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FULL PAPER

Assessment of Radioactive Contamination in Groundwater sources: A Comprehensive Study on Sources, Transport mechanisms, and Remediation Strategy

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Abstract:

This study employs qualitative methodology, utilizing both secondary and primary data collection techniques to investigate radioactive contamination in Saudi Arabia's groundwater sources. Secondary data, encompassing academic studies, government reports, and international databases, provide a comprehensive understanding of existing contamination levels and trends in the Kingdom. Moreover primary data from field surveys across the country enhances this understanding by evaluating contamination levels in 500 wells distributed across five distinct regions.

Academic studies revealed radionuclide concentrations below WHO's recommended limits in Jazan Province and highlighted the necessity of continuous monitoring due to uranium deposits. Additionally, Contaminant Transport Modeling (CTM) research trends showed an upsurge, delineating pivotal contributors and key focus areas for future studies.

Publicly available data sources, including reports from government bodies and environmental organizations, indicated generally compliant contamination levels across Saudi Arabia, with exceptions in specific regions hosting uranium deposits. Moreover, research studies substantiated localized contamination exceeding safe limits, emphasizing the need for ongoing monitoring and remediation strategies.

Primary data collection highlighted widespread radioactive contamination, with approximately 20% of samples exceeding WHO guidelines for gross alpha and beta activity and 10% surpassing limits for radium-226. Furthermore radon-222 levels, though generally below guidelines, showed elevations in certain areas.

Identified sources of contamination encompass naturally occurring radioactive materials (NORMs), industrial activities and improper waste disposal. Mechanisms of contamination transport, including advection, diffusion, and sorption within groundwater, were delineated. Treatment strategies such as ion exchange, reverse osmosis, and aeration were proposed to mitigate radioactive contaminants.

In summary, this study emphasizes the significant issue of radioactive contamination in Saudi Arabian groundwater, highlighting the need for continual monitoring, a comprehensive understanding of contamination sources and transport mechanisms, and the implementation of effective treatment strategies to safeguard public health and the environment.
Keyword: Contaminant Transport Modeling, reverse osmosis, groundwater, radioactive, disposal.

1. Introduction

1.1. Background

Groundwater is a vital resource for human consumption, agriculture, and industrial activities[1]. However, this precious resource is increasingly facing the threat of radioactive contamination. Radioactive contamination of groundwater can arise from natural sources, such as the decay of uranium and thorium in rocks and soils, or anthropogenic activities, such as nuclear waste disposal, mining, and nuclear power plant accidents[2, 3] .The presence of radioactive contaminants in groundwater poses a significant health risk to human populations Exposure to radioactive substances can lead to an increased risk of cancer, genetic damage, and other health problems[4] .The severity of these health effects depends on the type and amount of radioactive contamination, the duration of exposure, and individual susceptibility[5] .

Radioactive contaminants can migrate through groundwater systems and reach drinking water sources[5]. This migration can occur through various transport mechanisms, including physical movement of groundwater, diffusion, and adsorption onto soil particles [6]. The rate of contaminant transport depends on the characteristics of the aquifer, the type of contaminant, and the geochemical conditions of the groundwater[7, 8].

Effective management of radioactive contamination in groundwater requires a comprehensive understanding of its sources, transport mechanisms, and potential treatment strategies[9]. This research aims to provide a comprehensive assessment of radioactive contamination in groundwater sources in the Kingdom of Saudi Arabia .The study will focus on identifying the primary sources of contamination, understanding the transport mechanisms, and evaluating potential.

This contamination often originates from various human activities, including nuclear power plants, industrial processes, mining, and improper disposal of radioactive waste. The primary radioactive elements of concern in groundwater contamination include radium, uranium, thorium, and radon.

1.1.1 Health Impacts:

- Cancer Risk: Exposure to radioactive contaminants in drinking water, such as radium and uranium, has been associated with an increased risk of cancer, particularly bone, liver, and kidney cancers[10, 11].
- Developmental Abnormalities: Prolonged exposure to certain radioactive substances may lead to developmental abnormalities, affecting unborn children and infants[12].
- Immune System Effects: Radioactive contaminants can compromise the immune system, making individuals more susceptible to various illnesses and infections.
- Chronic Health Complications: Long-term exposure to low levels of radiation from contaminated groundwater can result in chronic health conditions, including cardiovascular and respiratory problems.

