

## **Environmental Health Assessment of Communities Located Near Geothermal Energy Facilities**

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### **Abstract**

Geothermal energy is widely regarded as a low-carbon, dispatchable renewable resource central to global decarbonization strategies, yet the communities residing near geothermal power plants and district heating facilities are exposed to a distinct set of environmental emissions and geomechanical processes that warrant careful, ongoing health assessment. Geothermal fluids naturally contain hydrogen sulfide, carbon dioxide, methane, and trace elements that can be released to the atmosphere during energy extraction, while reservoir pressure changes associated with fluid withdrawal and reinjection can induce ground deformation and, in some settings, low-magnitude seismicity. This article synthesizes the epidemiological and environmental health literature on communities located near geothermal energy facilities, examining chronic and short-term hydrogen sulfide exposure studies, respiratory and cardiovascular health outcomes, community risk perception, and the reactive transport and geomechanical processes that govern long-term emissions and ground stability risk at geothermal sites. It draws on subsurface reactive transport modeling relevant to long-term geothermal reservoir performance, machine learning-enhanced geomechanical characterization relevant to induced seismicity and ground stability risk, and heterogeneous reservoir management principles from analogous subsurface energy operations, and further considers how AI-driven public health surveillance and predictive analytics frameworks developed for national healthcare systems could be adapted to strengthen environmental health monitoring around geothermal facilities. The article concludes by identifying persistent challenges in exposure assessment precision, epidemiological study design, and integrated health-environment surveillance, and proposes a research agenda for advancing environmental health assessment of geothermal-adjacent communities toward more precise, continuously monitored practice.

**Keywords:** environmental health, geothermal energy, hydrogen sulfide exposure, community health, respiratory disease, geothermal reservoir, public health surveillance

## 1. Introduction

Geothermal energy, harnessing heat from the Earth's subsurface for electricity generation and direct heating applications, is increasingly promoted as a reliable, low-carbon component of the global energy transition, offering the dispatchable baseload generation capacity that many other renewable sources cannot provide. Unlike solar and wind generation, however, geothermal energy extraction involves the continuous withdrawal and, in many systems, reinjection of naturally occurring geothermal fluids that carry dissolved gases and trace elements to the surface, creating a distinct environmental exposure profile for communities residing near active geothermal fields. Since the 1990s, as geothermal energy development has expanded across regions including Italy, New Zealand, Iceland, and the western United States, the association between residential proximity to geothermal facilities and community health outcomes has become an increasingly relevant subject of environmental epidemiological research.

The principal environmental exposure associated with geothermal energy production is hydrogen sulfide ( $H_2S$ ), a naturally occurring geothermal gas released to the atmosphere both from natural geothermal manifestations and from power plant cooling towers and reinjection operations. Hydrogen sulfide is known to affect mucous membranes and the respiratory system, and has been associated in various epidemiological studies with respiratory, cardiovascular, and nervous system effects, though the overall evidence base remains characterized by inconsistency, limited exposure assessment precision, and predominantly ecological or cohort study designs. Beyond gaseous emissions, geothermal energy extraction can also induce ground surface deformation and, in some geologic settings, low-magnitude seismic activity associated with reservoir pressure changes from fluid withdrawal and reinjection cycles, introducing an additional dimension of community risk that must be considered alongside air quality-related health effects.

This article synthesizes the environmental health literature on communities located near geothermal energy facilities, integrating the 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) with subsurface science relevant to understanding the long-term emissions and ground stability processes underlying these exposures, including reactive transport modeling of geothermal reservoirs, machine learning-enhanced geomechanical characterization relevant to induced seismicity and wellbore stability risk, and heterogeneous reservoir management principles from analogous subsurface energy operations. It further considers how AI-driven public health surveillance, economic impact analysis, and predictive analytics frameworks developed for national healthcare systems (Nguyen, 2026a, 2026c, 2026d) might be adapted to strengthen the continuous, integrated health-environment surveillance that the current geothermal environmental health literature identifies as a priority need. The objective is to provide a comprehensive, integrative synthesis for public health researchers, environmental scientists, geothermal industry practitioners, and regulators seeking to advance environmental health assessment of geothermal-adjacent communities toward more precise, continuously monitored practice.

