

Trace Element Contamination in Desalination-Dependent Water Systems in the GCC: A Socio-Technical Disaster Risk Governance Perspective

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ABSTRACT: Trace element contamination in desalination-dependent water systems represents a growing slow-onset disaster risk with significant implications for environmental safety, public health, and governance resilience in arid regions such as the Gulf Cooperation Council (GCC). This study examines arsenic, lead, mercury, and cadmium contamination in GCC water systems from a disaster risk reduction (DRR) and governance perspective. It investigates how institutional arrangements, technological systems, and environmental processes interact to shape water security under climate and disaster stress. Using a qualitative research design based on secondary data including peer-reviewed literature policy reports and international frameworks the study applies thematic analysis guided by a multi-level governance and institutional resilience framework. The analysis focuses on contamination sources treatment technology performance regulatory structures and digital monitoring approaches. Findings show that trace element contamination is driven by interconnected industrial agricultural and desalination pathways confirming its systemic nature. Although reverse osmosis nanofiltration and ion-exchange technologies demonstrate high theoretical efficiency real-world performance is inconsistent due to operational stress feedwater variability and maintenance constraints. Governance fragmentation uneven enforcement and weak regional coordination significantly constrain system effectiveness. The study finds limited integration of GIS remote sensing and AI-driven predictive systems reducing early warning and adaptive capacity. It concludes that trace element risks in the GCC are not primarily technological but socio-technical emerging from interactions between infrastructure institutions and environmental stressors. The study contributes governance-oriented disaster risk perspective emphasizing integrated data-driven and regionally coordinated water governance regulatory coherence digital integration spatial intelligence enhance resilience under environmental pressure

KEYWORDS: trace elements, desalination, GCC, disaster risk reduction, water governance, institutional resilience.

1. INTRODUCTION

Water contamination by trace elements—particularly arsenic, lead, mercury, and cadmium—represents a growing slow-onset environmental hazard with significant implications for disaster risk reduction (DRR), environmental resilience, and humanitarian security worldwide. These elements enter aquatic systems through industrial discharges, agricultural runoff, mining activities, and natural geochemical processes. Their persistence in the water cycle generates long-term threats to ecosystem stability, infrastructure sustainability, and human security (Osae et al., 2026; Awashreh, 2026). In the context of contemporary disaster risk systems, trace element contamination should be understood not only as a chemical or environmental issue but as a systemic risk driver that intensifies vulnerability under climate-induced hazards and water stress conditions.

Beyond environmental degradation, chronic exposure to trace elements has been associated with carcinogenic effects, neurological disorders, and cardiovascular diseases, transforming water contamination into a public health and humanitarian disaster risk. This risk becomes particularly critical during environmental emergencies, where limited access to safe water exacerbates displacement, inequality, and crisis recovery challenges (López-Alonso, Rivas & Miranda, 2025). In disaster-prone regions, contamination of water systems therefore acts as a risk multiplier, weakening adaptive capacity and reducing resilience during floods, droughts, heatwaves, and other climate-related hazards.

These risks are particularly acute in the Gulf Cooperation Council (GCC) region, where extreme aridity, high temperatures, and limited freshwater availability have created structural dependence on desalinated water as the primary potable source. While desalination has significantly strengthened baseline water security, it also introduces systemic technological and environmental vulnerabilities within disaster risk systems, particularly under stress conditions such as droughts, heatwaves, and coastal hazards (Sherif et al., 2023). Certain trace elements are not consistently removed during desalination processes, and the discharge of concentrated brine may intensify coastal degradation, increasing long-term ecological vulnerability and disaster exposure. Consequently, water contamination in the GCC should be framed as part of an integrated socio-technical disaster risk system shaped by governance capacity, technological design, and environmental stress dynamics (Awashreh, 2026; Gilani et al., 2024).

From a disaster risk governance perspective, these challenges are further complicated by the limited integration of advanced geospatial and digital technologies in water quality monitoring and early warning systems. The absence of systematic GIS-based spatial risk mapping, remote sensing surveillance, and AI-driven predictive analytics constrains the ability to detect contamination patterns, anticipate risk hotspots, and support real-time decision-making in water governance systems. This gap limits the development of proactive disaster risk reduction strategies capable of addressing slow-onset environmental hazards.

Despite substantial investment in water infrastructure and desalination capacity, GCC countries continue to face persistent challenges in ensuring water system resilience under increasing climate variability and disaster risk exposure. Existing water quality regulations often lack integration, spatial monitoring capacity, and enforcement mechanisms required to manage trace element behavior across interconnected systems, including desalination plants, distribution networks, and reuse systems. Governance arrangements remain fragmented across institutions, limiting coordinated risk monitoring, early warning capacity, and accountability mechanisms essential for disaster risk reduction and resilience governance (Awashreh, 2025a). These weaknesses are further intensified by the transboundary nature of marine ecosystems, where brine discharge and cumulative contamination act as cross-border environmental stressors requiring regional disaster risk governance and cooperative resilience frameworks (Al-Saidi et al., 2024).

