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ASSESSING HOUSEHOLD GROUNDWATER CONTAMINATION RISK IN RURAL ROMANIA: A SEMI-QUANTITATIVE REGIONAL MODEL

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Abstract

This paper aims to evaluate groundwater contamination risks affecting household water supplies in rural Romania, where access to centralized infrastructure remains limited. A semi-quantitative risk assessment model was developed and applied to five representative counties—Bihor, Teleorman, Iași, Constanța, and Dolj—based on three dimensions: population exposure, likelihood of contamination, and severity of health impact. Data were collected from national statistics, environmental monitoring institutions, and international health guidelines. Risk scores revealed that Bihor and Teleorman counties face the highest vulnerability due to multiple contaminants (e.g., nitrates, arsenic, coliforms) and widespread reliance on untreated water. The exposed population across these counties is estimated to exceed 670,000 individuals. The study emphasizes the need for improved rural water infrastructure, regular well testing, and targeted policy interventions in agricultural areas. The model provides a useful tool for prioritizing regional investments and supporting water safety strategies under national and EU rural development frameworks.

Key words: *groundwater risk, rural water supply, contamination, Romania, health impact*

INTRODUCTION

Groundwater remains a vital source of drinking water for nearly half of the global population, with reliance especially high in rural and peri-urban areas [12, 33]. This largely invisible resource plays a critical role not only in ensuring household water security, but also in supporting agricultural productivity, maintaining ecosystem stability, and enhancing climate resilience. However, growing pressures from overextraction, contamination, and climate change are threatening its sustainability.

In many regions, aquifers are being depleted faster than they can naturally recharge. This results in falling water tables, land subsidence, reduced water availability, and long-term threats to socio-economic stability [31, 32]. Excessive groundwater exploitation is especially evident in arid and semi-arid regions, where the expansion of intensive agricultural systems and insufficient oversight of irrigation activities contribute significantly to aquifer depletion [7, 26]. At the same time, the overall quality of groundwater resources is declining worldwide. The excessive application of nitrogen-based fertilizers has led to widespread nitrate pollution, while industrial activities continue to introduce heavy metals, solvents, and synthetic chemicals into aquifers[12, 20]. Additionally, emerging contaminants such as pharmaceuticals, endocrine-disrupting compounds, and per- and polyfluoroalkyl substances (PFAS) have been detected across continents - often at concentrations exceeding health thresholds and resistant to conventional treatment technologies [11, 22].

Microbial contamination poses another significant, yet often under-monitored, threat. Pathogens such as *Escherichia coli*, *Salmonella*, and *Cryptosporidium*can enter groundwater through agricultural runoff, malfunctioning septic systems, or inadequately constructed wells. In low- and middle-income countries, over 60% of household water sources - including both protected and unprotected wells - have been found to contain *E. coli* contamination[3, 36]. Borchardt et al. (2021) [4] reported that private wells located near agricultural areas in the United States exhibited a markedly increased risk of microbial contamination, particularly in regions with elevated nitrate concentrations. Similarly, the U.S. Environmental Protection

Agency (2024) [28] highlighted increased risks of groundwater contamination during flooding events, especially in communities where concerns about water quality had already been raised.Compounding the issue, antimicrobial-resistant (AMR) bacteria are increasingly being detected in private groundwater supplies, posing an emerging public health concern [1, 10]. Despite advancements in sensor technologies and digital monitoring platforms, surveillance remains inconsistent - especially in regions with limited institutional capacity or funding [16].

In Romania, many of these global groundwater threats are not only present but often more severe. Approximately seven million people (predominantly in rural areas) depend on private groundwater sources, most commonly shallow and unregulated wells that are particularly vulnerable to chemical and microbial contamination[19]. In Eastern Romania, the Moldavian Plateau faces groundwater stress driven by intensive agricultural extraction and prolonged droughts[14]. In the northwest, groundwater used for domestic purposes has been found to contain elevated levels of arsenic, iron, and manganese, raising serious quality concerns [5, 25]. In the Romanian Plain, including the Târgoviște area, long-term nitrate pollution from fertilizer and livestock operations has been extensively documented, threatening the integrity of local aquifers [13]. Similar patterns of contamination have been documented in Romanian industrial and agricultural contexts, including petroleum hydrocarbons in Caras-Severin County [15] and nitrate leaching in horticultural areas of Constanța [9].

