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Rivers of Extraction: Mining, Water Landscapes, and Environmental Change in Northern Malawi: The Case of the Kayelekera Uranium Mine

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Abstract: This study evaluates land use change, riverine hydrological alteration, radiological contamination, and human-induced environmental impacts associated with the Kayelekera Uranium Mine from 1990 to 2025 using an integrated geospatial and environmental assessment approach. Results reveal substantial landscape transformation, with Land Cover Intensity (LCI) increasing sharply within 500 m (0.31–2.29) and 1 km (0.18–1.07) buffers, alongside expansion of bare land and built-up areas. Riverine hydrological analysis indicates an alarming 73.4% reduction in stream length and a substantial decline in drainage density from 0.612 to 0.163 km/km², reflecting severe channel fragmentation. Social-environmental results show high river dependence in Villages A–C (33–38%), while Village D is dominated by borehole use (39.2%). Health impacts are highest in Villages A and C, with mean skin and respiratory cases exceeding 230 and 180 inhabitants respectively. Radiological analysis shows strong relationships between U-238 concentrations and ELCR ($r = 0.999$; $R^2 = 0.998$; $p < 0.001$), particularly in downstream sites. Overall, findings demonstrate integrated environmental degradation and escalating socio-environmental risks linked to mining activities.

Key words: Uranium mining, Environmental change, Water landscapes, Remote sensing Geospatial analysis

1. Introduction

Mining is increasingly recognised as a major driver of environmental transformation within river basins and ecologically sensitive landscapes. Extractive activities alter land cover through vegetation clearance, excavation, waste disposal, and infrastructure expansion, frequently resulting in long-term ecological degradation and hydrological disruption (Bansal et al., 2024; Lamghari et al., 2026). Mining-related land clearing and excavation can accelerate erosion, sediment deposition, and surface runoff, thereby reduce drainage connectivity and alter river morphology (Han et al., 2025). Such impacts are particularly critical in catchments already vulnerable to climate variability and hydrological stress (Banda et al., 2024). River systems are particularly vulnerable because mining operations depend heavily on water abstraction, stream diversion, and tailings storage systems that modify drainage processes and aquatic ecosystems. These disturbances contribute to sedimentation, channel instability, declining biodiversity, and water quality deterioration (Shinde et al., 2017). In uranium mining contexts, environmental risks are further intensified by radionuclide mobility, acid mine drainage, and persistent contamination legacies that may extend beyond mine closure (Celeste et al., 2025). Recent scholarship increasingly conceptualises mining landscapes through hydro-social and political ecology perspectives, which frame water as a socio-natural system shaped by interactions among hydrology, governance, infrastructure, and power relations (Addison et al., 2020; Namin, 2009). Across sub-Saharan Africa, expanding extractive frontiers have integrated river basins into global mineral economies, intensifying environmental pressures on fragile ecosystems and rural livelihoods (Alonso-jim, 2026; Irandoost et al., 2025). At the same time, advances in remote sensing and GIS have enhanced the capacity to monitor

mining-induced landscape transformation, hydrological alteration, and environmental degradation across temporal scales (Bah et al., 2026).

In Malawi, large-scale mining activities are relatively recent but with significant environmental impacts. The Kayelekera Uranium Mine has been operational since 2009 within the North Rukuru catchment near Lake Malawi and, it was the country's first large-scale uranium extraction project. The latter mine triggered extensive hydrological infrastructure, including abstraction systems, waste rock dumps, and tailings facilities, which transformed surrounding terrestrial and riparian environments (Somerville & Green, 2018). Emerging evidence from Kayelekera has raised concerns regarding uranium and heavy metal mobilisation within adjacent water systems. Majawa et al., (2024) identified elevated uranium concentrations in sections of the Sere River and highlighted the need for continuous environmental monitoring. Riverine hydrological degradation associated with mining also has broader implications for community wellbeing because rural populations depend heavily on rivers and wetlands for domestic water supply, irrigation, fisheries, and livestock watering. Consequently, declining water quality and river degradation may intensify livelihood insecurity, public health risks, and socio-environmental vulnerability (IAEA, 2022).

Despite increasing scholarship on mining and environmental change, important knowledge gaps remain in Malawi. Existing studies have largely focused on radiological monitoring, economic performance, or policy debates, with limited integration of land use and land cover dynamics, hydrological alterations, and community-level impacts within a unified analytical framework. More specifically, there is an acute lack of spatial evidence regarding mining-induced stream loss, drainage disruption, and riparian transformation around the Kayelekera Uranium Mine. This study examines mining-induced environmental and hydrological transformations associated with the Kayelekera Uranium Mine using an integrated geospatial and socio-environmental approach. More specifically, this study aims to: (i) quantify land use and land cover changes around the mine, (ii) assess mining-induced hydrological alterations and stream loss, and (iii) examine socio-environmental impacts associated with water quality and human wellbeing.

2. Study area

The Kayelekera Uranium Mine is located in a hilly terrain that is drained by the Sere River and Muswanga River systems. Both of these rivers are tributaries of the North Rukuru River, which ultimately flows into Lake Malawi. This study was undertaken in the proximity of the Kayelekera Uranium Mine in Karonga District, in the northern part of Malawi. Thereby, located within the North Rukuru River catchment near the western shores of Lake Malawi. The area lies approximately between 9°45'S–9°58'S and 33°45'E–33°58'E and forms part of the southern segment of the East African Rift System, a geologically active region characterized by complex fluvial networks, wetlands, and ecologically sensitive riparian environments (Rodríguez-labajos, 2015). The region experiences a tropical sub-humid climate with pronounced wet (November–April) and dry (May–October) seasons. Mean annual rainfall ranges from 800–1,200 mm, while average temperatures vary between 20°C and 32°C, exerting significant control on hydrological processes, sediment transport, and flood dynamics (GoM, 2023). Hydrologically, the catchment is drained by the North Rukuru River and its tributaries, including the Sere River and numerous ephemeral streams that sustain wetlands, floodplains, and rural livelihoods through water supply, irrigation, fisheries, and livestock production (GoM, 2022).

