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Frameworks for risk management to protect underground sources of drinking water during oil and gas extraction

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Abstract

Oil and gas extraction activities, including hydraulic fracturing and well stimulation, pose potential risks to underground sources of drinking water (USDWs). To safeguard these vital water resources, robust risk management frameworks are essential. This review explores existing frameworks for risk management aimed at protecting USDWs during oil and gas extraction, highlighting key components and strategies. Effective risk management begins with comprehensive assessment and understanding of potential hazards and vulnerabilities associated with oil and gas extraction activities. This involves identifying potential pathways for contamination, assessing the integrity of well casings and cementing, evaluating geologic formations and hydrogeological conditions, and considering the proximity of extraction operations to USDWs. Frameworks for risk management typically involve multiple components, including regulatory standards, best practices, monitoring and surveillance programs, and emergency response plans. Regulatory standards establish minimum requirements and guidelines for well construction, operation, and closure to prevent contamination of USDWs. Best practices encompass industry-recommended techniques and technologies for mitigating risks, such as improved well design, casing materials, and cementing techniques, as well as comprehensive site characterization and environmental impact assessments. Monitoring and surveillance programs play a crucial role in early detection and mitigation of potential threats to USDWs. These programs involve regular monitoring of water quality, aquifer levels, and well integrity, as well as implementing real-time monitoring technologies, such as groundwater sensors and satellite imaging, to detect anomalies and deviations from baseline conditions. Early warning systems and trigger thresholds enable prompt response to potential contamination events, including shutting down operations, implementing remediation measures, and notifying relevant authorities and stakeholders. Emergency response plans outline procedures and protocols for addressing contamination incidents and minimizing the impact on USDWs and public health. These plans include contingency measures for containment, cleanup, and remediation, as well as communication strategies for notifying affected communities and coordinating response efforts with regulatory agencies and emergency responders. Integration of risk management frameworks with stakeholder engagement and public participation is essential for enhancing transparency, accountability, and trust in the regulatory process. Engaging with local communities, indigenous groups, environmental organizations, and other stakeholders enables meaningful input and feedback on risk management strategies, fosters dialogue and collaboration, and enhances public awareness and understanding of potential risks and mitigation measures. Frameworks for risk management play a critical role in protecting underground sources of drinking water during oil and gas extraction. By implementing robust regulatory standards, best practices, monitoring programs, and emergency response plans, stakeholders can mitigate risks, safeguard water resources, and ensure the long-term sustainability of groundwater supplies. Continued research, innovation, and collaboration are essential for enhancing risk management frameworks and addressing emerging challenges in protecting USDWs from the impacts of oil and gas extraction activities.

Keywords: Frameworks; Risk Management; Protection; Underground sources; Drinking water; Oil; Gas; Extraction

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1. Introduction

Underground sources of drinking water (USDWs) are invaluable resources that sustain human life, providing clean and potable water for communities around the world (McNabb and Swenson, 2023). Protecting these vital water sources is paramount to ensuring public health, environmental sustainability, and socioeconomic well-being. However, the extraction of oil and gas presents significant risks to USDWs, threatening their quality and availability (Martin *et al*., 2022). Robust risk management frameworks are essential to mitigate these risks and safeguard USDWs for current and future generations (Menzie *et al*., 2024). USDWs, including aquifers and groundwater reservoirs, serve as essential sources of drinking water for millions of people worldwide (Simpa *et al*., 2024). These subsurface water sources are typically replenished through natural processes such as rainfall and snowmelt, making them critical components of freshwater ecosystems and hydrological cycles. USDWs also support agricultural, industrial, and recreational activities, providing irrigation water, industrial process water, and habitat for aquatic species (Moran *et al*., 2021). The protection of USDWs is essential for maintaining public health and environmental sustainability. Contamination of USDWs can pose significant risks to human health, leading to waterborne diseases, chemical exposure, and long-term health impacts. Moreover, the degradation of USDWs can have adverse effects on ecosystems, biodiversity, and natural habitats, disrupting ecological balance and compromising ecosystem services. Ensuring the sustainable management and protection of USDWs is also crucial for supporting economic development and societal well-being (Campbell *et al*., 2023). Access to clean and reliable drinking water is essential for economic activities, public infrastructure, and community resilience. Protecting USDWs can also reduce reliance on costly water treatment and remediation measures, thereby saving resources and minimizing environmental liabilities (Solomon *et al*., 2024).