Microbial risks in Romania are equally alarming. Recent studies of karst springs revealed that over 80% of samples exceeded WHO microbial quality standards, with fecal contamination linked to shallow infiltration and surface-level human activities [27]. Rural well surveys conducted in the northeast have reported both microbiological and chemical exceedances, reflecting poor construction practices and minimal regulatory oversight [3]. Seasonal variability and flooding events further exacerbate contamination risks, particularly in vulnerable communities with limited access to water treatment technologies [2].

Given these intersecting challenges, there is an urgent need to strengthen groundwater protection through improved monitoring systems, robust regulatory frameworks, and context-specific risk management strategies. This paper aims to examine global groundwater quality challenges with a focus on household water supplies and associated health risks. It further analyzes the Romanian context through recent scientific studies, legislative instruments, and regional case studies. The goal is to provide evidence-based recommendations and promote community-scale, resilient solutions for sustainable groundwater use.

MATERIALS AND METHODS

Study Area and Scope

This study focuses on groundwater quality risks affecting household water supplies in Romania, particularly in rural areas where centralized water infrastructure is limited or absent. Five counties - Teleorman, Bihor, Iași, Constanța, and Dolj - were selected for regional analysis. These counties represent diverse geographical, hydrological, and land-use profiles and are known for documented groundwater quality concerns[17, 18, 24].

The objective is to assess the degree of exposure to groundwater contamination in these regions and to evaluate the potential public health risks associated with decentralized water sources, such as private wells and boreholes. The analysis integrates both global trends and national case studies, supported by a semi-quantitative risk assessment framework [30, 34].

Data Sources, Databases, and Search Strategy

To ensure a comprehensive and multidisciplinary foundation for the groundwater risk assessment, this study employed a structured search strategy incorporating both international and national data sources. The approach combined peer-reviewed scientific literature, institutional datasets, and regulatory frameworks to inform risk scoring parameters and regional

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comparisons. Fig.1 summarizes the data architecture and search process, highlighting the convergence of academic, legal, and environmental inputs that underpin the methodological framework.

Fig.1. Data sources and search strategy for groundwater risk assessment
Source:Authors' drawing based on institutional and scientific data review (WHO, US EPA, INS, ANPM) [34,35, 28, 18, 18].

Risk Assessment Framework

In rural Romania, this study utilized a semi-quantitative risk assessment approach to examine groundwater safety and potential public health risks, based on frameworks developed by the World Health Organization [34, 35] and the U.S. Environmental Protection Agency [30], which are commonly applied in global risk evaluations. The overall Risk Score is calculated as the product of three components: population exposure, contamination likelihood, and severity of health impact. Each component is scored between 0 and 1.

Risk Score = P(Exposure)×P(Contamination)×S(Severity)
where:

- P(Exposure) represents the proportion of the rural population relying on untreated groundwater;
- P(Contamination) estimates the likelihood of contamination, based on documented pollutant exceedances;
- S(Severity) reflects the health impact of the contaminants.

Each model component was defined and scored as follows:

- P(Exposure)

Population exposure was derived using the formula:

$$P(\text{Exposure}) = 1 - \frac{\text{Access to Piped Water } (\%)}{100}$$

Where necessary, values were adjusted to reflect water systems lacking treatment infrastructure.

- P(Contamination) – Likelihood of Contamination

This reflects the probability that groundwater is contaminated with one or more harmful substances. Contamination probability was assessed based on monitoring data from the National Environmental Protection Agency (ANPM), County Public Health Directorates (DSPs), and recent scientific literature (*sources in Romanian*).The scoring criteria used to assign contamination likelihood are detailed in Table 1.

