

# Environmental and Health Impacts of Geothermal Operations in Tiaty East Sub- County, Baringo County, Kenya: A Community-Based Statistical Analysis

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## ABSTRACT

**Background:** Geothermal energy is widely regarded as a clean and reliable renewable energy source, particularly in tectonically active regions such as the East African Rift System. Kenya has made substantial investments in geothermal power development; however, the rapid expansion of geothermal infrastructure has raised concerns regarding its localized environmental and public health impacts. In Tiaty East Sub-County, Baringo County, geothermal development occurs within ecologically sensitive landscapes and community dependent resource systems. This study assessed the impacts of geothermal power operations on vegetation cover, water quality, and community health to inform sustainable geothermal development.

**Materials and Methods:** A mixed-methods approach was adopted using an Integrated Impact Assessment Framework. Primary data were collected through 379 structured household questionnaires and key informant interviews. Water quality assessment employed a quasi-experimental design, comparing boreholes, Lake Baringo, and seasonal ponds within geothermal zones against distilled water as a control. Physical and chemical parameters were analyzed using standard laboratory procedures. Vegetation dynamics were assessed using GIS and remote sensing techniques, including land use/land cover classification and Normalized Difference Vegetation Index (NDVI) analysis of Landsat imagery from 2017, 2020, and 2025. Quantitative data were analyzed using SPSS (version 21.0) through descriptive statistics, chi-square tests, and t-tests at  $p < 0.05$ , while qualitative data were thematically analyzed.

**Results:** Vegetation degradation was significantly associated with geothermal operations ( $\chi^2 = 37.21$ ,  $p = 0.013$ ), with healthy vegetation cover declining from approximately 18% in 2017 to 6% in 2025 and a corresponding increase in bare land. Water sources exhibited significantly elevated temperatures, turbidity, fluoride, electrical conductivity, total dissolved solids, nitrate, and phosphate levels compared to distilled water ( $p < 0.05$ ), indicating geothermal and hydrogeochemical influence. Community perceptions corroborated laboratory findings, identifying water shortages (67%), contamination, and increased water temperatures as key concerns. A significant association was observed between geothermal activities and increased disease prevalence ( $\chi^2 = 31.14$ ,  $p = 0.008$ ), with respiratory illnesses predominating. Most respondents (>60%) considered existing mitigation measures ineffective.

**Conclusion:** Geothermal power development in Tiaty East Sub-County has resulted in measurable degradation of vegetation, deterioration of water quality, and adverse public health outcomes. Strengthened environmental governance, continuous monitoring, and community-led mitigation strategies are essential to align geothermal energy development with environmental sustainability and public wellbeing.

**Keywords:** Geothermal energy; vegetation change; water quality; public health; environmental sustainability; Kenya

## INTRODUCTION

Geothermal energy is derived from thermal energy generated within the Earth's interior through radioactive decay of naturally occurring isotopes and residual heat from planetary formation<sup>1</sup>. The Earth's total heat capacity is estimated at approximately  $1 \times 10^{19}$  TJ ( $2.8 \times 10^{15}$  TWh), with an average global conductive heat flow of about

44.2 TW<sup>2</sup>. Owing to its reliability, low carbon footprint, and baseload generation capability, geothermal energy is increasingly recognized as a critical component of global renewable energy transitions. Based on subsurface temperature regimes and geological characteristics, geothermal resources are commonly classified into high-enthalpy systems (>180 °C), medium-enthalpy systems (100–180 °C), and low-enthalpy systems (<100 °C)<sup>3</sup>. High-enthalpy systems are typically associated with active volcanism and mantle hotspot anomalies at depths exceeding 3.5 km, whereas medium- and low-enthalpy systems occur at shallower depths and are widely utilized for direct applications such as space heating, cooling, and industrial processes<sup>3</sup>.

Globally, the United States currently leads in installed geothermal power capacity; however, future growth is projected to be driven largely by emerging markets, including Turkey, Kenya, Indonesia, and the Philippines<sup>4,5</sup>. These countries possess favorable geological conditions and policy frameworks that support geothermal exploration and power generation. In Africa, geothermal resources are predominantly concentrated along the Great Rift Valley, a tectonic depression characterized by crustal thinning, upper mantle intrusions, silicic volcanism, and residual magmatic heat<sup>6</sup>. Kenya and Ethiopia have emerged as continental leaders in geothermal development, with Kenya demonstrating particularly rapid expansion along the East African Rift Valley System. Kenya's installed geothermal capacity increased from 45 MW in 1985 to approximately 972.5 MW by 2024, following renewed development efforts that intensified in the early 21st century<sup>7,8</sup>.

Geothermal exploration in Kenya has progressed spatially and technologically from early drilling activities at Eburru in the 1990s to large-scale developments at Menengai in 2011 and the Baringo–Silali geothermal block from 2019 onward. The Baringo–Silali block comprises several volcanic centers, including Paka, Silali, and Korosi volcanoes, as well as Lakes Bogoria and Baringo. The Arus–Paka geothermal system alone is estimated to possess a power generation potential exceeding 3000 MWe, supported by extensive surface manifestations such as fumaroles, hydrothermally altered rocks, and hot grounds<sup>8</sup>. These developments position Kenya as a strategic geothermal hub in sub-Saharan Africa.

Despite its classification as a clean and sustainable energy source, geothermal power development is not without environmental and social consequences. Exploration, drilling, steam extraction, and power generation activities may result in land subsidence, vegetation loss, groundwater depletion, air and water pollution, and ecosystem fragmentation<sup>9,10</sup>. Geothermal fluids often contain potentially hazardous constituents such as hydrogen sulfide, fluoride, arsenic, and boron, which can contaminate soil and water resources if not adequately managed. Such impacts may alter landscape structure, disrupt wildlife habitats, and compromise ecosystem services, thereby undermining the sustainability objectives of geothermal energy development<sup>11</sup>.