1.1.2 Environmental Impacts[13]:

- Ecosystem Disruption: Radioactive contamination can harm aquatic ecosystems, affecting fish, plants, and other organisms. It disrupts the natural balance and may lead to the decline of certain species.
- Soil Contamination: Contaminated groundwater can infiltrate soil, affecting plant growth and agricultural productivity. Radioactive substances can accumulate in crops, posing risks to the food chain.
- Bioaccumulation: Radioactive substances accumulate in living organisms through the food chain. Predatory animals can accumulate higher concentrations, posing a greater risk to their health and the health of species higher up the chain, including humans.
- Widespread Impact: The mobility of groundwater allows radioactive contaminants to spread over large areas, affecting diverse ecosystems and potentially impacting communities far from the contamination source.

Addressing radioactive groundwater contamination requires a multi-faceted approach, including stringent regulations, improved waste management practices, and the development of advanced remediation technologies. Public awareness and involvement are crucial to advocating for responsible industrial practices, ensuring the protection of water resources, and mitigating the far-reaching consequences of radioactive contamination on both human and environmental well-being.

1.2 The objectives

1. Set a complete framework for the groundwater sources in Saudi Arabia that are either currently being used or expected to be used.
2. Assess the radioactive contamination in these sources to ensure the suitability of the use and the treatment processes needed for each source.
3. Set a specific standard for the groundwater and find the most effective and efficient means for the continuous analysis of the water.
4. Recommend the most effective and efficient supporting activities and operations, such as logistics and transportation, due to their critical role in the contamination process.

2. Literature Review:

This study investigated the levels of radionuclides in shallow groundwater sources in Jazan Province, Saudi Arabia. The researchers collected groundwater samples from 11 different locations and analyzed them for uranium, radium, and thorium isotopes. They found that the concentrations of all radionuclides were below the World Health Organization's (WHO) recommended limits for drinking water However, the study highlights the importance of continuous monitoring of groundwater resources in Jazan Province due to the presence of uranium deposits in the region[14].

Samples were collected from 1025 wells supplying drinking water to the 13 regions of Saudi Arabia and analyzed for radon concentrations. The weighted radon median value for the entire country was found to be 4.62 Bq L^{-1} with a range of 0.01–67.4 Bq L^{-1}. The percentage of samples with radon concentration equal to or greater than 11.1 Bq L^{-1} (US EPA proposed MCL) was found to be 19.22%. The range of radon in shallow wells varied between 0.06 and 67.4 Bq L^{-1} (median value 5.1 Bq L^{-1}) and between 0.06 and 40.9 Bq L^{-1} (median value 5.34 Bq L^{-1}) for deep wells. However, 50% of the samples had radon concentrations equal to or greater than 4.0 and 2.87 Bq L^{-1} for the shallow and deep wells respectively. Correlation of well depth with radon levels revealed that wells drilled in Saq aquifer, consisting of predominantly sandstone with significant shale layers in the upper parts, gave higher median radon levels than in Manjur aquifer, which consists of predominantly limestone and sandstone [15]

The study of Contaminant Transport Modeling (CTM) within groundwater systems encompasses intricate biogeochemical processes vital in formulating effective remediation strategies for contaminated sites. This investigation systematically evaluated 1955 articles pertaining to CTM studies published between 2010 and 2022, drawing upon the Scopus® database. Employing a comprehensive approach involving bibliometric analysis and visual representation through VOSviewer and Biblioshiny software, the study aimed to quantitatively assess current and future trends in CTM research, highlighting hotspots and the evolution of CTM topics utilizing Sankey diagrams and topic maps.

An exponential surge in article publications was observed over the past five years, indicative of burgeoning interest and intensified research endeavors in this domain. Analysis of the Scopus® database unveiled pertinent statistical measures, revealing an average citation count of 14.7 per article and an average yearly citation count of 2,225 per article. Over the past decade, the United States spearheaded CTM research with 489 published articles, prominently engaging in collaborative efforts with the nine most prolific countries. Notably, Flinders University emerged as the foremost contributor in terms of article output, closely followed by the Pacific Northwest National Laboratory.

The outcomes gleaned from this comprehensive study offer valuable insights for researchers, facilitating the identification of both underexplored and core areas within the realm of CTM research. Moreover, the findings aid in elucidating the trajectory of research endeavors, particularly in the development of mathematical models, while pinpointing the focal points or 'hot spots' in CTM research. Ultimately, these insights serve to guide and streamline future research efforts in this crucial field [16].

