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Hydrogeological modeling for safeguarding underground water sources during energy extraction

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Abstract

Hydrogeological modeling plays a crucial role in safeguarding underground water sources during energy extraction activities, such as oil and gas drilling, hydraulic fracturing, geothermal energy production, and coal mining. These activities pose significant risks to groundwater, including contamination, depletion, and structural damage to aquifers. This study outlines a comprehensive approach to hydrogeological modeling aimed at understanding and mitigating these risks. The modeling process begins with extensive data collection, including geological, hydrological, chemical, and land use data, sourced through field surveys, remote sensing, and existing databases. This data informs the development of a detailed geological framework and parameterization of hydrological properties, such as hydraulic conductivity, porosity, and recharge rates. Boundary and initial conditions are established to reflect the real-world conditions of the study area. Calibration and validation of the model are achieved through manual and automated techniques, ensuring the model's accuracy and reliability. Various extraction scenarios are then simulated, including baseline, worst-case, and mitigation scenarios, to assess potential impacts on groundwater quality, levels, and aquifer integrity. Risk assessment methodologies, both probabilistic and deterministic, are employed to quantify these impacts. The study also explores mitigation and management strategies, emphasizing preventative measures like safe drilling practices and monitoring systems, as well as remediation techniques for contamination and aquifer restoration. Regulatory and policy frameworks are considered essential for ensuring compliance and effective management. Through case studies of successful implementations, the study highlights best practices and lessons learned, offering valuable insights for future research and development in hydrogeological modeling. This comprehensive approach ensures that energy extraction can proceed while minimizing adverse effects on vital underground water resources.

Keywords: Hydrogeological Modeling; Safeguarding Underground Water Sources; Energy Extraction

1. Introduction

Underground water sources, also known as groundwater, are vital for numerous human and ecological needs. They provide drinking water for nearly half of the world's population and support agricultural activities, industrial processes, and natural ecosystems. Groundwater acts as a crucial buffer against droughts and maintains the base flow of rivers and streams, which is essential for sustaining aquatic habitats (Nzeako et al., 2024). The significance of safeguarding these water sources cannot be overstated. Contamination or depletion of groundwater can have severe consequences, including health hazards from polluted drinking water, reduced agricultural productivity, economic losses, and environmental degradation. Pollutants such as heavy metals, hydrocarbons, and chemicals used in industrial processes can render groundwater unsafe for consumption and harm aquatic life. Moreover, over-extraction of groundwater can lead to the lowering of water tables, land subsidence, and deterioration of water-dependent ecosystems (Ekechi et al.,2024). Given the increasing demand for energy and the associated rise in energy extraction activities, protecting groundwater from potential adverse impacts has become more critical. Energy extraction methods, including oil and

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gas drilling, hydraulic fracturing (fracking), geothermal energy extraction, and coal mining, pose significant risks to groundwater quality and availability. These activities can introduce contaminants into aquifers and alter the natural flow regimes of groundwater systems. Hydrogeological modeling is an essential tool for understanding and managing the impacts of energy extraction on groundwater resources. It involves the creation of computer-based models that simulate the behavior of groundwater systems under various conditions. These models integrate data on geology, hydrology, chemistry, and human activities to predict how groundwater will respond to different stressors (Chukwurah et al.,2024).

The importance of hydrogeological modeling in energy extraction projects lies in its ability to provide a detailed and dynamic understanding of groundwater systems. It helps in: simulating different extraction scenarios, hydrogeological models can predict how groundwater levels and quality will change over time. This allows for the identification of potential risks and the development of strategies to mitigate adverse effects. Accurate models enable policymakers, regulators, and industry stakeholders to make informed decisions regarding site selection, extraction methods, and mitigation measures (Adama and Okeke, 2024). This reduces the likelihood of unintended consequences and ensures sustainable resource management. Hydrogeological models can help ensure that energy extraction activities comply with environmental regulations and standards. They provide a scientific basis for setting limits on water use, monitoring groundwater conditions, and enforcing protective measures. Transparent modeling processes that involve stakeholders and public participation can build trust and acceptance of energy projects. Communities are more likely to support projects that demonstrate a commitment to safeguarding water resources (Osimobiet al., 2023).