In Tiaty East Sub-County, Baringo County, geothermal power development presents a complex interaction between renewable energy expansion and environmental and public health sustainability. Communities residing near geothermal installations have reported increased incidences of respiratory and cardiovascular illnesses attributed to gaseous emissions, particularly hydrogen sulfide, as well as noise pollution from drilling and steam release<sup>12</sup>. In addition, declining vegetation cover, deteriorating water quality, and land degradation have adversely affected agricultural productivity, pastoral livelihoods, and biodiversity conservation. These impacts are exacerbated by arid and semi-arid climatic conditions, which heighten community vulnerability to environmental change.

Although Kenya has made significant progress in geothermal power development, existing studies have largely focused on technical feasibility, power generation capacity, and economic viability, with comparatively limited attention to integrated environmental and public health impacts at the local scale. Where environmental assessments exist, they are often project-specific, short-term, or fragmented across ecological and health domains. Furthermore, community perceptions and lived experiences are rarely integrated with empirical environmental data, resulting in limited understanding of how geothermal development affects socioecological systems in marginalized regions such as Tiaty East Sub-County. Weak environmental governance, limited stakeholder participation, and inadequate environmental education further constrain the effectiveness of existing mitigation measures<sup>13,14</sup>. Consequently, there remains a critical knowledge gap regarding the combined effects of geothermal power development on vegetation dynamics, water quality, and public health, as well as the effectiveness of mitigation strategies in resource-constrained settings.

This study seeks to address this gap by systematically assessing the environmental and public health impacts of geothermal power development in Tiaty East Sub-County, Baringo County. By integrating remote sensing

analysis, water quality assessment, and community health data, the study aims to generate evidence-based insights to inform policy, strengthen environmental governance, and promote community-led, sustainable geothermal development.

## LITERATURE REVIEW

Geothermal electricity generation is primarily associated with high-enthalpy geothermal systems, where geothermal systems, where reservoir temperatures range between 200 °C and 320 °C and geothermal fluids are typically extracted from depths of approximately 1200–3000 m<sup>1</sup>. Such systems are actively exploited in countries including Iceland, Kenya, and the United States, where favorable geological conditions permit commercial-scale power production. Compared with other renewable energy sources, geothermal energy is characterized by exceptionally high availability factors (>98%), low land-use intensity, minimal visual intrusion, and relatively low atmospheric and liquid emissions<sup>2</sup>. These attributes position geothermal energy as a strategically important component of low-carbon energy systems.

Advances in geothermal technologies, particularly in reservoir management and reinjection practices, have enhanced the long-term sustainability of geothermal resources. Optimized reinjection of spent geothermal fluids improves pressure maintenance, reduces surface disposal requirements, and minimizes the need for additional production wells, thereby lowering environmental disturbance and extending reservoir life<sup>1</sup>. Such technological improvements align geothermal development with global sustainability objectives and climate mitigation goals.

In Kenya, geothermal resources are concentrated along the Great African Rift Valley, with approximately 14 identified prospects associated with Quaternary volcanic centers and characterized by surface manifestations such as fumaroles, hot springs, geysers, and hydrothermally altered grounds<sup>15,16</sup>. Geothermal exploration in Kenya commenced in the early 1970s, culminating in the establishment of the Olkaria geothermal field, which remains the country's primary production site. Although earlier estimates placed Kenya's geothermal output at approximately 130 MW representing about 12% of installed electricity capacity subsequent expansions have significantly increased national geothermal generation. Kenya Electricity Generating Company (KenGen), a public-private utility, currently produces approximately 80% of the country's electricity, underscoring the central role of geothermal energy in national energy security.

Geothermal power is widely regarded as environmentally superior to fossil-fuel-based energy systems due to its lower greenhouse gas emissions and reduced land footprint<sup>21</sup>. Nonetheless, geothermal development presents distinct environmental challenges. Geological hazards<sup>18</sup>, including induced seismicity and land subsidence, may arise from fluid extraction and reinjection processes, while operational activities generate noise<sup>19</sup> and require substantial water resources<sup>20</sup>. Consequently, effective environmental stewardship remains a prerequisite for sustainable geothermal exploitation.

Geothermal reservoirs naturally contain non-condensable gases such as carbon dioxide, hydrogen sulfide (H<sub>2</sub>S), methane, and ammonia, which are released during energy production<sup>22</sup>. Although geothermal emissions are significantly lower than those associated with coal- or oil-fired power plants, they are not negligible and may pose localized environmental and health risks<sup>11</sup>. Early geothermal developments, such as the Wairakei geothermal plant in New Zealand, demonstrated that inadequate environmental controls could result in river contamination with hydrogen sulfide, arsenic, mercury, and carbon dioxide<sup>16</sup>. These early designs reflected limited environmental awareness and regulatory oversight, prompting subsequent recommendations for reinjection of waste fluids and improved effluent management.

Beyond gaseous emissions, geothermal systems present unique environmental risks, including pollutant generation that is not directly correlated with power output, unpredictable subsurface effluent migration pathways, thermal pollution, and environmental disturbances during exploration and testing phases<sup>10</sup>. Although modern geothermal technologies have mitigated many of these risks, challenges persist in the form of air and water pollution, land degradation, ecosystem fragmentation, and socio-cultural disruption. These impacts necessitate holistic environmental assessment approaches that extend beyond conventional project-level evaluations.

Geothermal fluids frequently contain elevated concentrations of hazardous constituents such as hydrogen sulfide, arsenic, fluoride, and mercury, which pose risks to soil and water quality if inadequately managed<sup>10</sup>. Economic and technical constraints may limit reinjection efficiency, increasing the likelihood of surface discharge and

subsequent contamination through rainfall runoff or equipment failure. While solid waste generation from geothermal power plants is relatively low, waste handling during construction and commissioning phases requires careful management<sup>23</sup>. Assessments by Argonne National Laboratory have highlighted the potential for toxic element mobilization in geothermal regions, emphasizing the importance of robust engineering design and continuous environmental monitoring.