## **2. Environmental Exposures Associated with Geothermal Energy Facilities**

### **2.1 Hydrogen Sulfide as the Principal Exposure of Concern**

Geothermal fluids brought to the surface during energy extraction consist of water vapor mixed with carbon dioxide, hydrogen sulfide, methane, and, to a lesser extent, rare gases and trace elements in volatile forms. Among these constituents, hydrogen sulfide has received the greatest epidemiological attention, given its characteristic odor at very low concentrations, its established toxicological profile affecting mucous membranes and the respiratory system, and its release both from natural geothermal manifestations and from geothermal power plant operations, including cooling tower emissions and, in some designs, non-condensable gas venting.

### **2.2 Spatial and Temporal Variability in Exposure**

Hydrogen sulfide concentrations near geothermal facilities vary substantially with meteorological conditions, plant operational status, and distance from emission sources, complicating efforts to characterize individual or community-level exposure with the precision needed for robust epidemiological analysis. Dispersion modeling, increasingly used to estimate spatial variability in chronic exposure across geothermal districts, has become a standard tool

for characterizing average long-term historical exposure alongside more recent, operationally specific exposure indicators, though such modeling ultimately remains an estimation approach requiring validation against field measurements.

### 2.3 Beyond Air Quality: Ground Deformation and Induced Seismicity

Beyond atmospheric emissions, geothermal energy extraction involves substantial subsurface fluid withdrawal and reinjection that can alter reservoir pressure and, in some geologic settings, induce ground surface deformation or low-magnitude seismic activity. While such geomechanical effects are generally less studied from a direct human health perspective than air quality exposures, they represent a relevant component of the broader environmental and safety risk profile for communities located near geothermal facilities, particularly in geologically complex or densely populated geothermal districts.

## 3. Epidemiological Evidence on Health Outcomes Near Geothermal Facilities

### 3.1 Systematic Review Evidence

Bustaffa et al. (2020) conducted a comprehensive review of health studies conducted in communities living near geothermal plants generating heat and electricity, synthesizing evidence from geothermal districts in New Zealand, Iceland, and Italy. The review found that most available studies employed ecological or cohort designs in which exposure was estimated on the basis of residence rather than direct personal measurement, and identified substantial inconsistencies across studies, with some evidence linking low-concentration hydrogen sulfide exposure to increased respiratory disease, while, counterintuitively, exposure to higher levels was in some studies associated with decreased cancer mortality. The authors concluded that existing studies are limited by their ecological design and inadequate exposure assessment precision, and explicitly recommended the development of an integrated health-environment surveillance system to address these limitations going forward.

### 3.2 Chronic Low-Level Exposure and Residential Cohort Evidence

Nuvolone et al. (2019) conducted a residential cohort study in the geothermal area of Mt. Amiata in Tuscany, Italy, investigating the association between chronic, low-level hydrogen sulfide exposure and mortality and hospital discharge outcomes for neoplasms and diseases of the respiratory, central nervous, and cardiovascular systems. The study evaluated spatial

variability in chronic H<sub>2</sub>S exposure using dispersion modeling, georeferencing residential addresses of cohort members across six municipalities in the geothermal district over a nearly two-decade study period from 1998 to 2016, and matching each subject with exposure metrics and socioeconomic status at the census tract level—a methodologically rigorous approach to ecological exposure assessment that nonetheless illustrates the field's continued reliance on residence-based rather than individually measured exposure.

### 3.3 Respiratory Function and the InVETTA Study

Extending residential cohort evidence toward direct, objective measurement of respiratory function, Stoppa et al. (2023) conducted the InVETTA cross-sectional survey in the Mt. Amiata geothermal area, enrolling over 2,000 adults and performing spirometry to objectively assess lung function in relation to modeled hydrogen sulfide exposure from geothermal power plant emissions. Using dispersion modeling to estimate both long-term historical exposure and more recent exposure indicators, and defining chronic obstructive pulmonary disease according to standard international criteria, the study's multivariable analyses did not find evidence of an association between increasing hydrogen sulfide exposure and chronic obstructive pulmonary disease, illustrating the genuinely mixed and inconsistent nature of the epidemiological evidence base that systematic reviews of this literature have identified.

