Title: Advanced Probabilistic Health Risk Assessment of Water Contamination: Evaluating PTE Exposure and Public Health Implications in Complex Hydrogeological Settings

Author Names: Zahra Sedghi, Ata Allah Nadiri, Frank T.-C. Tsai, Rahim Barzegar, Senapathi Venkatramanan & Abu Reza Md. Towfiqul Islam

Abstract:. Water resources contamination poses significant environmental and public health challenges in arid and semi-arid regions. This study examines water resources quality and related health risks in the Maku–Bazargan–Poldasht region of Iran through a detailed analysis of 60 water samples collected in October 2021. Physicochemical parameters, including pH, electrical conductivity (EC), major and minor ions, and potentially toxic elements (PTEs) such as arsenic (As), aluminum (Al), nickel (Ni), and lead (Pb), were measured. Results revealed pervasive contamination, with most parameters exceeding established safety thresholds. Multivariate statistical methods, including factor and cluster analyses, identified both anthropogenic and geogenic sources as major contributors to Ni and Pb contamination. To evaluate human health risks, we implemented a probabilistic framework based on Monte Carlo Simulation (MCS), quantifying exposure risks via ingestion and dermal pathways for nitrate (NO_3^-), fluoride (F^-), and PTEs. Unlike conventional deterministic risk assessments—which rely on single-point estimates and may oversimplify complex exposure dynamics—our probabilistic model captures the full spectrum of variability and uncertainty in exposure parameters (e.g., ingestion rate, exposure duration, and body weight), offering more realistic and precautionary risk estimates. The probabilistic results revealed substantial non-carcinogenic risks (Hazard Index, HI > 1) and carcinogenic risks (Total Cancer Risk, TCR > $1 \times 10^-$) across all age groups, especially children. Sensitivity analysis further identified ingestion rate (IR) and exposure duration (ED) as the most influential variables, guiding effective prioritization of mitigation strategies. By integrating spatial analysis, multivariate statistics, and uncertainty quantification, this study presents a novel, comprehensive health risk assessment model tailored to complex hydrogeological environments. We recommend urgent policy interventions including the implementation of regional-scale water treatment technologies, regular monitoring of high-risk aquifers, stricter regulation of agricultural and industrial discharges, and the development of targeted public health outreach programs. These measures are critical for reducing exposure, safeguarding vulnerable populations, and promoting sustainable water resource management in similarly affected regions worldwide.

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