Geothermal development in ecologically sensitive environments, including forests, wetlands, and rangelands, may result in habitat loss, biodiversity decline, and wildlife disturbance due to infrastructure expansion and chronic emissions<sup>24</sup>. Sulfurous emissions can impair plant physiological processes, reducing vegetation productivity, while alteration of natural thermal features may degrade culturally and ecologically significant geysers and hot springs<sup>17</sup>. Mitigation strategies such as soundproofing, controlled access, vegetation restoration, and rehabilitation of disturbed geothermal sites have been proposed to minimize environmental impacts<sup>13</sup>; however, their effectiveness varies across socio-ecological contexts.

From a public health perspective, exposure to hydrogen sulfide emissions has been associated with increased risks of respiratory diseases, neurological disorders, and, at high concentrations, elevated hospitalization and mortality rates<sup>10,11</sup>. Communities residing in close proximity to geothermal installations may therefore experience disproportionate health burdens<sup>25</sup>, particularly where environmental monitoring and health surveillance systems are weak.

Despite the extensive literature on geothermal energy technologies and environmental impacts, several critical gaps remain. First, most studies emphasize technical efficiency and emissions quantification, with limited integration of ecological, water quality, and public health dimensions within a single analytical framework. Second, empirical evidence linking community perceptions with measured environmental indicators remains scarce, particularly in developing-country contexts. Third, limited attention has been paid to geothermal development in arid and semi-arid ecosystems, where ecological resilience and water scarcity amplify vulnerability. Consequently, there is a pressing need for integrated, community-informed assessments that evaluate the cumulative environmental and health impacts of geothermal power development to inform sustainable policy and practice.

## **MATERIAL AND METHODS**

This study employed a mixed-methods approach, integrating both primary and secondary data to comprehensively assess the environmental and health impacts of geothermal energy development in Tiaty East Sub-County, Baringo County, Kenya. The methodology combined quantitative and qualitative techniques to evaluate vegetation, water quality, and community health outcomes within proximity to geothermal installations.

### **Study Design and Population**

A cross-sectional, quasi-experimental design was implemented. Primary data were collected from 379 respondents using structured questionnaires administered to households located within 1–3 km of geothermal wells. This distance was selected based on established exposure zones for geothermal emissions<sup>15</sup>. Key informant interviews were conducted with local community leaders, geothermal professionals, and health officers to capture nuanced perspectives on environmental changes and public health concerns. The quasiexperimental component involved comparative water quality analysis between treatment sites (adjacent to geothermal operations) and control sites (distilled water reference) to empirically assess contamination risks.

### **Secondary Data Collection**

Secondary data were sourced from published literature, reports, and institutional records relating to geothermal impacts on vegetation, water quality, and human health<sup>16–19</sup>. This included peer-reviewed studies, government and utility reports, and environmental monitoring documents. Secondary data provided baseline context, informed survey instruments, and supported triangulation of primary findings.

### **Data Collection Instruments**

Structured questionnaires captured quantitative measures of community perceptions regarding vegetation degradation, water quality deterioration, and health symptoms linked to geothermal activity. Open-ended

questions facilitated qualitative insights, including local knowledge of environmental changes, adaptive strategies, and perceived risks. Key informant interviews followed semi-structured guides focusing on operational procedures, mitigation measures, and institutional oversight.

Water samples were collected from both treatment and control sites following standard protocols to assess physicochemical parameters, including pH, temperature, electrical conductivity, and concentrations of heavy metals such as arsenic and mercury<sup>20</sup>. Sampling was conducted at consistent depths and times to minimize variability.

### Data Analysis

Quantitative survey data were coded and analyzed using SPSS Version 21.0. Descriptive statistics—including means, percentages, and frequency distributions—summarized demographic characteristics, perceptions, and exposure patterns. Inferential analysis was performed using Chi-square tests to assess associations between proximity to geothermal sites and reported environmental or health outcomes, with significance defined at  $p < 0.05$ . Qualitative responses from open-ended survey questions and interviews were analyzed thematically to identify recurring patterns, concerns, and local adaptation strategies.

Water quality data were statistically compared between treatment and control sites. Parameters exceeding World Health Organization (WHO) recommended limits were highlighted to identify potential public health risks<sup>21</sup>.

### Vegetation Assessment

To quantify vegetation cover and evaluate ecosystem impacts, GIS and remote sensing techniques were employed. Satellite imagery from the United States Geological Survey (USGS) was acquired for pre-operation (2018) and post-operation (2024) periods. Image preprocessing included geometric correction, radiometric calibration, and cloud masking. Supervised classification was performed to categorize land cover types, and change detection analyses identified areas of vegetation loss or degradation over time.

Vegetation health was further assessed using the Normalized Difference Vegetation Index (NDVI), calculated as:

$$NIR - RED$$

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where **NIR** represents near-infrared reflectance (Band 5) and **RED** represents red reflectance (Band 4)<sup>22</sup>. The Normalized Difference Vegetation Index (NDVI) was calculated using near-infrared reflectance (NIR, Band 5) and red reflectance (RED, Band 4). NDVI values range from -1 to +1 and provide an indication of vegetation health and coverage. Values between +0.6 and +1.0 correspond to dense, healthy vegetation, while values from 0.0 to +0.2 indicate sparse or stressed vegetation. NDVI values below 0 represent non-vegetated surfaces, such as water bodies or bare soil. Spatial analyses were performed in ArcGIS and ENVI software, with results exported to Excel for graphical presentation and integration with survey data.

### Ethical Considerations

Ethical approval was obtained from relevant institutional review boards. Informed consent was secured from all participants, and data confidentiality was maintained throughout. Water sampling and field activities were conducted in accordance with environmental safety standards, ensuring minimal ecological disturbance.

