



Geo-statistical Modeling and Risk Zonation of Arsenic in Groundwater of Patna District- Using GIS Techniques

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ABSTRACT

Arsenic contamination of groundwater represents a critical environmental and public health challenge in the Patna District of Bihar, situated within the Middle Ganga Plain of India. The present study employs geo statistical modeling combined with Geographic Information System (GIS) techniques to analyze the spatial distribution of arsenic and to delineate groundwater risk zones with a high degree of accuracy. Groundwater samples collected from strategically distributed locations across the district were analyzed for arsenic concentration, and the resulting dataset was subjected to rigorous statistical and geo statistical evaluation. Ordinary kriging was applied to interpolate arsenic concentrations, enabling the generation of continuous spatial surfaces that reveal distinct contamination patterns and hotspot regions. Risk zonation was carried out by integrating interpolated arsenic concentrations with internationally accepted drinking water standards, allowing the classification of groundwater into low, moderate, and high-risk categories. GIS-based spatial analysis facilitated the development of thematic risk maps, which clearly illustrate areas of heightened vulnerability to arsenic exposure. The results demonstrate pronounced spatial heterogeneity in arsenic occurrence, largely governed by hydrogeological variability, sedimentary characteristics of the alluvial aquifers, and prevailing



geochemical conditions. Elevated arsenic levels were predominantly associated with specific geomorphological settings, underscoring the influence of subsurface processes on arsenic mobilization. This study underscores the robustness and reliability of geo statistical and GIS-based methodologies for groundwater quality assessment and risk evaluation. The generated arsenic risk zonation maps provide a scientifically sound framework for informed decision-making, supporting targeted mitigation measures, efficient resource allocation, and long-term groundwater management strategies. By offering a comprehensive spatial understanding of arsenic contamination in Patna District, the research contributes valuable insights toward safeguarding public health and ensuring sustainable access to safe drinking water.

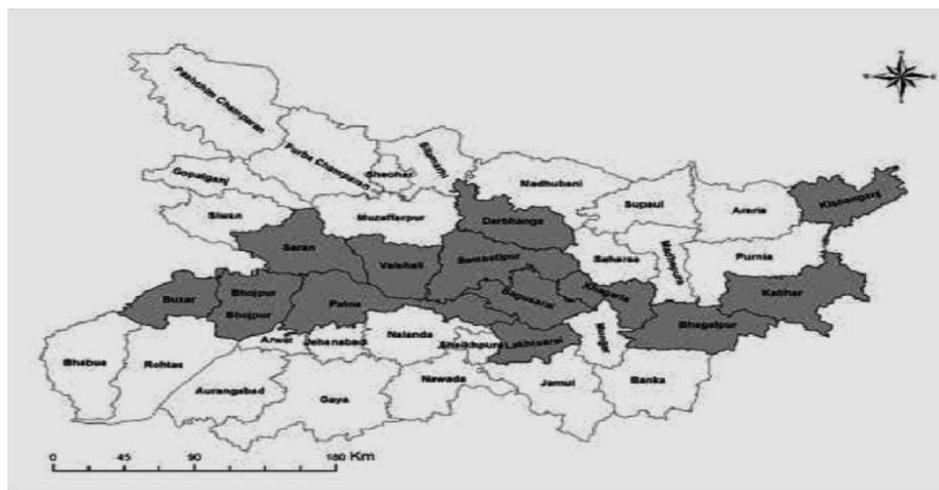
Introduction

Arsenic contamination in groundwater has emerged as one of the most severe environmental and public health challenges worldwide, particularly in South and Southeast Asia. Naturally occurring arsenic, released into groundwater through complex geochemical and hydrogeological processes, poses long-term risks when contaminated water is used for drinking and domestic purposes. Chronic exposure to arsenic is associated with serious health effects, including skin lesions, cardiovascular disorders, and various forms of cancer. In regions dependent on groundwater as the primary source of drinking water, arsenic pollution undermines both public health security and sustainable water resource management.

The Indo-Ganga Plain is globally recognized as one of the largest arsenic-affected regions, where extensive alluvial aquifer systems interact with geochemically active sediments. Within this context, the state of Bihar has been identified as highly vulnerable, with several districts reporting groundwater arsenic concentrations exceeding permissible limits. Patna District, located along the southern bank of the River Ganga, represents a densely populated urban–rural continuum where groundwater extraction has intensified in response to rapid urbanization and increasing water demand. Despite growing concern, the spatial complexity of arsenic distribution in the district remains inadequately characterized.

