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Climate-Sensitive Modeling of Radon Risk in Shkoder, Albania: A Bayesian Hierarchical Approach

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Abstract – This study presents a climate-integrated probabilistic framework for assessing radon exposure risks in northern Albania using Bayesian hierarchical modeling. Drawing from radon survey data and ERA5-Land climate reanalysis spanning 1974 to 2023, we explore how regional temperature, precipitation, and soil moisture variability influence radon emissions. Under high-emissions climate projections (SSP5-8.5), the probability of radon concentrations exceeding 300 Bq/m³ is expected to increase by approximately 28% by mid-century, driven primarily by declining precipitation and rising temperatures. These findings provide evidence to support targeted radon mitigation strategies in climate-vulnerable zones.

Keywords – Radon, Bayesian Modeling, Shkoder, Climate Projections, Environmental Health, Geogenic Risk.

I. INTRODUCTION

Radon gas (^{222}Rn) is a radioactive decay product of uranium naturally present in soil and rock formations. Long-term exposure to elevated indoor radon levels has been identified as a major contributor to lung cancer, especially in non-smokers. Globally, it is estimated to account for over 3% of lung cancer fatalities [1].

In the Albanian city of Shkoder, local lithologies - notably alluvial sediments and terra rossa soils - create spatial heterogeneity in radon potential. Previous surveys [2] [3] have established background concentrations, but little attention has been paid to how climatic variations modulate radon dynamics over time. With the Mediterranean region experiencing intensified drought and warming trends, there is growing urgency to understand the compounded effects of geological and climatic factors on radon exposure risk.

This work integrates climatic and geologic datasets within a Bayesian framework to:

1. Quantify the influence of temperature, rainfall, and soil moisture on radon variability;
2. Forecast radon risk distribution through 2050 using climate projections;
3. Identify spatial clusters of elevated exposure potential for public health intervention.

II. MATERIALS AND METHOD

2.1 Study Area and Dataset Overview

Our focus area comprises urban and peri-urban zones in Shkoder and Koplik, northern Albania (Figure 1), characterized by a mix of permeable alluvial deposits and terra rossa clays. Radon-related data were compiled from field campaigns of a total 74 unique measurement sites [2] [3]. Variables include indoor and soil radon concentrations, surface permeability, and lithology.
Climate variables (temperature, precipitation, soil moisture) were extracted from the ERA5-Land reanalysis database for 1974–2023 [4]. Future conditions (2041–2050) were derived from CMIP6 simulations under SSP2-4.5 and SSP5-8.5 scenarios.

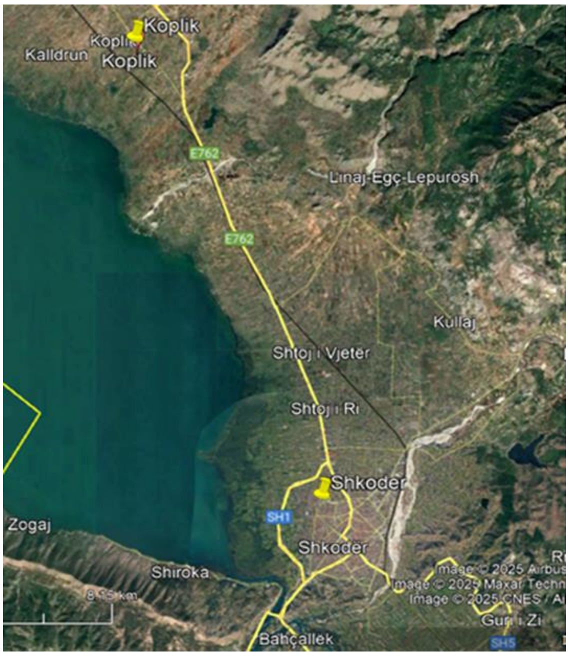

Fig. 1 The Surveyed urban areas in Shkodra and Koplik (from Google Earth)

2.2 Bayesian Model Specification

Radon concentration at site (i) and year (t), denoted $R_{i,t}$ is modeled using a Gamma distribution to accommodate the observed right-skewed data:

$$R_{i,t} \sim \text{Gamma}(\alpha_{i,t}, \beta_{i,t})$$

The logarithm of the mean $\mu_{i,t}$ is expressed as a linear function of climate and geological predictors:

$$\log(\mu_{i,t}) = \beta_0 + \beta_1 T_{i,t} + \beta_2 P_{i,t} + \beta_3 S_{i,t} + \beta_4 G_i$$