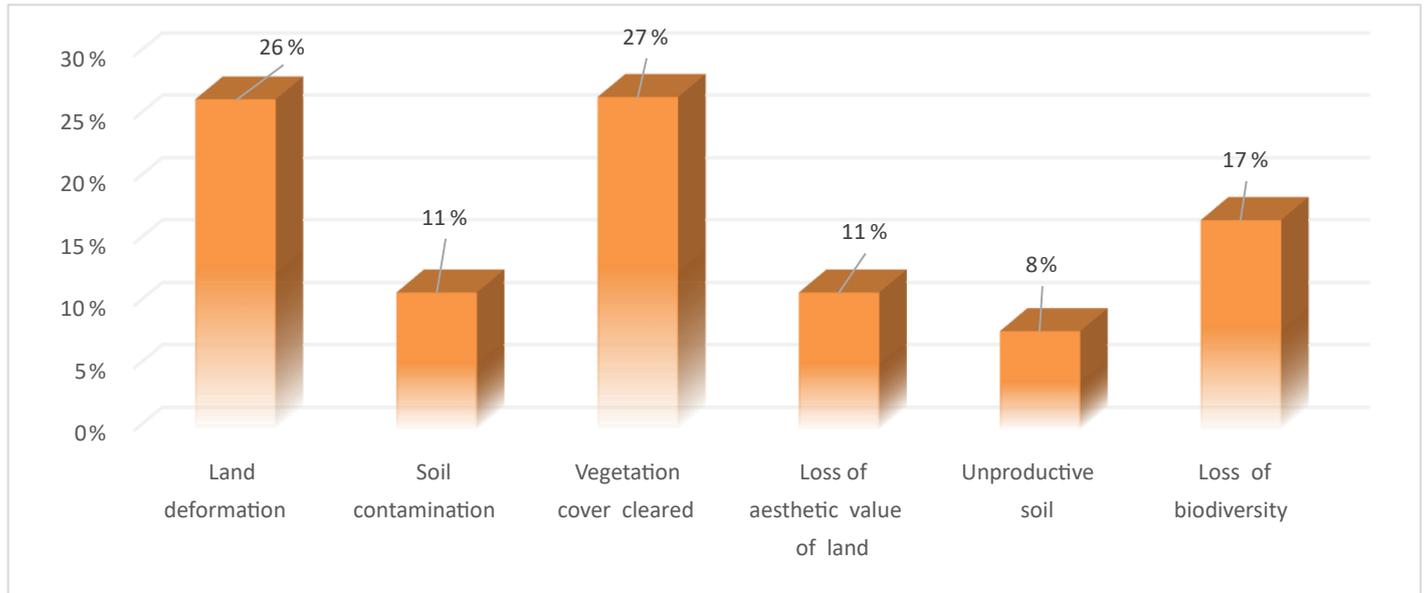
### Justification of Methodology

The mixed-methods design facilitated triangulation of data from multiple sources, enhancing the validity and reliability of findings. GIS and NDVI analyses provided objective, spatially explicit measures of vegetation change, complementing community-reported perceptions. The quasi-experimental water quality assessment allowed for empirical quantification of potential contamination risks. Collectively, these methods enabled an integrated evaluation of environmental and health impacts, directly addressing the identified research gap in community-informed, ecosystem-based assessment of geothermal energy development.

## RESULT

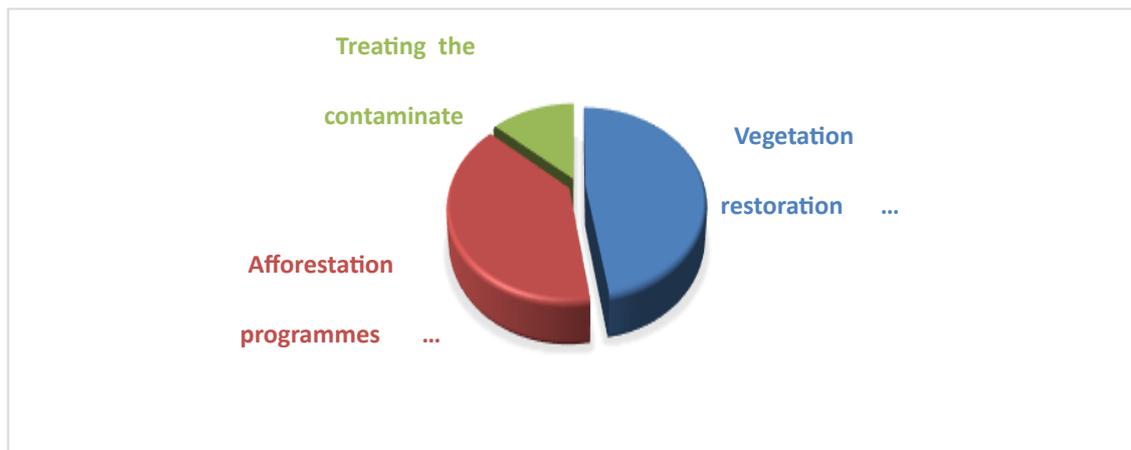
### Vegetation Degradation

Analysis of community perceptions and satellite imagery indicated a significant association between geothermal operations and vegetation degradation in Tiaty East Sub-County ( $\chi^2(1) = 37.21, p = 0.013$ ). Approximately 69% of respondents acknowledged that geothermal power development negatively affects the natural vegetation. Among the identified impacts, land deformation and clearing of vegetation cover were the most commonly reported (27% each), followed by loss of biodiversity (17%), soil contamination (11%), aesthetic degradation of land (11%), and unproductive soil (8%) (Figure 2).



**Figure 2. Vegetation effects**

Stakeholder interventions to mitigate vegetation loss were limited. Only 26% of respondents reported that any measures had been implemented, with 48% of these noting vegetation restoration, 39% afforestation programs, and 13% soil remediation efforts. The majority (74%) perceived no effective interventions (Figure 3).

