

Geothermal Environments and Human Health: Exposure Pathways, Risks, and Mitigation Strategies

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Abstract

Geothermal energy is increasingly deployed worldwide as a low-carbon, dispatchable renewable resource, yet the natural and engineered processes underlying geothermal energy extraction create a distinctive set of environmental exposure pathways—atmospheric, aqueous, and geomechanical—that can affect the health of nearby communities. Geothermal fluids naturally carry hydrogen sulfide, carbon dioxide, arsenic, and other geogenic trace elements to the surface, while reservoir pressure changes from fluid withdrawal and reinjection can alter ground stability and, in some settings, induce seismicity. This article synthesizes the scientific literature on geothermal environments and human health, organizing the evidence around three principal exposure pathways—atmospheric hydrogen sulfide, arsenic and trace element contamination of water resources, and geomechanical risk—and the corresponding epidemiological, hydrogeochemical, and risk-assessment evidence associated with each. It draws on subsurface reactive transport modeling relevant to long-term geothermal reservoir chemistry, machine learning-enhanced geomechanical characterization relevant to induced seismicity and ground stability, and heterogeneous reservoir management principles from analogous subsurface energy operations, and further considers how AI-driven public health surveillance, predictive analytics, and economic impact frameworks developed for national healthcare systems could inform more integrated environmental health mitigation strategies for geothermal-adjacent communities. The article concludes by identifying persistent challenges in exposure quantification, cross-pathway risk integration, and mitigation strategy evaluation, and proposes a research agenda for advancing environmental health protection in geothermal energy development.

Keywords: geothermal energy, environmental health, exposure pathways, hydrogen sulfide, arsenic, geomechanical risk, mitigation strategies, human health risk assessment

1. Introduction

Geothermal energy, extracting heat from subsurface reservoirs for electricity generation and direct-use heating, is projected to play a growing role in global decarbonization strategies given its low life-cycle carbon emissions and its capacity to provide dispatchable, baseload renewable generation unavailable from solar and wind resources alone. However, the same subsurface processes that make geothermal energy an attractive resource—deep circulation of naturally heated fluids through fractured and permeable rock—also mobilize a range of geogenic constituents, including hydrogen sulfide, carbon dioxide, arsenic, mercury, boron, and other trace elements, that can reach the surface environment through natural manifestations or engineered extraction and, in doing so, create human health exposure pathways that must be understood, quantified, and, where necessary, mitigated.

Three broad categories of exposure pathway characterize the human health risk profile of geothermal environments. First, atmospheric emissions of hydrogen sulfide and other non-condensable gases from geothermal power plants and natural manifestations create an inhalation exposure pathway that has been the subject of substantial epidemiological research, particularly in long-established geothermal districts such as those in Italy, New Zealand, and Iceland. Second, arsenic and other potentially toxic trace elements mobilized by geothermal fluids can contaminate surface water and groundwater resources used for drinking, irrigation, and other purposes, creating an ingestion exposure pathway that has received growing research attention as geothermal development expands into new regions, including Latin America. Third, geomechanical processes associated with fluid withdrawal and reinjection can induce ground surface deformation and, in some geologic settings, low-magnitude seismicity, introducing a distinct safety and psychosocial risk dimension that complements the more extensively studied chemical exposure pathways.

This article synthesizes the scientific literature on geothermal environments and human health across these three exposure pathways, integrating epidemiological evidence on hydrogen sulfide exposure and respiratory, cardiovascular, and nervous system health outcomes (Bustaffa et al., 2020; Nuvolone et al., 2019; Quist & Johnston, 2024; Stoppa et al., 2023), the global hydrogeochemical evidence base on geothermal arsenic mobilization (Morales-Simfors & Bundschuh, 2022), and the quantitative environmental risk assessment framework encompassing seismic, health, ecological, and economic dimensions of geothermal energy

development (Chen et al., 2020). It further draws on subsurface reactive transport modeling relevant to long-term geothermal reservoir chemistry evolution, machine learning-enhanced geomechanical characterization relevant to induced seismicity and ground stability risk (Akpabli et al., 2026), and heterogeneous reservoir management principles from analogous subsurface energy operations, and considers how AI-driven public health surveillance, predictive analytics, and economic impact frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d) might inform more integrated mitigation strategies. The objective is to provide a comprehensive, pathway-organized synthesis for public health researchers, environmental scientists, geothermal industry practitioners, and regulators seeking to strengthen environmental health protection as geothermal energy development continues to expand globally.