Table 1. Contamination Probability Scoring System

Score	**Risk Level**	**Description**
0.2	Low	Rare exceedances; good overall water quality
0.4	Moderate	Occasional exceedances of a single pollutant
0.6	High	Frequent exceedances; presence of one or more contaminants
0.8	Very High	Persistent exceedances; multiple pollutants frequently detected

Source: Authors' scoring scheme based on national monitoring data and WHO/US EPA guidance [34, 35, 28].

- S(Severity) – Health Impact Severity

This component reflects the health consequences of contaminants detected in groundwater. Scoring was informed by the WHO Guidelines for Drinking Water Quality (2022) [35], the EU Drinking Water Directive 2020/2184 [37], and national legislation [38]. The health impact scoring system and examples of associated contaminants are presented in Table 2.

The severity score in each county was derived from specific contaminants detected or reported in institutional monitoring data. The structure and scoring logic are illustrated in Fig. 2, which highlights how the model integrates population exposure, contamination probability, and health impact severity into a single composite risk index.

Table 2. Health Impact Severity Scoring

Score	Severity Level	Examples
0.3	Low	Iron, manganese (aesthetic, low health concern)
0.5	Moderate	Nitrates < 50 mg/L, chlorides (chronic, reversible effects)
0.7	High (vulnerable groups)	Nitrates > 50 mg/L, coliforms (risk to infants, immunocompromised)
0.9	Severe	Arsenic, pesticides, Cryptosporidium (carcinogenic/infectious)

Source: Authors' adaptation using WHO (2022), EU Directive 2020/2184, and Romanian legislation [35, 37].

To support the severity scoring and classification process, a set of priority groundwater contaminants was selected based on their occurrence in national monitoring data and their associated health effects. Table3. summarizes the key contaminants considered in the model, along with their primary sources, health impacts, legal thresholds, and the corresponding regulatory frameworks.

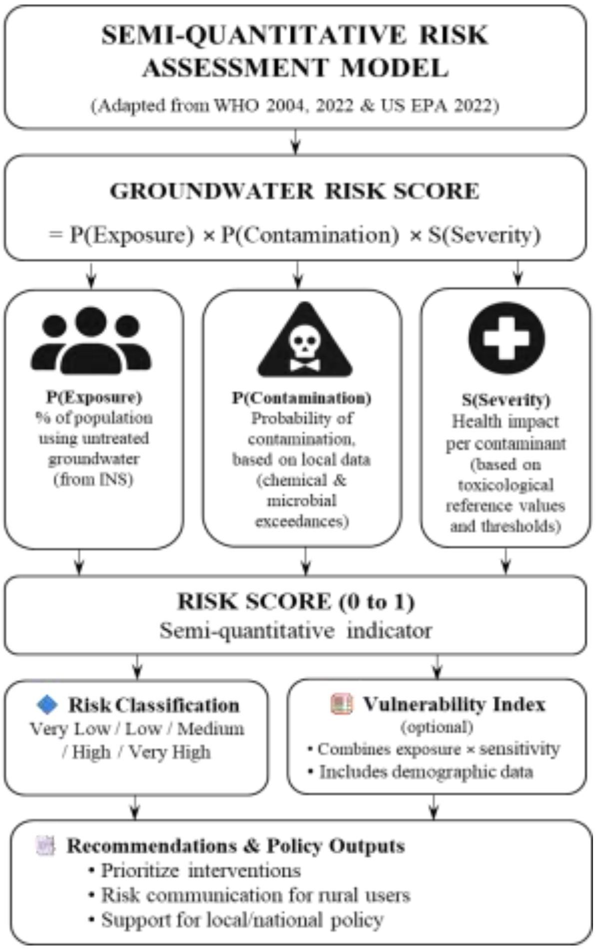

Fig.2. Conceptual structure of the semi-quantitative groundwater risk assessment model
Source: Authors' elaboration adapted from WHO (2004, 2022) and US EPA

Table 3. Key Groundwater Contaminants, Health Impacts, Legal Thresholds, and Regulatory Frameworks

