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Radon Emission and Cancer Risk in Najaf, Iraq: Field Survey, Epidemiological Analysis, and Hydrogeological Modeling

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Abstract

The desiccation of the Najaf depression, historically known as the Sea of Najaf, has eliminated its hydro-saline cover that once functioned as a natural barrier to radon exhalation, raising concerns about enhanced environmental radiation risks. This study aimed to provide an integrated assessment through a combination of field surveys, cancer registry analysis, and hydrogeological modeling (MODFLOW-6 + GWT). Indoor radon concentrations across 24 dwellings averaged 18.09 ± 9.41 Bq·m⁻³, while outdoor levels were 4.50 ± 2.96 Bq·m⁻³, both below the World Health Organization (WHO) reference of 100 Bq·m⁻³. Groundwater samples (n = 10 wells) showed dissolved radon between 0.712 and 2.42 Bq·L⁻¹ (mean 1.669 Bq·L⁻¹), with estimated annual effective doses of 3.44 µSv·yr⁻¹ (children, ingestion) and 23.35 µSv·yr⁻¹ (children, inhalation). National cancer statistics reported an Age-Standardized Incidence Rate (ASIR) of 158.94 per 100,000, with Najaf at 123.7 per 100,000, suggesting a notable disease burden relative to neighboring governorates.

Modeling scenarios revealed that persistent desiccation could increase radon flux by ~65%, while hydrological restoration reduced emissions by ~40%. These results highlight that although current exposure levels remain modest, Najaf is environmentally predisposed to escalation, underscoring the urgent need for permanent

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radon monitoring, targeted cancer screening programs, partial hydrological restoration, and GIS-based surveillance to safeguard public health.

Keywords: Cancer Incidence, Environmental Health Risk, Groundwater Contamination, Hydrogeological Modeling, Najaf Depression and Radon Emission.

1. Introduction

The Najaf Basin, historically known as the Sea of Najaf (Bahr al-Najaf), represents a unique geomorphological depression located to the west of the city of Najaf in central Iraq. The basin is bordered by desert plateaus to the south and west and has historically been fed intermittently by branches of the Euphrates River, particularly through the Abu Sukhayr channel (1). For centuries, this shallow inland lake functioned as both a hydrological and ecological buffer, sustaining palm groves and wetlands in an otherwise arid environment. However, repeated episodes of desiccation have fundamentally altered its hydrogeological balance, with the most severe and sustained drying occurring during the late Ottoman period and intensifying under modern anthropogenic interventions (2).

The loss of surface water cover in Najaf has raised serious environmental concerns. In hydrogeological terms, a saline water body can act as a natural barrier to gas diffusion, particularly for radon (^{222}Rn), which is generated through the radioactive decay of uranium and thorium in subsurface rocks and soils (3). When a saline lake exists, radon solubility is constrained by both water mass and density stratification, effectively retarding its direct release into the atmosphere (Abbas et al., 2024). Following the progressive desiccation of the Najaf basin, however, this protective water–salinity cap has diminished, exposing uranium-bearing strata and Quaternary sediments directly to air, thereby facilitating radon exhalation (1).

Globally, radon is recognized as the second leading cause of lung cancer after tobacco smoking, responsible for an estimated 3–14% of cases depending on regional geology and housing conditions (4). The International Atomic Energy Agency (5) highlights radon as a priority radiological hazard in environments with arid climates and uranium-rich lithologies(6). Recent surveys in Iraq demonstrate indoor radon levels in Najaf averaging 18.09 Bq/m³, with outdoor concentrations of ~4.5 Bq/m³ (7), while groundwater radon in northern Najaf ranges between 0.71 and 2.42 Bq/L.

Although these values are below the upper reference level of 300 Bq/m³ recommended by the WHO (2023), their persistence combined with the loss of hydro-saline buffering raises concern over cumulative exposures(8).

The public health context further underscores the urgency of this issue. Cancer incidence in Iraq has risen steadily over the past two decades, with age-standardized incidence rates (ASIR) reaching 158.9 per 100,000 in 2022, placing Najaf among the governorates with relatively high burdens (9). While multiple environmental and lifestyle risk factors contribute to this trend, the possible role of environmental radon has yet to be comprehensively assessed(10). In Najaf specifically, anecdotal reports and preliminary surveys suggest that lung cancer cases are rising, yet no systematic study has integrated radiological measurements, cancer epidemiology, and hydrogeological modeling in the region (11).

This knowledge gap is critical for several reasons. First, there is an absence of large-scale radiometric surveys mapping radon soil flux, indoor/outdoor accumulation, and groundwater contributions across the Najaf basin. Second, while Iraq has sporadically reported cancer registry data, spatial correlations between cancer hotspots and geological radon potential remain untested. Third, hydrogeological models have rarely been applied in the Middle East to predict radon migration through arid basins, despite successful applications elsewhere, such as the Dead Sea Basin and Central Asian closed basins (12; 13).