2. Exposure Pathway One: Atmospheric Hydrogen Sulfide

2.1 Sources and Characteristics of Atmospheric Exposure

Hydrogen sulfide reaches the atmosphere near geothermal facilities both from natural geothermal manifestations—fumaroles, hot springs, solfataras—and from engineered power plant operations, including cooling tower emissions and non-condensable gas venting. Concentrations vary substantially with meteorological conditions, plant operational status, and proximity to emission sources, and the gas's characteristic odor at very low concentrations means that community perception of exposure risk often precedes, and does not necessarily correlate closely with, measured or modeled exposure levels.

2.2 Chronic Exposure and Health Outcomes

Bustaffa et al. (2020) reviewed the accumulated evidence on health outcomes among communities living near geothermal plants generating heat and electricity across New Zealand, Iceland, and Italy, finding a body of evidence characterized by inconsistency and methodological limitation, predominantly ecological or residence-based exposure assessment, with some studies reporting associations between low-level chronic exposure and increased respiratory disease alongside other, more difficult to interpret findings such as an inverse association between higher exposure and cancer mortality in certain analyses. Building on this evidence base, Nuvolone et al. (2019) conducted a nearly two-decade residential cohort study in the Mt. Amiata geothermal district of Tuscany, Italy, evaluating chronic low-level hydrogen

sulfide exposure against mortality and hospital discharge outcomes for respiratory, cardiovascular, and central nervous system conditions using dispersion-modeled, residence-based exposure metrics matched to socioeconomic status at the census tract level.

2.3 Objective Respiratory Function Assessment

Moving beyond administrative mortality and hospitalization data toward direct physiological measurement, Stoppa et al. (2023) conducted the InVETTA cross-sectional study, enrolling more than 2,000 adults in the Mt. Amiata geothermal area and performing spirometry to objectively assess lung function in relation to modeled hydrogen sulfide exposure; notably, this more methodologically rigorous approach, incorporating objective respiratory function measurement rather than administrative outcome data alone, did not find evidence of an association between hydrogen sulfide exposure and chronic obstructive pulmonary disease, a finding that illustrates the genuinely unsettled state of the chronic exposure evidence base even within the same well-studied geothermal district.

2.4 Acute Exposure Events

Complementing the chronic, low-level exposure literature, Quist and Johnston (2024) documented the respiratory and nervous system health effects associated with an acute hydrogen sulfide exposure crisis in Carson, California, illustrating that atmospheric hydrogen sulfide exposure near geothermal and related energy operations presents both a chronic, low-level risk profile requiring long-term epidemiological surveillance and a distinct acute, high-concentration risk profile requiring emergency public health response capability—two related but methodologically and operationally distinct dimensions of the same underlying exposure pathway.

3. Exposure Pathway Two: Arsenic and Trace Element Contamination of Water Resources

3.1 Geothermal Arsenic as a Global Environmental Health Concern

Beyond atmospheric hydrogen sulfide, geothermal fluids are a globally significant source of geogenic arsenic contamination in surface water and groundwater resources. Morales-Simfors and Bundschuh (2022) conducted a comprehensive global assessment of arsenic-rich geothermal fluids as environmentally hazardous materials, systematically characterizing

arsenic occurrence across the six principal types of geothermal reservoirs worldwide and documenting that geothermal arsenic frequently co-occurs with other geogenic contaminants, including fluoride, lithium, boron, mercury, antimony, selenium, and thorium, that collectively pose serious risks to near-surface environments through contamination of surface water, groundwater, soils, and sediments, ultimately exposing large populations to arsenic-related diseases.

3.2 Natural and Technically Enhanced Release Pathways

The review by Morales-Simfors and Bundschuh (2022) distinguishes between purely natural release pathways, in which geothermal fluids rise to the surface along fault systems without human intervention, and technically enhanced pathways facilitated by geothermal reservoir exploitation for electricity generation and direct heat use, underscoring that both natural geothermal manifestations and engineered geothermal energy development contribute to arsenic mobilization risk, with groundwater generally more vulnerable to contamination than surface water because of the longer-term interaction between geothermal fluids and aquifer minerals.