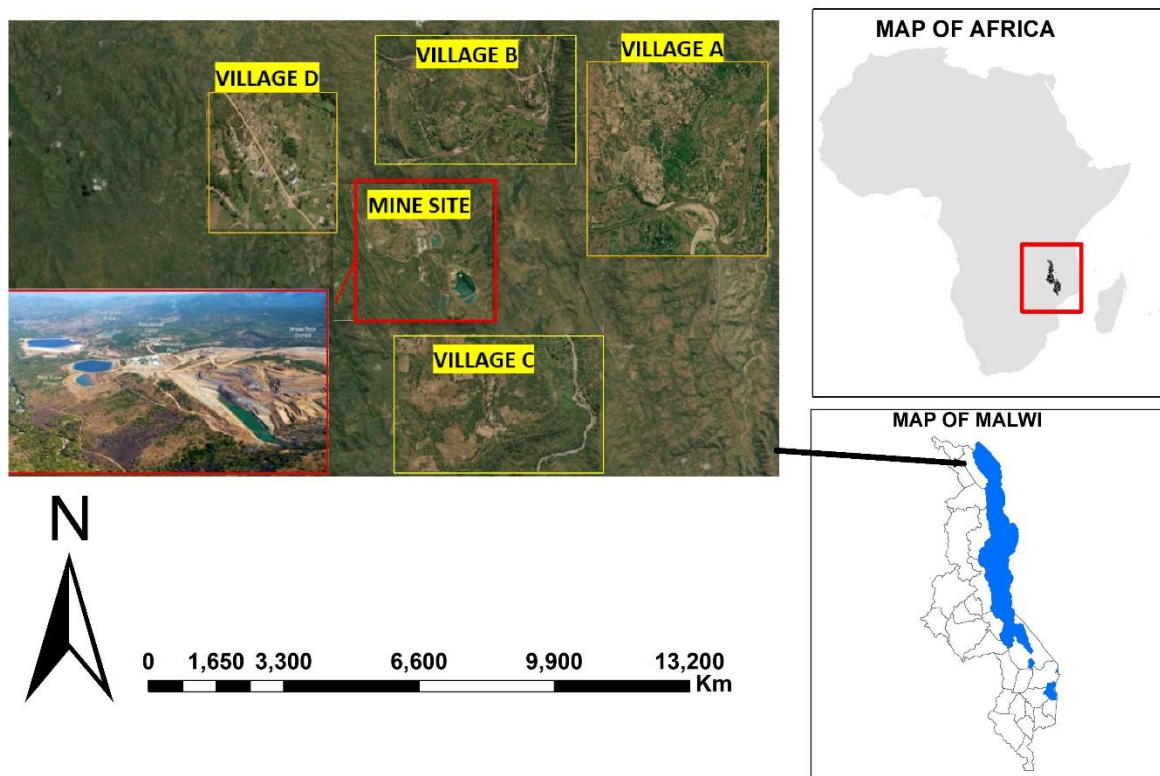


Figure 1. Study area

3. Materials and Methods

3.1 Research Design

This study adopts a three-dimensional design integrating the geospatial, social, and environmental impacts associated with the Kayelekera Uranium Mine using remote sensing, GIS-based spatial analysis, hydrological modelling, and socio-environmental assessment to quantify mining-induced, landscape and water system transformations. The framework evaluates spatio-temporal changes across two periods: the pre-mining baseline (pre-2009) and the operational phase (2009–2025), enabling robust temporal comparison of environmental change trajectories. A mixed-method approach integrates quantitative geospatial analysis with qualitative socio-environmental data obtained from household surveys, focus group discussions, and key informant interviews. This triangulation strengthens inference by linking spatially derived environmental indicators with lived experiences of water quality decline, health risks, and livelihood disruptions. The analytical framework consists of four components: (i) land use/land cover (LULC) change analysis, (ii) hydrological and drainage network analysis (iii) proximity-based spatial impact modelling to quantify exposure gradients relative to the mine and drainage pathways, and (iv) socio-environmental vulnerability assessment. To enhance interpretation and validation, the study incorporates archival environmental evidence from environmental impact assessments, regulatory monitoring reports, and peer-reviewed studies within the Kayelekera catchment.

3.2 Data Sources

Multiple datasets support the spatial, hydrological, and socio-environmental analyses (Table 1).

Table 1. Data sources and applications

Data	Source	Resolution	Purpose
Landsat TM/ETM+/OLI (1990–2025)	USGS	30 m	LULC classification and change detection
DEM (SRTM)	NASA	30 m	Terrain analysis, slope, drainage and hydrological modelling
HydroSHEDS	HydroSHEDS	Variable	Stream network extraction and validation

4. Data Processing and Analysis

4.1 Land Use and Land Cover (LULC) Change Analysis

Multi-temporal Landsat imagery was used to assess land use and land cover (LULC) dynamics for four representative periods: 1990 (pre-mining baseline), 2005 (pre-operational phase), 2015 (early operational influence), and 2025 (recent conditions). All images were selected from the dry season (May–October) to minimise cloud contamination and phenological variability. Preprocessing included atmospheric correction, radiometric normalisation, cloud and shadow masking, mosaicking, and image compositing. Supervised classification was performed using the Random Forest (RF) algorithm due to its high accuracy and robustness in heterogeneous and spectrally complex mining landscapes. Six LULC classes were defined: forest, vegetation, agriculture, water bodies, bare land and built-up areas. The RF classifier ($\hat{y}$) estimates the final class as the majority vote of multiple decision trees:

$$\hat{y} = \text{mode}\{h_1(x), h_2(x), \dots, h_{ntree}(x)\}$$

where $h_k(x)$ represents the predicted class from the k -th tree for feature vector x .