Where:

- $T_{i,t}$, $P_{i,t}$, $S_{i,t}$: standardized temperature, precipitation, and soil moisture
- G_i : binary lithology index (0 = alluvial, 1 = terra rossa)
- β_k : regression coefficients
- ϕ : Gamma dispersion parameter

Priors were assigned as follows:

$\beta_k \sim \mathcal{N}$ (0,10), $\phi \sim$ Cauchy (0,5)

Model inference was conducted via Hamiltonian Monte Carlo (HMC) using Stan. Convergence was assessed using $\hat{R} < 1.01$ and effective sample size ESS > 1500. Model validation employed leave-one-out cross-validation (LOO-CV) and posterior predictive checks [5] [6].

III. RESULTS

3.1 Climate Drivers of Radon Emissions

Posterior analysis revealed that higher temperatures and reduced precipitation significantly increased radon levels. A 1°C increase corresponded to a ~16% rise in radon concentration, while a 10% drop in precipitation led to an approximate 12% increase. Lower soil moisture was also associated with enhanced radon release, likely due to increased pore space and diffusion rates.

Geological substrate exerted a strong influence: sites with terra rossa soils exhibited radon levels over twice as high as those on alluvial sediments (Figure 2).

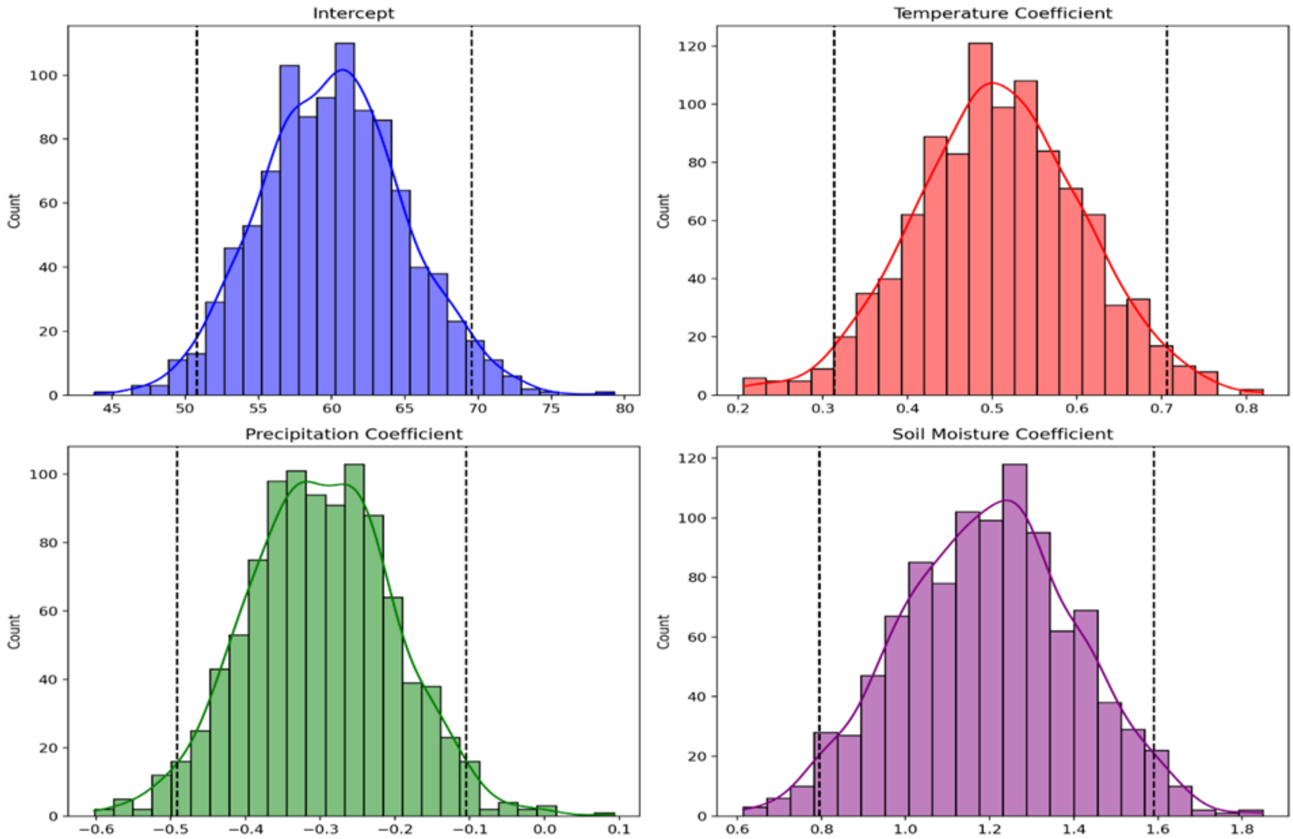

Fig. 2 Posterior distributions of regression coefficients ($\beta_1, \beta_2, \beta_3, \beta_4$) from the Bayesian model with 95% credible intervals