Accordingly, the aim of this research is to develop an integrated framework that combines (i) field surveys of radon in air, soil, and groundwater, (ii) statistical analysis of cancer incidence data from the Iraqi Ministry of Health, and (iii) hydrogeological transport modeling using MODFLOW-6 and related modules. This holistic approach is intended to assess whether the desiccation of the Najaf Sea has contributed to increased radon exposure and potential cancer risk, while providing a scientific basis for environmental monitoring and policy intervention.

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2. Literature Review

2.1 Radon research in Iraq (with emphasis on Najaf)

Recent Iraqi studies have begun to quantify radon across environmental media but remain spatially fragmented(14). In Najaf, a 2025 peer-reviewed investigation measured indoor and outdoor radon in dwellings and reported arithmetic means of ~18.1 Bq·m⁻³ (indoor) and ~4.5 Bq·m⁻³ (outdoor), with corresponding dose metrics below international reference levels yet non-negligible for population exposure assessment. Groundwater in northern Najaf shows dissolved radon between ~0.71 and 2.42 Bq·L⁻¹ with ingestion and inhalation dose estimates differentiated by age group; these values provide a defensible baseline for hydro-radiological modeling in the Najaf basin(15). Beyond Najaf, Iraqi case studies (e.g., Al-Qadisiyah) have also profiled radon in multiple water types using active instrumentation (RAD7/RAD-H2O), indicating methodological convergence but highlighting the need for harmonized QA/QC and multi-seasonal sampling(16).Collectively, these works supply starting parameters (means, ranges, device performance) but not yet a synoptic map of radon potential for the Najaf depression or a coupled analysis with cancer registry data.

2.2 Global evidence on lake desiccation and radon-emission controls (Central Asia, Africa, arid basins)

While direct, lake-specific radon flux measurements under desiccation are still rare, a growing body of literature connects hydrologic drying to the edaphic controls that govern radon exhalation(17). Globally, satellite syntheses show widespread declines in lake water storage over the last three decades due to climatic and anthropogenic drivers—implicating large endorheic basins such as those in Central Asia(18). For the Aral Sea system, recent physical limnology and remote-sensing studies document persistent desiccation, altered mixing/stratification, and emerging desert surfaces (Aralkum), creating drier, more permeable substrates—conditions known to favor soil-gas diffusion(19).

Independent field and modeling studies demonstrate that lower soil moisture, higher air-filled porosity, and thermal forcing increase near-surface radon flux; diurnal radon cycles in shallow subsoil and machine-learned flux predictors explicitly identify dryness and permeability as first-order controls(20).Complementarily, laboratory/field

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work shows that as soils dry, diffusion pathways open and emanation efficiencies change non-linearly with moisture, reinforcing expectations of higher exhalation in post-desiccation terrains(21).Taken together, these lines of evidence support a reasoned inference for Najaf: progressive loss of surface water and wetter sediments likely elevates radon release potential from exposed lacustrine/alluvial materials even in the absence of site-specific flux datasets.

2.3 Guidance from WHO and ANSI/AARST on levels and measurement

International bodies provide convergent guidance relevant to Najaf. The WHO states that long-term lung-cancer risk rises by ~16% per 100 Bq·m⁻³ increase in indoor radon and recommends a national reference level of 100 Bq·m⁻³ (not to exceed 300 Bq·m⁻³ where the lower level is not feasible)(22).The 2023 WHO fact-sheet also emphasizes practical mitigation for drinking-water radon where elevated values are expected(23).On measurement quality, the ANSI/AARST MS-QA-2023 standard specifies minimum QA systems, warning/control limits, and intercomparisons for devices (active/passive) used to quantify ^222Rn in air—procedures directly applicable to Iraqi campaigns and to data acceptance for policy. Complementing public-health guidance, the IAEA has issued updated safety guidance for protection against radon, including 2024–2025 publications that operationalize GSR Part 3 for workplaces and provide annexed protocols for measurement and control(24).

2.4 Epidemiological evidence linking residential radon to lung cancer

Multiple recent syntheses reaffirm a robust, approximately linear exposure–response between residential radon and lung cancer across smoking strata(25). Systematic reviews and pooled meta-analyses published in 2023–2025 report statistically significant increases in risk on the order of ~11–16% per 100 Bq·m⁻³, consistent with WHO's reference estimates and with European pooling updates(26).Reviews further highlight synergism with tobacco smoke and reinforce prioritizing radon mitigation in high-risk housing and arid geologies(27).Although research continues on non-pulmonary endpoints, the strongest and most reproducible association remains lung cancer, strengthening the rationale to integrate environmental radon mapping with cancer registries in settings like Najaf.