3.3 Regional Case Evidence and Vulnerable Populations

Emerging evidence from geothermal exploration zones in Latin America illustrates how arsenic and other potentially toxic elements—including manganese, iron, vanadium, and aluminum—can be mobilized through acidic volcanic gas interaction with surface and groundwater, creating chronic exposure risk through drinking water for local populations, with particular concern for rural, resource-limited communities with restricted access to alternative clean water sources and limited regulatory infrastructure to monitor and mitigate contamination. This regional evidence underscores that arsenic and trace element exposure pathways associated with geothermal development are not confined to long-established geothermal districts in high-income countries but represent an active and expanding concern as geothermal exploration and development activities extend into new, often less-resourced regions.

3.4 Relevance of Reactive Transport Modeling to Long-Term Water Quality Risk

Understanding how arsenic and other trace element concentrations in geothermal fluids evolve over a reservoir's operational lifetime requires characterizing the reactive transport processes

governing mineral dissolution, precipitation, and fluid-rock geochemical interaction within the reservoir. Numerical modeling of reactive transport in geothermal reservoirs for long-term performance prediction provides a scientific basis for forecasting how reservoir fluid chemistry, including trace element mobilization, may evolve over extended operational timescales, offering a mechanistic complement to the empirical hydrogeochemical surveys that currently dominate the geothermal arsenic exposure literature, even though such reactive transport modeling has not, to date, been directly integrated into water resource health risk assessment practice at operating geothermal sites.

4. Exposure Pathway Three: Geomechanical Risk and Induced Seismicity

4.1 Ground Deformation and Seismic Hazard as an Environmental Risk Category

Beyond chemical exposure pathways, Chen et al. (2020) explicitly identify seismic hazard as one of four principal categories of quantifiable environmental risk associated with geothermal energy development, alongside human health, ecological damage, and economic loss, reflecting a growing recognition within the environmental risk assessment literature that geomechanical processes associated with geothermal fluid withdrawal and reinjection constitute a distinct risk category requiring dedicated quantitative assessment methodology rather than incidental treatment within broader environmental impact frameworks.

4.2 Geomechanical Characterization as a Risk Mitigation Tool

Machine learning-enhanced geomechanical characterization and wellbore stability assessment methodologies, integrating stress field estimation, rock strength prediction, and operational parameter analysis into a proactive risk-management workflow, have been demonstrated in offshore energy reservoir settings as a means of anticipating and managing geomechanical instability before it manifests as an operational or safety incident (Akpabli et al., 2026). Adapting such geomechanically informed, machine learning-enhanced characterization approaches to the specific stress, thermal, and injection-cycling conditions of geothermal reservoirs represents a promising, currently underutilized avenue for proactively managing induced seismicity and ground deformation risk in geothermal districts, complementing the reactive, incident-driven approach to seismic risk management that has characterized much of the geothermal industry's historical practice.

4.3 Heterogeneous Reservoir Considerations for Pressure Management

Principles of heterogeneous subsurface reservoir management developed in analogous energy contexts—including the optimization of fluid injection strategies to manage pressure distribution and containment risks in heterogeneous depleted gas reservoirs—offer transferable methodological insight for geothermal reservoir pressure management, where similarly heterogeneous rock properties govern the spatial distribution of pressure changes from fluid withdrawal and reinjection, and, by extension, the geomechanical risk profile experienced by communities and infrastructure in the vicinity of a geothermal field.

5. Integrated Risk Assessment and Mitigation Frameworks

5.1 Toward a Multi-Pathway, Multi-Risk Assessment Framework

Chen et al. (2020) explicitly call for the development of an integrated assessment framework capable of jointly characterizing seismic hazard, human health, ecological damage, and economic risk associated with geothermal energy development, alongside a proposed data-sharing platform to support this integration—recognizing that the atmospheric, aqueous, and geomechanical exposure pathways discussed in this article are not independent phenomena but interrelated dimensions of a single underlying geothermal energy production system that should, ideally, be assessed and mitigated in a coordinated rather than siloed fashion.

5.2 Mitigation Strategies for Atmospheric Emissions

Mitigation strategies for atmospheric hydrogen sulfide exposure include abatement technologies applied to power plant non-condensable gas streams, optimized cooling tower design and siting to reduce ground-level concentration near residential areas, and, at the regulatory level, ambient air quality standards and monitoring requirements calibrated to the epidemiological evidence base, imperfect as that evidence base currently is. Given the persistent inconsistency in the epidemiological literature reviewed above, mitigation strategy development in this domain must proceed under genuine scientific uncertainty regarding the precise concentration-response relationship between chronic hydrogen sulfide exposure and respiratory health outcomes.