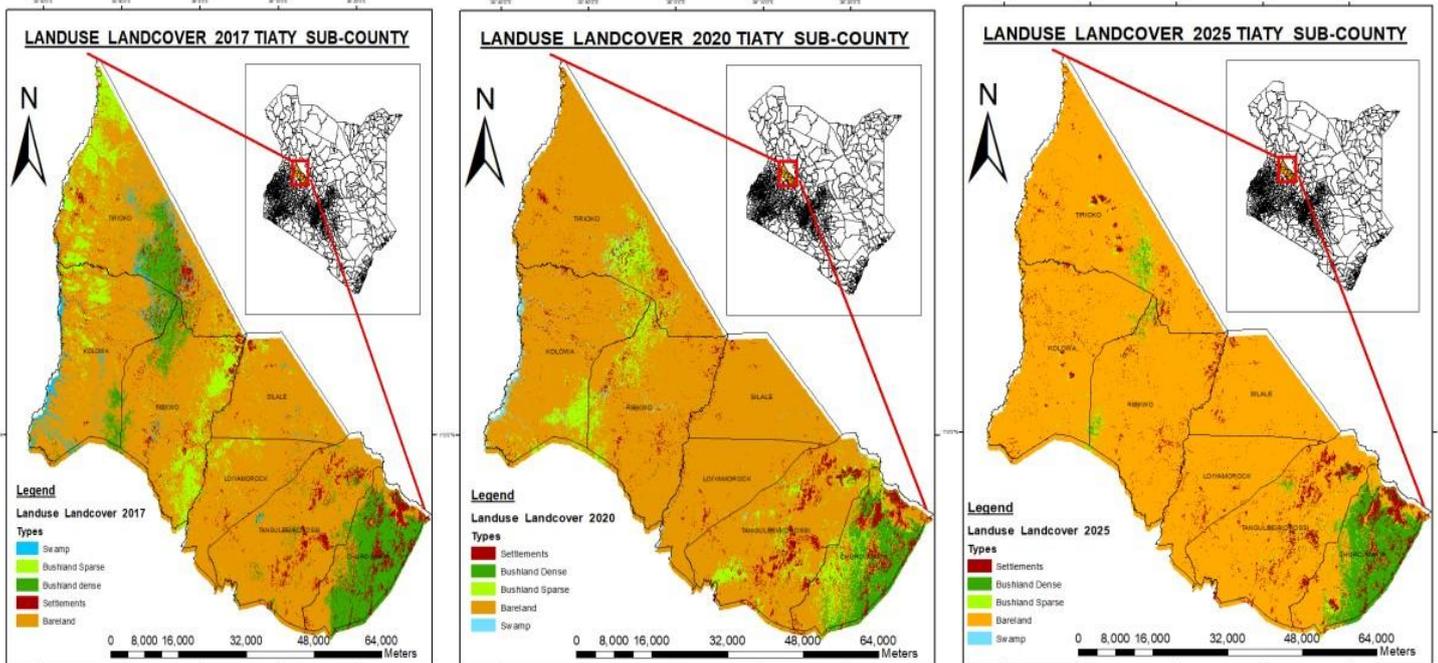


**Figure 3. Mitigation measures for vegetation degradation**

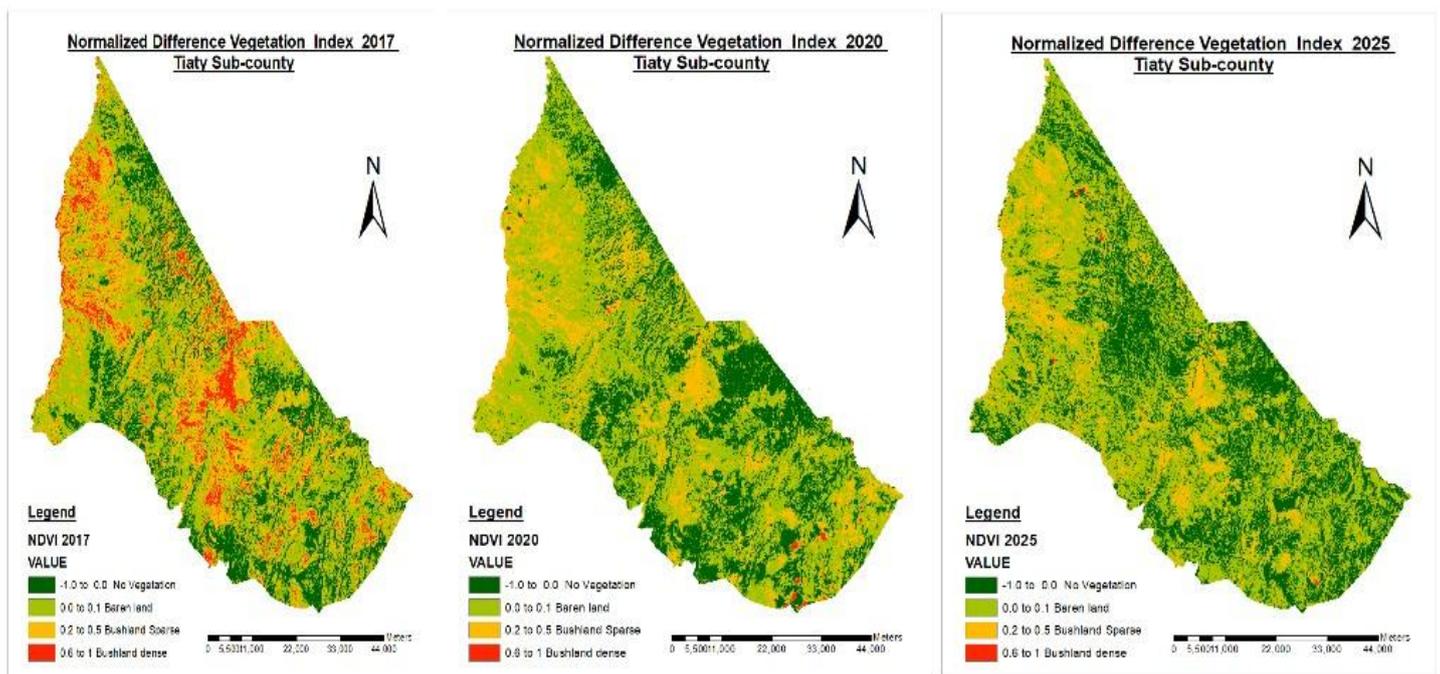
Remote sensing analyses corroborated these community perceptions. Landsat imagery from USGS (2017, 2020, 2025) revealed substantial declines in vegetation cover over time (Figures 4 and 5). Quantitative land cover assessment showed a decline in bushland-dense areas from 10.71% (47,701 ha) in 2017 to 5.39% (24,019 ha) in 2025, while sparse bushland decreased from 7.63% (34,005 ha) to 1.58% (7,049 ha) over the same period. Bare land expanded from 74.53% (331,982 ha) in 2017 to 88.22% (392,991 ha) in 2025 (Table 1; Figure 6). Swamp areas also diminished drastically from 2.02% to 0.02%, indicating a loss of critical wetland ecosystems.