### 3.4 Acute Exposure Events and Community Health Crises

Beyond chronic, low-level exposure studies, acute hydrogen sulfide exposure events near geothermal and related energy operations have prompted focused investigation of short-term respiratory and nervous system effects. Quist and Johnston (2024) examined the respiratory and nervous system effects of a hydrogen sulfide crisis in Carson, California, documenting the acute community health impact associated with a discrete, high-concentration exposure event and providing evidence complementary to the chronic, low-level exposure literature dominated by the Italian geothermal district studies, underscoring that both chronic and acute exposure scenarios warrant distinct epidemiological and public health response frameworks.

### 3.5 Synthesizing an Inconsistent Evidence Base

Taken together, the epidemiological literature on communities near geothermal facilities presents a genuinely mixed picture: some studies report associations between hydrogen sulfide

exposure and respiratory outcomes, while others, employing more rigorous objective lung function measurement, do not confirm such associations, and at least one line of evidence suggests a counterintuitive inverse association between higher exposure and cancer mortality that likely reflects unmeasured confounding or exposure misclassification rather than a genuine protective effect. This inconsistency, repeatedly acknowledged by the researchers conducting these studies themselves, reflects the field's persistent methodological challenges around exposure assessment precision and study design rather than a resolved scientific consensus in either direction.

#### **4. Subsurface Science Underlying Long-Term Emissions and Ground Stability Risk**

##### **4.1 Reactive Transport Processes Governing Long-Term Geothermal Reservoir Behavior**

Understanding the long-term trajectory of emissions and reservoir performance at geothermal facilities requires characterizing the reactive transport processes—mineral dissolution, precipitation, and geochemical evolution of the reservoir fluid-rock system—that govern how geothermal fluid composition and reservoir permeability evolve over the multi-decade operational lifetime of a geothermal facility. Numerical modeling of reactive transport in geothermal reservoirs for long-term performance prediction demonstrates how coupled thermal-hydraulic-chemical processes can be simulated to forecast reservoir behavior and fluid chemistry evolution over extended operational timescales, providing a scientific foundation for anticipating how the hydrogen sulfide and other gas concentrations available for surface emission might change as a geothermal field matures—information directly relevant to long-term environmental health risk characterization for surrounding communities, even though such reactive transport models have not, to date, been directly integrated into the epidemiological exposure assessment literature reviewed above.

##### **4.2 Geomechanical Characterization and Induced Seismicity Risk**

Beyond gas emissions, ground stability and induced seismicity risk at geothermal and related subsurface energy facilities depend on geomechanical factors including in-situ stress conditions, rock strength, and pressure changes associated with fluid withdrawal and reinjection. Machine learning-enhanced geomechanical characterization and wellbore stability assessment methodologies, as demonstrated in offshore energy reservoir settings, integrate stress field estimation, rock strength prediction, and operational parameter analysis into a

proactive risk-management workflow; analogous geomechanical characterization approaches, adapted to the specific stress and thermal conditions of geothermal reservoirs, represent an important and currently underutilized tool for anticipating and managing ground deformation and induced seismicity risk in geothermal districts, complementing the air quality-focused environmental health literature that has historically dominated geothermal community health research.

#### 4.3 Lessons from Heterogeneous Reservoir Management in Analogous Subsurface Energy Systems

Heterogeneous subsurface reservoir management principles developed in analogous energy contexts—such as the optimization of fluid injection strategies in heterogeneous depleted gas reservoirs to manage pressure distribution and containment risk—offer transferable methodological insight for geothermal reservoir management, where similarly heterogeneous rock properties govern the spatial distribution of pressure changes, fluid migration, and, by extension, the surface manifestations of reservoir operation that may affect nearby communities' environmental exposure and ground stability risk profiles.

### 5. Toward Integrated Health-Environment Surveillance

#### 5.1 The Case for Integration

A recurring conclusion across the geothermal community health literature is the need for an integrated health-environment surveillance system that combines precise, individually resolved exposure assessment with systematic health outcome monitoring, rather than the ecological, residence-based exposure estimation that has characterized most studies to date (Bustaffa et al., 2020). Achieving this integration requires combining environmental monitoring data—dispersion-modeled or directly measured hydrogen sulfide concentrations, geomechanical deformation monitoring—with health surveillance data capable of detecting emerging patterns in respiratory, cardiovascular, or nervous system health outcomes among residents of geothermal-adjacent communities.