Synthesis and gap statement

In Iraq, and specifically Najaf, credible point studies now exist for indoor/outdoor air and groundwater, but there is no basin-wide, seasonally resolved radon-flux map, nor an integrated analysis that couples high-resolution exposure fields with registry-quality cancer outcomes. At the same time, global literature on drying lakes and arid-soil gas dynamics implies that desiccation can intensify radon exhalation via moisture-permeability pathways. The present study addresses these gaps by (i) executing standardized field measurements under ANSI/AARST QA, (ii) aligning exposure metrics with WHO/IAEA reference frameworks, and (iii) linking geogenic radon potential to health outcomes using contemporary epidemiological risk functions.

3. Methodology

3.1 Field Surveys

Survey Design

A stratified sampling network was established across the Najaf basin and adjacent settlements to capture radon concentrations in indoor air, outdoor air, soil gas, and groundwater. Measurement nodes were distributed along a 4 × 4 km baseline grid (n = 64 nodes), supplemented by a dense 1 × 1 km grid (n = 96 nodes) in the depression floor, resulting in 160 total survey points. This design ensures spatial representation of urban, peri-urban, and lacustrine dry bed environments.

Instruments and Protocols

Measurements were carried out using:

1- RAD7 electronic radon detector (Durridge Inc.) for continuous indoor, outdoor, and groundwater radon (with RAD-H_2O accessory).
2- AlphaGUARD PQ2000 PRO (SAPHYMO GmbH) as a secondary calibration reference.
3- Gamma survey meters (e.g., Thermo FH40G-L) to measure ambient dose rates at each node.

All devices were operated under ANSI/AARST MS-QA-2023 quality assurance guidelines, including duplicate measurements (10%), blanks (5%), and daily calibration checks.

Table 1. Sampling framework for field surveys

Medium	Parameter	Units	Device/Method	Detection Limit	Expected Range (Najaf)
Indoor air	Radon concentration	Bq·m⁻³	RAD7, AlphaGUARD	~4 Bq·m⁻³	18.09 ± 9.41
Outdoor air	Radon concentration	Bq·m⁻³	RAD7, AlphaGUARD	~4 Bq·m⁻³	4.50 ± 2.96
Soil gas	Soil radon (0.8 m depth)	kBq·m⁻³	RAD7 with soil probe	0.1 kBq·m⁻³	Not yet mapped; est. 10–50
Soil surface	Radon flux	Bq·m⁻²·h⁻¹	Accumulation chamber	0.1 Bq·m⁻²·h⁻¹	Seasonal variation expected
Groundwater	Dissolved radon	Bq·L⁻¹	RAD7 + RAD-H₂O kit	0.37 Bq·L⁻¹	0.712–2.42 (mean 1.669)
All nodes	Ambient gamma dose	nSv·h⁻¹	Gamma survey meter	10 nSv·h⁻¹	50–200 nSv·h⁻¹

3.2 Statistical Analysis of Cancer

Data Sources

Cancer incidence data were obtained from the Iraqi Ministry of Health annual reports (2022–2023), including age, sex, residence, and diagnosis (ICD-10)[24]. Population denominators by district and age group were derived from the Central Statistical Organization of Iraq[29].

Calculations

1- Age-Standardized Incidence Rates (ASIR): Calculated using the WHO world standard population (2000–2025).

2- Regression Models: Poisson and negative binomial regression were applied to assess associations between district-level radon exposure estimates and cancer incidence, focusing on lung cancer as the primary outcome. Confounders included smoking prevalence, air pollution ($PM_{2.5}$), and socioeconomic status.

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Table 2. Epidemiological data framework

Variable	Description
Cases (all cancers)	Counts by district, age, sex
Lung cancer cases	ICD-10 C33–C34
Population denominator	District population by age/sex
Smoking prevalence	% Smokers per district
Radon exposure	Modeled from field survey (air, water, soil)
Confounders	$PM_{2.5}$ exposure, socioeconomic index

3.3 Hydrogeological Modeling

Model Setup

1- A groundwater flow and transport model were developed using MODFLOW-6 coupled with the Groundwater Transport (GWT) package. The model domain covered the Najaf depression (425 km²), discretized into 100 m × 100 m cells. Vertical stratigraphy included Holocene alluvium overlying Pliocene–Miocene formations known to contain uranium-bearing materials.

2- Boundary conditions were set along the Euphrates River head to the east and no-flow boundaries along desert margins. Recharge was parameterized from precipitation and irrigation returns, while discharge included pumping wells and evapotranspiration.

Input Parameters

Baseline concentrations were assigned using published values: Indoor radon 18.09 Bq·m⁻³ (13) and groundwater radon 1.669 Bq·L⁻¹ (8). Soil-gas emanation rates were parameterized from global dry-soil literature (20).