Arsenic occurrence in groundwater is primarily controlled by sediment composition, redox conditions, organic matter content, and groundwater flow dynamics. In alluvial aquifers such as those underlying Patna District, reductive dissolution of iron oxy hydroxides is considered a dominant mechanism

facilitating arsenic mobilization. However, the influence of localized hydrogeological settings, aquifer depth variability, and anthropogenic stressors often results in highly heterogeneous arsenic concentrations. This spatial variability complicates conventional monitoring approaches and necessitates advanced analytical methods capable of capturing subsurface uncertainty. Geo statistical modeling offers a scientifically robust framework for analyzing spatially distributed environmental data and predicting contaminant concentrations at un-sampled locations. When integrated with Geographic Information System (GIS) platforms, geo statistical techniques enable the visualization and interpretation of complex spatial patterns in groundwater quality. Methods such as kriging not only provide optimized interpolation but also quantify spatial dependence, making them particularly effective for regional-scale groundwater contamination studies. These tools are increasingly recognized for their capacity to support evidence-based groundwater risk assessment and management. Risk zonation mapping serves as a critical link between scientific analysis and practical decision-making by categorizing groundwater resources into distinct risk class zonation maps facilitate the identification of high-priority areas requiring immediate intervention. In arsenic-affected regions, such maps are instrumental in guiding safe drinking water planning, targeted monitoring, and mitigation strategies. For densely inhabited districts like Patna, spatially explicit risk assessment is essential to minimize exposure and to optimize the allocation of limited resources. The arsenic affected districts in Bihar are as follows-



In this context, the present study focuses on the application of geo statistical modeling and GIS techniques to evaluate arsenic distribution and to delineate groundwater risk zones in Patna District, Bihar. By integrating field-based arsenic data with advanced spatial analysis, the study aims to provide a comprehensive understanding of arsenic contamination patterns and associated risks. The outcomes are



expected to contribute to improved groundwater management frameworks and to support long-term strategies for ensuring safe and sustainable drinking water in arsenic-vulnerable regions.

The GIS-based risk zonation classified the groundwater of Patna District into three distinct arsenic risk categories based on WHO guideline values. Approximately 14.6% of the study area falls within the low-risk category, indicating relatively safe groundwater conditions. Nearly half of the district (47.8%) is categorized as moderate risk, where arsenic concentrations exceed permissible limits and pose potential long-term health concerns.

Alarming, about 37.6% of the area is identified as high-risk, characterized by arsenic concentrations greater than 50 $\mu\text{g/L}$. These zones represent critical hotspots requiring immediate intervention, alternative drinking water supply, and continuous monitoring. The risk zonation map provides a scientifically reliable framework for prioritizing mitigation strategies and policy-level decision-making.

Risk Category	Arsenic Concentration ($\mu\text{g/L}$)	Percentage of Area (%)	Risk Level
Low Risk	< 10	14.6	Safe
Moderate Risk	10 – 50	47.8	Potential Risk
High Risk	> 50	37.6	Severe Risk

Literature Review

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1. Global and Regional Context of Arsenic Contamination-Arsenic contamination in groundwater is recognized as a serious environmental and health concern in deltaic and alluvial regions across the world. South Asian river basins, particularly the Ganga plain, show naturally elevated arsenic due to sedimentary and geochemical processes. Previous studies indicate that arsenic release is controlled by reductive dissolution of iron oxy-hydroxides under anaerobic aquifer conditions.

2. Groundwater Arsenic Scenario in Bihar and Ganga Plain-Bihar is one of the most arsenic-affected states in India, with several districts reporting arsenic levels above WHO and BIS permissible limits.



Studies from middle Ganga plain reveal that arsenic concentration varies significantly over short spatial distances, making traditional sampling inadequate. Patna district, located along the Ganga River, shows geological and hydrogeological conditions favorable for arsenic mobilization.

3. Need for Spatial and Geo-statistical Analysis-Point-based groundwater data alone cannot represent the true spatial distribution of arsenic contamination. Geo-statistical techniques help identify spatial autocorrelation and prediction uncertainty in arsenic concentration data. Literature emphasizes the importance of spatial modeling for identifying hidden contamination zones between sampling locations.