Contaminant	Primary Source	Health Impact	Limit Value	Regulatory Reference
Nitrates (NO_3^-)	Agricultural fertilizers, livestock runoff	Blue baby syndrome (methemoglobinemia), chronic effects	50 mg/L	EU Nitrates Directive 91/676/EEC; WHO (2022)
Coliform Bacteria	Fecal contamination (latrines, septic tanks)	Diarrhea, gastrointestinal infections	0 CFU/100 mL	EU Drinking Water Directive 2020/2184; WHO (2022)
Arsenic (As)	Geogenic (natural bedrock), mining areas	Carcinogenic (skin, lung, bladder cancers)	10 µg/L	WHO (2022); EU Groundwater Directive 2006/118/EC
Ammonium (NH_4^+)	Organic waste, sewage infiltration	Indicator of organic pollution, indirect toxicity	0.5 mg/L	Romanian Law 458/2002; EU Drinking Water Directive
Pesticide Residues	Agricultural runoff, horticulture	Endocrine disruption, chronic toxicity	0.1 µg/L (per substance)	EU Drinking Water Directive 2020/2184
Iron (Fe)	Geogenic, corroded pipes	Aesthetic issues, discoloration, taste	0.2 mg/L	Romanian GO no. 7/2023 (for acceptability)
Manganese (Mn)	Geogenic, old plumbing	Neurological effects at high doses	0.05 mg/L	WHO (2022); Romanian Law 458/2002

Source: Authors' compilation from EU, WHO, and Romanian legal documents [37, 34, 35].

Exposure Estimation

To estimate the number of individuals at risk from contaminated groundwater, the model uses demographic data and piped water access statistics. The exposure indicator, P(Exposure), represents the share of the rural population relying on decentralized or untreated sources, such as shallow wells and boreholes.

The formula applied is:

$$P(\text{Exposure}) = \begin{matrix}\text{Rural}\\ \text{Population}\end{matrix} \times \left(1 - \frac{\begin{matrix}\text{Access to}\\ \text{Piped Water}\end{matrix}\ (\%)}{100}\right)$$

where:

- Access to piped water (%) is taken from county-level infrastructure data published by the National Institute of Statistics[19].
- Adjustments were made in select cases where piped networks exist but are not equipped with functional water treatment (e.g., lack of disinfection or filtration), based on expert judgment and field reports.

Additionally, the model estimates the absolute number of exposed individuals using the following equation:

$$\begin{matrix}\text{Exposed}\\ \text{Population}\end{matrix} = \begin{matrix}\text{Rural}\\ \text{Population}\end{matrix} \times P(\text{Exposure})$$

This allowed the model to identify regions with both high proportional and high absolute vulnerability, which is crucial for prioritizing public health interventions and infrastructure planning.

For example, while Constanța County had a lower exposure percentage (40%), its total exposed population remained significant due to residual contamination and lack of routine well testing. By contrast, Teleorman County had a near-total reliance on private wells (P = 1.0), contributing heavily to its final risk score.

RESULTS AND DISCUSSIONS

The risk assessment model was applied to five counties in Romania—Bihor, Teleorman, Iași, Constanța, and Dolj—using a composite score derived from population exposure, contamination likelihood, and health impact severity.

The highest risk was recorded in Bihor County, primarily due to the presence of arsenic, nitrates, and coliform bacteria. Arsenic levels in certain areas of Bihor have exceeded WHO limits (10 µg/L), while microbial contamination has been associated with shallow wells and inadequate sanitation infrastructure.

In Teleorman, although fewer types of contaminants were documented, the county exhibits a very high population exposure rate (100%) and widespread nitrate pollution, largely attributed to intensive agricultural practices and livestock farming. Coliform bacteria have also been detected in rural wells.

Dolj and Iași counties show moderate to high contamination likelihood due to persistent nitrate and microbial pollution, particularly in unregulated groundwater sources. In both counties, nitrate concentrations often approach or exceed the 50 mg/L threshold, especially in areas with high fertilizer usage.

Constanța County, though relatively better served by piped water infrastructure, presents regional nitrate contamination in areas with sandy soils and shallow aquifers, along with occasional pesticide residues from horticultural activities.