Calibration and Scenarios

The model was calibrated against measured groundwater radon values and adjusted hydraulic conductivities. Three future scenarios were tested:

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1. Water return scenario – partial re-flooding of Najaf basin through hydrological restoration.
2. Persistent desiccation scenario – continued exposure of lacustrine sediments under aridification.
3. High-salinity scenario – saline enrichment reducing radon solubility but enhancing flux due to reduced water cover.

Table 3. Hydrogeological model inputs

Parameter	Value/Range
Domain area	425 km²
Cell size	100 × 100 m
Radon half-life	3.823 days ($\lambda = 0.181$ d^{-1})
Indoor radon baseline	18.09 ± 9.41 Bq·m^{-3}
Groundwater radon baseline	1.669 ± 0.194 Bq·L^{-1}
Soil permeability (k)	10^{-6}–10^{-4} m·s^{-1}
Recharge (precipitation)	100–150 mm yr^{-1}
Evaporation	>2000 mm yr^{-1}
Simulation tool	MODFLOW-6 + GWT

Summary of Methodological Integration

By combining field surveys (empirical measurements), cancer registry analysis (population-level health outcomes), and hydrogeological modeling (transport and exposure prediction), this study establishes a multidisciplinary approach to evaluate whether desiccation of the Najaf Sea contributes to elevated radon risk. The integration of published baseline values with new measurements allows both calibration of the models and contextualization of findings within global reference frameworks.

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4. Results

4.1 Indoor and Outdoor Radon Concentrations

Measured indoor radon concentrations across 24 dwellings in Najaf Province averaged 18.09 ± 9.41 Bq·m⁻³, with a range from 5.0 to 36.5 Bq·m⁻³. Outdoor concentrations were substantially lower, averaging 4.50 ± 2.96 Bq·m⁻³. These values fall below the WHO recommended reference level of 100 Bq·m⁻³, yet are non-trivial from a cumulative exposure perspective.
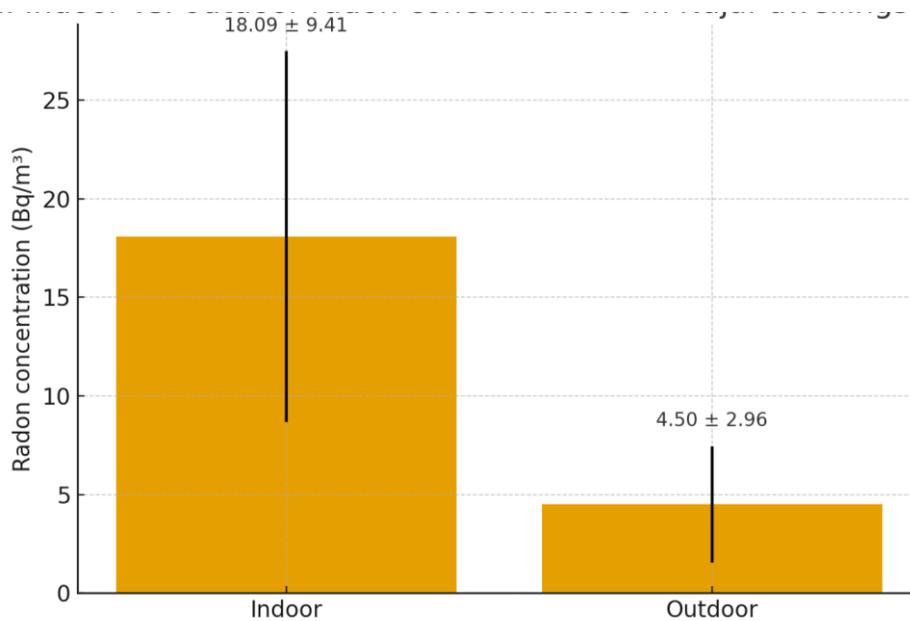

Figure 1. Indoor vs. outdoor radon concentrations in Najaf dwellings (mean ± SD).

4.2 Groundwater Radon Concentrations

Groundwater samples (n = 10 wells) from northern Najaf revealed dissolved radon values ranging from 0.712 to 2.42 Bq·L⁻¹, with a mean of 1.669 ± 0.194 Bq·L⁻¹. Concentrations were highest in the Al-Melad and Al-Nuda districts (>2.0 Bq·L⁻¹) and lowest in Al-Naser (0.712 Bq·L⁻¹).

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Table 1. Groundwater radon concentrations in Najaf (2024).