Oil and gas extraction activities, including drilling, hydraulic fracturing (fracking), and well stimulation, can pose significant risks to USDWs due to the potential for contamination and pollution (Hardberger, 2024; Obasi *et al*., 2024). These risks stem from various sources, including spills, leaks, inadequate well construction, and improper waste disposal practices. Key risks associated with oil and gas extraction activities include. Accidental spills and releases of drilling fluids, hydraulic fracturing fluids, and produced water can contaminate surface water bodies and infiltrate groundwater aquifers, leading to contamination of USDWs (Soeder *et al*., 2021). Inadequate well construction, casing failures, and cementing defects can result in leakage of fluids and gases from oil and gas wells into surrounding aquifers, compromising the integrity of USDWs. The use of chemicals in hydraulic fracturing fluids, such as biocides, surfactants, and corrosion inhibitors, can pose risks of chemical contamination to USDWs if not properly managed or contained. Hydraulic fracturing and wastewater injection activities can induce seismic events, leading to ground shaking and potential damage to wellbores, casing integrity, and USDWs (Ring *et al*., 2021; Simpa *et al*., 2024). Excessive extraction of groundwater for hydraulic fracturing and other oil and gas activities can deplete aquifer resources, leading to reduced water availability and potential impacts on ecosystems and communities. Improper disposal of drilling waste, produced water, and flowback fluids can result in surface and groundwater contamination, soil degradation, and ecosystem impacts (Vakylabad *et al*., 2023).

Given the potential risks associated with oil and gas extraction activities, there is an urgent need for robust risk management frameworks to protect USDWs and ensure their long-term sustainability (Islam *et al*., 2024; Solomon *et al*., 2024). These frameworks should encompass comprehensive assessment, prevention, mitigation, monitoring, and response measures to address the diverse and complex risks posed by oil and gas operations. Identifying and assessing potential hazards and vulnerabilities associated with oil and gas extraction activities. Implementing preventive measures and best practices to minimize the likelihood of contamination and pollution (Obiuto *et al*., 2024). Monitoring and surveillance programs to detect early signs of contamination and respond promptly to potential threats. Emergency response plans to mitigate the impact of contamination incidents and protect public health and safety (Adekugbe and Ibeh, 2024). By implementing robust risk management frameworks, stakeholders can effectively manage and mitigate the risks associated with oil and gas extraction activities, safeguarding USDWs and ensuring access to clean and reliable drinking water for current and future generations (Di Filippo *et al*., 2024; Simpa *et al*., 2024).

2. Hazard Assessment and Identification in Protecting Underground Sources of Drinking Water (USDWs) during Oil and Gas Extraction

Hazard assessment and identification are critical components of risk management frameworks aimed at protecting underground sources of drinking water (USDWs) during oil and gas extraction activities (Schultz *et al*., 2023). This delves into the various aspects of hazard assessment and identification, including the identification of potential pathways for contamination, assessment of well integrity, casing, and cementing, evaluation of geologic formations and hydrogeological conditions, and consideration of proximity to USDWs.

Accidental spills and leaks of drilling fluids, hydraulic fracturing fluids, and produced water can migrate through surface pathways, such as runoff, surface water bodies, and infiltration, potentially reaching and contaminating USDWs (Ossai *et al*., 2020; Obasi *et al*., 2024). Inadequate well construction, casing failure, and cementing defects can compromise the integrity of oil and gas wells, allowing fluids and gases to migrate vertically along the wellbore and reach USDWs. Migration of fluids, gases, and contaminants through subsurface pathways, such as natural fractures, faults, and permeable formations, can transport pollutants from oil and gas reservoirs to overlying aquifers and USDWs (Askar and Illangasekar, 2023). Hydraulic fracturing and wastewater injection activities can induce seismic events, leading to ground shaking and potential damage to wellbores, casing integrity, and surrounding geologic formations, facilitating the migration of fluids and contaminants. Natural groundwater flow patterns, influenced by geologic structures, hydrogeological conditions, and regional aquifer properties, can transport contaminants over time and distance, affecting the vulnerability of USDWs to contamination (Fakhreddine *et al*., 2021; Simpa *et al*., 2024).

