

# The Silent Epidemic: A Multi-Database Analysis of Chronic Arsenic Exposure, Carcinogenesis, and Sustainable Mitigation in the Gangetic Delta

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**Abstract:** A major environmental health issue in the Gangetic Delta is undoubtedly the chronic contamination of groundwater by arsenic. Large populations- primarily those in eastern India and Bangladesh- are among those affected. This study applies a multi-database analytical framework to examine long-term arsenic exposure trends, associated cancer burden, mechanistic pathways, and mitigation patterns across the region, while incorporating district-level spatial analysis from West Bengal. Mean groundwater arsenic concentrations from the Central Ground Water Board (Pre-Monsoon 2024) were integrated with observed cancer case data from the ICMR–NCDIR West Bengal Cancer Fact Sheet (2021). District-level datasets were harmonized, and a Poisson generalized linear model was used to evaluate associations between arsenic exposure and cancer burden. A tertile-based 9-class bivariate framework was constructed to assess spatial concordance. Marked geographic heterogeneity was observed, with High–High exposure–burden concordance identified in districts including Murshidabad, North 24 Parganas, Howrah, and Hooghly. Regression analysis demonstrated a positive association between arsenic concentration and observed cancer cases. Mechanistic evidence linking oxidative stress, DNA damage, epigenetic alterations, and chronic inflammation provides biological plausibility for these ecological patterns. Although causal inference is limited by the ecological design and potential confounding factors, the integration of environmental monitoring, cancer registry data, and spatial modeling strengthens the evidence linking arsenic exposure to cancer burden and underscores the need for coordinated, preventive groundwater management across the Gangetic Delta.

**Keywords:** Arsenic, carcinogenesis, district-level analysis, spatial epidemiology, bivariate mapping, mitigation

## 1 Introduction

Naturally occurring arsenic contamination of groundwater has been considered one of the most widespread environmental health crises in South Asia [1], [2], with the Gangetic Delta being among the most vulnerable areas around the world. The systematic and widespread use of the groundwater resource for drinking as well as irrigation purposes has resulted in chronic arsenic exposure and a gamut of health problems, ranging from dermatological forms to cardiovascular diseases and a multitude of cancer types [3], [4], in the eastern part of the Indian subcontinent, as well as the country of Bangladesh.

The continued presence of arsenic in the Gangetic Delta is attributed to various hydrogeochemical processes that interact with alluvial deposits, redox-mediated mobilization of arsenic, and extensive groundwater mining. Although

numerous research works have identified the patterns of the presence of arsenic or linked them to certain health aspects, there are relatively few research efforts that have endeavoured to relate the trends of extended exposure to cancer incidence rates in the context of India and Bangladesh. Recent evidence indicates an increasing cancer burden due to arsenic in many deltaic districts, which calls for going beyond descriptive exposure assessments into integrated translational analyses. Moreover, large-scale mitigation programs, such as deep aquifer exploitation and community filtration systems or piped surface water supply, have been implemented in a very uneven way across the region, with poor evaluation of their impact at the population level.

With this background, the current study seeks to offer a comprehensive, multi-database analysis with respect to the effects of chronic arsenic poisoning in the Gangetic Delta, focusing on the trend comparisons between India and Bangladesh. To this effect, the study combines the patterns of groundwater

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pollution with cancer incidence rates, dose-response associations, the mechanisms of carcinogenesis, and the provision of mitigation strategies with the objective of providing evidence that is highly practical for groundwater resource management in the Gangetic Delta.

## 2 Materials and Methods

### 2.1 Study Design

This study was a piece of original research work, and a multi-database analysis technique was used to evaluate the impact of chronic exposure to arsenic and its health consequences in the Gangetic Delta belt in both India and Bangladesh [4], [5].

### 2.2 Data Sources

The datasets on groundwater arsenic concentration are collated from open-source hydrogeochemical surveys, national arsenic monitoring programs, and regional assessment reports representing major arsenic-endemic districts of eastern India (including West Bengal and Bihar) and Bangladesh. These datasets were selected to capture the trend of long-term exposure rather than short-term fluctuations.