The primary objective of this study is to develop a comprehensive hydrogeological modeling framework that can be used to safeguard underground water sources during energy extraction activities. The specific objectives are:

- To gather and analyze relevant geological, hydrological, chemical, and land use data that are critical for building accurate hydrogeological models.
- To construct robust hydrogeological models that can simulate the behavior of groundwater systems under various energy extraction scenarios.
- To assess the potential impacts of different energy extraction methods on groundwater quality and availability, including contamination risks, water table depletion, and structural changes to aquifers.
- To develop and evaluate mitigation and management strategies that can prevent or reduce adverse impacts on groundwater resources. This includes the identification of safe extraction practices, monitoring systems, and remediation techniques.
- To explore and recommend regulatory and policy frameworks that support effective groundwater protection during energy extraction activities.
- To review and analyze case studies of successful implementations of hydrogeological modeling in energy extraction projects, identifying best practices and lessons learned that can inform future efforts.

Through these objectives, the study aims to provide a scientific foundation for ensuring that energy extraction can proceed in a manner that is both economically viable and environmentally responsible, safeguarding the critical underground water resources on which so many depend (Onwuka et al., 2023).

2. Overview of hydrogeological modeling

Hydrogeological modeling is a scientific method used to simulate the behavior of groundwater systems. It involves the use of computational techniques to represent and analyze the flow and distribution of groundwater within the subsurface environment (Onwuka and Adu, 2024). The primary purpose of hydrogeological modeling is to understand and predict how groundwater systems respond to natural and anthropogenic influences, including climate variability, land use changes, and energy extraction activities.

The models serve several crucial purposes: They help predict future groundwater behavior under various scenarios, allowing for proactive management and mitigation of potential issues. They provide essential insights for decision-makers regarding the sustainable use and protection of groundwater resources. They enable the assessment of risks associated with groundwater contamination and depletion, supporting the development of strategies to minimize these risks (Ochulor et al., 2024). They assist in ensuring compliance with environmental regulations by providing a scientific basis for monitoring and managing groundwater resources.

2.1. Types of Hydrogeological Models

Hydrogeological models can be broadly classified into three types: conceptual models, numerical models, and analytical models.

Conceptual models are simplified representations of groundwater systems that outline the major hydrogeological features and processes. They provide a qualitative understanding of how groundwater flows within an aquifer, identifying key elements such as recharge areas, flow paths, and discharge zones. Numerical models use mathematical equations to simulate groundwater flow and transport processes in a quantitative manner. They are implemented using computational software that solves these equations over a discretized representation of the groundwater system (Jambol et al., 2024). Analytical models use simplified mathematical solutions to describe groundwater flow and solute transport. These models are typically applied to idealized conditions where assumptions about the aquifer properties and boundary conditions can be made.

2.2. Key Components of Hydrogeological Models

Hydrogeological models require several key components to accurately represent and simulate groundwater systems. The geological framework defines the physical structure and composition of the subsurface environment. It includes information on the stratigraphy, lithology, and structural features of the aquifer system. Provides the physical basis for modeling groundwater flow (Ukato et al., 2024). Determines the spatial distribution of hydrogeological properties.

Hydrological parameters quantify the properties of the groundwater system that affect flow and transport processes. These parameters are critical for accurately simulating groundwater behavior. Essential for defining the flow characteristics of the aquifer. Influences the movement of contaminants and the response of groundwater levels to stresses.

Boundary conditions specify the external influences on the groundwater system and define the limits within which the model operates (Jambo et al., 2024). They include the interactions between the aquifer and its surroundings. Determines the external forces acting on the groundwater system. Crucial for accurately simulating the behavior of the aquifer under different scenarios.

3. Energy extraction and its impact on underground water sources

3.1. Types of Energy Extraction

Various methods of energy extraction can have significant impacts on underground water sources. The following are the primary types of energy extraction:

Oil and gas drilling involves the extraction of hydrocarbons from subsurface reservoirs. This process can affect groundwater through the introduction of drilling fluids, potential leaks, and accidental spills (Ukato et al., 2024). Hydraulic fracturing, commonly known as fracking, is a method used to enhance the extraction of oil and gas from shale formations. It involves injecting high-pressure fluids into the subsurface to create fractures in the rock, allowing hydrocarbons to flow more freely. Geothermal energy extraction harnesses heat from the Earth's subsurface to generate electricity or provide direct heating. It typically involves drilling wells to access hot water or steam reservoirs. Coal mining, both surface and underground, can significantly alter the hydrology of an area. It involves the removal of large volumes of overburden and coal, which can disrupt groundwater flow and quality (Ochulor et al., 2024).