Evaluation of well construction practices, including casing design, material selection, and cementing techniques, is essential for ensuring the integrity and isolation of oil and gas wells from surrounding aquifers and USDWs (Osimobi *et al*., 2023). Inspection and testing of well casing and cementing integrity, using techniques such as cement bond logs, casing pressure tests, and wellbore integrity surveys, can identify potential defects and vulnerabilities that may compromise well integrity and lead to contamination. Continuous monitoring of wellbore conditions, pressures, and temperatures, using downhole sensors and surveillance technologies, enables early detection of anomalies and deviations from expected performance, signaling potential risks to well integrity and USDWs. Implementation of remediation measures, such as casing repairs, cementing treatments, and well integrity enhancements, can address identified deficiencies and mitigate risks to USDWs posed by wellbore integrity failures (Simpa *et al*., 2024).

Characterization of subsurface geologic formations, including lithology, porosity, permeability, and structural features, provides insights into the potential pathways and migration routes for fluids and contaminants within the subsurface environment (Onwuka *et al*., 2023; Ekechi *et al*., 2024). Assessment of hydrogeological conditions, such as groundwater flow direction, velocity, and gradient, helps to understand the movement and transport of fluids and contaminants through aquifers and subsurface pathways, informing risk assessments and mitigation strategies. Evaluation of aquifer properties, including hydraulic conductivity, transmissivity, storativity, and vulnerability, enables quantification of groundwater vulnerability to contamination and identification of high-risk areas requiring enhanced protection measures. Consideration of regional hydrogeological settings, such as regional aquifer systems, recharge areas, discharge zones, and groundwater flow regimes, is essential for understanding the broader context of groundwater resources and potential risks to USDWs posed by oil and gas extraction activities.

Consideration of setback distances and buffer zones between oil and gas wells and USDWs helps to minimize the risk of contamination by maintaining a safe separation distance and reducing the likelihood of direct impacts on groundwater resources. Mapping of aquifer vulnerability, based on hydrogeological characteristics, land use practices, and proximity to potential contamination sources, provides spatial insights into areas of elevated risk and informs land use planning and regulatory decision-making (Shaikh and Birajdar, 2024; Digitemie and Ekemezie, 2024). Identification of wellhead protection areas, delineated based on hydrogeological considerations, regulatory requirements, and risk assessments, establishes priority zones for groundwater protection and management, guiding land use planning and development activities. Implementation of groundwater monitoring and surveillance programs, including baseline assessments, regular sampling, and trend monitoring, in proximity to USDWs enables early detection of potential impacts and informs adaptive management strategies to protect groundwater quality (Romanak and Dixon, 2022). Hazard assessment and identification are fundamental steps in protecting USDWs during oil and gas extraction activities. By systematically identifying potential pathways for contamination, assessing well integrity, casing, and cementing, evaluating geologic formations and hydrogeological conditions, and considering proximity to USDWs, stakeholders can better understand the risks and vulnerabilities associated with oil and gas operations and implement targeted measures to safeguard groundwater resources for present and future generations.

3. Components of Risk Management Frameworks in Protecting Underground Sources of Drinking Water (USDWs) during Oil and Gas Extraction

Risk management frameworks play a pivotal role in safeguarding underground sources of drinking water (USDWs) during oil and gas extraction activities. These frameworks encompass a range of components aimed at identifying, assessing, preventing, monitoring, and responding to risks associated with oil and gas operations (Onwuka and Adu, 2024). This explores the key components of risk management frameworks, including regulatory standards, best practices, monitoring and surveillance programs, and emergency response plans.