Post-classification comparison was used for change detection, enabling explicit quantification of land transitions between classes. The transition probability (P_{ij}) from class i to class j is given by:

$$P_{ij} = \frac{A_{ij}}{\sum_j^n A_{ij}}$$

where A_{ij} is the area converted from class i to class j .

4.2 Hydrological and River System Analysis

Hydrological analysis was conducted using a DEM-based terrain modelling approach. Preprocessing steps included sink filling, flow direction (D8 algorithm), flow accumulation, and watershed delineation. Flow accumulation (FA) at a cell (x, y) is defined as:

$$FA = \sum_{i=1}^n inflow_i$$

where $inflow_i$ represents contributing upstream cells. Stream networks (S) were extracted using a threshold-based approach:

$$S(x, y) = \begin{cases} 1, & FA(x, y) > T \\ 0, & \text{otherwise} \end{cases}$$

where T is the contributing area threshold (1ha, determined through sensitivity analysis). Drainage density (D_d), a key indicator of hydrological connectivity, was computed as:

$$D_d = \frac{\sum L}{A}$$

where $\sum L$ is total stream length (km) and A is basin area (km²). Temporal comparison (1990–2025) quantified stream network dynamics, including stream loss, diversion and drainage density reduction. Stream Loss Rate (SLR) was computed as:

$$SLR = \frac{L_{t1} - L_{t2}}{L_{t1}} \times 100$$

Buffer analysis (500m, 1km, 3 km, and 5 km) around mining infrastructure was applied to assess spatial gradients of impact. Within each buffer, land cover pressure was quantified using the land cover change intensity (LCI):

$$LCI = \frac{\Delta BA + \Delta BL}{\Delta b}$$

where ΔBA is bare land change, ΔBL is built-up change, and A_b is buffer area. Sedimentation susceptibility was estimated using the Surface Disturbance Index (SDI):

$$SDI = \frac{BA + ML}{TV}$$

where BA is bare land, ML is mining land, and TV is total vegetation cover within each buffer zone.

4.3 Human and Environmental Impact Analysis

A quantitative and multivariate approach was employed to evaluate mining-related human and environmental impacts in four villages surrounding the Kayelekera Uranium Mine. Household survey data encompassing livelihoods, perceptions of environmental change, water-use practices, and health outcomes were analysed to characterise exposure pathways and spatial vulnerability patterns. To ensure representativeness across varying exposure gradients, a stratified sampling design was adopted, incorporating downstream, near-mine, and upstream control communities. The required sample size (n_0) was calculated using Cochran's formula (Sadiq et al., 2025), providing statistically robust village-level representation for subsequent analyses.

$$n_0 = \frac{Z^2 p(1 - p)}{e^2}$$

where $Z=1.96Z$ at 95% confidence level, $p=0.5$ (maximum variability assumption), and $e=0.1$ (precision level). This yielded a minimum sample size of 96 households. The final sample ($n = 166$ households) exceeded the minimum requirement and was proportionally allocated across villages ($A = 42$, $B = 42$, $C = 42$, $D = 40$), ensuring balanced spatial representation.

4.4 Statistical Analysis

Survey data were standardised as proportional frequencies relative to village totals. Livelihood impacts (multiple-response), environmental change attribution, and water-source dependency were analysed using descriptive statistics and cross-tabulations (Skinner & Skinner, 2018). Perceived water contamination was modelled as a categorical response variable (Contaminated, Not Contaminated, Not Sure), stratified by water source and village. Associations between variables were evaluated using Pearson's chi-square tests of independence (Mchugh, 2013). Statistical robustness was assessed through bootstrap resampling (1,000 iterations) to estimate 95% confidence intervals for contamination

proportions(Sadiq et al., 2025). A Poisson log-linear model was subsequently applied to examine higher-order interactions among village location, water source, and perception categories (Althubaiti, 2023).

5.0 Results

5.1 Land Cover Land Use alterations

The temporal land use and land cover analysis around the Kayelekera Uranium Mine revealed substantial landscape transformation and hydrological disturbance between 1990 and 2025. Results indicate a progressive increase in bare land and built-up surfaces across all buffer zones, reflecting the expansion of mining infrastructure, excavation activities, waste disposal areas, and associated anthropogenic modifications. The most pronounced changes were observed within the 500 m and 1 km buffers, where Land Cover Intensity (LCI) values increased from 0.31 and 0.18 in 1990 to 2.29 and 1.07 in 2025, respectively, indicating severe environmental degradation near the mining core. Similarly, bare land expanded significantly within the 5 km buffer from 168.4 ha in 1990 to 710.8 ha in 2025, while built-up land increased from 61.3 ha to 310.2 ha over the same period.

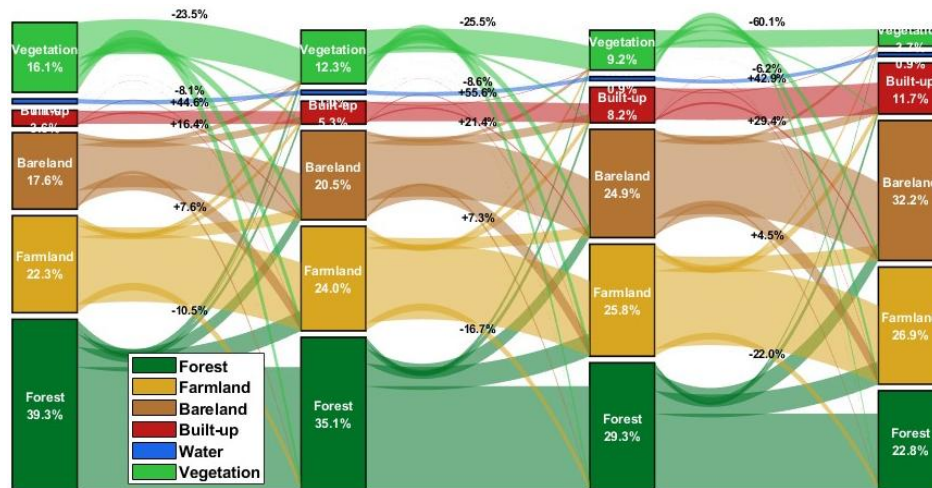


Figure 2. Land use land cover change results

5.2 Riverine Hydrological Impacts

Hydrological analysis revealed substantial degradation of stream network integrity within the Kayelekera mining catchment between 1990 and 2025. Drainage density declined significantly from 0.612 km/km² in 1990 to 0.163 km/km² in 2025, with a mean value of 0.407 km/km² and a standard deviation of 0.227, indicating pronounced temporal hydrological variability. Overall stream reduction reached 73.40%, reflecting severe channel fragmentation and loss of hydrological connectivity. Annual stream loss rates increased from 0.719 km/year during 1990–2005 to 0.915 km/year during 2005–2025.