4. Application of GIS in Groundwater Quality Assessment-GIS has been widely used as a powerful tool for storing, analyzing, and visualizing groundwater quality data. Integration of arsenic concentration data with spatial layers such as aquifer depth, river proximity, geomorphology, and land use enhances interpretation. GIS-based thematic mapping allows clear identification of contamination patterns and high-risk areas.

5. Use of Kriging and Interpolation Techniques-Kriging is the most commonly applied geo-statistical interpolation technique in arsenic studies due to its ability to incorporate spatial dependence. Semivariogram modeling is used to understand spatial continuity and scale of arsenic variation. Literature reports that kriging provides more reliable prediction results compared to deterministic methods like IDW when data shows spatial structure.

6. Risk Zonation and Hazard Mapping Approaches-Risk zonation maps classify regions into low, moderate, and high arsenic risk categories based on predicted concentration values. Several studies adopt threshold-based classification using WHO (10 $\mu\text{g/L}$) and BIS (50 $\mu\text{g/L}$) standards. Hazard maps generated using GIS serve as decision-support tools for groundwater management and public health planning.

7. Integration of Multi-Criteria Analysis with GIS-Recent studies integrate geo-statistical outputs with multi-criteria decision-making techniques such as AHP and weighted overlay analysis. Environmental factors like soil type, groundwater depth, lithology, and distance from rivers are assigned weights based on their influence on arsenic occurrence.

Such integrated models improve risk prediction accuracy and spatial realism.



8. Limitations Identified in Previous Studies-Many studies suffer from limited sampling density, leading to interpolation uncertainty. Seasonal variation of arsenic concentration is often ignored in spatial modeling. Lack of district-level high-resolution risk zonation is identified as a major research gap for Patna district.

9. Research Gap and Scope for Present Study-Existing literature provides regional-scale arsenic assessment but lacks focused geo-statistical modeling for Patna district. There is limited application of GIS-based risk zonation specifically using local groundwater data. The present study aims to bridge this gap by developing a scientifically robust, GIS-based geo-statistical model for arsenic risk assessment in Patna district.

10. Significance of GIS-Based Geo-statistical Modeling-Literature confirms that GIS-integrated geo-statistical modeling enhances spatial understanding of groundwater arsenic contamination. Risk zonation maps help identify priority areas for mitigation, alternative water supply planning, and policy intervention. Such approaches are essential for sustainable groundwater management in arsenic-prone regions like Patna district.

Research Methodology

1. Study Area Description-The study focuses on Patna District, Bihar, located in the middle Gangetic plain. The district is characterized by alluvial deposits, shallow aquifers, and intensive groundwater use.

The Ganga River and its floodplain strongly influence groundwater recharge and geochemistry.

2. Groundwater Sample Collection-Groundwater samples were collected from hand pumps and tube wells used for drinking and domestic purposes. Sampling locations were selected to ensure uniform spatial coverage of the entire district. Geographic coordinates (latitude and longitude) of each sampling point were recorded using GPS.

3. Laboratory Analysis of Arsenic-Arsenic concentration in groundwater samples was analyzed using standard analytical techniques (AAS / HG-AAS / ICP-MS). Quality control measures included blank samples, duplicate analysis, and standard calibration. Arsenic values were compared with WHO (10 µg/L) and BIS (50 µg/L) drinking water standards.



4. Database Creation and GIS Integration-A spatial database was created using ArcGIS / QGIS environment. Groundwater arsenic concentration data were linked with their corresponding GPS coordinates. Attribute tables were prepared for further spatial and statistical analysis.

5. Exploratory Data Analysis (EDA)-Descriptive statistical parameters such as mean, minimum, maximum, and standard deviation were computed. Data normality was checked using histogram and skewness analysis. Outliers were identified and evaluated to avoid distortion in spatial modeling.

6. Geo-statistical Analysis

Spatial autocorrelation of arsenic concentration was examined using semi variogram analysis. Experimental variograms were fitted with theoretical models (spherical, exponential, or Gaussian).

Variogram parameters such as nugget, sill, and range were optimized.

7. Spatial Interpolation Using Kriging-Ordinary Kriging was applied to interpolate arsenic concentrations across the district. Kriging weights were calculated based on variogram models to minimize prediction error. Cross-validation was performed to assess model accuracy using RMSE and mean prediction error.