Regulatory standards establish minimum requirements for well construction, operation, and closure to prevent contamination of USDWs. These standards typically include specifications for casing design, cementing techniques, wellbore integrity testing, and abandonment procedures to ensure the integrity and isolation of oil and gas wells from surrounding aquifers and groundwater resources. Regulatory agencies develop guidelines and protocols for preventing contamination of USDWs, including requirements for well siting, setback distances, surface spill prevention, and wastewater management (Abid, 2020; Popoola *et al*., 2024). These guidelines aim to minimize the risk of groundwater contamination and ensure compliance with environmental regulations and water quality standards.

Best practices encompass industry-recommended techniques and technologies for mitigating risks associated with oil and gas extraction activities. These practices include the use of advanced drilling technologies, such as directional drilling and multistage hydraulic fracturing, to maximize resource recovery and minimize environmental impacts (Ekemezie and Digitemie, 2024). Best practices emphasize the importance of improved well design, casing materials, and cementing techniques to enhance well integrity and prevent leaks and failures. This includes the use of corrosion-resistant casing materials, multiple layers of cement, and centralizers to ensure proper casing placement and bonding. Best practices advocate for comprehensive site characterization and environmental impact assessments to identify potential hazards and vulnerabilities associated with oil and gas operations (Emeka-Okoli *et al*., 2024; Joel and Oguanobi, 2024). This includes conducting baseline assessments, groundwater monitoring, and risk assessments to evaluate the potential impacts on USDWs and surrounding ecosystems.

Monitoring and surveillance programs involve regular monitoring of water quality, aquifer levels, and well integrity to detect changes and deviations from baseline conditions (Ekemezie and Digitemie, 2024). This includes sampling and analysis of groundwater samples for contaminants, as well as monitoring of aquifer levels and flow rates to assess groundwater availability and trends over time. Advancements in real-time monitoring technologies, such as groundwater sensors, remote sensing, and satellite imaging, enable continuous monitoring of oil and gas operations and potential impacts on USDWs. These technologies provide early warning of potential contamination events and facilitate prompt response and mitigation measures. Monitoring programs incorporate early warning systems and trigger thresholds to alert operators and regulatory agencies to potential risks and deviations from established standards (Mustafa *et al*., 2023). This includes setting thresholds for key parameters such as groundwater quality, wellbore pressure, and seismic activity, triggering automatic alarms and notifications when thresholds are exceeded.

Emergency response plans outline procedures and protocols for addressing contamination incidents and minimizing the impact on USDWs and public health (Esho *et al*., 2024). This includes establishing response teams, coordinating with regulatory agencies and emergency responders, and implementing containment, cleanup, and remediation measures. Emergency response plans include contingency measures for containing spills, leaks, and releases of contaminants, including the deployment of booms, barriers, and absorbent materials to prevent further migration and spread of pollutants. Cleanup and remediation measures involve removing contaminants from soil and groundwater, restoring affected areas, and mitigating potential long-term impacts on USDWs and ecosystems (Oguanobi and Joel, 2024). Effective communication strategies are essential for notifying affected communities, stakeholders, and regulatory agencies about contamination incidents and emergency response efforts. This includes providing timely updates, information, and guidance to affected individuals, coordinating public meetings and outreach events, and fostering transparency and accountability throughout the response process. The components of risk management frameworks play a critical role in protecting underground sources of drinking water during oil and gas extraction activities. By establishing regulatory standards, promoting best practices, implementing monitoring and surveillance programs, and developing emergency response plans, stakeholders can effectively manage and mitigate risks to USDWs, ensuring their long-term sustainability and availability for present and future generations. Continued research, innovation, and collaboration are essential for enhancing risk management frameworks and addressing emerging challenges in protecting USDWs from the impacts of oil and gas operations (Menzie *et al*., 2024; Digitemie and Ekemezie, 2024).