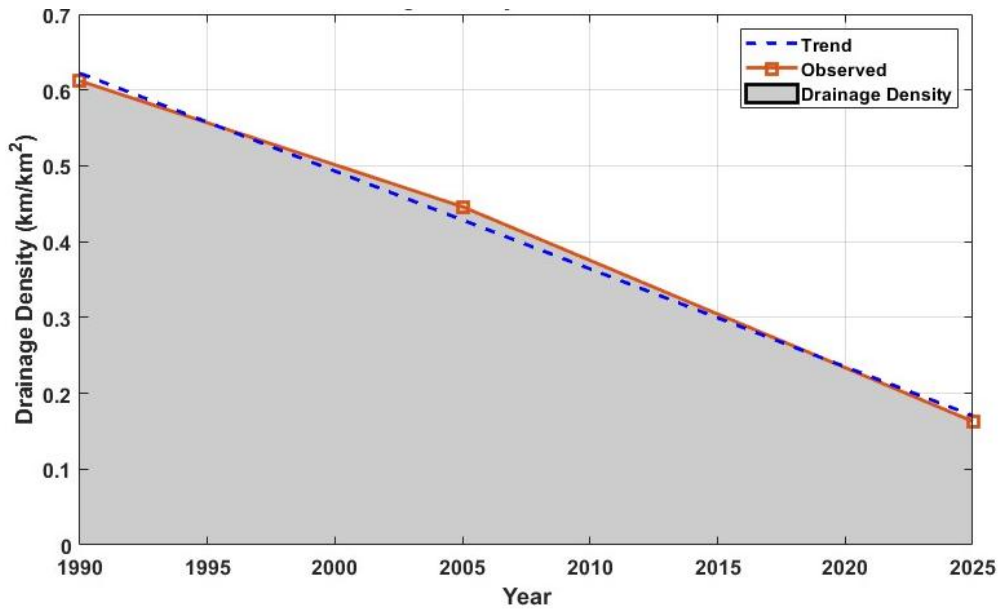


Figure 3: Temporal variation in stream network length and drainage density within the Kayelekera Uranium Mine catchment.

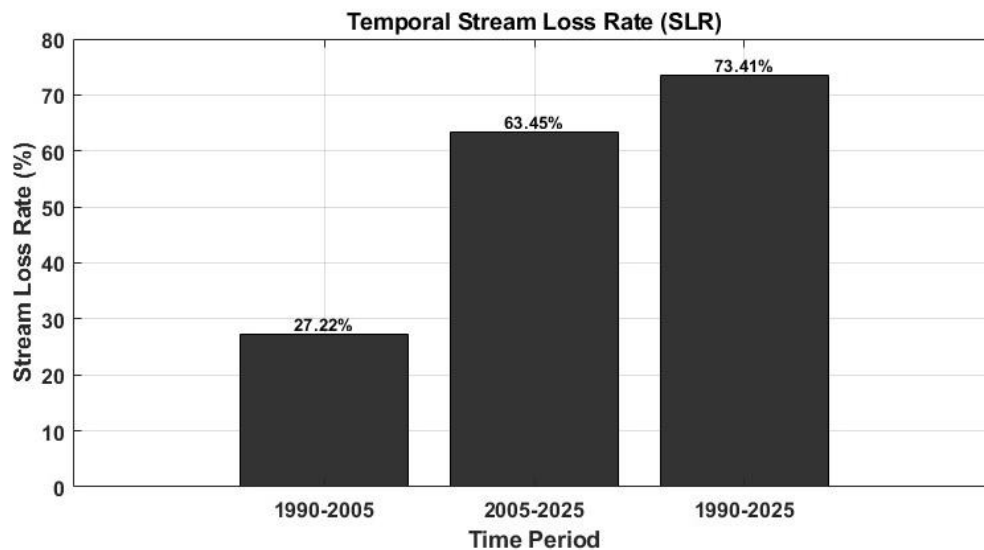


Figure 4: Stream Loss Rate (SLR) trends and annual hydrological decline across the study periods.

5.3 Human and Environmental Impacts

5.3.1 Primary water sources for villages A, B, C, and D

The household water source distribution across Villages A–D shows distinct spatial variability in access patterns. The proportions of river water usage for each village were as follows; 34.0% in Village A, 33.0% in Village B, 38.3% in Village C, and 13.7% in Village D. Borehole use represents 29.8% in Village A, 28.6% in Village B, 23.4% in Village C, and 39.2% in Village D. The percentages of water from ‘Protected Wells’ contribute to 17.0% in Village A, 19.6% in Village B, 14.9% in Village C, and 17.6% in Village D. The share of water drawn from ‘Unprotected Wells’ remains relatively low at 8.5% in Village A, 10.9% in Village B, 8.5% in Village C, and 3.9% in Village D. Rainwater harvesting is minimal, recorded at 0% in Villages A and B, and 4.3% in both Villages C and D.