**Table 1.** Land use land cover of 2017, 2020 and 2025 in Ha.

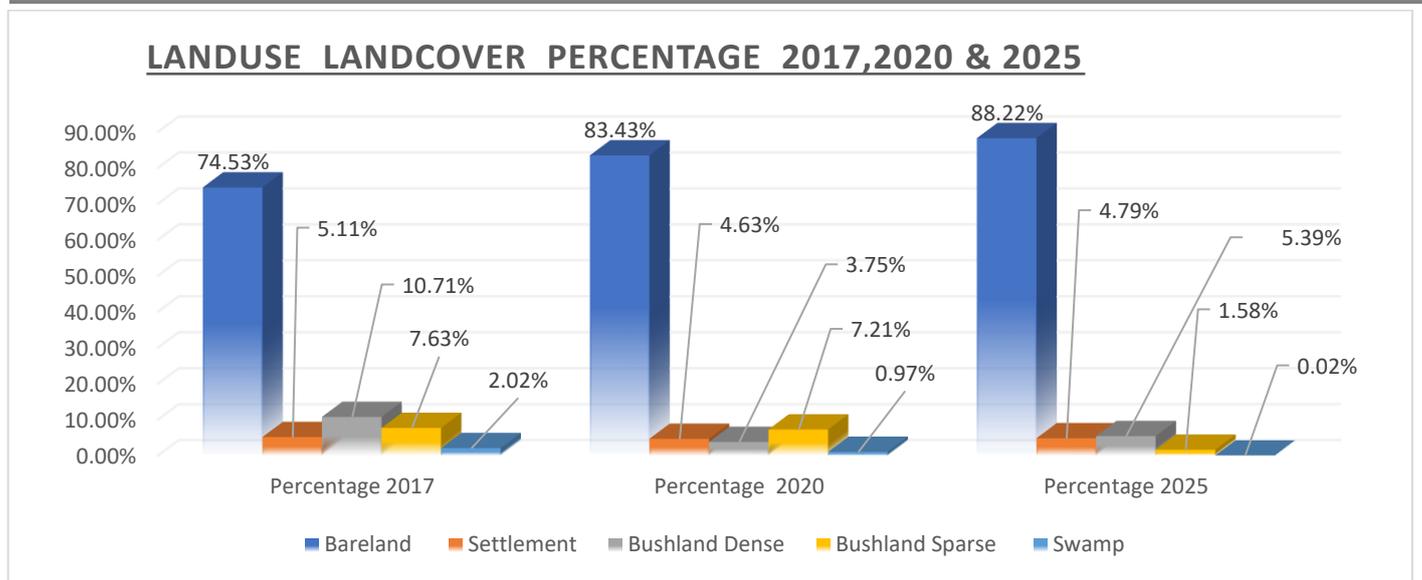
LANDUSE LANDCOVER	Area_Ha 2017	Percentage 2017	Area_Ha 2020	Percentage 2020	Area_Ha 2025	Percentage 2025
Bare land	331981.88	74.53%	371644.94	83.43%	392990.54	88.22%
Settlement	22758.98	5.11%	20620.75	4.63%	21330.54	4.79%
Bushland Dense	47700.76	10.71%	16725.37	3.75%	24019.28	5.39%
Bushland Sparse	34005.26	7.63%	32133.43	7.21%	7049.35	1.58%
Swamp	9013.39	2.02%	4343.16	0.97%	83.3	0.02%
	445460.27		445467.65		445473.01	



**Figure 4.** Classified Landsat images for 2017, 2020 and 2025



**Figure 5.** Normalized Difference Vegetation Index Result.



**Figure 6. Landuse land cover 2017, 2020 & 2025 Percentage source: Landsat images obtained at USGS on (2025)**

The NDVI analysis further confirmed that vegetation health deteriorated post-geothermal operation. Healthy vegetation, indicated by NDVI values >0.6, declined from 18% of land area pre-operation (2017) to 11% in 2020 and further to 6% in 2025. This represents a 12% absolute reduction in vegetation cover within eight years, highlighting significant ecological disruption. These findings align with previous studies reporting that geothermal infrastructure, particularly drilling, well pads, and access roads, contributes to habitat fragmentation, soil compaction, and vegetation loss<sup>23–25</sup>.

### Water Quality and Physical Properties

The physical properties of water sources including boreholes, Lake Baringo, and seasonal ponds were significantly affected by geothermal operations ( $\chi^2(1) = 19.62, p = 0.021$ ). Borehole temperatures ranged from 25–38°C, ponds from 22–35°C, and Lake Baringo from 26–30°C, all elevated compared to distilled water (25°C), indicating geothermal heat transfer (Table 2).

**Table 2.** Physical characteristics of water points in Tiaty Sub-County, Baringo County, Kenya.

Water Source	Temperature (°C)	Turbidity (NTU)	pH
Boreholes	25–38°C	5–25 NTU	6.5–8.5
Lake Baringo	26–30°C	10–40 NTU (seasonal)	7.5–9.0
Ponds (seasonal)	22–35°C	15–60 NTU	6.0–8.0
Distilled Water Value	25°C	0 NTU	7.0

Turbidity levels frequently exceeded WHO limits, particularly in ponds and boreholes, reflecting sediment mobilization and mineral dissolution. pH values were generally neutral to slightly alkaline, with Lake Baringo showing higher pH due to evaporative concentration and geothermal mineral input. T-test analysis confirmed these differences as statistically significant (Table 3), indicating a direct influence of geothermal activity on water usability and ecological health.