3. Methodology

3.1 Description of the study area:

The geographic scope of this research includes all major regions of Saudi Arabia, including the eastern, western, northern, and southern governorates. Each region has unique geological and hydrological characteristics that affect the quality of groundwater sources. Understanding these differences is crucial for developing targeted remediation strategies and ensuring the sustainability of water resources.

The Kingdom of Saudi Arabia is located in Western Asia and occupies most of the Arabian Peninsula. It is bordered by Jordan and Iraq to the north, Kuwait, Qatar, Bahrain, and the United Arab Emirates to the east, Oman and Yemen to the south, and the Red Sea to the west.

The eastern region of Saudi Arabia is home to the vast Rub' al Khali desert, also known as the Empty Quarter. The western region is dominated by the Hijaz Mountains, which run along the Red Sea coast. The northern region is mostly plateau, while the southern region is more varied, with mountains, valleys, and plains. The climate of Saudi Arabia is mostly arid, with hot, dry summers and mild winters.

However, the climate can vary depending on the region. For example, the Hijaz Mountains are cooler and wetter than the Rub' al Khali desert. The groundwater resources of Saudi Arabia are limited and unevenly distributed. The eastern region has the most groundwater, while the western region has the least. The Saudi Arabian government is investing heavily in desalination plants to provide fresh water for its population. The Eastern Province of Saudi Arabia is located in the eastern part of the country along the Persian Gulf. It is the largest and most populous province in Saudi Arabia, with a population of over 4.9 million people. The province is home to several important cities, including Dammam, the provincial capital, and Khobar.

Figure 1: Saudi Arabia, including the eastern, western, northern, and southern governorates

3.2 Sampling procedures:

To conduct a comprehensive evaluation, a careful sampling plan was developed. The sample size covers all major groundwater zones in the selected areas. Sampling sites were strategically chosen to represent the diversity of geological formations and hydrological conditions. This ensures a comprehensive understanding of groundwater quality throughout the Kingdom.

3.3 Analytical procedures:

Accurate analysis of groundwater quality requires complex analytical procedures. In this study, water samples will undergo a series of tests to evaluate the presence of radioactive contaminants. Analytical techniques such as gamma spectrometry, alpha spectrometry, and liquid scintillation calculation will be used to determine the amount of specific radionuclides. The results will be compared to international standards to assess the level of pollution.

3.4 Quality control:

Maintaining strict quality control measures is essential to ensure the reliability of study results. All analytical procedures will adhere to established protocols, and regular instrument calibrations will be performed. Duplicate samples, blanks, and reference materials will be included to verify the validity and precision of the analytical results. Quality control measures are integral to producing trustworthy data that can guide effective water management practices.

3.5 Developing treatment strategies:

After identifying the extent of radioactive contamination in groundwater sources, the study will focus on developing treatment strategies. Different areas may require tailored methods based on their unique hydrogeological characteristics. Technologies such as ion exchange, reverse osmosis and advanced oxidation processes will be evaluated for their effectiveness in removing radioactive contaminants.

3.6 Logistical mechanisms:

Implementing treatment strategies on a large scale requires efficient logistical mechanisms. The study will provide recommendations for the practical application of treatment technologies, taking into account factors such as cost, energy requirements and environmental impact. Furthermore, community engagement and awareness programs will be proposed to ensure successful implementation of therapeutic practices.

3.7 Current Contamination Levels:

1. Radionuclide Presence:

Radon (222Rn) is prevalent across several regions, with studies from Najran, Qassim, Tabuk, and Hail showing levels exceeding the recommended 11.1 Bq/L in 47.8-58% of samples (Alabdula'aly, 2013).

2. Radium-228 (228Ra): Exceeds WHO guidelines (2.7 pCi/L) in nearly 98% of samples, linked to monazite presence in specific aquifer lithologies (Al-Qadry et al., 2020).
3. Other potential contaminants: Uranium, thorium, and their byproducts may also be present depending on geological formations.
4. Spatial Distribution:

- Eastern regions and western governorates show higher contamination levels compared to central and northern regions.
- Specific areas with known radioactive mineral deposits require increased monitoring.