8. Generation of Arsenic Distribution Map-Interpolated arsenic concentration surfaces were generated in GIS. Spatial patterns showing arsenic enrichment and depletion zones were identified. Continuous raster maps were prepared for further classification.

9. Risk Zonation Mapping-Arsenic concentration maps were reclassified into risk categories:

Low risk (<10 µg/L) Moderate risk (10–50 µg/L) High risk (>50 µg/L), risk zonation maps were produced to visualize vulnerable areas.

10. Final Map Preparation and Interpretation-Final arsenic risk zonation maps were prepared with appropriate legends and scale. High-risk zones were identified for priority intervention. Results were interpreted in relation to hydrogeological and geomorphological conditions.

11. Ethical and Environmental Considerations-Sampling was conducted without disturbing local water sources. Study results are intended for scientific and public welfare purposes. Data confidentiality and accuracy were maintained throughout the research process.



12. Geographical Information System (GIS)-This is a powerful computer-based tool used for the collection, storage, analysis, and visualization of spatial and attribute data. In groundwater quality studies, GIS enables the integration of arsenic concentration data with geographic coordinates, allowing researchers to understand the spatial distribution of contamination. Since arsenic occurrence in groundwater is highly heterogeneous, GIS provides an effective platform to capture spatial variability and identify patterns that cannot be detected through conventional data analysis.

In arsenic contamination studies, GIS plays a crucial role in organizing groundwater sampling data and linking it with environmental and hydrogeological factors. Sampling locations are geo-referenced using GPS, and laboratory-analyzed arsenic values are stored in a spatial database. GIS facilitates the overlay of multiple thematic layers such as aquifer depth, geomorphology, land use, and proximity to rivers, which influence arsenic mobilization and distribution.

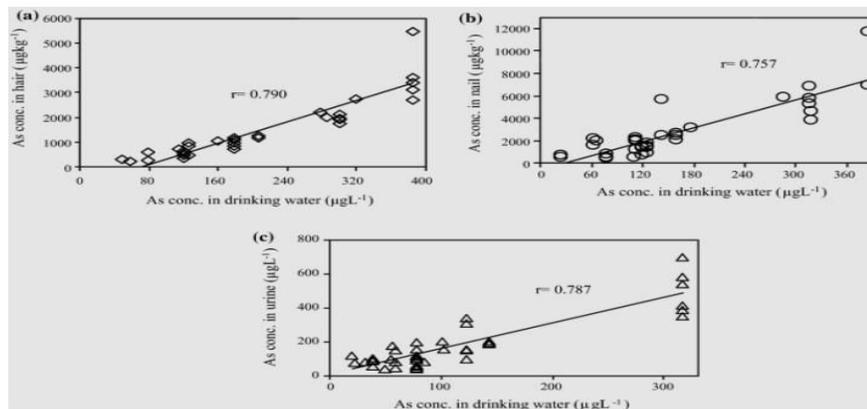
GIS is also essential for applying geo-statistical techniques, particularly spatial interpolation methods like kriging. Through semivariogram analysis, GIS helps evaluate spatial autocorrelation in arsenic concentration data and supports accurate prediction at unsampled locations. The interpolated surfaces generated using GIS provide continuous arsenic distribution maps, which serve as the basis for further risk assessment and zonation.

Finally, GIS enables the classification of arsenic concentration maps into different risk categories based on international and national drinking water standards. Risk zonation maps produced through GIS offer a clear visualization of low, moderate, and high arsenic-affected areas. These outputs are valuable for groundwater management, public health planning, and decision-making, making GIS an indispensable tool for arsenic risk assessment studies.

Discussion

The present study demonstrates that arsenic contamination in the groundwater of Patna District exhibits a distinct spatial variability, which can be effectively analyzed using geo-statistical modeling integrated with GIS techniques. The generated spatial distribution maps reveal that arsenic concentration is not uniformly distributed but is clustered in specific zones, particularly in low-lying alluvial regions adjacent to the Ganga River. This spatial heterogeneity highlights the importance of using geo-statistical tools rather than conventional interpolation methods for reliable contamination assessment.