**Table 3.** T-Statistics for Physical Properties

Parameter	T-Statistic	P-Value	Interpretation
Temperature	~6.0–8.0	< 0.001	Significantly warmer than distilled water due to geothermal heat
Turbidity	~15.0+	< 0.0001	Highly significant geothermal and sediment loading
pH	~2.5–3.5	< 0.05	Slightly acidic geothermal mineral input



**Plate 1. Land Deformation**

Chemical analyses revealed elevated concentrations of fluoride, electrical conductivity (EC), total dissolved solids (TDS), nitrate, ammonia, and phosphate across natural water sources (Table 4).

**Table 4.** Chemical Properties of water points in Tiaty Sub-County

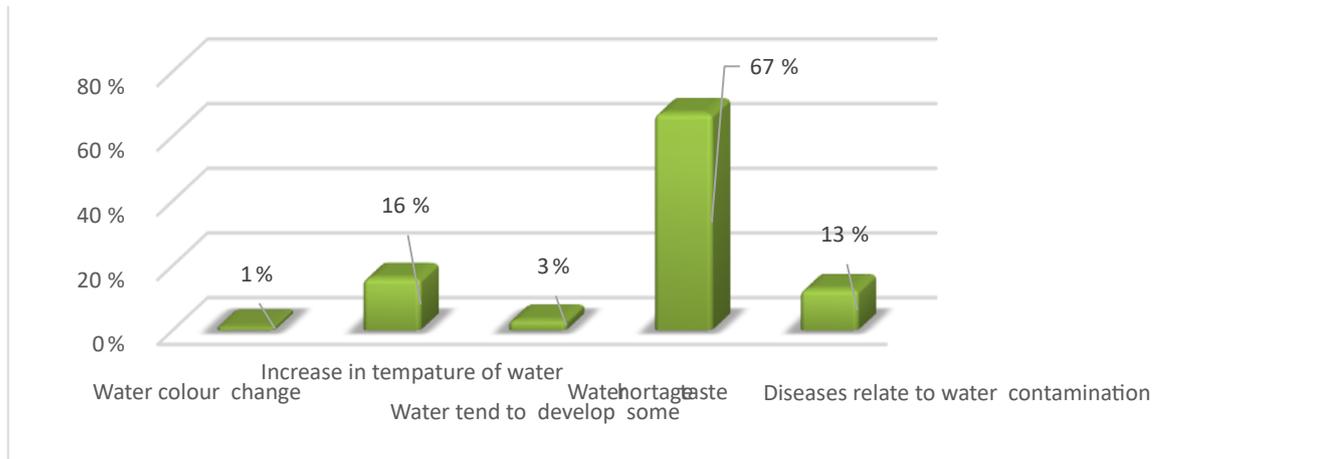
Water Source	Fluoride (mg/L)	EC ( $\mu\text{S/cm}$ )	TDS (mg/L)	Nitrate ( $\text{NO}_3^-$ )	Ammonia ( $\text{NH}_3$ )	Phosphate ( $\text{PO}_4^{3-}$ )
Boreholes	1.5–6.0	300–800	250–600	0.1–4.5	0.1–0.8	0.2–1.5
Lake Baringo	0.5–2.0	224–543	181–433	0.09–5.11	0.09–0.77	0.25–2.9
Ponds (seasonal)	1.0–4.0	250–700	200–500	0.2–3.5	0.1–0.6	0.3–2.0
Distilled Water Value	0.0	~0–5	~0–10	0.0	0.0	0.0

Borehole fluoride levels ranged from 1.5–6.0 mg/L, often exceeding the WHO limit of 1.5 mg/L, posing potential risks of dental and skeletal fluorosis. EC values ranged from 224–800  $\mu\text{S/cm}$  and TDS from 181–600 mg/L, indicating enhanced ionic content from geothermal fluid-rock interactions. Nutrient enrichment was observed, with nitrate and phosphate levels peaking in Lake Baringo and ponds, suggesting eutrophication risks exacerbated by geothermal seepage and surface runoff. T-tests comparing these chemical parameters to distilled water confirmed statistically significant differences ( $p < 0.05$ ) (Table 5).

**Table 5.** T-Statistics for Chemical Properties

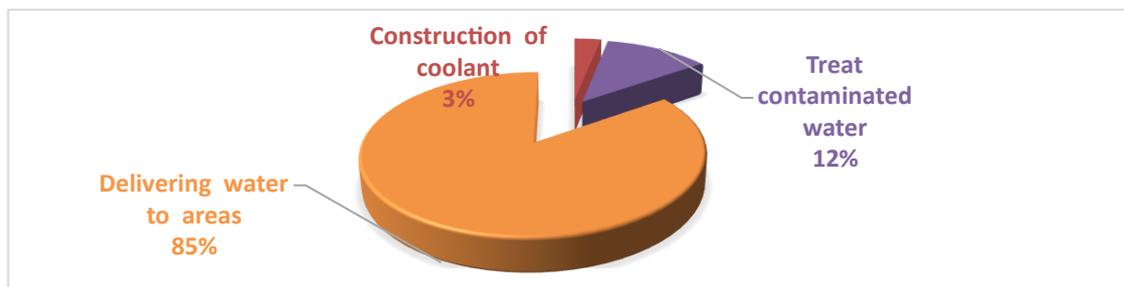
Parameter	Mean samples	Mean (Distilled)	T-Statistic	P-Value	Significance (YES/NO)	Geothermal Impact Summary
Fluoride (mg/L)	3.72	0.0	~6.5	< 0.001	YES	Leaching from geothermal rocks; health risk
EC ( $\mu\text{S/cm}$ )	518	~0	~9.2	< 0.0001	YES	Mineralization from geothermal fluids
TDS (mg/L)	394	~0	~8.7	< 0.0001	YES	Dissolved solids from rock-water interaction
Nitrate (mg/L)	2.86	0.0	~7.1	< 0.001	YES	Nutrient loading from geothermal and surface runoff
Phosphate (mg/L)	1.48	0.0	~6.8	< 0.001	YES	Eutrophication risk; geothermal seepage contribution

Community perceptions mirrored laboratory findings. Fifty-eight percent of respondents reported that geothermal operations adversely affect water resources, with 67% identifying water shortages as the primary impact. Additional concerns included elevated temperatures (16%), contamination (12%), changes in taste (3%), and color (1%) (Figure 7).