#### 5.2 AI-Driven Public Health Surveillance as a Transferable Framework

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). Adapting this precision public health framework to the specific context of geothermal-adjacent communities—integrating individually resolved environmental exposure estimates with continuously updated health surveillance data—could directly address the integrated health-environment surveillance gap that geothermal community health researchers have consistently identified as a priority need, moving the field beyond the ecological, residence-based exposure assessment that has limited the interpretability of existing studies.

### 5.3 Predictive Analytics for Identifying High-Risk Subpopulations

National-scale predictive analytics frameworks applied to Medicare and Medicaid populations demonstrate how AI-driven models can identify high-risk populations for targeted follow-up and intervention from large, heterogeneous health and administrative datasets (Nguyen, 2026d). An analogous approach applied to geothermal-adjacent communities could help identify which specific residents or sub-neighborhoods—based on proximity, meteorological exposure patterns, occupational factors, or pre-existing respiratory or cardiovascular vulnerability—warrant more intensive environmental and health monitoring, thereby directing limited surveillance and clinical resources toward those most likely to benefit, rather than applying uniform monitoring intensity across an entire geothermal district regardless of individual risk profile.

### 5.4 Economic Considerations for Surveillance 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 health-environment surveillance infrastructure around geothermal facilities (Nguyen, 2026c). Given that inconsistent exposure assessment has been repeatedly identified as the central methodological limitation of the existing geothermal community health literature, an economically justified investment in more precise, continuously updated surveillance infrastructure could plausibly generate returns through earlier identification of genuine health effects where they exist, more efficient allocation of environmental monitoring resources, and stronger evidentiary support for the risk communication that geothermal operators and public health authorities must provide

to concerned communities.

## 6. Challenges and Limitations

Despite decades of research attention, several challenges continue to constrain the environmental health assessment of communities near geothermal facilities.

Exposure assessment precision. As repeatedly acknowledged across the reviewed literature, most studies rely on ecological, residence-based exposure estimation via dispersion modeling rather than direct, individually resolved personal exposure measurement, introducing exposure misclassification that likely contributes to the inconsistent associations reported across studies. Inconsistent and sometimes counterintuitive findings. The evidence base includes associations in both expected directions (low-level exposure associated with increased respiratory disease) and counterintuitive directions (higher exposure associated with decreased cancer mortality), findings that most plausibly reflect unresolved confounding and exposure misclassification rather than genuine, opposing biological effects, underscoring the need for more rigorous study designs.

Limited geographic and demographic diversity in the evidence base. The strongest and most methodologically developed epidemiological evidence on geothermal community health derives predominantly from Italian geothermal districts, with additional but comparatively sparse evidence from New Zealand and Iceland, and acute exposure event evidence from California; this geographic concentration limits confidence in the generalizability of findings to geothermal districts with different demographic, climatic, and geologic characteristics, including many rapidly developing geothermal regions elsewhere in the world.

Disconnection between subsurface science and epidemiological practice. Reactive transport modeling capable of forecasting long-term reservoir emissions trajectories and geomechanical characterization capable of anticipating induced seismicity risk remain largely disconnected from the epidemiological exposure assessment literature, representing an underexplored opportunity for more mechanistically grounded, forward-looking environmental health risk characterization.

Absence of integrated, continuously updated surveillance infrastructure. Despite explicit calls for an integrated health-environment surveillance system (Bustaffa et al., 2020), no such system appears to have been comprehensively implemented at any studied geothermal district to date, leaving the field reliant on periodic, retrospective epidemiological studies rather than

continuously updated, prospective surveillance.

## 7. Future Directions

Future research should prioritize the development of more precise, individually resolved exposure assessment methodologies for geothermal community health studies, potentially combining dispersion modeling with personal or near-residence air quality monitoring to reduce the exposure misclassification that has limited the interpretability of existing ecological and residence-based studies (Bustaffa et al., 2020; Nuvolone et al., 2019; Stoppa et al., 2023). Extending the geographic and demographic diversity of the evidence base beyond the currently dominant Italian geothermal district studies represents a further important direction, particularly as geothermal energy development continues to expand into new regions with distinct demographic, climatic, and geologic characteristics.