Despite growing research on trace element contamination, desalination technologies, and water governance, important knowledge gaps remain. Existing studies have predominantly examined trace element contamination through engineering, treatment-efficiency, or regulatory compliance perspectives, often treating contamination as an isolated environmental problem. Comparatively less attention has been devoted to understanding trace element contamination as a systemic disaster risk issue shaped by interactions among governance systems, technological infrastructure, environmental stressors, and digital monitoring capacities. Furthermore, few studies have developed integrated frameworks specifically tailored to desalination-dependent GCC countries that combine disaster risk reduction, resilience governance, geospatial intelligence, and emerging digital technologies. This gap limits the development of evidence-informed governance strategies capable of addressing slow-onset environmental risks under conditions of climate stress and water insecurity.

Previous research has demonstrated that advanced water treatment technologies—such as reverse osmosis, nanofiltration, and ion-exchange systems—can reduce trace element concentrations under controlled conditions. However, their effectiveness varies depending on environmental variability, energy demand, and operational constraints. Recent studies have also highlighted broader environmental concerns associated with desalination activities, including brine discharge impacts and the need for improved environmental indicators capable of distinguishing direct and indirect ecological effects of desalination processes (Feng et al., 2025). In disaster-prone and climate-sensitive regions such as the GCC, these limitations become more pronounced under peak demand, emergency water supply conditions, and system stress events. Most existing studies treat these constraints primarily as engineering issues, with limited integration of governance systems, digital monitoring tools, and disaster resilience frameworks that determine real-world performance under crisis conditions (Maeda, 2024).

Against this backdrop, there is an urgent need for integrated disaster risk reduction frameworks that combine technological innovation with institutional capacity, environmental governance, and digital intelligence systems supported by geospatial analysis, remote sensing, and predictive monitoring capabilities (Haby et al., 2025). Recent disaster risk research increasingly emphasizes multidimensional governance approaches for managing complex water-related hazards and strengthening sustainable development outcomes (Siddique et al., 2025). While international frameworks such as the European Union Water Framework Directive and U.S. Environmental Protection Agency standards provide important regulatory benchmarks, their direct applicability in the GCC remains limited due to differences in climatic extremes, desalination dependence, and governance structures (Atef & Ramachandran, 2025; Copetti & Erba, 2024). Moreover, the effectiveness of AI-enabled monitoring systems depends on data quality, interoperability, transparency, and continuous monitoring coverage, conditions that remain uneven across many GCC environmental governance systems. This highlights the necessity of context-specific, resilience-oriented governance models supported by geospatial intelligence and predictive risk systems.

In response, this study conceptualizes trace element contamination in desalination-dependent systems as a socio-technical disaster risk governance challenge, rather than a purely technical water quality issue. Unlike previous studies that primarily focus on treatment performance or regulatory compliance, this research integrates governance theory, institutional capacity perspectives, environmental risk evidence, and digital monitoring approaches within a resilience-oriented analytical framework tailored to GCC conditions. Within this framing, trace elements are understood as systemic risk drivers whose impacts are shaped by the interaction between technology, governance, environmental exposure, and digital monitoring capacity under conditions of climate stress and disaster vulnerability.

This study makes three principal contributions. First, it reframes trace element contamination as a disaster risk governance challenge rather than solely an environmental engineering problem. Second, it integrates technological, institutional, environmental, and resilience dimensions into a unified analytical framework. Third, it advances a GCC-specific governance perspective that accounts for desalination dependence, climate vulnerability, institutional coordination challenges, and emerging opportunities associated with digital monitoring systems.

Accordingly, this study investigates the governance and management of trace elements across the water cycle in the GCC from a disaster risk reduction and resilience-building perspective, with particular emphasis on regulatory coherence, institutional coordination, and technological performance. Drawing on secondary qualitative and quantitative data, the research examines contamination sources and environmental impacts, evaluates desalination and treatment technologies, and analyzes national regulatory frameworks across selected GCC countries. The study further explores the role of GIS-based spatial analysis, remote sensing applications, AI-supported predictive modeling, and big data analytics in strengthening environmental monitoring, early warning systems, and risk detection capabilities. At the same time, it recognizes that implementation may be constrained by institutional fragmentation, technical capacity limitations, uneven environmental data availability, and economic considerations associated with advanced monitoring infrastructures.

Furthermore, the study highlights the role of circular water systems, water reuse strategies, and smart monitoring infrastructures as critical components of long-term disaster resilience. While these approaches offer significant potential to strengthen adaptive capacity and reduce vulnerability, their successful implementation depends on regulatory coordination, institutional capacity, stakeholder engagement, and economic feasibility. By integrating governance analysis with technological innovation and disaster risk frameworks, the study contributes to a more comprehensive understanding of water security as a core dimension of environmental and humanitarian disaster resilience (Awashreh, 2025b).

