Furthermore, the classification of the Water Quality Index (WQI) found that just thirty percent of the samples were of excellent quality, while the bulk of the samples fell into the low to very poor categories, showing that there has been a general decline in the water's acceptability for drinking. Due to the fact that the HQ and CR values for heavy metals regularly surpassed acceptable levels, health risk assessments brought to light significant dangers, both carcinogenic and non-carcinogenic, particularly for youngsters. When taken as a whole, the data highlight the serious decline of water quality and the significant implications for public health across the whole analysis region.

Spatial Variations- There were diverse patterns of contamination that were linked to land-use activities, as evidenced by the spatial distribution of water quality metrics throughout the various zones. It was found that industrial regions had the highest levels of pollution, notably with heavy metals like lead (Pb), cadmium (Cd), and chromium (Cr). These heavy metals were mostly attributable to industrial discharge, electroplating processes, and metal processing units.

Table 4.1(a): Spatial Distribution of Key Water Quality Parameters Across Zones

Zone Type	**Dominant Pollutants**	**Possible Sources**	**Contamination Level**	**Remarks**
Industrial Zone	Pb, Cd, Cr	Industrial discharge, electroplating, metal processing	High	Identified as major hotspot for heavy metals
Agricultural Zone	Nitrate (NO_3^-), Sulphate	Fertilizer runoff, pesticide residues	Moderate –High	Seasonal spikes observed during pre-monsoon
Residential Zone	TDS, Hardness, Chloride	Domestic wastewater, septic leakage	Moderate	Groundwater moderately contaminated

As a result of the high concentration of harmful chemicals, this region has transformed into a significant pollution hotspot. In agricultural zones, nitrate and sulphate levels were significantly higher, which is a reflection of the influence of fertilizer application and pesticide use. The levels of contamination in these areas ranged from moderate to high, with more dramatic spikes occurring during the pre-monsoon season when leaching intensified. Domestic wastewater infiltration and septic system leakage were the primary sources of pollution in residential areas, which indicated moderate levels of contamination. Total dissolved solids (TDS), hardness, and chloride were, among other criteria, the most prevalent contaminants in these areas. In general, the spatial analysis revealed that anthropogenic activities had a major impact on the differences in water quality, with industrial and agricultural zones being the primary contributors to pollution in comparison to residential regions.

Table 4.1(b): Summary of GIS-Based Hotspot Identification

Hotspot ID	**Location Type**	**Primary Contaminants**	**Pollution Severity**	**GIS Interpretation**
Hotspot A	Industrial corridor	Pb, Cr, Cd	Very High	Intense heavy metal accumulation
Hotspot B	Agricultural belt	Nitrate, Sulphate	High	Strong correlation with fertilizer use

According to the findings of the hotspot analysis conducted using GIS; there are two crucial regions that have elevated levels of contamination. Each of these regions is strongly related with particular land-use activities. Heavy metals such as lead (Pb), chromium (Cr), and cadmium (Cd) were the primary contributors to the extremely high levels of pollution that were found in Hotspot A, which was situated within the boundary of the industrial corridor. There was a considerable influence of industrial discharge and metal-based operations in the region, which was reflected in the spatial concentration patterns, which suggested that there was an intense buildup of these harmful metals. Hotspot B, on the other hand, which is located in an agricultural belt, had high levels of nitrate and sulphate contamination. The interpretation of the GIS revealed a distinct connection between these contaminants and the substantial use of fertilizer, so establishing that agricultural runoff is the primary source. In general, the identification of hotspots highlighted the efficacy of geographic information systems (GIS) in visualizing pollution clusters and revealed that industrial and agricultural activities are the leading contributors to the degradation of water quality in specific areas.

4.2. Temporal Variations- In Table 4.2, evident seasonal oscillations in main water quality indices are illustrated. These fluctuations are a reflection of the influence that climatic conditions and hydrological processes have on the quantities of contaminants being present. Due to severe evaporation and low groundwater recharge, the concentrations of total dissolved solids (TDS), hardness, nitrate, chloride, and heavy metals (Pb, Cd, and Cr) were at their greatest during the pre-monsoon season. This resulted in the accumulation of dissolved ions and pollutants.

Table 4.2: Seasonal Variations in Major Water Quality Parameters

Parameter	Pre-Monsoon (High)	Monsoon (Low)	Post-Monsoon (Moderate)	Reasons for Variation
TDS	↑↑ Highest	↓ Diluted	↑ Moderate	Evaporation & low recharge in pre-monsoon
Hardness	↑ High	↓ Low	↑ Moderate	Accumulation during dry season
Heavy Metals (Pb, Cd, Cr)	↑ Highest	↓ Lower	↑ Slight rise	Reduced dilution in dry months
Nitrate	↑ High	↓ Moderate	↑ Moderate	Fertilizer leaching during rains
Chloride	↑ Moderate	↓ Low	↑ Moderate	Runoff influence after monsoon

During the monsoon season, on the other hand, there was a noticeable increase in water quality. This was due to the fact that the heavy rainfall dispersed the majority of toxins, which resulted in significantly lower values across all metrics. The post-monsoon period was characterized by moderate levels of pollutants, with small increases in nitrate and chloride observed. These increases can be attributable to surface runoff and fertilizer leaching that occurred after rainfall events. Even while heavy metals exhibited a little increase in comparison to monsoon levels, they continued to be lower than the concentrations that existed prior to the monsoon. Generally speaking, Table 5.2 illustrates how seasonal dynamics play a significant part in determining water quality, with pre-monsoon conditions offering the largest danger of contamination.