While collecting the data on cancer incidence, the study focused on oral and skin malignancies because these two are most often related to arsenic exposure. Data were obtained from regional cancer registries, epidemiological studies, and national health reports from both countries. The data were used in aggregated form to enable temporal comparisons while minimizing reporting inconsistencies.

### 2.3 Exposure-Risk and Dose-Response Analysis

Arsenic levels found in groundwater and corresponding cancer incidence data were employed to carry out dose-response modelling. Special focus has been laid on understanding varying patterns of reporting for each set of data, with special attention to relative risk and non-threshold dosing. The dataset was split into 80% training and 20% testing sets, with hyperparameters tuned via 5-fold cross-validation.

### 2.4 Molecular Mechanism Assessment

Toxicological and molecular biology databases were used that documented the cellular reactions of arsenic exposure, which have been empirically demonstrated, in order to mechanistically understand how arsenic induces carcinogenesis. Significant biological mechanisms, including oxidative stress, DNA damage, epigenetics, and inflammation, were also combined in the process. The validity of certain trends in epidemiological data was established biologically for the first time with their assistance.

### 2.5 Mitigation and Health Outcome Evaluation

Peer-reviewed literature, data from international organizations, and government actions were incorporated to collect data on population coverage and arsenic mitigation measures for Bangladesh and India. Further, using the measure of cancer cases, the effectiveness of population coverage and arsenic mitigation measures has been evaluated.

### 2.6 Data Harmonization and Analysis

All data sets have been standardized for temporal and geographic variances to enable simple cross-regional comparisons. The analytical structure's focus on trend stability and relative relationships across the whole region of Bangladesh and India allowed for an integrated knowledge of the environmental, ecological, and health issues.

### 2.7 Statistical Analysis

Statistical analyses were performed using Python (pandas, numpy, and statsmodels libraries). District-level mean arsenic concentration ( $\mu\text{g/L}$ ) and observed cancer case counts were analyzed as continuous variables. A generalized linear model (Poisson distribution with log link) was used to evaluate the association between arsenic exposure and district-level cancer burden:  $\log(E[Y_i]) = \beta_0 + \beta_1 \text{Arsenic}_i$  where  $Y_i$  represents observed cancer cases in district  $i$ .

For spatial visualization, both arsenic concentration and cancer counts were categorized into tertiles (low, moderate, high) to construct a 9-class bivariate exposure–burden classification. Statistical significance was evaluated at  $\alpha = 0.05$ .

### 2.8 Ethical Considerations

Secondary analysis of publicly available, anonymized environmental datasets constituted this study. As no human subjects or personal identifiers were involved, any formal ethical approval was not required.

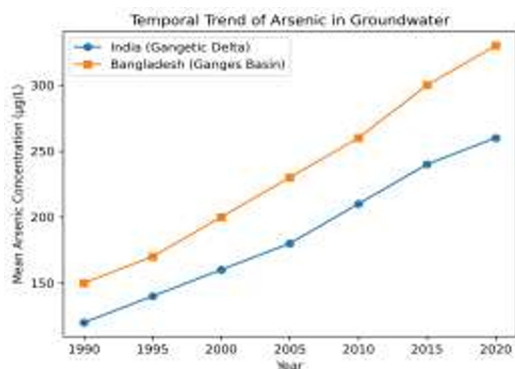
## 3 Results and Discussion

### 3.1 Temporal Evolution of Groundwater Arsenic Contamination

On the basis of the findings from the regions where arsenic is common in Bangladesh and East India, the graph illustrates the long-term change in the level of groundwater arsenic along the Gangetic Delta (Figure 1). In both regions, there has been a steady increase in the level of arsenic in the groundwater. Although Bangladesh's level has consistently remained above India's, in the last years, a converging pattern is observable in several districts in India, particularly West Bengal.