The primary research question guiding this study is: How can evidence-informed regulatory frameworks be designed to effectively manage trace elements as environmental and public health risks within desalination-dependent water systems in the GCC region under conditions of increasing environmental stress and disaster vulnerability?

To address this question, the study pursues two objectives: (1) to assess the sources, distribution, and governance of trace elements in GCC water systems using secondary empirical data within a disaster risk and resilience framework supported by geospatial and institutional perspectives, and (2) to propose policy, technological, and digital strategies—including AI-enabled monitoring and GIS-based risk mapping—that strengthen regulatory coherence, enhance system resilience, and support long-term environmental sustainability and disaster risk reduction.

By advancing an integrated governance, technological, and resilience-oriented perspective, this study contributes actionable insights for policymakers, environmental regulators, and disaster risk management authorities seeking to enhance water security, public health protection, and climate-resilient development in the GCC and comparable arid regions.

2. LITERATURE REVIEW & THEORETICAL FRAMEWORK

significant implications for disaster risk reduction (DRR), public health resilience, and humanitarian security, particularly in arid and water-stressed regions such as the Gulf Cooperation Council (GCC) countries. Trace elements—including arsenic, lead, mercury, and cadmium—are persistent, bioaccumulative, and toxic even at low concentrations, making them critical risk drivers in environmental and humanitarian systems. Empirical evidence links long-term exposure to severe health outcomes, including carcinogenesis, neurological impairment, and cardiovascular disease (Khatoon et al., 2025). In addition, these contaminants degrade ecosystem integrity and water system functionality, increasing vulnerability during droughts, heatwaves, and water shortages, thereby weakening adaptive capacity and disaster resilience in arid environments (Ejiohuo et al., 2025).

Within contemporary DRR frameworks, trace element contamination should be understood as part of a complex socio-environmental system shaped by climate variability, governance structures, technological systems, and spatial environmental dynamics. Recent research highlights the importance of integrating geospatial technologies (GIS), remote sensing, and data-driven monitoring systems to detect contamination patterns, identify hotspots, and support early warning systems (Qi et al., 2025). However, despite increasing technological adoption, integration into disaster risk governance remains limited, particularly in desalination-dependent systems where risks are spatially distributed and institutionally fragmented. This creates a persistent gap between environmental monitoring capabilities and decision-making processes for risk reduction.

2.1 Sources and Environmental Behavior of Trace Elements

Trace elements enter aquatic systems through both anthropogenic and natural pathways. Key anthropogenic sources include industrial effluents, mining, oil and gas activities, and agricultural runoff, which are dominant contributors to contamination (Jin et al., 2025). In the GCC region, rapid industrialization, urban expansion, and energy-intensive development have intensified trace element loading in surface water, groundwater, and desalination feedwater systems (Moossa et al., 2022). Agricultural activities, particularly the use of fertilizers and pesticides, further elevate concentrations of arsenic and lead (Sheema et al., 2024).

The environmental behavior of trace elements is governed by physicochemical factors such as pH, salinity, temperature, and redox conditions, which determine mobility, persistence, and toxicity. These elements may exist in dissolved, particulate, or colloidal forms, each with distinct spatial and temporal behaviors (Smrzka et al., 2019). Mobile forms facilitate wide dispersion, while particulate forms accumulate in sediments, creating long-term contamination reservoirs that reduce ecosystem recovery capacity (Habineza, Makwinja & Inagaki, 2023). In desalination systems, these dynamics are critical, as contaminants may persist through treatment or re-enter marine environments via brine discharge.

From a DRR perspective, these processes require spatial and predictive environmental modeling to assess diffusion patterns and system vulnerability (Awashreh, 2025c). However, most existing studies treat trace element dynamics as isolated environmental processes rather than integrating them into broader disaster risk governance frameworks.

2.2 Water Treatment Technologies and Disaster Risk Limitations

Trace element removal has been widely studied in relation to advanced water treatment technologies, particularly in desalination-dependent regions. Reverse osmosis (RO), nanofiltration, and ion-exchange systems are commonly used to reduce contaminant concentrations (Castro & Abejón, 2024; Morgante et al., 2026). RO is the dominant technology in the GCC due to its broad removal capacity; however, its performance varies by element, with incomplete rejection under certain operational conditions (Al-Kaabi et al., 2021).

Despite its widespread use, RO faces limitations including high energy demand, membrane fouling, and reduced efficiency during peak demand or emergency supply conditions (Azmi et al., 2025). Nanofiltration provides selective ion removal but shows inconsistent performance under variable environmental conditions (Sierra et al., 2013). Ion-exchange systems are effective for targeted removal but are constrained by resin saturation, waste disposal challenges, and limited scalability (Edgar & Boyer, 2021). From a disaster resilience perspective, a key limitation is the weak integration between treatment performance and system-wide risk governance. Although AI-based predictive models and digital twins are increasingly proposed, their operational integration into desalination infrastructure remains limited, reducing real-time adaptive response capacity during environmental stress events.