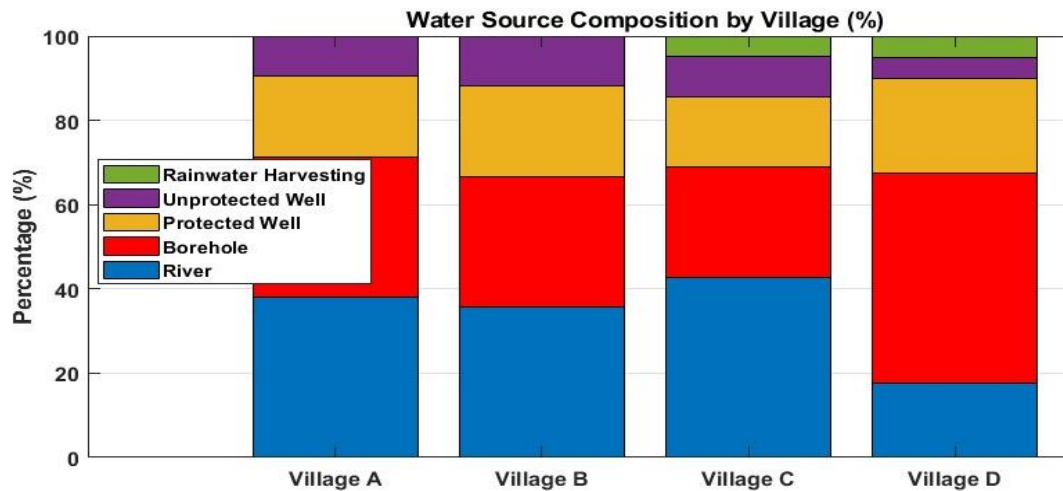


Figure 5: Distribution of household primary water sources across Villages A–D

5.3.2 Perception of Water Contamination across the Villages

The perceived water contamination across Villages A–D shows clear spatial differentiation supported by descriptive statistics. River water is most strongly associated with high contamination perception, accounting for 38.3% in Village C and 34.0% in Village A, compared to 13.7% in Village D. Apprehended contamination from boreholes represents 39.2% in Village D while representing 23.4%–29.8% in other villages. Protected wells show relatively uniform moderate-risk perception (14.9%–18.8%), indicating stable but limited reliance. Unprotected wells are consistently classified as high risk across all villages. Rainwater harvesting is perceived as low risk.

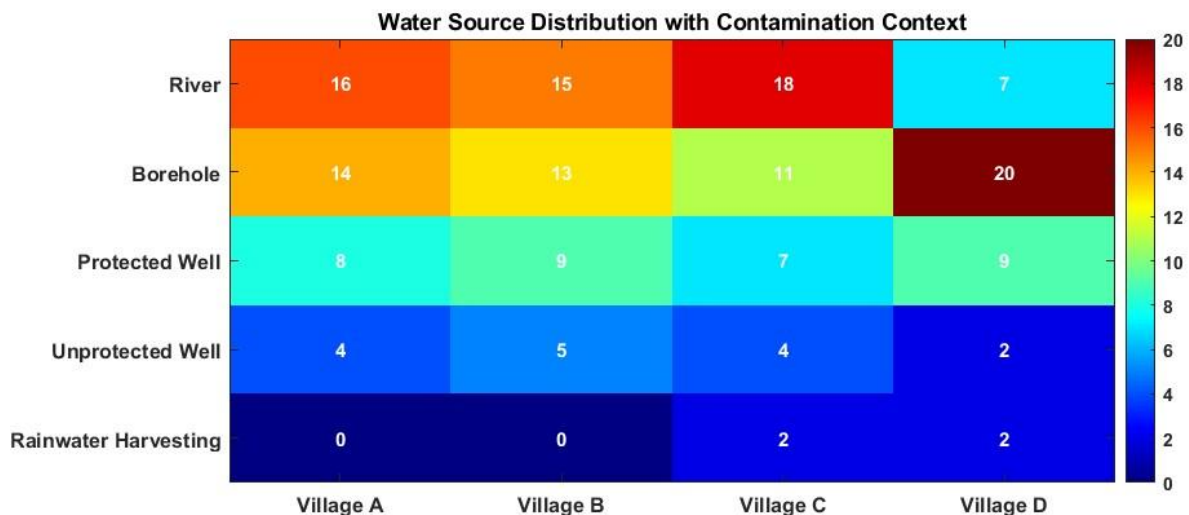


Figure 6: Heatmap illustrating perceived contamination risk intensity across water sources in Villages A–D

5.3.3 Livelihood Impacts Reported by Households

The indicators used for evaluating impacts on livelihood were; Fish Catch, Crop Yield, Water Shortage, Livestock Loss, Medical Cost, Land Loss and Income Loss. The livelihood impact patterns across Villages A–D exhibit clear spatial heterogeneity in both magnitude and distribution across impact categories. Village C recorded the highest overall burden with fish catch loss (32 households, 26.7%), crop yield reduction (30, 25.0%), water shortages (19, 15.8%), livestock loss (18, 15.0%), medical

expenses (23, 19.2%), land loss (15, 12.5%), and income loss (28, 23.3%), with a minimal proportion reporting no impact (2 households, 1.7%). Village B shows moderate impact levels, dominated by fish catch loss (29, 23.6%), crop yield reduction (27, 22.0%), and income loss (24, 19.5%). Village A exhibits a similar but slightly lower pattern, with fish catch (21.7%) and crop yield (20.0%) losses being most prominent. In contrast, Village D consistently records the lowest impact levels across all categories (3–7 households, <10% each), except for a dominant no-impact response (18 households, 45.0%).