**Figure 7. Effect brought about by the operation of geothermal power energy on water quality and effects on physical properties.**

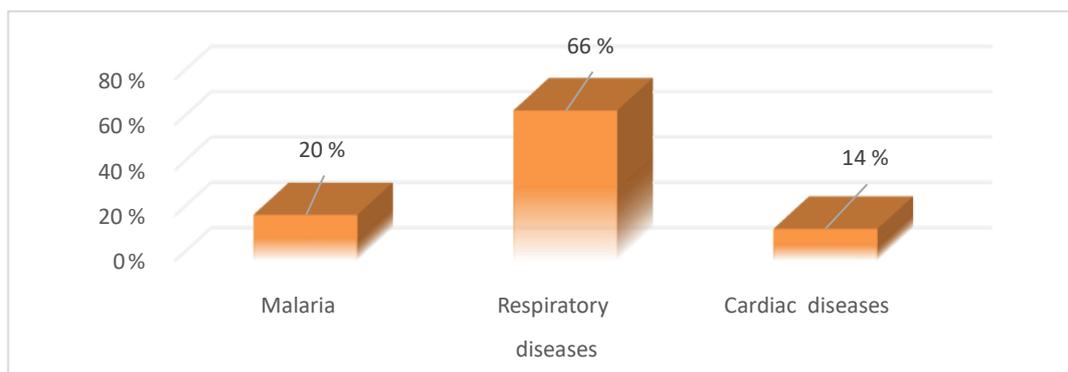
Mitigation measures, such as water delivery (85%), treatment of contaminated water (12%), and construction of cooling systems (3%), were considered largely insufficient by 64% of respondents (Figure 8). These results underscore the spatial heterogeneity of geothermal impacts on water resources and highlight the need for context-specific interventions.



**Figure 8. Mitigation measures on water resource**

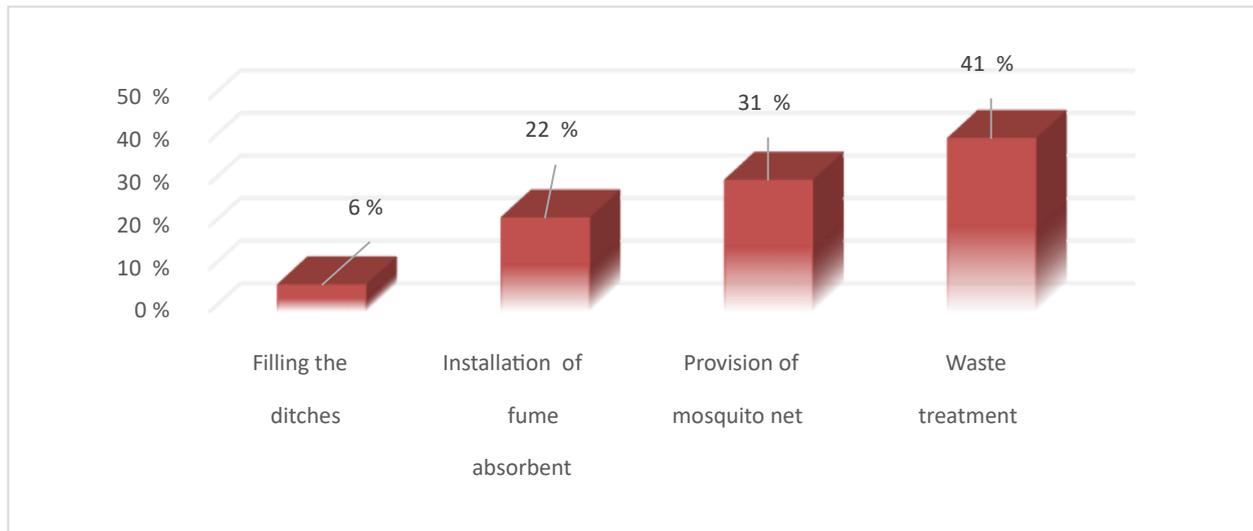
### Health Impacts

Geothermal operations were significantly associated with increased community health concerns ( $\chi^2(1) = 31.14$ ,  $p = 0.008$ ). The predominant illnesses reported were respiratory conditions (66%), malaria (20%), and cardiac diseases (14%) (Figure 9).



**Figure 9. Diseases brought about by the operation of geothermal power energy**

Exposure to hydrogen sulfide (H<sub>2</sub>S) and other geothermal emissions likely contributes to respiratory and cardiovascular morbidity<sup>26–27</sup>. Community-reported mitigation efforts included waste treatment (41%), installation of fume-absorbing devices (22%), and filling of mosquito breeding sites (6%). Despite these measures, 66% of respondents considered interventions inadequate (Figure 10), emphasizing the need for comprehensive environmental health strategies.



**Figure 10. Mitigation measures to control ill-health situations.**

### Synthesis of Findings

The findings demonstrate a clear link between geothermal power operations and environmental degradation in Tiaty East Sub-County. Vegetation cover and health have declined sharply due to land clearing, soil contamination, and habitat fragmentation. Water quality has been altered both physically and chemically, with elevated temperature, turbidity, ionic content, and nutrient enrichment. These environmental changes correlate with increased health risks, particularly respiratory and cardiovascular illnesses.

The results confirm previous research highlighting that geothermal energy, while renewable and low-carbon, is not without ecological and social trade-offs<sup>23, 26, 28</sup>. Effective mitigation requires integrated management strategies that combine land restoration, sustainable water management, emissions control, and community engagement.

### CONCLUSION

The findings emphasize a disconnect between geothermal energy development and sustainable resource management. Geothermal operations in Tiaty East Sub-county significantly affect vegetation, water resources, and public health. Mitigation efforts have not translated into measurable improvements, urging a rethink in strategy. Community-led, evidence-based interventions are essential for inclusive energy transitions. This research underscores the importance of integrating local perceptions in geothermal development policies to ensure environmental sustainability and public wellbeing.

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