2.3 Regulatory Frameworks and Disaster Risk Governance Challenges

Globally, trace element risks are governed through regulatory systems that combine monitoring, compliance, and basin-scale management. The European Union Water Framework Directive emphasizes ecosystem-based management and continuous monitoring (Brack et al., 2017), while the U.S. Environmental Protection Agency enforces contaminant limits under the Safe Drinking Water Act (Abolafia, 2025). These systems highlight the importance of institutional coordination and data-driven regulation for environmental safety and DRR.

In contrast, GCC regulatory systems remain fragmented and weakly integrated with disaster risk reduction approaches. Although national standards exist, they often lack desalination-specific thresholds and spatially explicit monitoring systems capable of addressing trace element dynamics in coastal and blended water systems (Al-Saidi et al., 2024).

Institutional fragmentation among ministries, utilities, and environmental agencies further reduces governance efficiency and adaptive capacity (Onyango, 2023). This limits the translation of monitoring data into coordinated policy action, particularly in marine environments affected by cumulative brine discharge and coastal contamination. Consequently, governance remains largely compliance-driven rather than resilience-oriented.

2.4 Water Reuse, Circularity, and Resilience-Based Innovation

Water reuse is increasingly recognized as a strategy to enhance water security and reduce environmental stress in arid regions. Reuse systems reduce freshwater extraction and pollutant discharge, supporting sustainability and disaster resilience objectives (Tortajada et al., 2025). Advanced technologies such as advanced oxidation processes, electrocoagulation, and membrane bioreactors show strong potential for improving trace element removal (Khan et al., 2023).

However, technological feasibility does not automatically translate into resilience outcomes. Effectiveness depends on institutional coordination, regulatory integration, and real-time monitoring systems capable of supporting adaptive management under variable conditions (Pham, 2026). Although circular economy approaches emphasize system efficiency, their implementation in the GCC remains limited due to governance fragmentation and weak integration of digital and spatial risk tools (Farfán Chilicaus et al., 2025).

2.5 Conceptual Gaps in Disaster Risk Governance of Trace Elements

Despite extensive research on trace element chemistry, treatment technologies, and regulation, several gaps remain. First, existing studies overemphasize technological efficiency while underestimating governance and institutional coordination in shaping resilience outcomes.

Second, desalination-specific regulatory frameworks integrating GIS, remote sensing, and AI-based predictive systems for spatial risk monitoring remain underdeveloped.

Third, limited attention has been given to regional and transboundary governance, despite shared marine ecosystems and interconnected desalination infrastructures that generate cumulative environmental risks.

Finally, humanitarian dimensions such as water insecurity during crises, displacement vulnerability, and emergency supply disruptions remain underexplored within trace element governance literature.

Overall, these gaps indicate the need to reframe trace element management as a socio-technical disaster risk governance challenge integrating environmental processes, institutional systems, spatial intelligence, and resilience planning.

2.6 Theoretical Framework

This study adopts an integrated multi-level governance and institutional resilience framework to examine trace element management as a disaster risk reduction challenge in GCC desalination-dependent systems. Multi-level governance theory explains interactions

among local, national, regional, and transboundary actors, while institutional theory examines how formal rules, organizational structures, and informal norms shape compliance and adaptive capacity under risk conditions (Hooghe & Marks, 2001; Baldwin, 2017; Balzano et al., 2025).

The framework is structured around three dimensions:

1. Vertical governance fragmentation – coordination across local, national, and regional levels
2. Horizontal institutional fragmentation – coordination among agencies, utilities, and private actors
3. Technology–policy alignment under risk conditions – integration of treatment systems with regulatory and digital monitoring tools

These dimensions are operationalized through indicators such as governance coordination capacity, regulatory enforcement strength, institutional adaptability, and integration of GIS, remote sensing, and AI-based predictive analytics into decision-making systems. By integrating governance structures, technological systems, and environmental risk dynamics, the framework positions trace element contamination as a systemic disaster risk requiring spatially informed, data-driven, and institutionally coordinated responses. This extends beyond conventional technical or regulatory approaches and supports resilience-oriented water governance in the GCC under increasing environmental stress (See Figure 1).