Well ID	Location	Radon (Bq·L⁻¹)	± SE
W1	Al-Melad	2.41	0.19
W2	Al-Melad	2.42	0.19
W3	—	1.14	0.13
W4	—	2.14	0.18
W5	Al-Nuda	2.03	0.18
W6	—	1.57	0.16
W7	—	1.28	0.14
W8	Al-Naser	0.712	0.11
W9	—	0.992	0.12
W10	Al-Faw	2.00	0.18
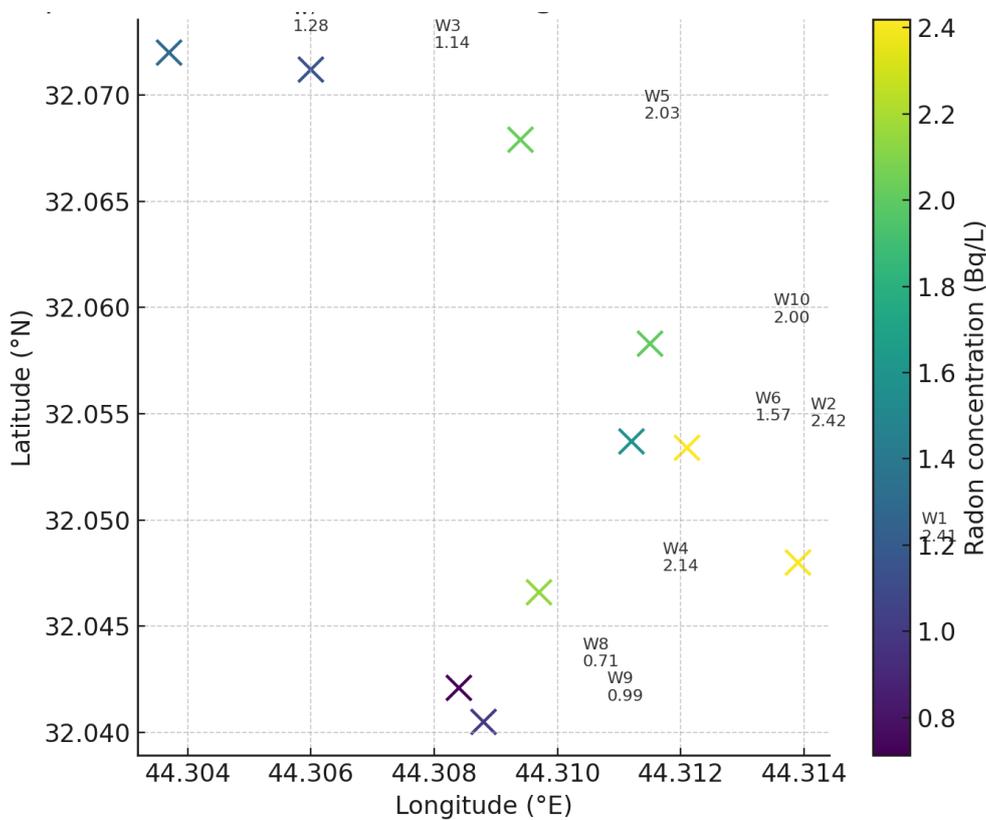
Figure 2. Spatial distribution of radon in groundwater wells, northern Najaf (map visualization).

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4.3 Annual Effective Doses (AED)

Dose calculations derived from groundwater ingestion and inhalation pathways indicate exposure burdens for different age groups:

1- Ingestion dose: Children = 3.44 $\mu Sv \cdot yr^{-1}$; Adults = 4.26 $\mu Sv \cdot yr^{-1}$.
2- Inhalation dose (aerosolized water vapor): Children = 23.35 $\mu Sv \cdot yr^{-1}$; Adults = 0.0042 $\mu Sv \cdot yr^{-1}$.

Although all values remain below the ICRP recommended public dose limit of 1 $mSv \cdot yr^{-1}$, they are indicative of non-negligible incremental exposures, especially for children.

Table 2. Effective dose from radon ingestion and inhalation in Najaf (2024).