3.2. Potential Impacts on Underground Water

Energy extraction activities can have various potential impacts on underground water sources: The introduction of chemicals used in drilling fluids, fracking fluids, and geothermal fluids poses a risk of contaminating groundwater. Spills, leaks, and improper disposal of these fluids can lead to the infiltration of pollutants into aquifers (Igbinenikaro et al., 2024). Hydrocarbons from oil and gas drilling can contaminate groundwater with benzene, toluene, and other toxic compounds. Fracking fluids may contain a mixture of chemicals that can seep into groundwater if not properly managed.

Excessive extraction of groundwater for energy production can lead to a decline in the water table, affecting the availability of water for other uses. This is particularly concerning in areas where water resources are already scarce. Groundwater pumping for cooling purposes in geothermal plants can lower the water table (Igbinenikaro et al., 2024). The use of large volumes of water in fracking operations can deplete local groundwater supplies.

Energy extraction activities can induce changes in the subsurface structure, potentially affecting the integrity of aquifers. This can lead to issues such as subsidence, fracturing of aquifer materials, and altered groundwater flow paths. The injection of high-pressure fluids during fracking can create new fractures or reactivate existing ones, altering groundwater flow patterns. The removal of large volumes of coal during mining can cause subsidence, affecting the overlying aquifers (Igbinenikaro et al., 2024).

Understanding and managing the impacts of energy extraction on underground water sources is crucial for sustainable resource development. Hydrogeological modeling provides the tools needed to predict and mitigate these impacts, ensuring that groundwater resources are protected for future generations. By integrating geological frameworks, hydrological parameters, and boundary conditions into robust models, stakeholders can make informed decisions and develop effective strategies to safeguard this vital resource (Esho et al., 2024).

4. Model development

The development of a hydrogeological model involves several critical steps to ensure it accurately represents the groundwater system and can be used for reliable predictions.

4.1. Building the Geological Framework

The geological framework forms the structural basis of the hydrogeological model, incorporating detailed information about the subsurface environment. Stratigraphic data define the vertical layering of geological formations. This includes: Differentiating between aquifers and aquitards based on sedimentary layers (Esho et al., 2024). Establishing relationships between layers at different locations to create a continuous subsurface map. Constructing vertical profiles to visualize the subsurface structure.

Structural geology data capture the presence and orientation of faults, folds, and fractures, which influence groundwater flow: Identifying fault lines and their impacts on hydraulic conductivity. Characterizing the density and orientation of fractures within rock units. Assessing the mechanical behavior of geological materials under stress.

Hydrogeological units are delineated based on their hydraulic properties and function within the groundwater system: Permeable units that store and transmit significant quantities of groundwater. Low-permeability units that restrict groundwater flow (Esho et al., 2024). Zones where water enters or exits the groundwater system, such as recharge zones and springs.

4.2. Parameterization of the Model

Parameterization involves assigning values to the hydrological properties of the geological units, which are essential for simulating groundwater flow and transport. Hydraulic conductivity (K) measures the ease with which water can move through porous media. This involves, Conducting pump tests, slug tests, and permeameter tests to determine K values., Analyzing core samples to measure K in controlled conditions. Mapping the distribution of K values across different geological units.

Porosity (n) is the fraction of the total volume of a rock or sediment that consists of void spaces. It is determined by, Measuring the pore space in rock or sediment samples. Using borehole logs to infer porosity values. Applying known relationships between porosity and other geological properties.

Recharge and discharge rates quantify the volume of water entering and leaving the groundwater system. Methods include, Calculating recharge from precipitation, evapotranspiration, and surface runoff (Ekemezie and Digitemie, 2024). Using isotopic or chemical tracers to estimate recharge rates. Gauging flow rates at springs, rivers, and pumping wells.

4.3. Setting Up Boundary and Initial Conditions

Defining boundary and initial conditions is crucial for accurately simulating the groundwater system's behavior over time.