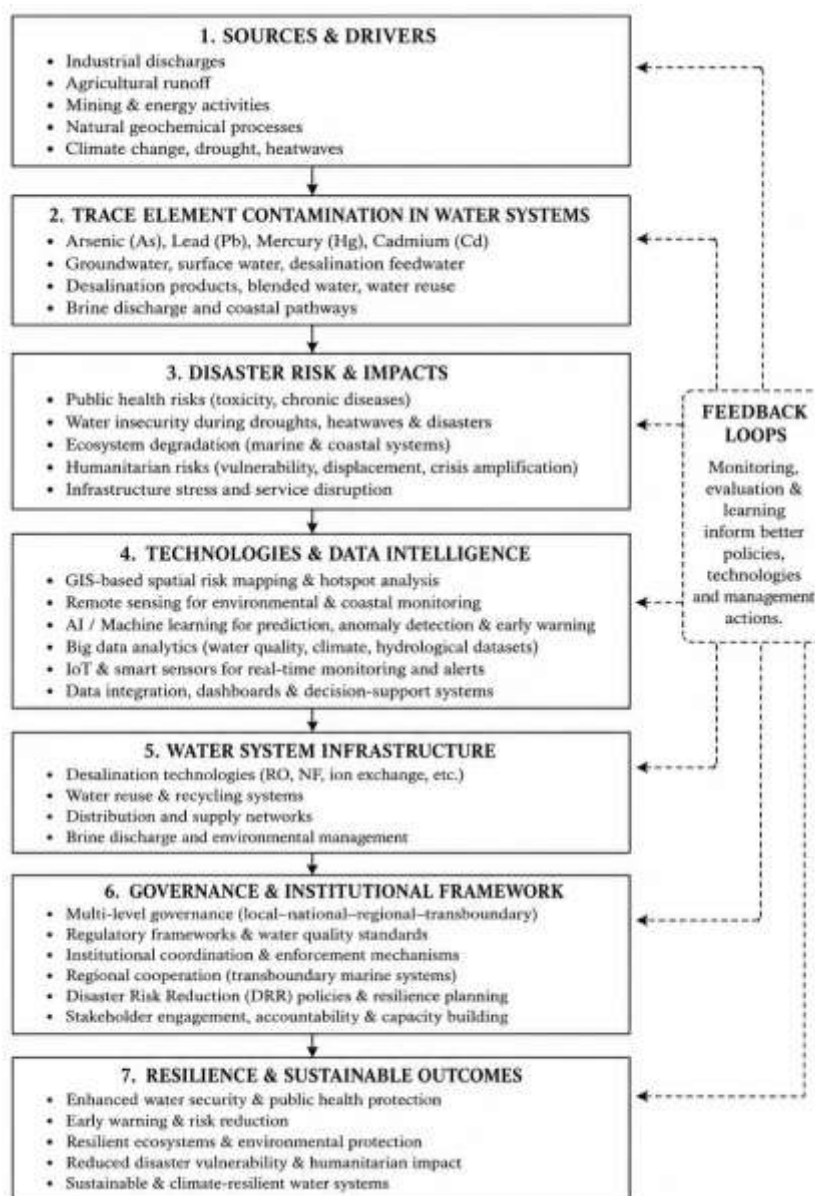


Figure 1 Conceptual Framework

Source: developed by the authors

3. METHODOLOGY

This study adopts a qualitative research design based on secondary data analysis to investigate trace element management within desalination-dependent water systems in the Gulf Cooperation Council (GCC) region, with a focus on environmental risk

governance and disaster resilience. A qualitative research design based on secondary data is considered appropriate because it enables systematic interpretation of complex socio-technical interactions among governance structures, institutional arrangements, environmental processes, and water treatment technologies that shape risk outcomes.

The study relies exclusively on secondary data sources, including peer-reviewed journal articles, policy and technical reports, governmental publications, and international frameworks related to water quality management and disaster risk reduction. These sources were selected through a structured and transparent document retrieval process to ensure relevance, credibility, and coverage of environmental, technological, and governance dimensions of trace element management. These sources are used to build a comprehensive evidence base on trace element contamination, regulatory responses, and technological interventions in water systems.

Data were collected through systematic document review and analyzed using thematic analysis. Key themes were identified related to contamination sources and pathways, technological performance of desalination and treatment systems, regulatory and institutional capacity, and governance challenges across multiple levels. Thematic analysis followed an iterative coding process involving data familiarization, initial coding, theme development, and refinement to ensure consistency and analytical rigor. The analysis is guided by a combined multi-level governance and institutional theory framework, which supports interpretation of coordination mechanisms, regulatory fragmentation, and technology–policy alignment.

This methodological approach enables the synthesis of dispersed knowledge and supports a holistic understanding of trace element risks as part of broader environmental disaster risk systems. It further allows for cross-case comparison of governance practices and identification of recurring patterns across GCC countries within secondary literature. It also facilitates the development of evidence-informed insights into improving regulatory coherence, institutional coordination, and resilience in GCC water governance systems.