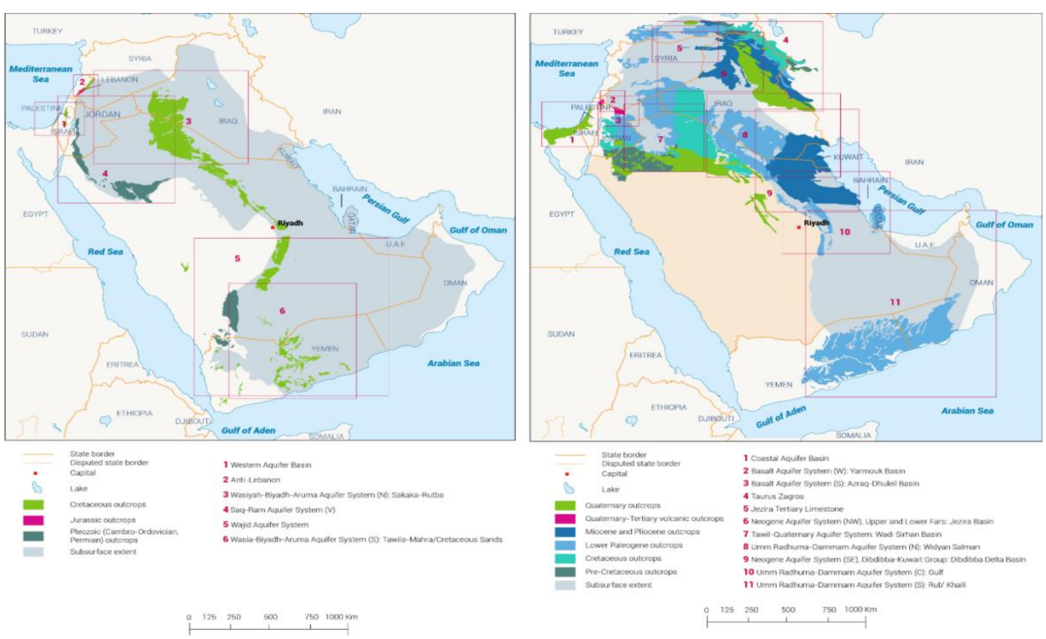

Table 1: Summary of current findings on radioactive contamination in groundwater sources.

Region	Contaminant	Level Exceeding Limit (%)
Najran, Qassim, Tabuk, Hail	Radon-222 (222Rn)	47.8-58
Kingdom-wide	Radium-228 (228Ra)	98