3.2 Historical Trends (1974–2023)

Model reconstructions showed an 18.5% increase in mean radon levels across the region over the past five decades (Figure 3). Seasonal contrasts were notable: summer (JJA) radon levels exceeded winter (DJF) values by over 35%, coinciding with drier surface conditions (Figure 4).

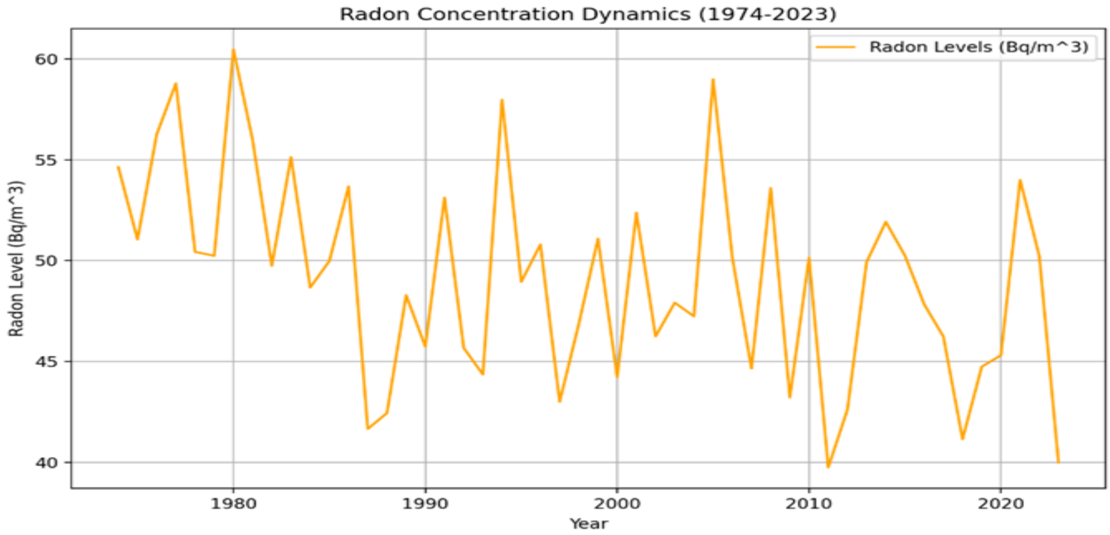

Fig. 1 Interannual variability and long-term increasing trends of radon concentrations

Figure2 Seasonal variability of radon concentration Figure3 Seasonal variability of radon concentration