4. Integration with Stakeholder Engagement in Protecting Underground Sources of Drinking Water (USDWs) during Oil and Gas Extraction

Stakeholder engagement plays a crucial role in the effective management and protection of underground sources of drinking water (USDWs) during oil and gas extraction activities. Meaningful engagement with local communities, indigenous groups, environmental organizations, and other stakeholders is essential for promoting transparency, accountability, and trust, as well as fostering dialogue, collaboration, and shared decision-making (Larson *et al*., 2022; Igbinenikaro *et al*., 2024). This explores the importance of integration with stakeholder engagement in protecting USDWs, including the facilitation of meaningful input and feedback, fostering dialogue and collaboration, and enhancing public awareness and understanding of potential risks and mitigation measures.

Local communities and indigenous groups often have deep cultural, spiritual, and traditional ties to the land and water resources affected by oil and gas extraction activities (Redvers *et al*., 2023). Engaging with these communities and groups is essential for respecting their rights, values, and interests, as well as addressing potential impacts on cultural heritage, sacred sites, and traditional livelihoods. Local communities and environmental organizations may have concerns and perspectives regarding the potential risks and impacts of oil and gas operations on USDWs, public health, and the environment. Engaging with these stakeholders enables operators and regulatory agencies to better understand community concerns, address questions and misconceptions, and incorporate local knowledge and perspectives into decision-making processes (Tilt *et al*., 2022; Ekemezie and Digitemie, 2024). Engaging with environmental organizations and advocacy groups can lead to partnerships and collaborative initiatives aimed at promoting environmental stewardship, conservation, and sustainable development. These partnerships can facilitate knowledge sharing, capacity building, and joint efforts to address common challenges and achieve shared goals related to protecting USDWs and promoting environmental sustainability.

Stakeholder engagement processes, such as public consultations, workshops, and stakeholder meetings, provide opportunities for stakeholders to provide input, feedback, and suggestions on risk management strategies and decision-making processes (Alamanos *et al*., 2021; Joel and Oguanobi, 2024). Meaningful engagement involves actively listening to stakeholder concerns, addressing questions and inquiries, and incorporating stakeholder input into decision-making processes. Providing transparent and accessible information about oil and gas operations, potential risks, and mitigation measures is essential for fostering informed decision-making and building trust with stakeholders. This includes sharing relevant data, reports, studies, and monitoring results with stakeholders in a timely and accessible manner, as well as providing opportunities for stakeholders to ask questions and seek clarification on technical matters. Developing community engagement plans, in collaboration with stakeholders, helps to formalize engagement processes, define roles and responsibilities, and establish mechanisms for communication and feedback (Edlmann and Grobbelaar, 2021; Oguanobi and Joel, 2024). These plans outline objectives, strategies, and activities for engaging with stakeholders throughout the lifecycle of oil and gas projects, from planning and permitting to operation and closure, ensuring ongoing dialogue and collaboration.

Establishing multi-stakeholder forums, advisory committees, and working groups can facilitate dialogue, collaboration, and consensus-building among stakeholders, regulators, and industry representatives (Vat *et al*., 2021; Esho *et al*., 2024). These forums provide opportunities for stakeholders to exchange information, share perspectives, and work together to address complex issues and challenges related to protecting USDWs. Regulatory agencies play a critical role in overseeing oil and gas operations and ensuring compliance with environmental regulations and water quality standards. Engaging with regulatory agencies and participating in regulatory processes, such as permit reviews, environmental assessments, and public hearings, enables stakeholders to provide input, raise concerns, and advocate for protective measures to safeguard USDWs. Promoting transparency and accountability in the regulatory process enhances public trust and confidence in decision-making processes and regulatory outcomes (Igbinenikaro *et al*., 2024). This includes transparently communicating regulatory requirements, permitting decisions, enforcement actions, and monitoring results to stakeholders, as well as providing opportunities for public review, comment, and appeal of regulatory decisions.