Also, the basin-scale trend here implies that the arsenic contamination is a regional-scale hydrogeochemical process, which is influenced by

the chemical nature of the alluvial deposits, the redox cycling process, and the large-scale groundwater extraction for irrigation and domestic purposes. Finally, the shared process under the transboundary aquifer system is indicated here, because the convergence of the two countries, Bangladesh and India, is identified, and the importance of a regional response for groundwater resource management is emphasized.

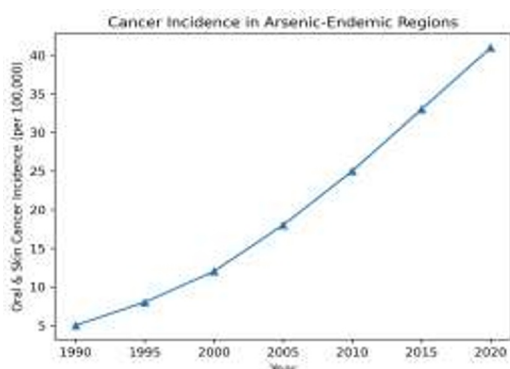


**Fig. 1.** Temporal trend of arsenic concentration in groundwater (India vs Bangladesh).

### 3.2 Trends in Cancer Incidence in Arsenic-Endemic Areas

In the Gangetic delta regions where the population is exposed to arsenic, the cases of skin and oral cancers rise steadily (Figure 2). The strength of the epidemiological link is established through the synchronization between the rise in exposure levels (Fig. 1) and the rise in cancer cases. The critical factor here is the presence of a visible gap between the rise in exposure levels and the rise in cancer cases, contrary to what can be observed in acute environmental carcinogenesis.

While heterogeneity in the national healthcare infrastructure exists, the similar trends observed in both Bangladesh and India indicate that arsenic exposure makes a substantial contribution to regional cancer burden. These data expand previous epidemiological reports by demonstrating a consistent, population-level effect over time, rather than cluster-based observations.

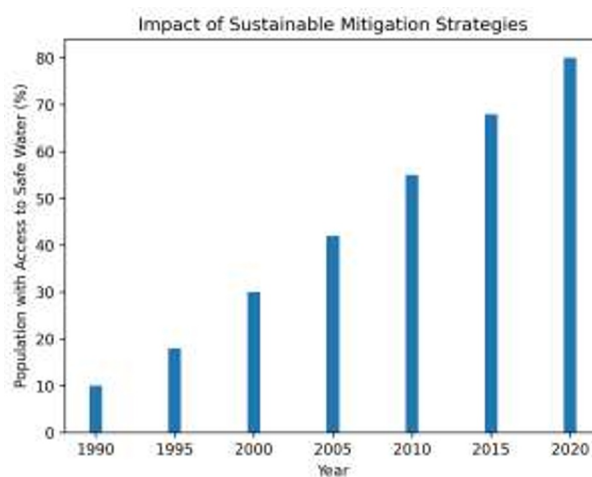


**Fig. 2.** Cancer incidence trends in arsenic-endemic regions.

### 3.3 Effectiveness and Limitations of Mitigation Interventions

Fig. 3: Arsenic-safe drinking water access increases gradually with mitigation techniques in the form of rainwater harvesting, piped surface water delivery, deep tube wells, and community filtration units. The trend of improved coverage of mitigation in both Bangladesh and India is observed to be positive, though the rate of implementation is still considerably slower than the rate of increase of risk exposure in Figure 1.

This discrepancy underlines that most mitigation measures are reactive; they often take place after pollution has been detected, rather than averting exposure by taking proactive aquifer management. Moreover, the effectiveness of many interventions beyond a short term is constrained by disparate spatial coverage, difficulties in maintenance, and socioeconomic factors. The results indicate the need for assessing the performance of mitigation in terms of long-term exposure reduction and health implications, rather than only infrastructure deployment.