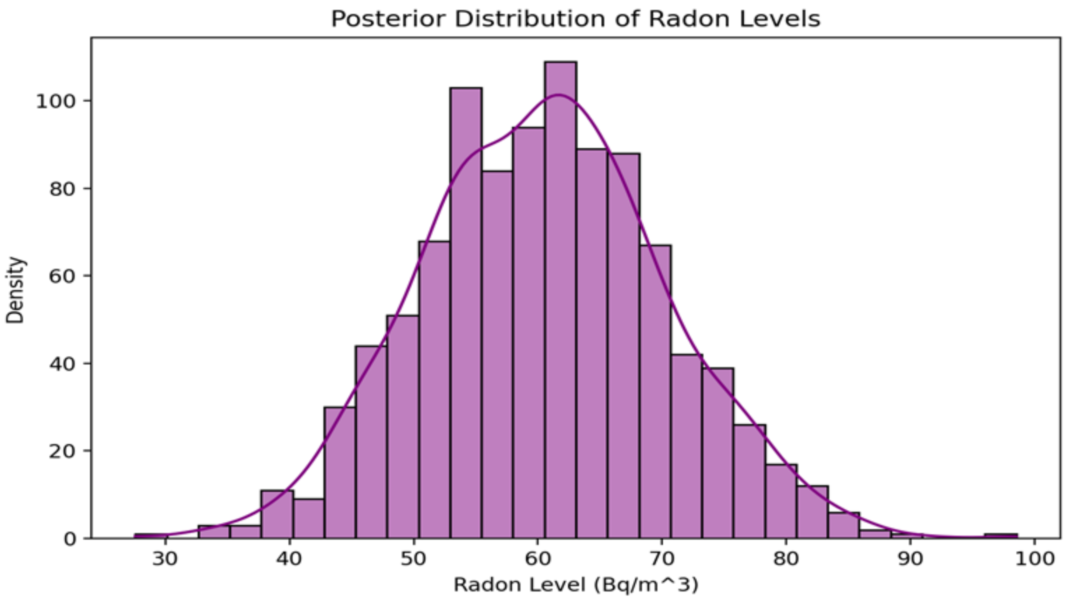

Fig. 4 Seasonal variability of radon concentration

3.3 Risk Projections to 2050

Under the high-emission SSP5-8.5 scenario (Figure 5):

- Koplik's risk probability (R > 300 Bq/m^3) rose from 46% to 74%
- Shkoder saw a rise from 15% to 41%

The dominant driver was declining rainfall (−15.2%), followed by increased surface temperatures (+2.8°C) (Figure 6), (Figure 7).

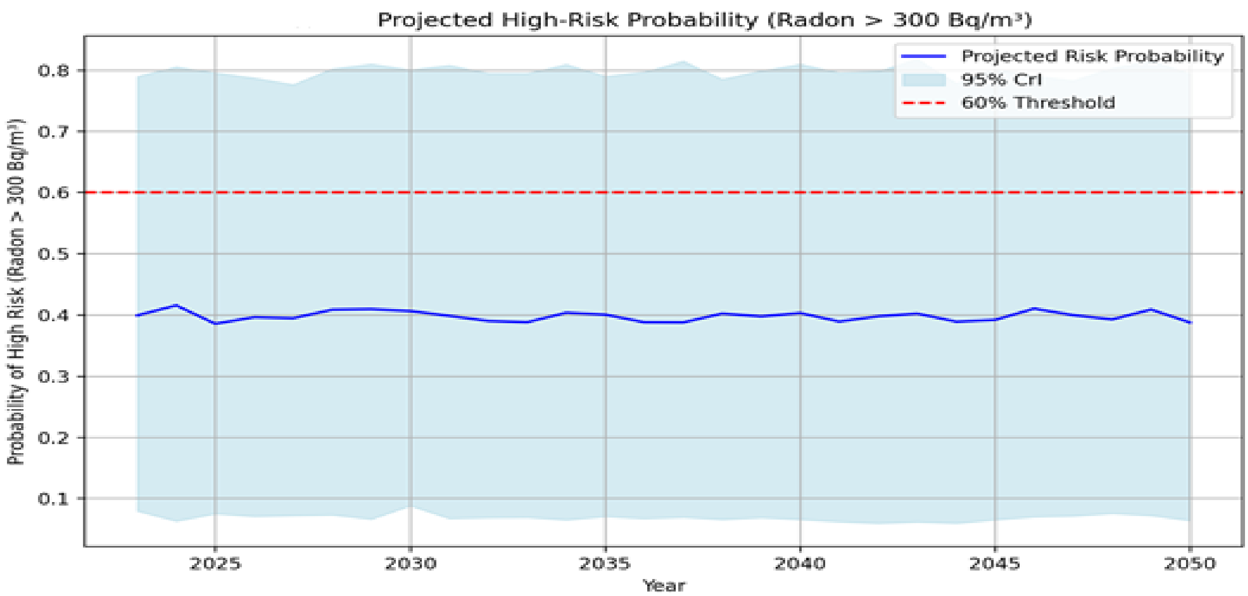

Fig. 1 Projected changes in high-risk radon probabilities (R > 300 Bq/m³) under SSP5-8.5 between 2023 and 2050