Conducting public education and outreach campaigns helps to raise awareness and understanding of the potential risks and impacts of oil and gas operations on USDWs, public health, and the environment (Williams *et al*., 2023). These campaigns provide information about risk management strategies, pollution prevention measures, emergency response procedures, and available resources for stakeholders to access. Providing technical assistance and training to stakeholders, including local communities, indigenous groups, and environmental organizations, enhances their capacity to participate effectively in decision-making processes and engage meaningfully on technical matters related to USDW protection. This includes offering workshops, webinars, and technical resources on topics such as groundwater hydrology, water quality monitoring, and pollution prevention technologies. Establishing community-based monitoring programs empowers local communities and stakeholders to actively participate in monitoring and surveillance efforts to protect USDWs (Hunt *et al*., 2021). These programs involve training community members to collect water quality samples, monitor groundwater levels, and report potential pollution incidents, providing valuable data and insights for regulatory agencies and operators to respond effectively to emerging risks and concerns. Integration with stakeholder engagement is essential for effectively protecting underground sources of drinking water during oil and gas extraction activities. By engaging with local communities, indigenous groups, environmental organizations, and other stakeholders, operators and regulatory agencies can foster dialogue, collaboration (Blesia *et al*., 2021)

5. Conclusion

In conclusion, the protection of underground sources of drinking water (USDWs) during oil and gas extraction activities necessitates the implementation of robust risk management frameworks. Throughout this review, various components of such frameworks, including regulatory standards, best practices, monitoring and surveillance programs, and emergency response plans, as well as the integration of stakeholder engagement. Establishing minimum requirements for well construction, operation, and closure, along with guidelines for preventing contamination, is essential for ensuring compliance and minimizing risks to USDWs. Implementing industry-recommended techniques and technologies, improving well design and construction, conducting comprehensive site characterization, and environmental impact assessments are critical for mitigating risks associated with oil and gas extraction. Regular monitoring of water quality, aquifer levels, well integrity, real-time monitoring technologies, and early warning systems are vital for early detection of potential contamination events and prompt response. Developing procedures and protocols for addressing contamination incidents, implementing contingency measures, and communication strategies for stakeholders are crucial for effective emergency response and mitigation of impacts.

Continued research, innovation, and collaboration are essential for advancing risk management frameworks and addressing emerging challenges in protecting USDWs. Research efforts should focus on developing new technologies, methodologies, and tools for assessing risks, monitoring impacts, and implementing mitigation measures. Innovation in well construction, drilling techniques, waste management, and water treatment technologies can enhance environmental performance and reduce risks to USDWs. Collaboration among stakeholders, including industry, regulatory agencies, academia, environmental organizations, and local communities, is key to sharing knowledge, best practices, and resources, as well as fostering dialogue, trust, and collaboration. By working together, stakeholders can leverage collective expertise, experiences, and insights to develop and implement effective risk management strategies tailored to local conditions and challenges.

In light of the potential risks and impacts associated with oil and gas extraction activities on USDWs, there is an urgent need for the implementation of robust risk management frameworks. These frameworks should prioritize the protection of USDWs as a fundamental objective, ensuring the long-term sustainability and availability of clean and potable drinking water for present and future generations. Stakeholders, including operators, regulatory agencies, policymakers, and communities, must prioritize the protection of USDWs in their decision-making processes, policies, and practices. This includes adopting proactive measures to prevent contamination, enhance monitoring and surveillance, and improve emergency preparedness and response capabilities. Furthermore, regulatory agencies should strengthen enforcement mechanisms, enhance oversight and compliance monitoring, and establish transparent and accountable regulatory processes to ensure the effective implementation of risk management frameworks. Public participation and engagement should be encouraged and facilitated throughout the entire lifecycle of oil and gas projects, from planning and permitting to operation and closure. Safeguarding underground sources of drinking water during oil and gas extraction activities requires a concerted effort from all stakeholders, guided by robust risk management frameworks. By implementing proactive measures, fostering innovation and collaboration, and prioritizing the protection of USDWs, we can ensure the sustainable management of water resources and protect public health, environmental integrity, and socioeconomic well-being for generations to come.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest exists among the Authors.

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