



Potential arsenic–mercury–lead–chromium co-contamination in the mid-Gangetic plains, India: Hydrogeochemical processes and health perspectives

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The co-contamination of groundwater in shallow alluvial aquifers with toxic metals such as arsenic (As), mercury (Hg), lead (Pb), and chromium (Cr) has emerged as a critical global environmental health concern in the 21st century. This varies with redox conditions, and land use patterns. The present study aims to address the influence of oxidation-reduction potential, geochemical signatures, and human activities on the co-contamination of As, Hg, Pb, and Cr in groundwater and river water systems through laboratory assays and multivariate statistical analysis. Physicochemical parameters, including pH and alkalinity, were found to play a critical role in the mobility of these metals. Elevated concentrations of As and Cr in river water were attributed to industrial discharges, while Hg and Pb were more prevalent in groundwater, likely due to geogenic and anthropogenic sources. The concentration hierarchy of trace metals in groundwater followed the order Hg > Pb > Cr > As, whereas in river water, it was Cr > As > Pb > Hg. Longer residence times and evaporation processes were identified as key factors enhancing the concentration of major ions and trace metals, particularly Hg, which is predominantly of anthropogenic origin. Piper diagrams revealed the dominance of Ca²⁺-Mg²⁺-HCO₃⁻, mixed Ca²⁺-Mg²⁺-SO₄²⁻, and Na⁺-Cl⁻ water types, indicating influences of precipitation, rock weathering, and anthropogenic activities. Gibbs plots demonstrated the impact of evaporation on groundwater and rock-water interactions on river water chemistry. Probability exceedance indicated the inverse correlation between the concentration levels of contaminants and the likelihood of these concentrations surpassing the established regulatory thresholds. The R-mode clustering identifies three distinct clusters. Cluster 1 indicates halite dissolution and industrial effluents, suggesting mixed. The second cluster represents the role of the industrial contribution of the trace/heavy metals, which is also the reason why it is associated with surface or river water as could be observed from the HCA matrix. Cluster 3 represents the mobilization of important trace metalloids like As via competitive desorption due to the presence of anions like HCO₃⁻ especially in river water samples. Health risk assessment indicated significant non-carcinogenic risks associated with elevated As and Cr levels. The findings emphasize the pressing need for continuous monitoring and effective management strategies to mitigate the risks posed by toxic metal contamination in freshwater systems. This study contributes to a deeper understanding of hydrogeochemical processes and the interplay of natural and anthropogenic factors driving metal co-contamination in the region.

Keywords: arsenic, chromium, lead, mercury, redox, co-contamination