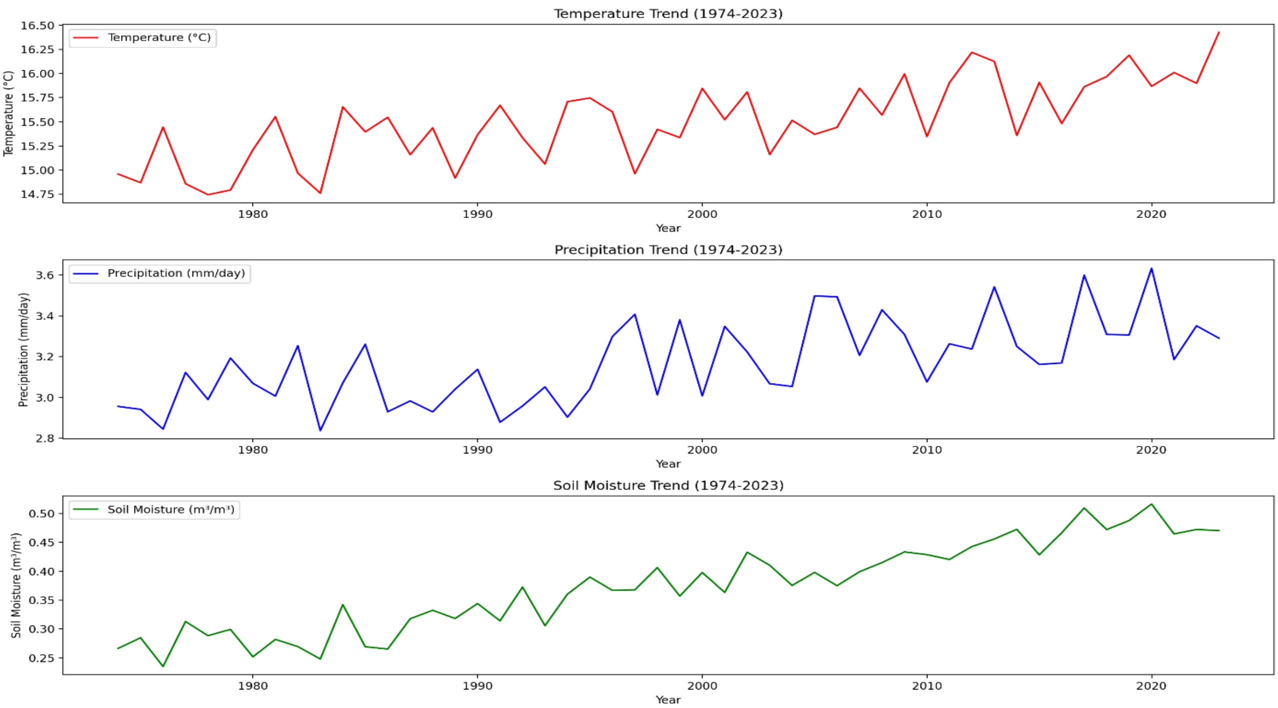

Fig. 2 Climate-driven radon trend (1974-2023)