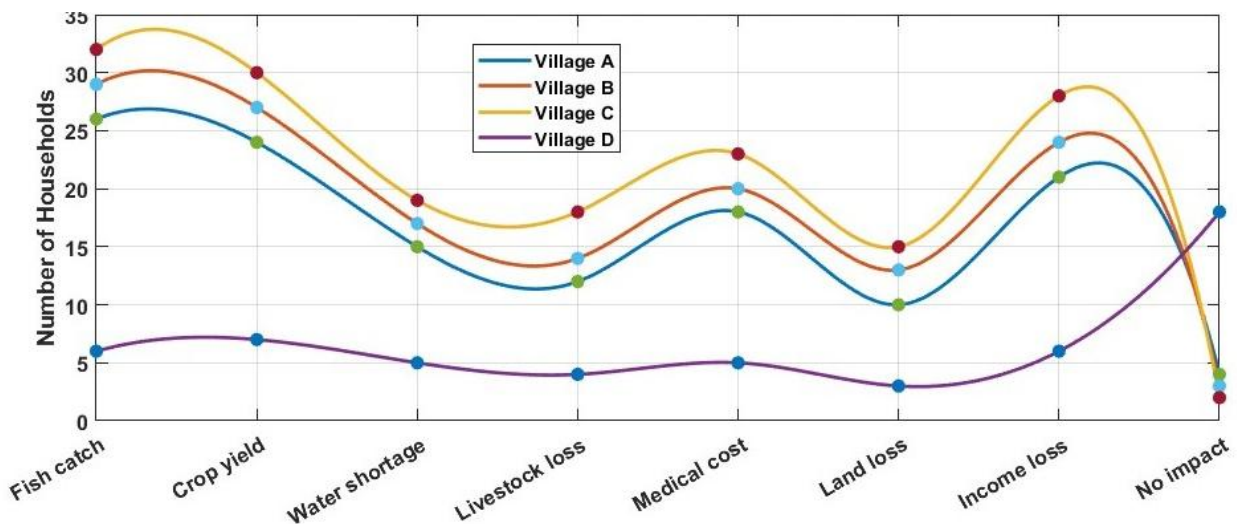


Figure 7: Livelihood impact distribution across Villages A–D showing spatial variation in household-reported impacts, with highest burdens in Village C and lowest in Village D.

5.3.4 Spatial Patterns of Environmental Health Impacts in Communities Surrounding the Kayelekera Uranium Mine

Across the four villages, the results revealed a pronounced spatial gradient and statistically distinct health burden patterns between 2017 and 2025. Villages A and C consistently record the highest mean disease loads, with skin rates averaging above 230 cases in Village A and 240 cases in Village C, compared to less than 110 cases in Village B and below 75 cases in Village D. Respiratory illnesses are relatively high in Villages A and C, with mean values frequently exceeding 180–250 cases, while Village D remains comparatively low (≈ 54 –85 cases). Diarrheal diseases peak in Village C (up to 297.66) and remain persistently high in Village A (>240), indicating strong waterborne risk clustering. Standard deviations (up to ± 56.1 in skin rates and ± 66.2 in livestock impacts) highlight substantial intra-village variability, particularly in Villages A and C, suggesting episodic environmental stress events. In contrast, Village D shows minimal variability and consistently high “No Issue” means (>700), reinforcing its role as a low-exposure baseline.

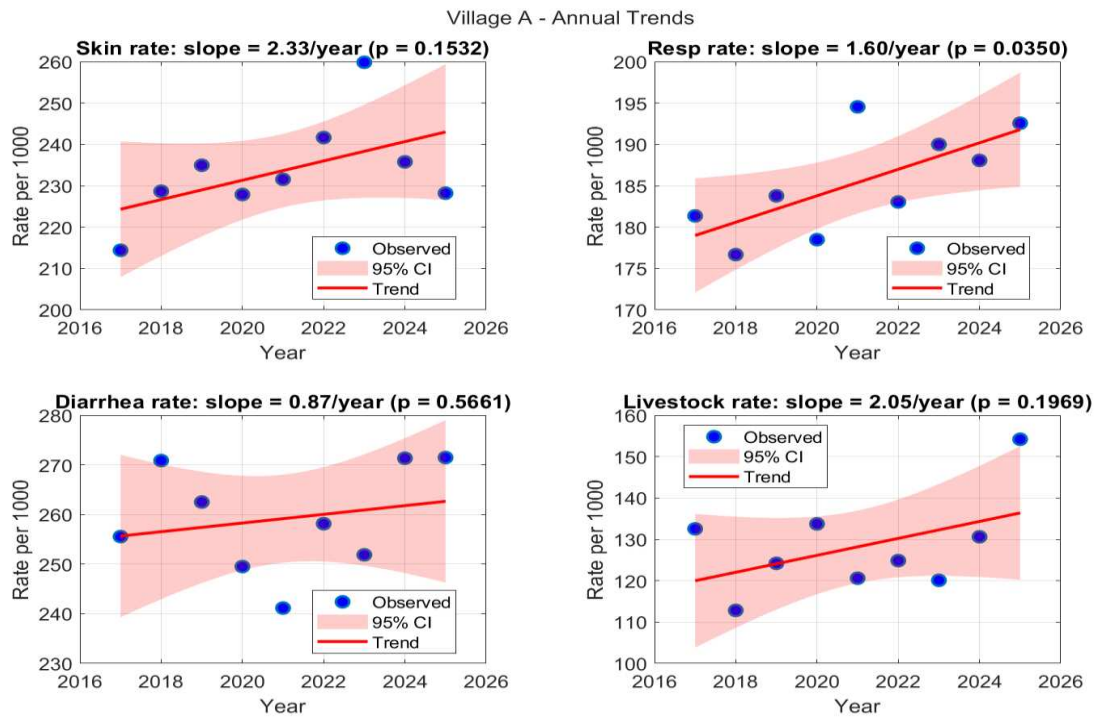


Figure 8: Temporal variation of mean skin, respiratory, diarrheal, livestock impact, and no-issue rates in Village A