The application of variogram modeling and kriging interpolation proved effective in capturing the spatial structure of arsenic distribution. The semi-variogram parameters indicate moderate to strong spatial dependence, suggesting that both natural geological processes and localized hydro-geochemical conditions control arsenic mobilization. Sediment composition, reductive dissolution of iron oxides, and prolonged groundwater residence time appear to be the dominant factors influencing arsenic enrichment in the study area. The reliability of the kriging output enhances confidence in the risk zonation maps produced.



Risk zonation analysis based on World Health Organization (WHO) drinking water standards clearly identifies high-risk and moderate-risk zones within the district. Several blocks show arsenic concentrations exceeding the permissible limit, posing a serious threat to public health. The GIS-based risk map provides a valuable decision-support tool for prioritizing mitigation measures, such as alternative water supply planning, well-depth regulation, and targeted arsenic testing programs. This zonation approach allows policymakers to focus resources efficiently on the most affected areas.

Overall, the integration of geo-statistical modeling with GIS offers a scientifically robust framework for understanding arsenic contamination patterns in groundwater. The findings emphasize the need for continuous monitoring and region-specific groundwater management strategies in Patna District. The methodology adopted in this study can be replicated in other arsenic-affected regions of the Indo-Gangetic Plain, contributing to sustainable water resource management and public health protection.

Results

The analysis of groundwater samples collected across Patna District reveals considerable variation in arsenic concentration, indicating a heterogeneous contamination pattern. The measured arsenic values range from low to significantly elevated levels, with several sampling locations exceeding the World



Health Organization (WHO) guideline value for drinking water. Descriptive statistical analysis shows a positively skewed distribution, suggesting the presence of localized arsenic enrichment rather than uniform contamination throughout the district. Spatial interpolation using ordinary kriging successfully generated a continuous arsenic concentration surface for the study area. The kriging model produced a smooth and realistic spatial pattern, effectively reducing estimation errors in data-sparse zones. Cross-validation results indicate acceptable prediction accuracy, confirming the suitability of the geo-statistical approach for arsenic mapping. The interpolated map highlights distinct arsenic hotspots primarily concentrated in specific blocks and floodplain regions.

Variogram analysis reveals moderate to strong spatial dependence of arsenic concentration, indicating that natural hydro-geological controls play a significant role in governing arsenic distribution. The optimal variogram model shows a well-defined range, suggesting spatial continuity of arsenic levels within a certain distance. This spatial structure supports the hypothesis that arsenic mobilization is influenced by sediment characteristics and groundwater flow dynamics rather than random anthropogenic inputs alone. Based on interpolated arsenic concentrations and WHO drinking water standards, a GIS-based risk zonation map was developed. The study area was classified into low-, moderate-, and high-risk zones. High-risk zones are mainly located in areas with shallow aquifers and fine-grained alluvial sediments, whereas deeper aquifer regions generally fall within low-risk categories. This zonation provides a clear spatial framework for identifying vulnerable regions within Patna District.

Overall, the results confirm that a significant portion of the groundwater in Patna District is unsuitable for direct human consumption without treatment. The integration of geo-statistical modeling and GIS techniques proves effective in accurately identifying arsenic-contaminated zones. These findings provide a scientific basis for groundwater management, public health intervention, and long-term monitoring strategies aimed at mitigating arsenic-related risks in the region.

Government Approach

The findings of this study underline the need for a coordinated government-led response to address arsenic contamination in groundwater across Patna District. Public health agencies and water resource departments should prioritize regular groundwater quality monitoring, particularly in identified high-risk zones. The implementation of arsenic mitigation programs—such as installation of arsenic removal units, promotion of safe alternative water sources, and regulation of well depth—can significantly reduce exposure risks. Integration of GIS-based risk maps into government planning frameworks would support



evidence-based decision-making and enable targeted intervention. Community awareness programs and capacity building at the local level are also essential to ensure sustainable management of groundwater resources.

Conclusion

The present study demonstrates that geo-statistical modeling combined with GIS techniques provides an effective and reliable framework for assessing arsenic contamination and delineating risk zones in the groundwater of Patna District. The results reveal pronounced spatial variability in arsenic distribution, with several areas exceeding recommended drinking water standards. The developed risk zonation map offers a valuable tool for groundwater management and public health protection. Overall, the study emphasizes the importance of scientific mapping, continuous monitoring, and region-specific mitigation strategies to ensure safe and sustainable groundwater use in arsenic-affected regions.

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