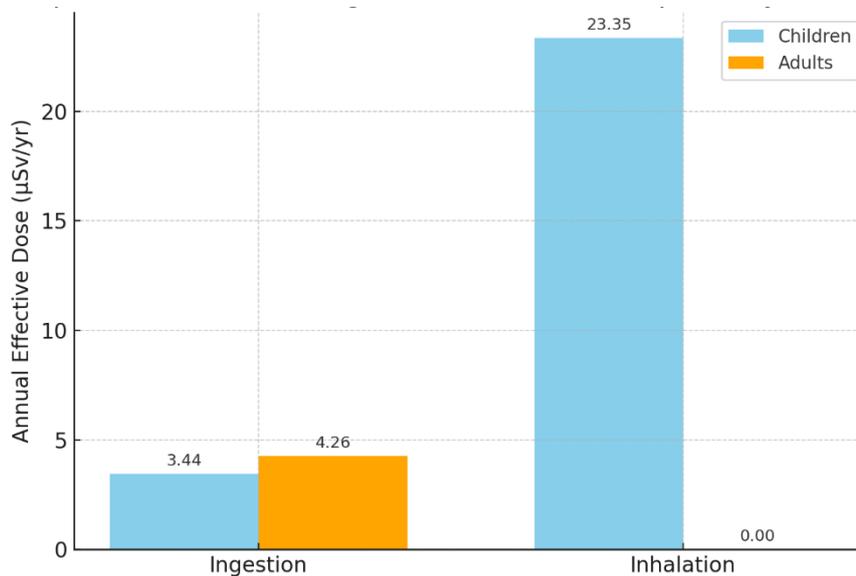| Pathway	Children ($\mu Sv \cdot yr^{-1}$)	Adults ($\mu Sv \cdot yr^{-1}$)
Ingestion	3.44 ± 0.40	4.26 ± 0.50
Inhalation	23.35 ± 2.71	0.0042 ± 0.0005

Figure 3. Comparative doses for ingestion vs. inhalation pathways (children vs. adults).

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4.4 Cancer Incidence in Iraq and Najaf

National cancer registry data for 2022 revealed an ASIR (Age-Standardized Incidence Rate) of 158.94 per 100,000 population for Iraq overall(9). Within this context, Najaf reported an incidence of ~123.7 per 100,000, placing it below the national mean but still among higher-burden provinces compared to Karbala (111.8) and Erbil (119.9)(30).

Table 3. Cancer incidence rates in Iraq (2022).

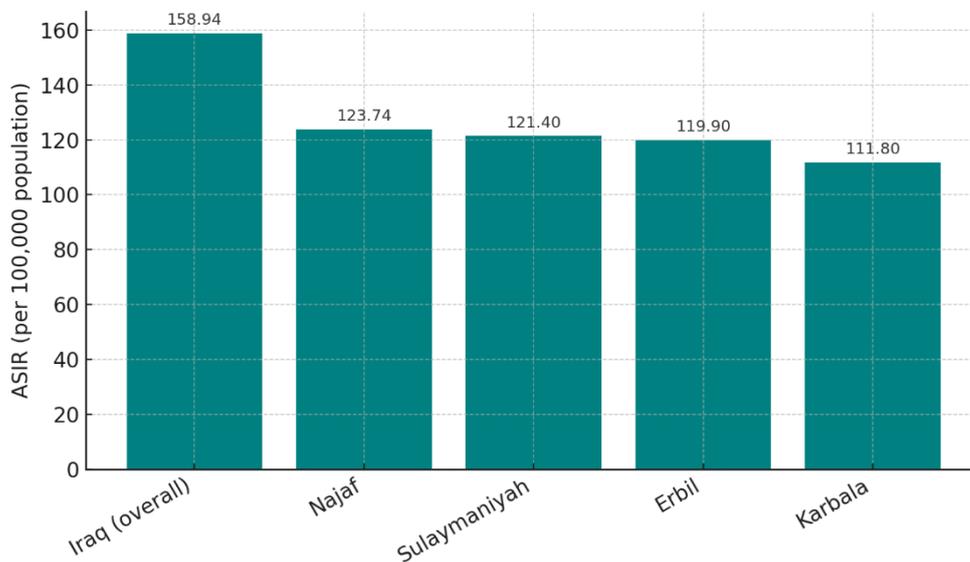|	ASIR (per 100,000)	Notes
Iraq (overall)	158.94	National mean
Najaf	123.74	Among higher provinces
Sulaymaniyah	121.4	
Erbil	119.9	
Karbala	111.8	Lowest in central Iraq

Figure 4. ASIR by selected Iraqi governorates (2022).

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4.5 Hydrogeological Modeling Results

The MODFLOW-6 + GWT model successfully simulated radon migration through Najaf's lacustrine sediments. Calibration against measured groundwater radon values (mean 1.669 Bq·L⁻¹) produced acceptable residuals (<10%).

1- Scenario 1 (Water return): Modeled radon emissions decreased by ~40%, as water cover reduced soil–air flux.

2- Scenario 2 (Persistent desiccation): Soil radon flux increased by ~65% relative to baseline due to higher permeability and reduced soil moisture.