Each county was evaluated using the composite risk formula based on the three core dimensions. The risk classifications are aligned with thresholds defined in the Integrated Risk Evaluation Matrix (Table 5). While none of the counties exceeded the Critical Risk threshold (> 0.8), Bihor reached the High-Risk range due to the co-occurrence of chemical and microbial pollutants. The other counties displayed Moderate Risk scores, warranting targeted actions related to infrastructure upgrades, enhanced monitoring, and public health planning.

The results of the risk assessment are presented in Table 4, which summarizes the calculated scores and primary contaminants in each county. To support interpretation, Table 5 presents the Integrated Risk Evaluation Matrix used to classify overall groundwater safety levels based on the combined scoring dimensions.

Table 4. Groundwater Risk Scores and Contaminants by County

County	P(Exposure)	P(Contamination)	S(Severity)	Risk Score	Risk Classification	Main Contaminants
Bihor	0.70	0.80	0.90	0.504	High	Arsenic, nitrates, coliforms
Teleorman	1.00	0.60	0.70	0.420	Moderate	Nitrates, coliforms
Dolj	0.65	0.70	0.80	0.364	Moderate	Nitrates, coliforms
Iași	0.60	0.70	0.80	0.336	Moderate	Nitrates, coliforms, ammonium (localized)
Constanța	0.50	0.60	0.70	0.210	Moderate	Nitrates, pesticides, occasional coliforms

Source: Own calculation based on risk model and regional environmental data.

Table 5. Integrated Risk Evaluation Matrix for Groundwater Contamination**

Health Impact Severity → Contamination Probability ↓	High (0.8)	Medium (0.6)	Low (0.4)	Very Low (0.2)
Severe (e.g. arsenic, pesticides)	High–Critical (0.5–0.9)	Moderate–High (0.4–0.6)	Moderate (0.3–0.4)	Low (0.2)
Moderate (e.g. nitrates > 50 mg/L)	Moderate–High (0.4–0.6)	Moderate (0.3–0.5)	Low–Moderate (0.2–0.4)	Low (0.2)
Low (e.g. iron, manganese)	Low–Moderate (0.2–0.4)	Low (0.2–0.3)	Very Low (≤ 0.2)	Very Low (≤ 0.2)

Legend:
High–Critical Risk: Score > 0.5
Moderate Risk: 0.2 – 0.5
Low Risk: 0.2 – 0.3
Very Low Risk: ≤ 0.2
*Note: Risk score calculated using the formula: Risk Score = P(Exposure) × P(Contamination) × S(Severity)
Thresholds adapted from WHO (2004) and US EPA (2012) guidance.
Source:Authors' matrix adapted from WHO (2004) and US EPA (2012) classification systems [34, 28].

Estimation of Rural Exposure to Contaminated Groundwater

To estimate the rural population potentially exposed to untreated or contaminated groundwater, the analysis used national infrastructure data published by the National Institute of Statistics [19].

Exposure levels were calculated by assessing the share of rural residents lacking access to piped water systems in each county.

Fig.3 shows the exposure distribution across the five counties included in the assessment. While Iași and Dolj have the highest number of exposed individuals, all counties show substantial reliance on untreated water sources. This emphasizes the need for targeted health and infrastructure interventions in rural areas.

The results underscore not only spatial inequalities in access to safe water, but also the urgency of incorporating groundwater safety into rural development and public health strategies.

Although classified with moderate risk scores, counties such as Dolj and Iași stand out due to their large rural populations combined with limited water infrastructure—factors that significantly increase the absolute number of households vulnerable to groundwater contamination.

Even in Constanța, where access to piped water is relatively higher, a substantial portion of the rural population remains potentially exposed to nitrates, pesticide residues, and microbial contaminants.