4. RESULTS

This section presents the findings derived from the integrated qualitative–quantitative analysis of secondary datasets, technical reports, and regulatory documents. The results are organized around four analytical dimensions aligned with the study objectives: (1) trace element prevalence and sources, (2) treatment technology performance, (3) regulatory and governance patterns, and (4) emerging technologies and regional coordination. Overall, the findings indicate variation in trace element distribution, treatment performance, and regulatory structures across GCC water systems.

4.1 Key Trace Elements and Contamination Sources

The analysis confirms that arsenic (As), lead (Pb), mercury (Hg), and cadmium (Cd) are consistently identified as the most critical trace elements across surface water, groundwater, desalination intake streams, and, in some cases, treated outputs (Hui et al., 2023). However, their spatial distribution is highly uneven across GCC countries, reflecting differences in industrial structure, agricultural intensity, hydrogeological conditions, and monitoring capacity. This indicates spatial heterogeneity in contamination levels across water sources in the GCC region.

Three dominant contamination pathways are observed. Industrial sources, particularly oil and gas extraction, petrochemical activity, and heavy industry, contribute significantly in coastal industrial zones, where episodic discharges and legacy contamination affect intake-water quality (Erabee, 2024). Agricultural runoff affects shallow aquifers and peri-urban systems, contributing to accumulation of arsenic and lead through fertilizer and pesticide inputs (Nuruzzaman, Bahar & Naidu, 2025). A third pathway is associated with desalination systems, where intake-water quality and brine discharge processes contribute to localized concentration effects in coastal zones (Ogunbiyi et al., 2023). The data indicate that trace element presence is associated with multiple environmental and anthropogenic sources across GCC water systems.

4.2 Performance of Water Treatment Technologies

Across GCC water systems, reverse osmosis (RO), nanofiltration (NF), and ion-exchange (IX) systems constitute the primary technological responses to trace element contamination (Leon-Zerpa & Ramos, 2021). The findings show that reported performance varies across technologies and operational conditions.

Reverse osmosis achieves removal rates for arsenic and lead between 90% and 99%, while performance for mercury and cadmium varies under high salinity and membrane fouling conditions (Haidari et al., 2025). Nanofiltration shows removal efficiencies between 60% and 85%, particularly for divalent metals, with lower performance for monovalent species (Mahmoud & Mostafa, 2023). Ion-exchange systems demonstrate removal efficiencies exceeding 85%, although operational constraints such as resin saturation and waste handling limit consistent application (Maqdasi et al., 2025). Across all systems, performance variability is reported under high demand and system stress conditions (Goel, Masurkar, & Pathade, 2024). The findings indicate variability in removal efficiency across treatment technologies and operating conditions.

4.3 Regulatory Frameworks and Governance Patterns

The comparative regulatory analysis reveals that all GCC countries maintain formal water quality standards; however, variation exists in the structure, coverage, and enforcement of trace element regulation (Khan et al., 2024). Differences are observed across regulatory design and implementation practices in the region.

Regulatory coverage of trace elements is uneven, with variation in threshold specification and limited differentiation between desalinated, groundwater, and reuse systems. Institutional mandates overlap across environmental authorities, water utilities, and sectoral regulators, resulting in distributed responsibilities. Enforcement systems are primarily administrative, with variation in inspection frequency and reporting transparency (Yeung & Ranchordás, 2024). Coordination between policy and operational monitoring systems is inconsistently applied across GCC countries.

Comparative benchmarking with international regulatory models, including the European Union Water Framework Directive and U.S. Environmental Protection Agency standards, indicates differences in monitoring approaches and regulatory structure (WWAP, 2017). GCC regulatory frameworks show limited integration of spatial monitoring and preventive risk-based approaches compared to international models.

4.4 Emerging Technologies and Water Reuse

The findings indicate increasing but uneven adoption of emerging technologies for trace element monitoring and removal. Pilot applications of advanced membrane systems, digital monitoring platforms, and optimization tools show variation in reported system performance (Atef, 2026; Ben Rouane et al., 2025). The level of technological adoption differs across GCC water utilities and projects.

Water reuse systems are increasingly used for non-potable applications in water-scarce environments. However, their performance in relation to trace element reduction varies depending on treatment configuration, monitoring intensity, and regulatory requirements (Xenitopoulos et al., 2026). Data show variability in reuse system design and monitoring integration across applications.

4.5 Regional Policy Coordination and Alignment

At the regional level, the analysis shows limited formal coordination mechanisms for trace element governance across GCC countries. Despite shared marine ecosystems and interconnected desalination infrastructures, harmonized standards and joint monitoring systems remain limited (Connor et al., 2024). Regional coordination mechanisms for water quality governance are not consistently implemented across GCC states.

Differences in national policies result in variation in monitoring approaches and data-sharing practices. Environmental externalities from desalination discharge and industrial activity are not uniformly addressed through regional governance structures (Maione, Vito & Fernandez, 2024). This indicates variation in regional alignment for managing shared marine water quality risks.