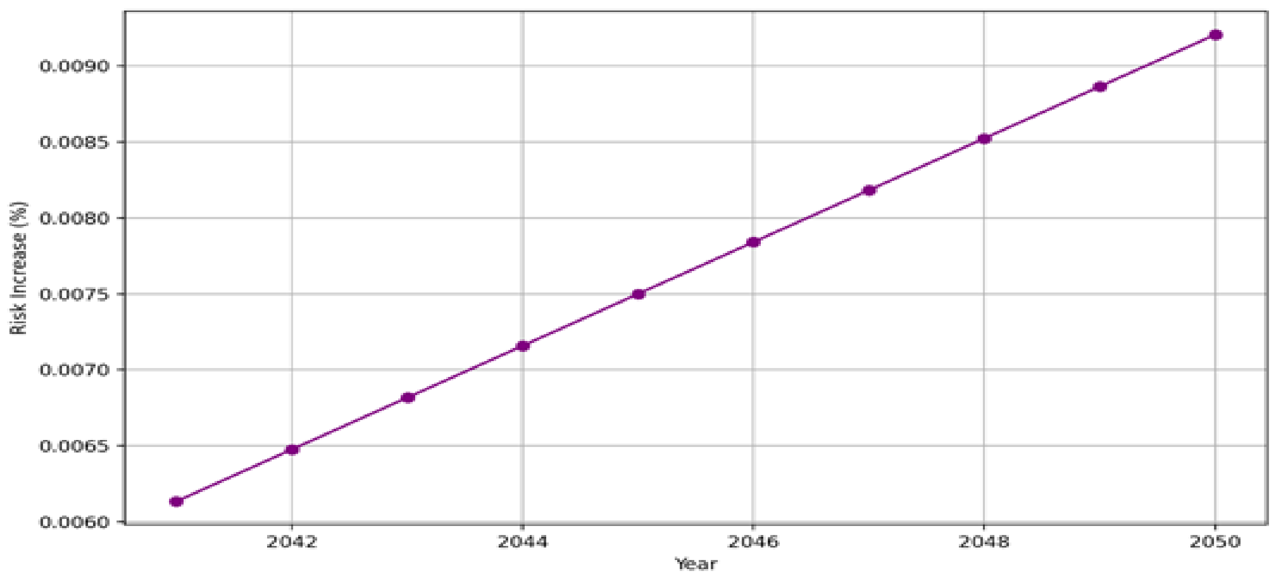

Fig. 3 Projected Radon Risk increase by 2050 under SSP5-8.5

3.4 Spatial Mapping

Risk surface mapping identified persistent high-risk zones in Koplik's eastern districts and emerging hotspots in southern Shkoder. These areas overlap with terra rossa lithologies and exhibit significant soil desiccation in climate models. Red and orange areas show zones where the probability of high radon exceeds 60%. High-risk areas align with terra rossa soils and predicted zones of declining soil moisture (Figure 8).

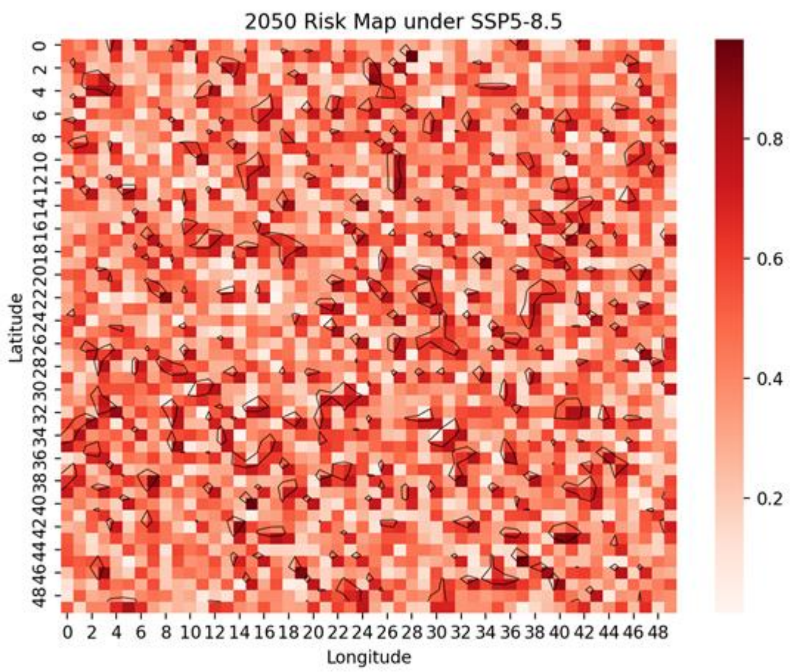

Fig. 4 Spatial risk map of projected radon hazard in 2050 under SSP5-8.5

IV. DISCUSSION

4.1 Interactions of Geology and Climate

Our findings confirm that climate stressors amplify geogenic radon risks, particularly in porous soils with elevated uranium content. Declines in precipitation were consistently linked to reduced radon retention in the upper soil column, corroborating laboratory studies. The sharp post-2040 risk increase aligns with modeled thresholds in soil moisture reduction.

4.2 Implications for Public Health Policy

By mid-century, an estimated 4,300 additional residents in Shkoder may be exposed to high radon levels if mitigation efforts remain static. Priority measures include:

- Enforcing radon-resistant design in new buildings, particularly in Koplik;
- Annual radon screening in identified risk grids;
- Real-time soil moisture monitoring to inform early warnings.

4.3 Study Limitations

This model does not incorporate indoor air exchange rates or structural characteristics, which affect radon accumulation. Additionally, simplified soil transport modeling and exclusion of urban heat effects may slightly bias projections.

V. CONCLUSION

This study introduces a climate-informed, probabilistic framework for forecasting radon exposure in northern Albania. Results emphasize:

- Precipitation as the dominant driver of future radon trends;
- A projected 28% increase in radon risk under SSP5-8.5 by 2050;
- Elevated risk in terra rossa zones, warranting targeted intervention.

Policy Recommendations:

- Integrate radon risk into regional climate adaptation strategies;
- Apply risk maps to guide zoning and construction codes;
- Support public awareness campaigns on radon health hazards.

ACKNOWLEDGMENT

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