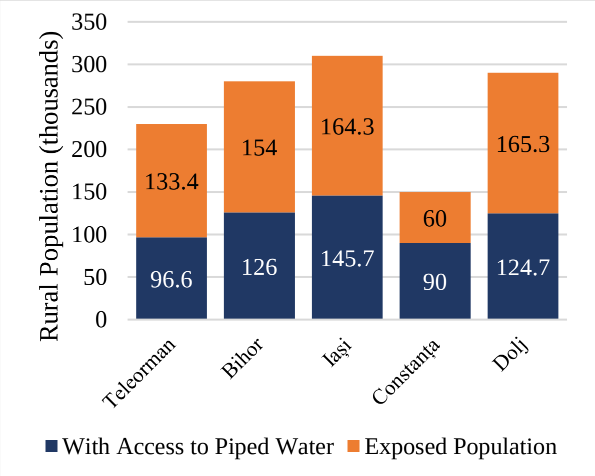

Fig.3. Rural Population Access to Safe Drinking Water in Selected Romanian Counties
Source: Own calculation based on National Institute of Statistics (INSSE), 2022 [19].

Comparative Insights: Romania vs. Western EU Approaches

In contrast to Western EU countries such as the Netherlands, where nearly the entire population is connected to centralized and monitored water supply systems (coverage >99.9%), Romania's rural regions rely heavily on private wells, which are largely unregulated and untested [19, 35].

This disparity is further illustrated in Table 6, which provides an international comparison of groundwater access and safety, highlighting significant differences between countries in terms of infrastructure, regulation, and water quality monitoring.

Table 6. International Comparison of Groundwater Access and Safety

Category	Netherlands	Romania (rural)
Population using private wells	<1%	~70%
Annual testing of private wells	Not applicable	Not mandatory
Access to centralized water	>99.9%	42%
Cost of UV treatment (EUR)	Not required	€100–250 (+ maintenance)
Availability of public subsidies	Yes (via public utilities)	Rare or absent

Source: Authors' comparison using INSSE data, EEA reports, and national policy sources [19].

The lack of legal obligation to test private wells, combined with limited public funding for household treatment systems, places a financial and health burden on vulnerable rural families. By comparison, France and Germany offer subsidies or public investment programs for rural water safety improvements - something Romania currently lacks. While environmental due diligence and risk-based assessments are becoming more common in Western contexts, similar structured assessments are still limited in Romanian practice despite a few emerging examples [9, 15].

Structural Drivers of Rural Vulnerability: Disparities in Access to Safe Water Infrastructure

A major contributor to groundwater-related health risks in Romania is the ongoing gap in safe water access between urban and rural areas. Urban populations are largely served by centralized, treated networks, while many rural communities still rely on unregulated and often untested groundwater sources like shallow wells and boreholes. Data from the National Institute of Statistics [19] indicate that in 2022, more than 98.7% of the urban population had access to piped water, whereas only 42% of the rural population benefited from such access.

This disparity is depicted in Fig. 4, which presents the progression of water infrastructure coverage between 2010 and 2022, highlighting the persistently limited improvement in rural areas despite sustained high levels of urban access.

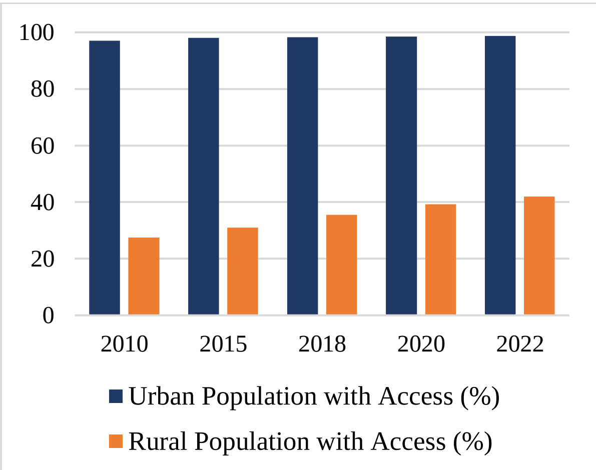

Fig.4.Trends in Access to Piped Water in Urban and Rural Areas of Romania (2010–2022)
Source: Own representation based on Tempo Online Database (INS), 2010–2022 [19].