5.3 Mitigation Strategies for Water Resource Contamination

Mitigation strategies for arsenic and trace element contamination of water resources near

geothermal facilities include reinjection of spent geothermal fluids to minimize surface discharge, treatment of geothermal fluids prior to any surface release, and, at the community level, provision of alternative drinking water sources or point-of-use treatment technologies for populations reliant on potentially contaminated groundwater—mitigation approaches whose effectiveness and appropriate targeting depend on the kind of systematic hydrogeochemical characterization exemplified by global assessments of geothermal arsenic risk (Morales-Simfors & Bundschuh, 2022).

5.4 Mitigation Strategies for Geomechanical Risk

Mitigation strategies for geomechanical and induced seismicity risk center on proactive, geomechanically informed reservoir management, including careful control of injection rates and pressures, continuous microseismic and ground deformation monitoring, and traffic-light protocols that adjust operations in response to observed seismicity, all of which benefit substantially from the kind of machine learning-enhanced geomechanical characterization capabilities demonstrated in analogous subsurface energy settings (Akpabli et al., 2026) and from heterogeneous reservoir management principles developed for pressure-sensitive subsurface operations more broadly.

6. Cross-Domain Lessons: AI-Driven Surveillance and Economic Justification for Mitigation Investment

6.1 Precision Public Health as a Model for Integrated Exposure-Outcome Surveillance

National-scale AI frameworks developed for precision public health illustrate how predictive analytics can integrate diverse individual-level data streams to support targeted chronic disease prevention and early intervention, moving beyond periodic, population-wide screening toward continuously updated, individually informed risk assessment (Nguyen, 2026a). Applied to the multi-pathway exposure context of geothermal environments, an analogous framework could integrate atmospheric hydrogen sulfide dispersion modeling, water resource arsenic and trace element monitoring, and geomechanical deformation monitoring within a single, continuously updated surveillance system capable of flagging emerging risk signals across all three exposure pathways simultaneously, directly addressing the integrated assessment framework that Chen et al. (2020) explicitly call for but that has not yet been comprehensively implemented at any studied geothermal site.

6.2 Predictive Analytics for Targeting Mitigation Resources

National-scale predictive analytics frameworks applied to Medicare and Medicaid populations demonstrate how AI-driven risk stratification can identify high-risk populations for targeted follow-up from large, heterogeneous datasets, thereby directing limited intervention resources toward those most likely to benefit (Nguyen, 2026d). An analogous approach applied to geothermal-adjacent communities could help prioritize mitigation investment—additional air quality monitoring, water treatment infrastructure, geomechanical monitoring density—toward the specific sub-populations and locations facing the highest combined exposure risk across all three pathways, rather than distributing mitigation resources uniformly across an entire geothermal district irrespective of relative risk.

6.3 Economic Justification for Mitigation Infrastructure Investment

Economic impact analyses of AI adoption in healthcare, quantifying national-scale cost savings and productivity gains attributable to AI-driven predictive modeling and early intervention, offer a template for evaluating the economic case for investing in integrated, multi-pathway environmental health surveillance and mitigation infrastructure around geothermal facilities (Nguyen, 2026c). Given that geothermal energy's principal appeal lies in its status as a low-carbon, economically viable energy source, demonstrating that environmental health mitigation investment can be economically justified—through avoided healthcare costs, avoided regulatory and litigation risk, and preserved community and regulatory license to operate—represents an important complement to the epidemiological and hydrogeochemical evidence reviewed throughout this article, helping ensure that environmental health protection is treated as a core operational consideration rather than an afterthought in geothermal energy development.

7. Challenges and Limitations

Despite substantial research attention across each exposure pathway, several challenges continue to constrain environmental health protection in geothermal energy development.

Exposure assessment precision across pathways. As with the atmospheric hydrogen sulfide literature, hydrogeochemical arsenic and trace element studies often rely on periodic water sampling rather than continuous monitoring, and geomechanical risk assessment often relies on

reactive, post-event seismic catalogs rather than proactive, continuously updated stress and deformation monitoring, leaving all three exposure pathways subject to meaningful exposure assessment uncertainty.