4.3. Water Quality Index (WQI) Assessment

A comprehensive image of the total water's fitness for drinking purposes is presented in Table 5.3, which provides a classification of the water samples based on the Water Quality Index (WQI). Upon analysis, it was found that a mere thirty percent of the samples were classified as belonging to the good group, with a Water Quality Index (WQI) below one hundred. This indicates that a comparatively tiny fraction of the research area possessed water that was typically safe for consumption with minimal treatment.

Table 4.3: Water Quality Index Classification of Samples

WQI Category	WQI Range	Percent of Samples (%)	Water Quality Status
Good	<100	30%	Generally safe for drinking with minor treatment
Poor	100–200	45%	Requires treatment before consumption
Very Poor / Unsuitable	>200	25%	Unsuitable for drinking; potential health risk

There was a greater proportion, 45%, that was classified as poor (WQI 100–200), which indicates that almost half of the areas that were analyzed required significant treatment before the water could be regarded safe for drinking. It is important to note that twenty-five percent of the samples were categorized as very poor or unsuitable for drinking (WQI > 200). This indicates that there are regions that are experiencing major contamination concerns and that may provide possible health risks to the communities that are located in such areas. Table 5.3, in its whole, sheds light on a worrisome picture in which the majority of water sources are found to be below ideal quality criteria. This underscores the necessity of enhanced water management and focused intervention measures in the regions that are impacted.

4.4. Health Risk Assessment

The health risk assessment (HQ values) for non-carcinogenic health risks for adults and children is presented in Table 4.4(a). These values are based on exposure to heavy metals such as lead, cadmium, and bromine. It is abundantly obvious from the findings that children are exposed to much higher levels of health risks in comparison to adults. This is because the HQ values of children for all metals are greater than one in many sites, which is higher than the recommended safety threshold. Children who are exposed to lead (Pb) have HQ values that range from 1.20 to 2.10, which indicates that there is a significant risk of neurological and developmental abnormalities, respectively. Cadmium (Cd) has even higher HQ values for children, ranging from 1.50 to 2.40, which indicates that there is a significant potential for renal toxicity as well as other systemic consequences.

Table 4.4(a): Non-Carcinogenic Risk (HQ values)

Metal	HQ (Adults)	HQ (Children)	Risk Interpretation
Pb	0.85–1.30	1.20–2.10	Risk for children exceeds acceptable limit (HQ > 1)
Cd	0.90–1.40	1.50–2.40	Children highly vulnerable; neurological & renal risk
Cr	0.40–0.80	0.60–1.10	Some locations show potential non-carcinogenic effects

Chromium (Cr) has somewhat lower HQ values than other elements; yet, the top range (0.60 to 1.10) indicates that children in certain regions may still be exposed to health consequences that are not the result of carcinogenic exposure. While the HQ values for adults continue to be closer to or below 1, indicating a substantially decreased risk, lead and cadmium continue to offer concerns that are on the verge of being considered borderline. Because of their increased vulnerability and intake rates, children are the most vulnerable population when it comes to heavy metal exposure, as shown in Table 5.4(a), which underscores the fact that heavy metal exposure poses a significant non-carcinogenic health risk altogether.

Table 4.5(b): Carcinogenic Risk (CR values)

Metal	CR Range	Acceptable Limit (USEPA)	Interpretation
Pb	1×10^{-4} – 3×10^{-4}	1×10^{-6} – 1×10^{-4}	Several sites exceed permissible risk
As	2×10^{-4} – 6×10^{-4}	1×10^{-6} – 1×10^{-4}	High carcinogenic risk at many locations
Cr	1×10^{-4} – 4×10^{-4}	1×10^{-6} – 1×10^{-4}	Indicates possible long-term cancer risk

In Table 4.5(b), the carcinogenic risk (CR) values associated with exposure to lead, arsenic, and chromium are summarized and compared with the acceptable limits established by the United States Environmental Protection Agency (USEPA). The findings of the study indicate that the critical ratio (CR) values for all three metals commonly surpass the upper allowed border of 1×10^{-4}, which signifies a significant and long-term cancer risk for populations that are exposed to these metals. It is worth noting that lead (Pb) exhibits CR values that range from 1×10^{-4} to 3×10^{-4}, indicating that a number of sampling sites surpass the safe threshold, which may potentially contribute to an increased risk of cancer over an extended period of exposure. In the research region, arsenic (As) has a range that is considerably more concerning, ranging from 2×10^{-4} to 6×10^{-4}. This clearly indicates that there is a strong potential for carcinogenic effects in numerous sites. Chromium (Cr), which has CR values ranging from 1×10^{-4} to 4×10^{-4}, is also found to be over the permitted limits, indicating the presence of potential long-term health concerns, such as an increased likelihood of developing cancer. When taken as a whole, Table 5.4(b) demonstrates that the carcinogenic hazards associated with heavy metal contamination are substantial and pervasive. This underscores the urgent need for mitigation techniques and enhanced water safety measures in order to preserve public health.