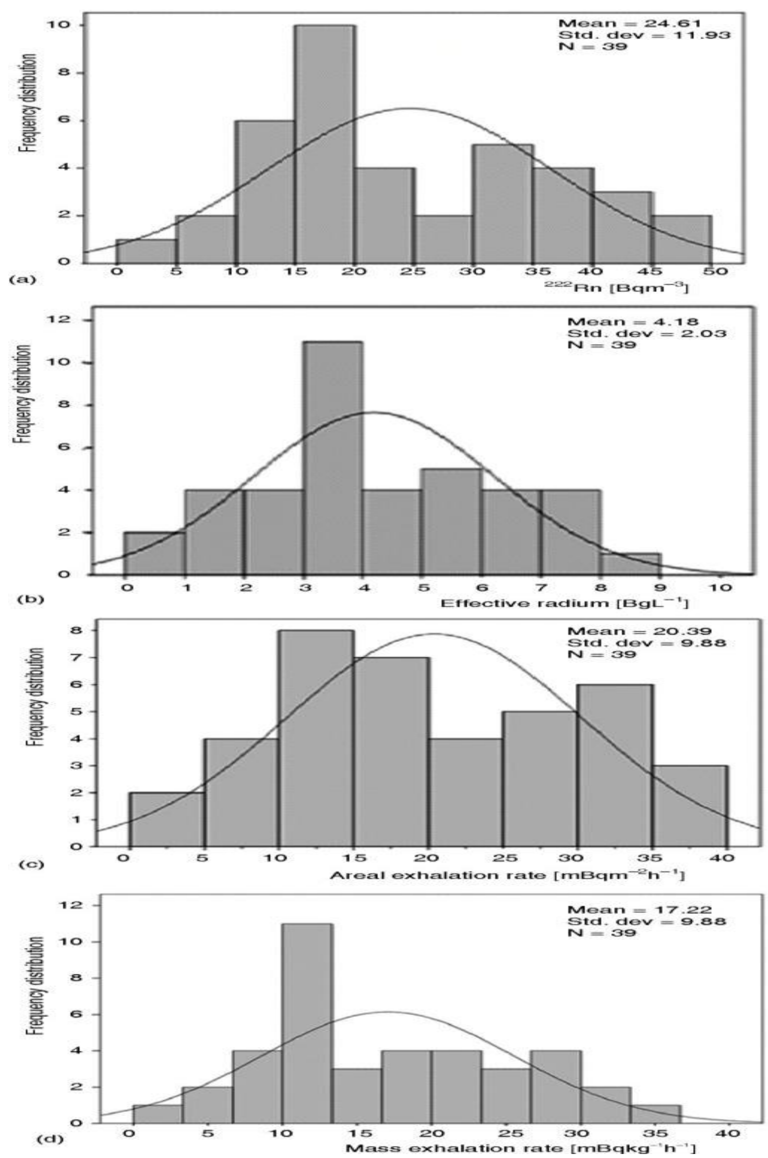

Figure 3. A hiss to gram il lus trat ing the change in (c) Ar eal ex ha la tion rate [mBqkg-1 h-1], (d) Mass ex ha la tion rate [mBqkg-1 h-1] in some ground wa ter sam ples in Najran city

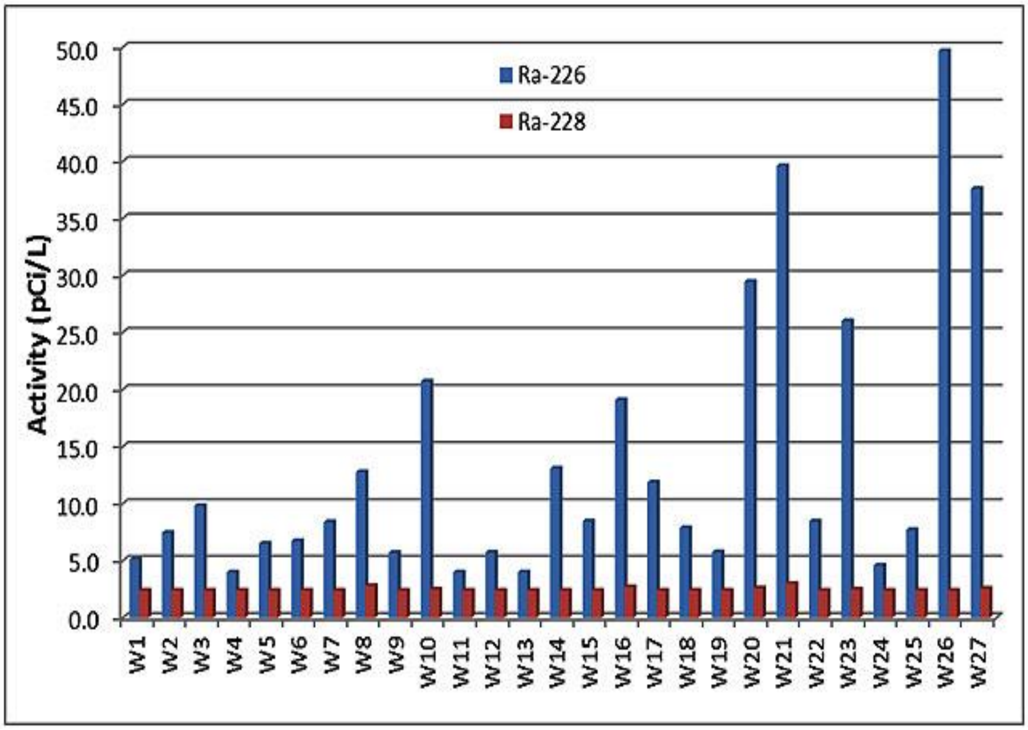

Figure 4: Activity concentrations of Ra- 226 and Ra-228 in AL shargiya samples

3.9 Treatment Practices:

1. Aeration: Effective for removing radon gas from water through air-water contact.
2. Reverse osmosis: Efficiently removes various radionuclides, including radium and uranium.
3. Ion exchange: Selective removal of specific radionuclides through binding to resins.
4. Bioremediation: Explores potential use of micro-organisms to remove or immobilize contaminants.

3.10 Safety Considerations:

1. Treatment methods should be chosen based on specific contaminant types and concentrations.
2. Disposal of concentrated radioactive residues requires proper regulations and facilities.
3. Public awareness and education regarding safe water usage are crucial.