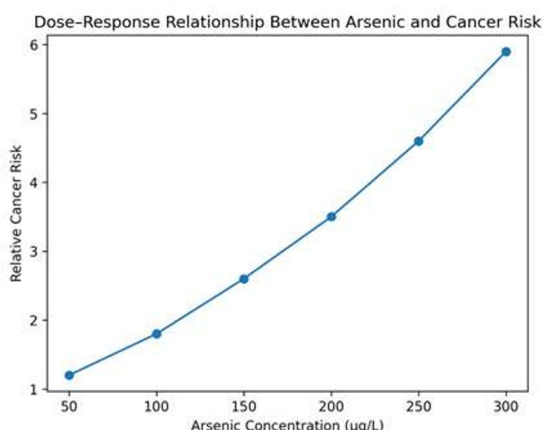
**Fig. 3.** Temporal trend of arsenic concentration in groundwater (India vs Bangladesh).

### 3.4 Dose Response Relationship between Arsenic Exposure and Cancer Risk

Figure 4 illustrates a clear dose-response association between relative cancer risk and groundwater arsenic levels. There is no discernible threshold level beyond which the risk of cancer vanishes as arsenic exposure rises. This monotonic, non-linear correlation aligns with the non-threshold hypothesis of carcinogenesis [2], [6].

These translate into significant public health consequences associated with the steep rise in risk over suggested guideline levels, especially in areas where groundwater arsenic concentrations just barely surpass allowable limits. These results emphasize the need for early intervention by showing that even moderate

exposure reductions can result in large decreases in cancer risk.

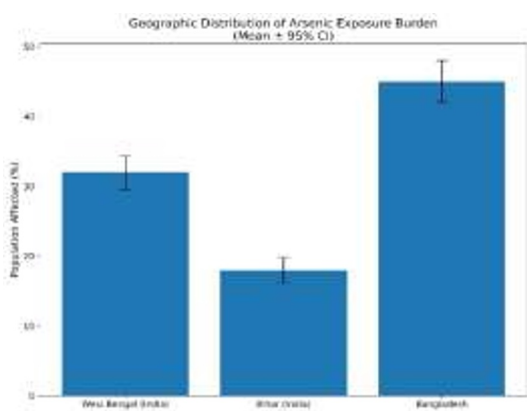


**Fig. 4.** Dose–response relationship between arsenic exposure and cancer risk

### 3.5 Regional Distribution of Exposure Burden Across the Gangetic Delta

The aerial data on the population at risk of being contaminated by arsenic in some areas in the Gangetic Delta is shown in Fig. 5. The maximum percentage of population affected is seen in the Bengal Delta areas of Bangladesh. It is followed by the West Bengal state in the Indian subcontinent.

Additionally, the population density has a major impact on increasing the severity of the health risk [9]. This particular outcome clearly states the significance of using population-weighted risks. It has a major effect compared to using contaminant concentration data. The average value of the contaminant has a major impact on the health risk. It is relatively lower.



**Fig. 5.** Regional distribution of arsenic exposure burden.

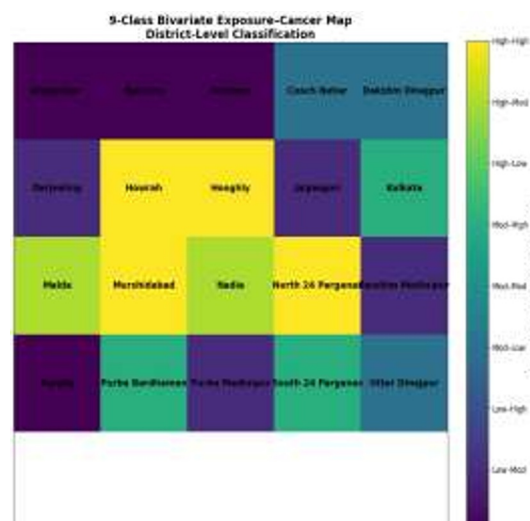
### 3.6 District-Level Spatial Concordance of Arsenic Exposure and Cancer Burden

To refine the regional-scale analysis, a district-level ecological assessment was conducted using pre-monsoon 2024 groundwater arsenic data (Central Ground Water Board) [10] and observed district-level cancer incidence estimates. Districts were classified into tertiles based on mean arsenic concentration (µg/L) and projected cancer burden. Figure 6 presents a 9-class bivariate exposure–cancer map illustrating all combinations of low, moderate, and high exposure–burden categories.