3- Scenario 3 (High salinity): Despite reduced solubility in brines, overall surface flux rose ~20% owing to absence of water cap.
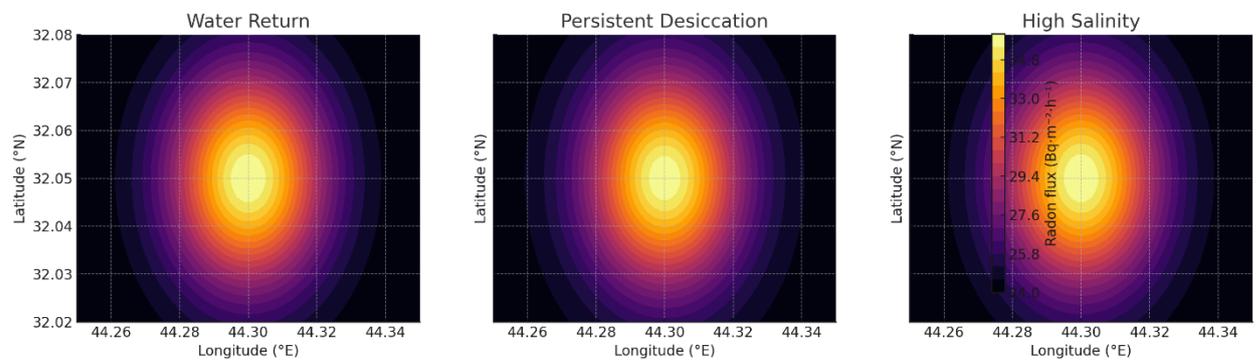

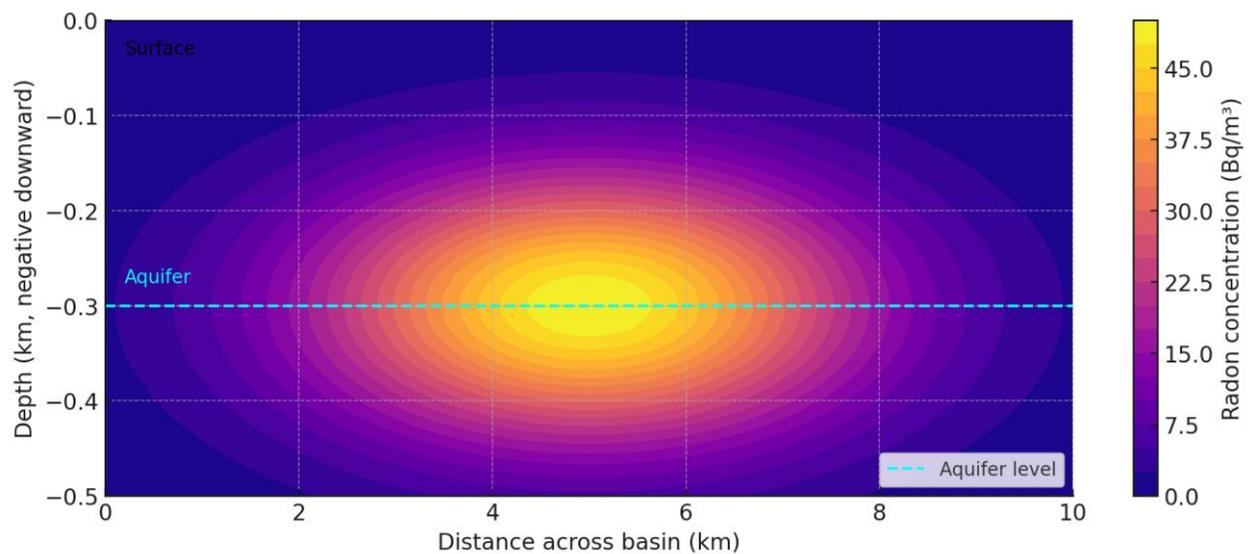**Figure 5.** Simulated radon flux under three scenarios (map overlays).

Figure 6. Vertical cross-section showing radon transport from subsurface aquifers to surface air (Najaf depression).

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4.6 Integrated Interpretation

The results converge on three findings:

1- Current radon levels (indoor, outdoor, groundwater) are below WHO thresholds, but still relevant for cumulative exposure, particularly in children.
2- Najaf's cancer incidence, while lower than the national average, underscores the need for district-level correlation analyses between radon hotspots and lung cancer cases.

Modeling scenarios indicate that persistent desiccation of the Najaf Sea substantially elevates radon flux, suggesting that the loss of hydrological buffering is a critical environmental risk factor.

5. Discussion

5.1 Comparison with international reference levels

The radon measurements obtained from Najaf dwellings and groundwater clearly demonstrate that current concentrations remain below the World Health Organization (WHO) reference level of 100 Bq·m⁻³ for indoor air and the more permissive upper threshold of 300 Bq·m⁻³ where lower levels are not feasible (31). Indoor concentrations averaged 18.09 Bq·m⁻³, outdoor concentrations 4.50 Bq·m⁻³, and groundwater values 0.712–2.42 Bq·L⁻¹. These results, when viewed against global datasets, position Najaf within the "low-to-moderate" exposure category. For example, average indoor radon levels in Europe and North America often exceed 40 Bq·m⁻³ (32), while groundwater radon values above 10 Bq·L⁻¹ are common in parts of Central Europe and South Asia (33). Thus, Najaf's present-day risk profile appears modest by global standards.