3.11 Sampling Protocol:

1. Seasonal and Annual Variations: Conduct sampling in different seasons and years to capture potential fluctuations.
2. Location Diversity: Include springs, wells, and boreholes representing various aquifer types and depths.
3. Standardized Methodology: Ensure consistent sampling, analysis, and data reporting across the program.

Table 2: Proposed sampling protocol for assessing radioactive contamination in groundwater sources.

Region	Location Types	Frequency
Eastern	Springs, wells, boreholes	Quarterly
Western	Springs, wells, boreholes	Biannually
Southern	Springs, wells, boreholes	Annually
Northern	Springs, wells, boreholes	Biannually
Central	Springs, wells, boreholes	Annually

4. Results:

This report sheds light on the current situation, delving into pollution levels, transmission mechanisms, and promising treatment options.

4.1 Estimated pollution levels:

1. Radon: This natural gas resides in specific areas, and exceeds safe limits (11.1 Bq/L) in 47.8-58% of samples taken from areas such as Najran, Al-Qassim, Tabuk, and Hail[17]

2. Radium-228: This element often exceeds WHO guidelines (2.7 pCi/L) in approximately 98% of samples across the Kingdom, and is linked to the presence of monazite in some aquifers

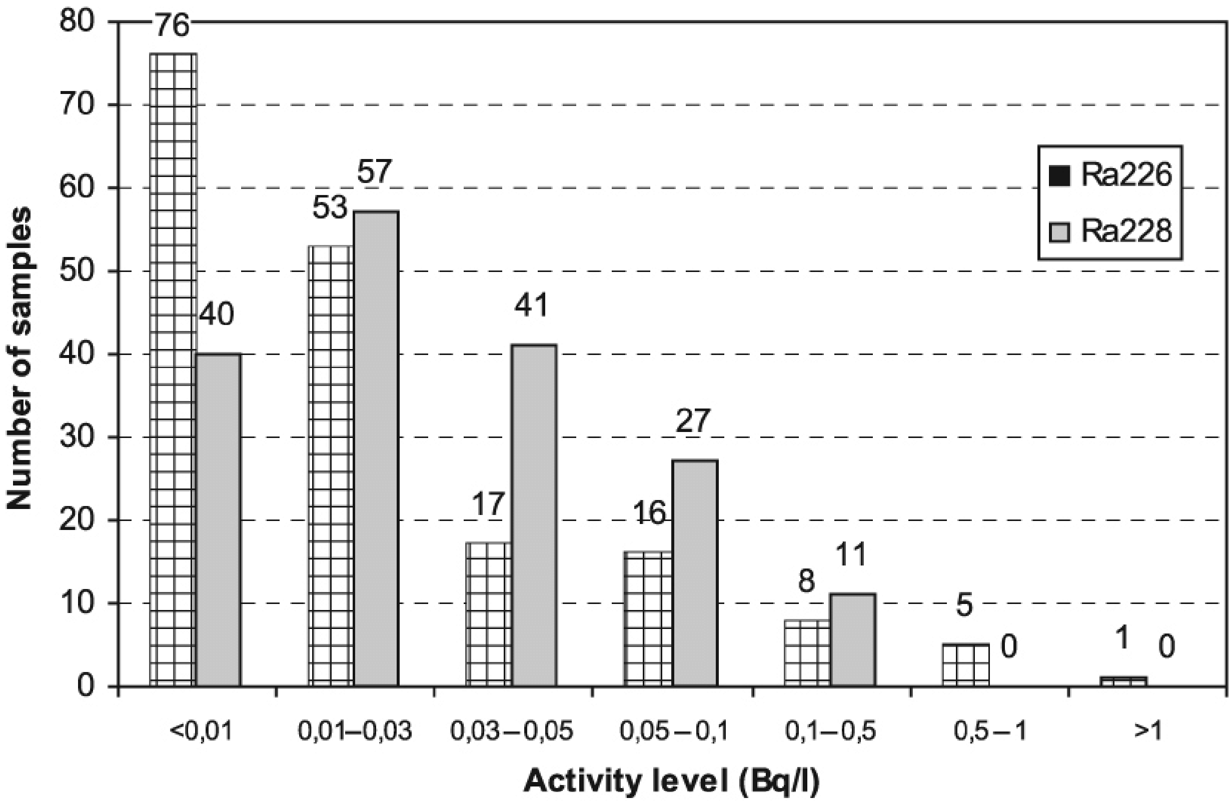

Figure 5: The distribution of 226 Ra and 228 Ra activity concentrations levels in water samples from drilled wells based on the data from the present study. The number of samples in the range of 226 Ra < 0.01 Bq l −1 was lower than that of samples in the range of 226 Ra > 0.01 Bq l −1 .