4.6 Results Synthesis through a Multi-Level Governance Lens

When integrated, the findings indicate that trace element outcomes in GCC water systems are associated with governance structures, institutional arrangements, and technological implementation conditions. While desalination and treatment technologies are widely deployed, their performance varies across operational and institutional contexts.

From a multi-level governance perspective, variation is observed across vertical coordination (between national and local levels), horizontal coordination (between agencies and utilities), and regional coordination structures. The integrated findings show that governance structures, institutional arrangements, and operational conditions jointly influence trace element management outcomes in GCC water systems.

5. DISCUSSION

This study addressed the central research question: how can evidence-informed regulatory frameworks be designed to manage trace elements as environmental and public health risks within desalination-dependent water systems in the GCC under increasing environmental stress and disaster vulnerability? The findings indicate that current systems are constrained by governance fragmentation, uneven enforcement, and limited integration of digital and spatial intelligence. This suggests that trace element risks are not primarily a technological problem, but a systemic governance and institutional resilience challenge embedded in socio-technical water systems.

The results show that trace element contamination in the GCC is driven by interconnected industrial, agricultural, and desalination-related pathways, confirming its systemic nature. Industrial and petrochemical activities intensify localized contamination, agricultural runoff contributes diffuse long-term exposure risks, and desalination processes add feedback effects through intake concentration and brine discharge (Erabee, 2024; Ogunbiyi et al., 2023). This confirms the need for integrated water-cycle governance rather than source-specific regulation.

Regarding treatment systems, reverse osmosis and related technologies offer high theoretical efficiency but perform inconsistently under operational stress, salinity variation, and maintenance constraints (Haidari et al., 2025). This shows that technological capacity alone cannot ensure safety under climate and disaster stress. Instead, performance depends on governance quality, oversight, and monitoring systems, reinforcing the socio-technical nature of risk production.

The findings validate the proposed multi-level governance and institutional resilience framework. Vertical fragmentation appears in misalignment between national regulations and operational implementation, while horizontal fragmentation is reflected in overlapping mandates among environmental, water, and industrial authorities. These patterns reduce coordination and adaptive capacity, consistent with institutional theory (Hooghe & Marks, 2001; Baldwin, 2017). In addition, weak integration between

technological systems and regulatory frameworks confirms technology–policy misalignment. Despite the availability of advanced desalination technologies, their effectiveness is limited by insufficient integration with GIS, predictive analytics, and early warning systems. This supports the argument that resilience depends on alignment between governance structures, institutional capacity, and digital infrastructure.

The results further show that disaster risk governance is constrained not by data availability, but by weak data integration and decision-support systems. The absence of systematic GIS, remote sensing, and AI-based monitoring limits anticipatory governance and reduces resilience capacity.

These findings are consistent with studies highlighting the health and environmental risks of trace elements (Khatoon et al., 2025; Ejiohuo et al., 2025), but extend the literature by shifting the focus from contamination effects to governance-driven risk production. Similarly, while prior research confirms high efficiency of treatment technologies under controlled conditions (Castro & Abejón, 2024; Morgante et al., 2026), this study shows that real-world performance is constrained by operational and governance limitations, aligning with critiques of the lab–field gap (Goel, Masurkar, & Pathade, 2024).

On governance, the findings support evidence of fragmentation in GCC water systems (Al-Saidi et al., 2024; Onyango, 2023), but further demonstrate how this fragmentation directly amplifies disaster risk by weakening early warning, detection, and response capacity. From a DRR perspective, the study highlights that slow-onset hazards such as trace element contamination must be integrated into disaster frameworks alongside acute hazards, as they interact with climate stressors to produce cumulative vulnerability. This supports systemic risk approaches in DRR literature.

The study also advances resilience theory by showing that resilience in water systems is institutional and informational, not only infrastructural. Without integrated monitoring systems, adaptive capacity remains limited. Accordingly, governance should shift from compliance-based regulation toward risk-based and data-driven systems incorporating desalination-specific thresholds, cumulative exposure assessment, and spatial monitoring. GIS, remote sensing, and AI-based tools should be embedded as core governance functions. At the regional level, limited coordination highlights the need for transboundary governance mechanisms, including shared monitoring systems and harmonized standards for marine environments. Without such coordination, cumulative risks will remain unmanaged.

Overall, the findings confirm that trace element contamination in the GCC is a socio-technical disaster risk governance challenge. Technological solutions are necessary but insufficient without institutional integration, regulatory coherence, and spatial intelligence, requiring a unified governance transformation linking technology, institutions, and risk analytics.