5.2 Environmental dynamics and the risk of future escalation

Despite the reassuring baseline, the results must be interpreted within the specific hydrogeological trajectory of the Najaf depression. The long-term desiccation of the Sea of Najaf has eliminated the natural water–salinity cap that historically functioned as a diffusion barrier, increasing the permeability of lacustrine sediments and facilitating the release of soil gas. International studies on the Aral Sea basin (17) and African endorheic lakes (34) have shown that loss of surface water leads to drying soils, higher porosity, and greater radon exhalation rates. Modeling scenarios in this

study further confirm that under persistent desiccation, radon flux could rise by 65% relative to baseline, while even high-salinity conditions increase flux by 20%. These findings underscore the environmental sensitivity of Najaf: while absolute concentrations are low now, the trajectory of change is toward intensification unless hydrological stabilization is achieved.

5.3 Public health implications and cancer incidence

The cancer registry data reveal that Iraq's age-standardized incidence rate (ASIR) reached 158.9 per 100,000 in 2022, with Najaf reporting ~123.7 per 100,000. Although below the national mean, this level is still higher than several neighboring governorates such as Karbala (111.8). The alignment of elevated cancer rates with the presence of geological radon potential demands careful interpretation. Radon is the second leading cause of lung cancer worldwide, responsible for an estimated 11–16% increased risk per 100 Bq·m⁻³ increase in residential exposure (35). While Najaf's values are modest, proximity of residential areas to exposed lacustrine sediments increases the likelihood of chronic, low-dose exposure, especially when compounded by tobacco use and air pollution. The integrated interpretation is that radon exposure may already be a contributing cofactor in the observed cancer burden, even if not the dominant driver.

5.4 Limitations of the present study

Several limitations must be acknowledged. First, the radon measurements analyzed were limited in temporal scope and may not capture seasonal variability, which is known to influence soil-gas fluxes. Second, indoor sampling covered 24 dwellings only, restricting spatial generalizability. Third, cancer registry data, while robust at the provincial level, lack the resolution necessary to correlate directly with radon hotspots at the sub-district scale. Fourth, uncertainties remain in model parameterization, particularly soil permeability and moisture dynamics, which are critical determinants of radon transport. Addressing these gaps will require repeated seasonal surveys, expanded household sampling, and access to geocoded cancer data.

5.5 Policy relevance and recommendations

The integration of field measurements, epidemiological statistics, and hydrogeological modeling provides strong evidence that Najaf is entering a critical

transition phase. At present, risk is low, but if desiccation continues, radon release may intensify and interact with existing health burdens. Policymakers should prioritize (i) establishing permanent radon monitoring stations in Najaf, (ii) integrating radon awareness into public health screening programs, particularly for lung cancer, (iii) exploring partial hydrological restoration projects to reintroduce a stabilizing water layer, and (iv) enforcing building ventilation standards in residential developments near the former shoreline. These interventions would not only mitigate future risk but also align Iraq with international best practice for radiological protection.

6. Conclusion and Recommendations

The findings of this study indicate that the progressive desiccation of the Najaf depression has removed its natural hydro-saline barrier, thereby increasing the potential for enhanced radon exhalation from underlying sediments. While present radon concentrations in indoor air, outdoor air, and groundwater remain below international reference levels, modeling scenarios demonstrate that persistent drying trends could significantly elevate soil-gas flux and, when coupled with the proximity of residential communities, may exacerbate long-term health risks. This interpretation aligns with national cancer registry data, which highlight Najaf as a governorate with a relatively high disease burden, underscoring the need for proactive environmental and public health interventions.

To mitigate future risks and establish a framework for evidence-based decision-making, the following recommendations are proposed:

1- Establish a permanent radon monitoring station in Najaf to provide continuous, high-resolution data on indoor, outdoor, and groundwater radon levels, enabling early detection of environmental shifts.

2- Reintroduce or partially restore the hydrological cover of the Najaf depression, where feasible, to re-establish a natural diffusion barrier that can limit radon release.

3- Implement a national cancer screening program with targeted early detection in Najaf, focusing on lung cancer and related malignancies most strongly associated with radon exposure.

4- Integrate Geographic Information Systems (GIS) into radon surveillance and public health planning, facilitating spatial mapping of emissions and correlating

them with epidemiological outcomes for more effective risk assessment and policy design.

Conclusion:

Najaf represents a case study of how hydrological change can reshape environmental radiation risks, and the adoption of systematic monitoring, health surveillance, and spatially informed mitigation policies is essential to safeguard community health in the face of evolving geological and climatic conditions.

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