Integrating reactive transport modeling of long-term geothermal reservoir emissions trajectories and machine learning-enhanced geomechanical characterization of induced seismicity and ground stability risk directly into environmental health risk assessment frameworks represents a promising avenue for moving beyond retrospective, exposure-outcome association studies toward more mechanistically grounded, forward-looking risk characterization capable of anticipating how emissions and ground stability risk may evolve as individual geothermal fields mature. 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 context of geothermal-adjacent communities offers a concrete pathway toward the integrated, continuously updated health-environment surveillance system that geothermal community health researchers have long identified as a priority need but have not yet achieved in practice.

## 8. Conclusion

The environmental health assessment of communities located near geothermal energy facilities remains an active and methodologically challenging area of environmental epidemiology, characterized by a genuinely inconsistent evidence base linking hydrogen sulfide exposure to respiratory, cardiovascular, and nervous system health outcomes across studies conducted primarily in Italian, New Zealand, Icelandic, and, for acute exposure events, Californian geothermal districts. This inconsistency reflects persistent methodological challenges in

exposure assessment precision and study design rather than a resolved scientific consensus, and researchers in this field have explicitly and repeatedly called for the development of integrated health-environment surveillance systems capable of addressing these limitations. Subsurface reactive transport modeling and machine learning-enhanced geomechanical characterization, though not yet integrated into epidemiological practice, offer mechanistically grounded tools for anticipating long-term emissions and ground stability risk trajectories at geothermal facilities, while AI-driven precision public health and predictive analytics frameworks developed for national healthcare systems offer a transferable template for the integrated, continuously updated surveillance infrastructure this field has long sought. Advancing environmental health assessment of geothermal-adjacent communities will require sustained investment in exposure assessment precision, geographic and demographic diversification of the evidence base, and the integration of subsurface science with public health surveillance—investments essential to ensuring that geothermal energy can continue to expand as a low-carbon energy source while genuinely protecting the health of the communities who live alongside it.

## References

1. Bustaffa, E., Cori, L., Manzella, A., Nuvolone, D., Minichilli, F., Bianchi, F., & Gorini, F. (2020). The health of communities living in proximity of geothermal plants generating heat and electricity: A review. *Science of the Total Environment*, 706, Article 135998. <https://doi.org/10.1016/j.scitotenv.2019.135998>
2. Nguyen, T. T. (2026a). AI-powered precision public health: A national framework for targeting chronic disease prevention and early intervention. *International Journal of Emerging Trends in Computer Science and Information Technology*, 7(3), 10–20.
3. Nguyen, T. T. (2026c). The economic impact of AI adoption in healthcare: Estimating national cost savings, productivity gains, and long-term health outcomes. *International Journal of Artificial Intelligence, Data Science, and Machine Learning*, 7(3), 1–11.
4. Nguyen, T. T. (2026d). National-scale predictive analytics for Medicare and Medicaid: An AI-driven approach to identifying high-risk populations and reducing healthcare costs. *Journal of Advanced Scientific Research*, 17(6), 1–10.
5. Nuvolone, D., Petri, D., Pepe, P., & Voller, F. (2019). Health effects associated with chronic exposure to low-level hydrogen sulfide from geothermoelectric power plants. A residential

- cohort study in the geothermal area of Mt. Amiata in Tuscany. *Science of the Total Environment*, 659, 973–982. <https://doi.org/10.1016/j.scitotenv.2018.12.402>
6. Quist, A. J. L., & Johnston, J. E. (2024). Respiratory and nervous system effects of a hydrogen sulfide crisis in Carson, California. *Science of the Total Environment*, 906, Article 167480. <https://doi.org/10.1016/j.scitotenv.2023.167480>
  7. Stoppa, G., Nuvolone, D., Petri, D., Centi, L., Nisticò, F., Crocetti, E., Barbone, F., & Voller, F. (2023). Exposure to low levels of hydrogen sulphide and its impact on chronic obstructive pulmonary disease and lung function in the geothermal area of Mt. Amiata in Italy: The cross-sectional InVETTA study. *PLOS One*, 18(11), Article e0293619. <https://doi.org/10.1371/journal.pone.0293619>