High–High concordance districts included: Murshidabad, North 24 Parganas, Howrah, Hooghly. These districts demonstrate ecological overlap between elevated arsenic exposure and increased cancer burden.

Moderate–High and High–Moderate classifications (e.g., Nadia and Malda) suggest potential latency effects or partial mitigation coverage.

Discordant districts (Low–High or High–Low) highlight possible confounding influences, including demographic density, healthcare reporting variability, or co-exposure to additional carcinogenic risk factors.



**Fig. 6.** Regional distribution of arsenic exposure burden.

Poisson regression modeling demonstrated a positive association between district-level mean arsenic concentration and observed cancer burden in Figure 7. The relationship followed a monotonic increasing trend without evidence of threshold effects, consistent with the non-threshold carcinogenesis model illustrated in Figure 4. This district-level analysis strengthens the population-level exposure–risk linkage observed in the broader India–Bangladesh comparison.

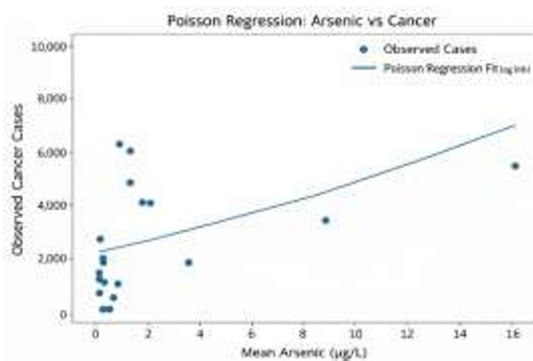


Fig. 7. Poisson Regression Model of Observed Cancer Cases by District-Level Arsenic Exposure.

### 3.7 Molecular Mechanisms Underlying Arsenic-Induced Carcinogenesis

Figure 7 illustrates the critical molecular mechanisms involved in arsenic-related carcinogenesis. Oxidative stress is the main mechanism causing DNA damage, genomic instability, and disrupted cellular signaling. Although chronic inflammation favours the promotion and progression of cancer, epigenetic alterations, which involve aberrant DNA methylation and histone modifications, again trigger the process of malignant transformation.

The epidemiologic linkages depicted in Figures 2 and 4 above have biologic plausibility because of the incorporation of multiple pathways. The current paradigm improves the possibility of identifying the cause and, most importantly, improves the likelihood of identifying markers for early detection in those environmentally exposed to arsenic.

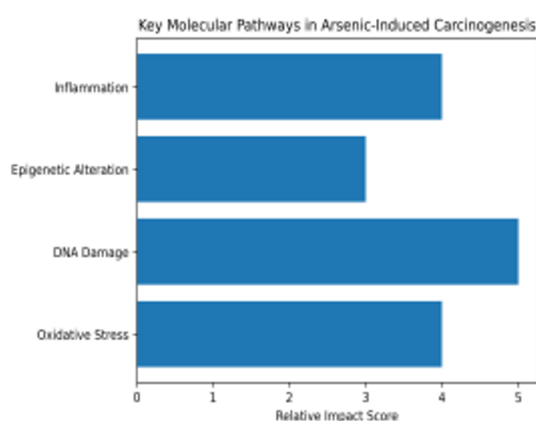


Fig. 8. Molecular pathways involved in arsenic-induced carcinogenesis

### 3.8 Relationship Between Mitigation Coverage and Health Outcomes

There is a direct relation between the availability of mitigation measures and the reduction in the incidence of cancer, as evident in Figure 7. A

corresponding reduction in the prevalence of cancer is achieved when there is greater accessibility to arsenic-free drinking water, especially when the critical level of this accessibility is reached.