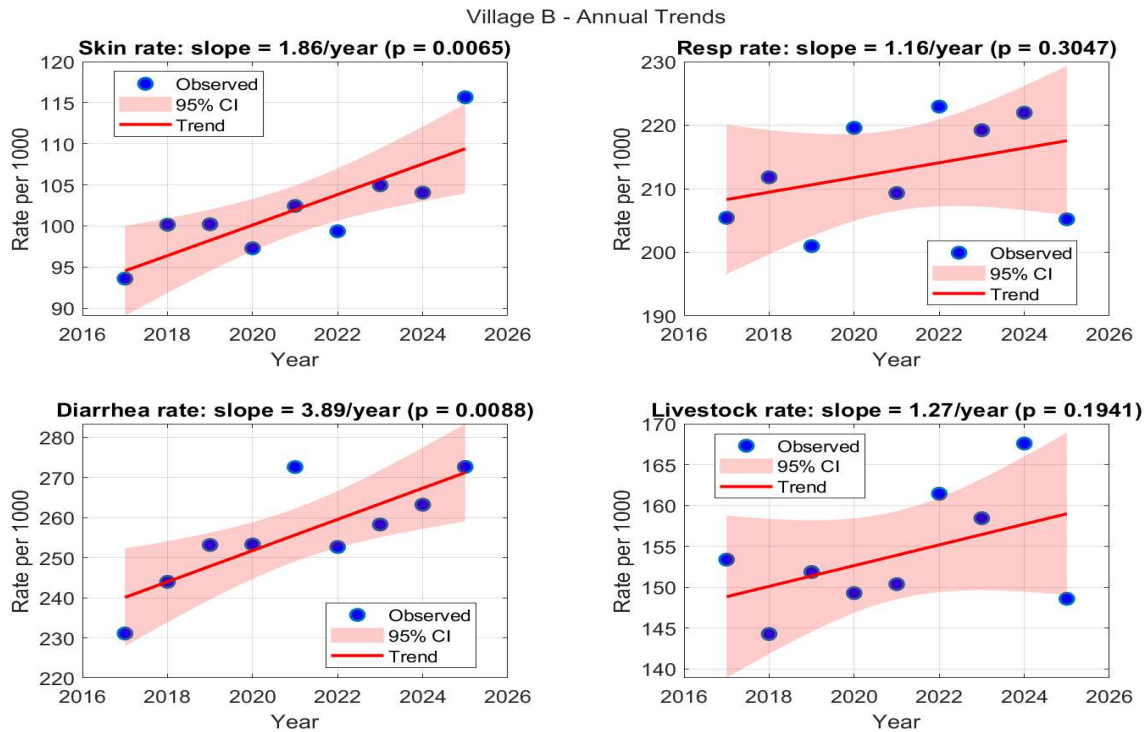


Figure 9: Temporal variation of mean skin, respiratory, diarrheal, livestock impact, and no-issue rates in Village B

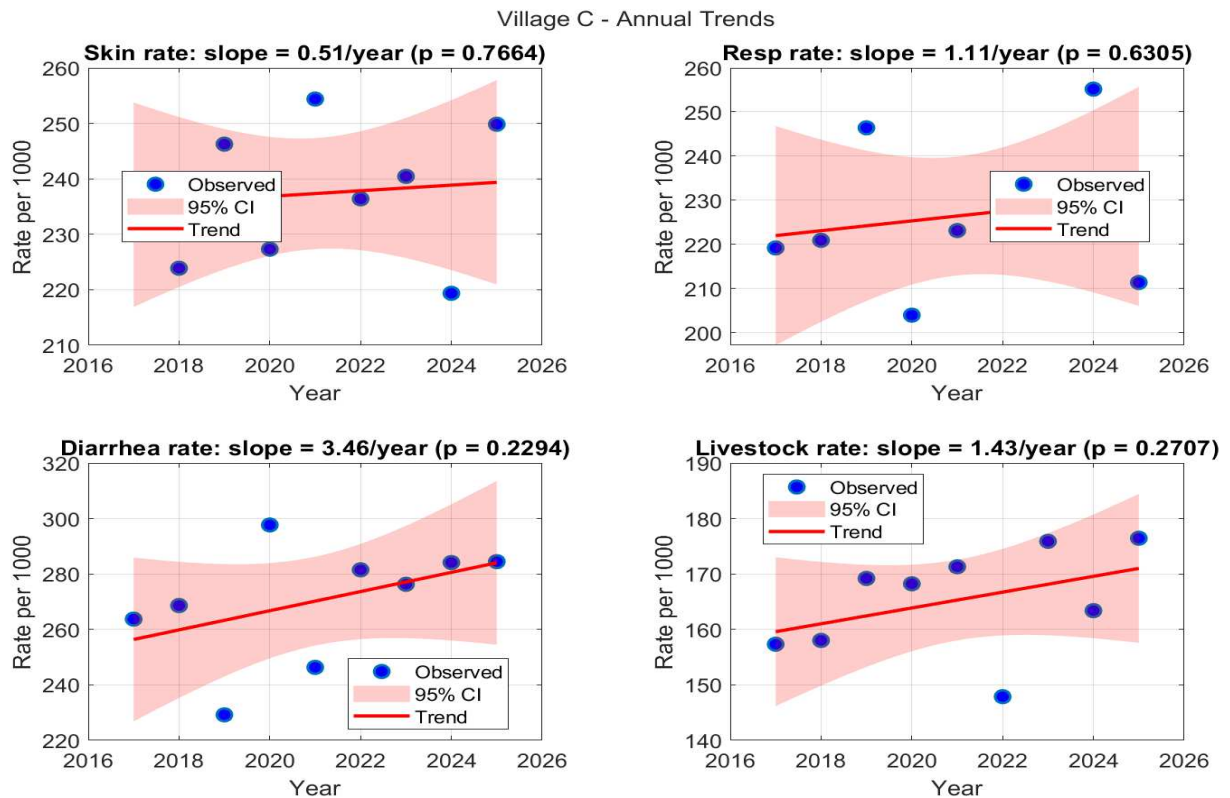


Figure 10: Temporal variation of mean health outcome rates in Village C.