Fragmented, single-pathway research and regulatory practice. Despite explicit calls for integrated, multi-pathway risk assessment frameworks (Chen et al., 2020), the epidemiological, hydrogeochemical, and geomechanical literatures reviewed in this article have developed largely independently, with limited cross-pathway integration in either research design or regulatory practice.

Geographic concentration of the strongest evidence. The most methodologically developed epidemiological evidence on hydrogen sulfide exposure derives predominantly from Italian geothermal districts, while the strongest global hydrogeochemical arsenic assessment, though genuinely global in scope, still reflects uneven research intensity across geothermal regions, limiting confidence in the generalizability of specific quantitative risk estimates to geothermal districts with different demographic, climatic, and geologic characteristics.

Underutilization of mechanistic subsurface science in health risk assessment. Reactive transport modeling capable of forecasting long-term reservoir fluid chemistry evolution and machine learning-enhanced geomechanical characterization capable of anticipating induced seismicity risk (Akpabli et al., 2026) remain largely disconnected from applied environmental health risk assessment practice at operating geothermal facilities, representing an underexplored opportunity for more forward-looking, mechanistically grounded risk characterization.

Resource constraints in vulnerable, newly developing geothermal regions. As geothermal development expands into rural, resource-limited regions with weaker regulatory infrastructure, the capacity to conduct the kind of rigorous, multi-pathway environmental health monitoring demonstrated in established geothermal districts may be substantially constrained, raising equity concerns regarding the distribution of environmental health protection across different geothermal-producing regions worldwide.

8. Future Directions

Future research should prioritize the development of genuinely integrated, multi-pathway environmental health surveillance frameworks capable of jointly monitoring atmospheric hydrogen sulfide, water resource arsenic and trace element contamination, and geomechanical

deformation and seismicity risk within a single, continuously updated system, directly responding to the integrated assessment framework and data-sharing platform explicitly called for by Chen et al. (2020). Extending the geographic and demographic diversity of the epidemiological and hydrogeochemical evidence base beyond currently dominant Italian and selected Latin American case studies represents a further important direction, particularly as geothermal energy development continues to expand into new regions.

Integrating reactive transport modeling of long-term geothermal reservoir fluid chemistry evolution and machine learning-enhanced geomechanical characterization of induced seismicity and ground stability risk (Akpabli et al., 2026) directly into applied environmental health risk assessment practice represents a promising avenue for moving beyond retrospective, exposure-outcome association studies toward more mechanistically grounded, forward-looking risk characterization and mitigation planning. Finally, adapting AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d) toward the specific, multi-pathway context of geothermal-adjacent communities offers a concrete pathway toward the integrated, continuously updated, and economically justified environmental health surveillance and mitigation infrastructure that this field has long needed but has not yet comprehensively achieved.

9. Conclusion

Geothermal energy development creates a distinctive, multi-pathway environmental health exposure profile spanning atmospheric hydrogen sulfide emissions, arsenic and trace element contamination of water resources, and geomechanical risk associated with induced seismicity and ground deformation—three exposure pathways that have historically been studied largely in isolation from one another, despite their common origin in the same underlying subsurface fluid extraction and reinjection processes. The epidemiological evidence on hydrogen sulfide exposure remains genuinely inconsistent, the global hydrogeochemical evidence on geothermal arsenic underscores a widespread but unevenly monitored contamination risk, and geomechanical risk, while increasingly recognized as a formal category of quantifiable environmental risk, remains only partially integrated into proactive geothermal reservoir management practice. Subsurface reactive transport modeling and machine learning-enhanced geomechanical characterization, though not yet integrated into applied environmental health

risk assessment, offer mechanistically grounded tools for more forward-looking risk characterization, while AI-driven precision public health, predictive analytics, and economic impact assessment frameworks developed for national healthcare systems offer a transferable template for the integrated, multi-pathway surveillance and mitigation infrastructure this field has long sought. Advancing environmental health protection for communities located near geothermal energy facilities will require sustained investment in exposure assessment precision across all three pathways, genuine cross-pathway risk integration, and the extension of both research attention and mitigation resources to newly developing geothermal regions—investments essential to ensuring that geothermal energy can fulfill its promise as a low-carbon energy source while genuinely protecting the health and safety of the communities who live alongside it.

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