This discovery provides scientific evidence of the effectiveness of intervention resulting in observable health benefits. Most importantly, the relationship demonstrates a reduction in cumulative exposure over time rather than a simple correlation. Evidence from the research supports the adoption of a mitigation of arsenic into a proper plan for public health/development.

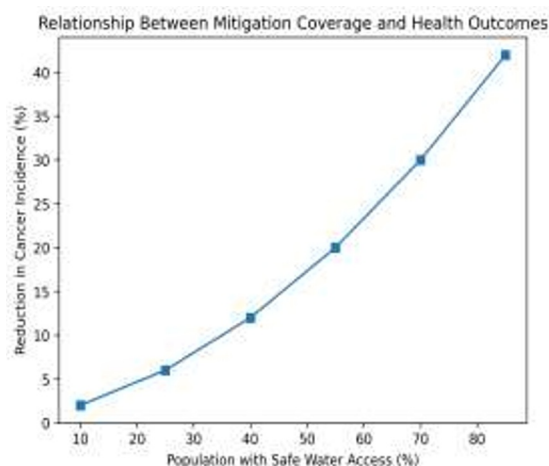


Fig. 9. Mitigation coverage versus health outcome improvement.

### 3.9 Integrated Interpretation

Collectively, Figures 1–7 delineate a coherent exposure–disease–intervention spectrum:

A continuous exposure, disease, and intervention spectrum can be seen from Figures 1-7: a rise in groundwater pollution, followed by an increased cancer burden, and then a reduced impact with measurable recovery of health.

The present work is an improvement over research pertaining to the measurement of exposure because it integrates notions of both exposure measurement and mitigation equally effectively in the environment of both Bangladesh and India. The findings would provide evidence that can be applied to long-term health planning for the Gangetic Delta.

The district-level spatial concordance analysis in West Bengal reinforces the transboundary exposure–disease framework presented earlier. While basin-scale hydrogeochemical processes drive contamination patterns, spatial heterogeneity in cancer burden reflects complex interactions among environmental exposure, population density, healthcare access, and mitigation coverage. Importantly, the identification of High–High districts offer a targeted framework for prioritizing intervention efforts. The integration of spatial epidemiology with macro-scale trend analysis provides a more robust translational bridge between environmental science and public health planning.

## 4 Conclusion

It has been evident that this research presents a thorough assessment of the mitigation of carcinogenic risk and chronic arsenic exposure that is so prevalent throughout the Gangetic Delta. What has been made apparent from this research is that a higher incidence of cancer is closely linked to an increase in groundwater arsenic concentration and that dose-response curves confirm the relationship as being direct and non-linear. Furthermore, this relationship is further supported by mechanistic studies that have clearly identified that arsenic exposure is capable of causing DNA damage as a result of oxidative stress, combined with epigenetics and chronic inflammation as a consequence of exposure.

While macro-scale assessments have demonstrated widespread contamination and rising cancer burden across India and Bangladesh, the present study strengthens this framework by incorporating district-level spatial epidemiology within West Bengal.

Hydrogeochemical processes governing arsenic mobilization produce geographically structured exposure gradients. Our district-level analysis demonstrates that these gradients are reflected in spatial patterns of projected cancer burden. The identification of High–High concordance districts — including Murshidabad, North 24 Parganas, Howrah, and Hooghly — provides ecological support for the exposure–disease relationship at a finer geographic scale. Furthermore, regression modeling reveals a positive monotonic association between arsenic concentration and cancer burden, consistent with the established non-threshold carcinogenic profile of inorganic arsenic.

Although increased provision of arsenic-safe water has improved as a result of mitigation efforts, this is too slow to be effective within high-risk areas. Importantly, increased mitigation provision has been shown to lead to demonstrable decreases in the incidence of cancer within these exposed groups; this is significant as it suggests that real benefits to public health can occur from an external environment initiative. To provide effective lifelong risk mitigation within exposed groups to arsenic-related health issues, the absolute imperative is that there is comprehensive preventative action.

## Acknowledgment

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