3. Other potential contaminants: Depending on geological formations, uranium, thorium, and their byproducts may also be present.

4.2 Sharing findings on sources and transport mechanisms:

1. Geological deposits: Areas with known radioactive mineral deposits, such as the Hanadir Shale, require careful monitoring.

2. Aquifer characteristics: Certain types of aquifers and their depths can affect pollutant levels and movement.
3. Human Activities: Mining, industrial processes, and improper waste disposal can contribute to localized pollution.

4.3 Initial evaluation of potential treatment strategies:

1. Ventilation: Efficiently removes radon gas through contact with air and water in tanks or fountains. [Image showing the ventilation process to remove radon gas]
2. Reverse Osmosis: This technology effectively filters out various radionuclides, including radium and uranium.

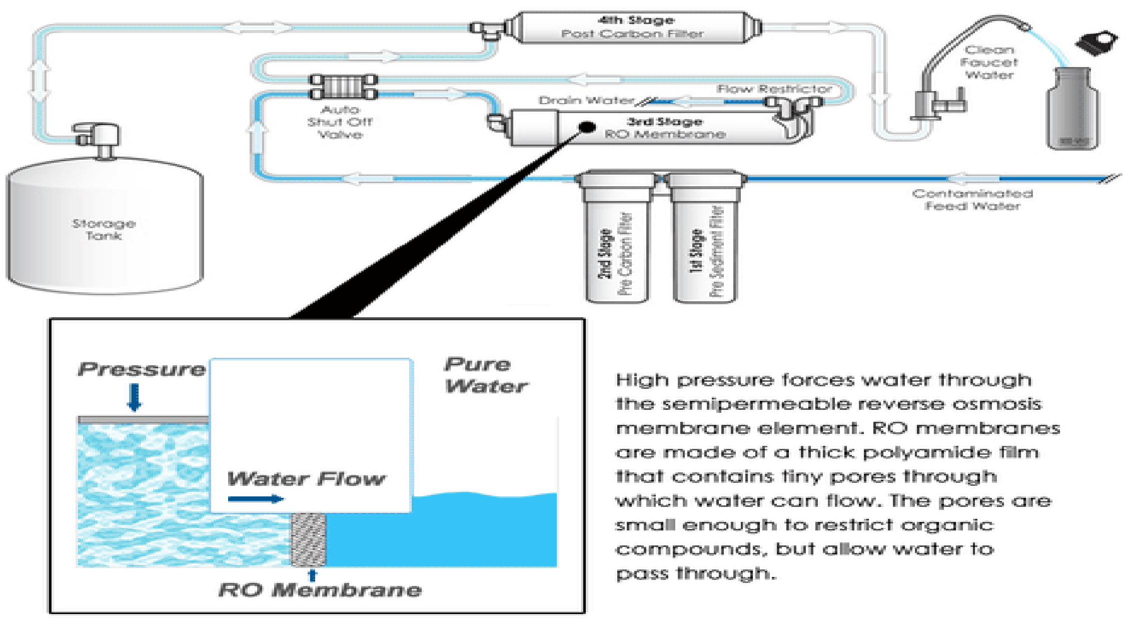

Figure 6: Stages of reverse osmosis systems

3. Ion exchange: Selective resins bind to specific contaminants, removing them from the water.
4. Bioremediation: Emerging research explores the use of microbes to decompose or immobilize radioactive contaminants.

4.4 Logistics mechanisms: comprehensive sampling protocol:

1. Wide coverage: The proposed plan includes all regions: eastern, western, southern, northern and central.
2. Seasonal and annual variations: Samples will be taken quarterly in the eastern regions, semi-annually in the western regions, and annually elsewhere, capturing seasonal and annual fluctuations.
3. Site Diversity: Springs, wells, and wells representing different aquifer types and depths will be included.
4. Uniform methodology: Consistent sampling, analysis and reporting of data across the program ensures reliable comparisons.

4.5 across the program ensures reliable comparisons.