The widening infrastructure gap continues to exacerbate public health risks, particularly in agricultural regions where nitrate and microbial contamination from fertilizers and livestock waste are common.

Despite gradual improvements over the past decade, rural areas remain substantially underserved. In the absence of regular water testing or treatment mechanisms, households depending on private wells face significantly elevated exposure to microbial and chemical contaminants. This reality reinforces the importance of infrastructure as both a public health determinant and a strategic investment area under national and EU rural development priorities.

Policy Relevance and Strategic Recommendations

The findings of this study underscore the urgent need for targeted policy interventions in rural groundwater governance. Several persistent gaps were identified: inadequate rural water infrastructure coverage [8], lack of legal mandates for testing private wells[38], fragmented environmental–health coordination [23], and low public awareness of nitrate, microbial, and arsenic risks [29, 35].To address these challenges, the following strategic actions are proposed: expanding groundwater monitoring to include private wells [6], introducing mandatory testing protocols supported by subsidies [30], launching educational campaigns [21], and aligning water safety strategies with EU funding mechanisms such as the CAP and Cohesion Policy.

Groundwater contamination risks in rural Romania are further amplified by climate-related stressors, including prolonged droughts, erratic precipitation, and local flooding. These conditions alter aquifer recharge patterns and promote surface contamination through shallow wells. For instance, microbial contamination may surge after heavy rainfall or septic overflow events [29]. In nitrate-vulnerable regions, drought-driven irrigation also accelerates fertilizer leaching into groundwater.

These climate-linked processes function as risk multipliers in areas with limited infrastructure and intensive agriculture. The findings align with recent EU water policy initiatives, including the 2023 revision of the Groundwater Directive and the launch of the Water Resilience Initiative under the European Green Deal. In Romania, the National Recovery and Resilience Plan (PNRR) includes targeted investments for environmental health and rural infrastructure.

Limitations and Future Research Directions

While the applied risk assessment model offers a practical framework for estimating regional groundwater safety, several limitations should be acknowledged. The model relies on aggregated datasets and proxy indicators (e.g., piped water access, reported contamination frequency) rather than high-resolution or real-time monitoring data.

In many rural areas, private wells remain untested, and microbial contamination events (e.g., *Escherichia coli*, *Cryptosporidium*) are likely underreported—especially following extreme weather, which can cause contamination spikes [29]. Moreover, the scoring thresholds for contamination likelihood and severity are based on WHO (2022), EU Directive 2020/2184, and national standards (Gov. Ordinance No. 7/2023), which may overlook local and seasonal variations - such as fluctuating nitrate levels in sandy or clay aquifers. Still, the model offers a conservative and useful tool for identifying at-risk populations and supporting public health actions.

Future research should explore the use of longitudinal data, the integration of sensor-based monitoring, and the engagement of citizen-science networks (European Commission, 2024).These enhancements could improve spatial accuracy and validate exposure estimates across different hydrogeological and land use contexts.

CONCLUSIONS

This study assessed groundwater quality risks affecting household water supplies in five rural counties of Romania using a semi-quantitative risk model incorporating exposure, contamination likelihood, and severity of health impact. The findings reveal that over 670,000 rural residents in the selected counties may be exposed to untreated or contaminated groundwater, with Bihor County registering the highest composite risk due to arsenic, nitrate, and microbial pollutants.

Despite moderate contamination scores in other counties, the combination of high exposure rates and inadequate infrastructure places significant health burdens on populations in Teleorman, Dolj, Iași, and Constanța. The results highlight not only the uneven spatial distribution of risks but also the structural drivers—such as limited monitoring, unregulated private wells, and low testing frequency—that contribute to groundwater vulnerability in rural settings.

Comparative analysis with Western EU countries highlights Romania's gaps in regulation, household water treatment, and financial support. Climate-related challenges like droughts and floods further increase contamination risks. The study recommends expanding rural monitoring, mandating well testing, promoting water safety education, and aligning with EU policies such as the CAP and Water Resilience Initiative. Despite data gaps, the model serves as a practical tool for targeting interventions and supporting progress toward the EU Water Framework Directive and SDGs.

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