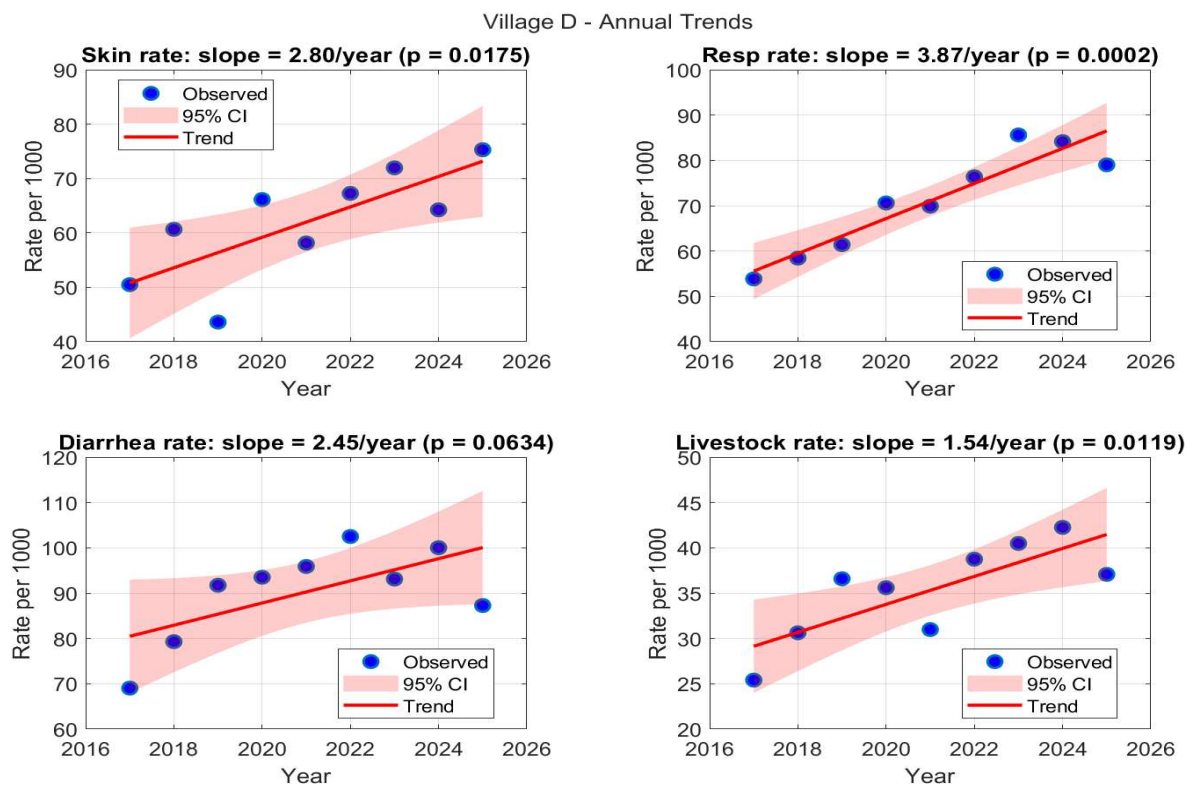


Figure 11: Temporal variation of mean health outcomes in Village D

6.0 Discussion & Conclusion

The findings demonstrate that uranium mining activities have substantially altered the hydro-environmental conditions surrounding the Kayelekera Uranium Mine since the onset of its activities. The expansion of bare land and built-up surfaces, coupled with declining vegetation cover and a 73.40% reduction in stream connectivity, indicates significant watershed disturbances and hydrological degradations. Such landscape modifications are known to increase runoff, erosion, sediment transport, and contaminant mobility within river systems (Sonter et al., 2015; Tarolli & So, 2016). The health assessment revealed pronounced spatial heterogeneity in disease burden across the study area. Villages A and C consistently recorded the highest prevalence of dermatological diseases (>230 and >240 cases, respectively), respiratory illnesses (180–250 cases), and diarrheal diseases (>240 and up to 297.66 cases), whereas Village D exhibited substantially lower disease incidences and the highest proportion of households reporting no health issues (>700). The large standard deviations observed in Villages A and C (up to ± 56.1 for skin diseases) further indicate localized exposure variability and environmental stress. These findings are consistent with previous studies that associate degraded water resources and environmental contamination with increased public health burdens in rural mining communities (WHO, 2017.; Prüss-üstün et al., 2019). The observed health patterns are further supported by environmental evidence from the Kayelekera region. Majawa et al., (2022) reported elevated concentrations of naturally occurring radionuclides in soils surrounding the mine, particularly U-238 in locations proximal to mining operations, highlighting the need for periodic environmental monitoring. Similarly, Majawa et al., (2024) detected elevated U-238 concentrations at downstream water sampling points (SW05 and DW01) and concluded that although radiological doses remained below international guideline limits, long-term ingestion exposure could present cumulative health concerns. In the present study, archival hydro-radiological regression analysis revealed exceptionally strong relationships between U-238 concentrations and ingestion dose and Excess Lifetime Cancer Risk ($R^2 = 0.998$, $p < 0.001$), indicating the persistence and mobility of mine-derived contaminants within aquatic systems. Furthermore, concerns regarding radioactive waste generation, on-site disposal practices, and documented spill incidents at Kayelekera have been highlighted by (Rodríguez-labajos, 2015), suggesting potential pathways for environmental contamination through surface water transport.

7.0 Limitations of the Study

Despite integrating multi-source geospatial, hydro-radiological, and public health datasets, this study has several limitations. Firstly, reliance on secondary health records may introduce reporting bias. Secondly, temporal gaps in environmental monitoring data limit continuous assessment of contamination dynamics. Thirdly, spatial resolution of satellite-derived indicators may not fully capture micro-scale exposure variations within villages. Finally, although strong statistical associations were observed, causal inference between uranium contamination and health outcomes cannot be definitively established.

Declarations

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Ethical Approval

This study was conducted in accordance with the Government of Malawi research ethics guidelines and relevant institutional and local authority requirements. Ethical approval for household survey data collection and community engagement was obtained prior to fieldwork. Participation was entirely voluntary, and informed consent was obtained from all respondents. All collected data were handled with strict confidentiality and used solely for academic research purposes, ensuring anonymity and protection of participants' identities.

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