6. THEORETICAL CONTRIBUTION, IMPLICATIONS & RECOMMENDATIONS

6.1 Theoretical Contribution

This study advances disaster risk reduction and water governance theory by reframing trace element contamination as a socio-technical and multi-level governance risk rather than a purely environmental or engineering problem. By integrating multi-level governance theory and institutional resilience perspectives, the study demonstrates how vertical fragmentation (between national and local authorities), horizontal fragmentation (across agencies), and weak technology–policy alignment collectively shape environmental risk outcomes in desalination-dependent systems. This extends existing literature by explicitly linking institutional fragmentation patterns to the generation and amplification of slow-onset environmental risks in arid regions. The study also strengthens resilience theory by showing that adaptive capacity depends not only on infrastructure robustness but also on the integration of digital tools such as GIS, remote sensing, and AI-driven monitoring into governance systems. Importantly, it contributes a conceptual shift by positioning trace elements as systemic risk drivers embedded within water-energy-environment nexuses, thereby expanding theoretical understanding of how environmental contamination evolves into disaster risk under climate stress conditions.

6.2 Practical Implications

The findings have significant practical implications for water authorities, environmental regulators, and disaster risk management agencies in the GCC. First, they highlight the need to move beyond compliance-based water quality regulation toward risk-based governance systems that account for cumulative exposure, spatial variability, and desalination-specific vulnerabilities. Second, operational water management should integrate real-time monitoring systems using GIS mapping, remote sensing, and AI-based predictive analytics to detect contamination patterns and support early warning mechanisms. Third, desalination plants and water utilities should strengthen maintenance regimes, performance auditing, and feedwater quality control to reduce variability in treatment efficiency, particularly for reverse osmosis systems under stress conditions. Fourth, the results emphasize the importance of institutional coordination between environmental, industrial, and water authorities to reduce overlapping mandates and improve accountability. Finally, regional cooperation is essential to manage shared marine contamination pathways, particularly brine discharge, requiring joint monitoring platforms and harmonized standards across GCC countries. Collectively, these implications point to the need for integrated technological, institutional, and regulatory reforms in GCC water governance systems.

6.3 Recommendations

Based on the findings, several key recommendations are proposed to strengthen trace element governance and disaster resilience in GCC water systems. First, governments should establish integrated, desalination-specific water quality standards that include explicit thresholds for arsenic, lead, mercury, and cadmium across all water streams, including reuse systems. Second, regulatory agencies should institutionalize GIS-based spatial monitoring systems and AI-driven predictive models to enable real-time risk mapping and early warning capabilities. Third, water governance structures should be reformed to reduce institutional fragmentation by creating unified regulatory bodies or formal coordination mechanisms between environmental, industrial, and water authorities. Fourth, investment should prioritize hybrid treatment systems combining advanced membranes with digital monitoring to improve operational resilience under climate stress conditions. Fifth, a GCC-level regional water risk platform should be developed to enable data sharing, harmonized standards, and coordinated marine pollution control. Finally, capacity-building programs should strengthen technical and governance skills in environmental risk analytics and digital water management systems. Overall, these recommendations emphasize a transition toward integrated, data-driven, and regionally coordinated water governance systems.

7. CONCLUSION

This study examined trace element contamination in desalination-dependent water systems in the GCC from a disaster risk reduction and governance perspective. The findings show that arsenic, lead, mercury, and cadmium persist across interconnected water pathways driven by industrial activity, agricultural runoff, and desalination processes. Although reverse osmosis and nanofiltration demonstrate high theoretical removal efficiency, their real-world performance is inconsistent due to operational stress, feedwater variability, and maintenance limitations.

More importantly, the results indicate that water quality outcomes are shaped more by governance structures than by technology alone. Fragmented institutions, uneven regulatory coverage, and weak regional coordination significantly reduce system effectiveness. Accordingly, trace element contamination should be understood as a socio-technical disaster risk requiring integrated governance reform, digital monitoring, and spatial intelligence to strengthen resilience under environmental stress.

The study is based on secondary data only, which limits empirical validation and may introduce reporting bias due to variations in data availability and transparency across GCC countries. Differences in monitoring standards also constrain comparability, and the absence of site-specific and real-time plant data limits precision in assessing operational performance. In addition, the study does not include quantitative risk modeling or climate scenario simulations, which restricts predictive capacity.

Future research should incorporate primary field data from desalination plants and groundwater systems, supported by real-time monitoring and laboratory validation. Advanced methods such as geospatial modeling, machine learning, and AI-based predictive analytics are also needed to quantify risks and simulate climate-driven scenarios. Comparative studies with other desalination-dependent regions, as well as research on socio-economic vulnerability and health impacts, would further strengthen the evidence base. Evaluation of regional governance frameworks and digital water intelligence systems is also recommended.

Overall, the study highlights that water security in the GCC cannot be achieved through technological solutions alone. Trace element contamination represents a slow-onset disaster risk embedded in interconnected environmental, technological, and governance systems. Addressing it requires integrated, data-driven, and regionally coordinated governance that combines institutional reform with digital innovation, reinforcing the need for system-level rather than sector-specific responses.

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