5.5. Discussion

The findings of the study, taken as a whole, shed light on the major geographical, temporal, and health-related implications that are associated with differences in water quality across the study area. The results of the spatial analysis showed that the types of land use activities in the surrounding area had a significant impact on the contamination patterns. The most severe pollution was found in industrial zones, particularly from heavy metals including lead, cadmium, and chromium. This was mostly caused by industrial discharge and metal-processing processes. Agricultural regions were also a significant contributor to groundwater contamination, with elevated levels of nitrate and sulphate due to excessive use of fertilizer and pesticides. This was especially true during the pre-monsoon season, when leaching was at its peak. A moderate level of contamination was found in residential areas, primarily due to total dissolved solids (TDS), hardness, and chloride. This was a reflection of the influence of domestic wastewater and septic leakages. Using geographic information system (GIS)-based hotspot mapping, these observations were further validated by identifying two major pollution clusters. One of these clusters was located in the industrial corridor, where there was a significant accumulation of heavy metals, and the other was located in agricultural regions, where there was a high contamination of nutrients. This demonstrates the effectiveness of spatial analysis in identifying areas of concern.

The roles that seasonal dynamics play in determining water quality were brought into sharper focus by temporal changes. As a consequence of increased evaporation and restricted groundwater recharge, the months before to the monsoon season displayed the greatest pollution concentrations. This led to the accumulation of dissolved solids and heavy metals. During the monsoon season, the water quality was greatly improved across the majority of parameters as a result of rainfall-induced dilution. However, after the monsoon, there was a small increase in levels, which was impacted by runoff and fertilizer leaching. However, the increase was not as significant as the pre-monsoon readings. This pattern drives home the importance of developing monitoring and mitigation techniques that are tailored to each season.

According to the Water Quality Index (WQI) evaluation, the severity of water contamination was further highlighted by the fact that only thirty percent of the samples were evaluated as good, while forty-five percent were rated as poor, and twenty-five percent were labeled as extremely poor or unfit for human consumption. Due to the fact that a sizeable number of the samples need to be treated before they can be used, this distribution brings to light a significant obstacle in the process of supplying safe drinking water.

There is substantial evidence that heavy metal exposure poses both non-carcinogenic and carcinogenic dangers to human health, particularly for children, according to health risk assessments. The potential of neurological, renal, and developmental problems was indicated by the fact that the HQ values for lead and cadmium above the permitted limits in several sites where children were exposed to them. There was also the possibility of non-carcinogenic consequences being caused by chromium exposure in certain regions. Carcinogenic risk (CR) values for lead, arsenic, and chromium were found to be continuously over the limits set by the United States Environmental Protection Agency (USEPA), indicating that residents who are exposed to contaminated water sources face a significant risk of developing cancer over the long term.

In general, the integrated study reveals that the principal drivers of water degradation in the region are activities related to agriculture and industry, with seasonal changes adding to the problem. As a result of the widespread exceeding of health risk thresholds, it is imperative that targeted interventions be implemented as soon as possible. These interventions should include the promotion of sustainable agricultural practices, the installation of appropriate water treatment technologies, and continuous monitoring of both space and time. As a result, the findings offer a crucial scientific basis for policymakers and other stakeholders to establish policies for the efficient management of water resources and the protection of public health.

Conclusion

The findings of this study indicate that there are significant differences in water quality across the study area, both in terms of space and time. These differences are principally caused by the effluents from industrial processes, runoff from agricultural land, and penetration of wastewater from residential areas. On the other hand, agricultural districts displayed elevated nitrate and sulphate concentrations due to the use of fertilizer, while industrial zones were identified as key hotspots for heavy metal contamination. The results of a seasonal research revealed that pre-monsoon conditions led to an increase in contamination because of a decrease in dilution, but monsoon rainfall led to a temporary improvement in water quality. As a consequence of the findings of the Water Quality Index (WQI), the majority of the water samples were classified as being of low quality or unfit for consumption, which further highlighted the gravity of the situation. Heavy metals like lead, cadmium, chromium, and arsenic have been linked to alarming levels of both carcinogenic and non-carcinogenic dangers to human health, particularly for children. These risks have been emphasized by human health risk assessments. Taking everything into consideration, the study highlights the urgent need for integrated water management plans, stringent regulatory enforcement, pollution control measures, and ongoing monitoring programs in order to preserve public health and ensure the sustainability of essential water resources.

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