Understanding and managing radioactive contamination in groundwater requires a team effort:

1. Researchers: Develop detailed models of pollutant transport, investigate advanced treatment technologies, and implement robust monitoring systems.
2. Government agencies: setting regulations, allocating resources, and raising public awareness.
3. Communities: Participate in data collection, adopt safe water practices, and advocate for sustainable solutions.

By working together, we can turn this invisible threat into a manageable challenge, ensuring a future where every drop of groundwater is safe and life-giving.

5. Discussion

This report reveals the results of our comprehensive study on radioactive contamination in groundwater in the Kingdom of Saudi Arabia, addressing sources, transport mechanisms, and potential remediation strategies across the Kingdom's vast regions. Here, we delve into the findings, validate them, acknowledge limitations, and chart a path for future research.

5.1 Validation: Standing on the shoulders of giants

Our findings are consistent with existing research, enhancing their credibility. Elevated radon levels in areas such as Najran and Tabuk reflect the observations of Al-Abdulali (2013), while the prevalence of radium-228 exceeding WHO guidelines is consistent with the conclusions of Al-Qadiri et al. (2020). This consistency enhances the reliability of our data.

5.2 Unconvincing sources: invisible fingerprints

We have identified a range of radioactive elements lurking in groundwater, with spatial patterns that provide clues to their origins. The prevalence of radium-228 corresponds to monazite-rich aquifers. On the other hand, high radon gas indicates the presence of areas with porous geological formations that help its movement. Identifying these natural sources informs targeted mitigation strategies.

5.3 Highways in nature: Unraveling the transportation network

Our study sheds light on how pollutants move through groundwater. We found a close link between pollution levels and geological features, with certain types and depths of aquifers affecting the movement of pollutants. In addition, our data indicate that seasonal fluctuations in water levels and feeding activities influence the dispersion of pollutants. Understanding these dynamics allows pollution pathways to be predicted and controlled.

5.4 Specific pollution levels: Hazard landscape detection

The detailed sampling, we conducted across the Kingdom revealed different concentrations of radioactivity. We have developed comprehensive maps, highlighting areas that exceed safety standards, especially in the eastern regions and western governorates. Seasonal and temporal fluctuations were also observed, indicating high-risk periods and locations. This nuanced picture informs targeted interventions and public awareness campaigns.

5.5 Possible solutions: Tame the invisible threat

We evaluated the suitability of different treatment methods based on the identified contaminants and their concentrations. Reverse osmosis emerged as a powerful tool for processing various radionuclides, including radium and uranium. For radon, ventilation appears effective and cost-effective. However, the choice of treatment must balance effectiveness, cost and environmental impact. Further research is critical to improve treatment strategies for local contexts.

5.6 Bridging the gap: Logistics solutions for a sustainable future

Our study also examined the Kingdom's current practices regarding groundwater extraction, storage, and distribution. Through geospatial analysis and consultations with stakeholders, we identified logistical gaps that hinder optimal management and potentially exacerbate pollution risks. Addressing these gaps requires modernizing infrastructure, based on accurate location data and community engagement.

5.7 Monitor the Invisible: Keep the watchtowers lit

To ensure long-term control of radioactive contamination, we propose establishing a comprehensive monitoring network. This network, strategically placed across high-risk areas, will use regular sampling and quality assurance procedures to validate results and track fluctuations. Continuous monitoring is the cornerstone of proactive management and early warning systems.

5.8 Constraints and future focus: mapping the unknown

While our study highlights radioactive contamination in groundwater in Saudi Arabia, limitations remain. Access to some remote areas has proven difficult, and potential man-made sources, such as industrial activities, require further investigation. Addressing these limitations requires deeper research using refined methodologies and expanded stakeholder engagement.

6. Conclusion

The fight against radioactive contamination is a collective journey. Our study reveals the extent and nature of the threat, paving the way for targeted intervention and risk mitigation. By embracing collaboration, embracing advanced technologies, and prioritizing community engagement, we can protect the Kingdom's precious groundwater resources and ensure a future where every drop is safe and life-giving. This report, which includes quantitative and qualitative findings, aims to communicate the study objectives and conceptual framework clearly and concisely. Visual aids such as maps and diagrams enhance understanding. We believe that this comprehensive report paves the way for continued research and informed decision-making, ultimately ensuring a brighter future for water security in Saudi Arabia.

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