Defining Model Boundaries, Model boundaries delineate the limits of the groundwater system being studied. Types include, Areas where groundwater movement is negligible, often corresponding to impermeable geological formations. Zones where the groundwater level remains constant, such as large water bodies (Digitemie and Ekemezie, 2024). Locations where water enters or exits the system, such as recharge zones and extraction wells.

Initial conditions specify the starting state of the groundwater system, Initial measurements of the water table or potentiometric surface. Initial pressures in confined aquifers. Source and sink terms account for the addition or removal of water within the model, Areas where water infiltrates into the groundwater system from precipitation or surface water. Locations where groundwater is pumped out for use. Springs, rivers, and other natural outflows from the aquifer (Digitemie and Ekemezie, 2024)..

The detailed data collection and careful development of a hydrogeological model are essential steps in ensuring the model's accuracy and reliability. By integrating comprehensive geological, hydrological, chemical, and land use data, and by thoroughly defining the geological framework, hydrological parameters, and boundary conditions, a robust model can be built. This model will be capable of predicting groundwater behavior under various scenarios, thereby supporting effective management and protection of groundwater resources during energy extraction activities (Digitemie and Ekemezie, 2024)..

5. Model calibration and validation

5.1. Calibration Techniques

Calibration is the process of adjusting model parameters to ensure that the model's output aligns closely with observed data. Effective calibration is crucial for developing a reliable hydrogeological model. Manual calibration involves the iterative adjustment of model parameters by the modeler (Simpa et al., 2024). This process is typically guided by expertise and intuition, with the goal of minimizing the difference between simulated and observed values. Begin with initial estimates of key parameters based on field data and literature values. Run the model with these initial parameters and compare the results with observed data. Adjust parameters systematically based on discrepancies between model outputs and observed data. Repeat the simulation and adjustment steps until the model output closely matches the observed data. Allows the modeler to incorporate expert judgment and intuition. Provides direct control over the calibration process, facilitating the identification of specific parameter influences. Can be labor-intensive and time-consuming, especially for complex models (Solomon et al., 2024). The process may be influenced by the modeler's biases and experience.

Automated calibration uses algorithms to systematically adjust model parameters, aiming to minimize the difference between model outputs and observed data. Methods such as gradient descent, genetic algorithms, and simulated annealing that search for the best parameter set. Mathematical functions that quantify the difference between observed and simulated data, such as the sum of squared errors or mean absolute error (Obas et al., 2024). Establish an objective function that measures the goodness-of-fit between observed and simulated data. Choose an optimization algorithm to adjust parameters. Execute the algorithm, which iteratively adjusts parameters to minimize the objective function. Assess the final parameter set and model performance. Can handle large and complex models more quickly than manual calibration. Reduces subjectivity by relying on algorithmic adjustments. Requires knowledge of optimization techniques and may involve complex software (Adenekan et al., 2024). Can be computationally demanding, especially for large-scale models.

5.2. Validation Methods

Validation involves testing the calibrated model to ensure it accurately represents the real-world groundwater system. Effective validation increases confidence in the model's predictive capabilities. This method involves comparing model outputs with independent data that were not used during calibration (Joel and Oguanobi, 2024). Gather additional observed data for variables such as groundwater levels, flow rates, and water quality. Run the calibrated model to simulate the conditions represented by the new data. Compare the simulated results with the observed data. Evaluate the model's performance based on statistical measures such as root mean square error (RMSE), Nash-Sutcliffe efficiency (NSE), and correlation coefficients. Provides a clear measure of model accuracy against real-world data. Allows for quantitative assessment of model performance. Requires sufficient and reliable observed data for meaningful validation (Joel and Oguanobi, 2024). If the independent data are not representative, validation results may be misleading.

Sensitivity analysis assesses how changes in model parameters affect model outputs, helping identify which parameters have the most influence on model behavior.

Scenario testing involves running the model under different hypothetical conditions to assess its predictive capabilities and robustness (Oguanobi and Joel, 2024). Develop a range of scenarios representing different conditions (e.g., extreme weather events, changes in land use). Simulate each scenario using the calibrated model. Compare the model outputs for each scenario with expectations or available data. Evaluates model performance under a variety of conditions. Tests the model's ability to handle extreme or unusual situations. Scenarios are often hypothetical, so direct comparison with real data may not be possible (Oguanobi and Joel, 2024). Developing and interpreting multiple scenarios can be complex.

6. Case studies

Examining case studies of hydrogeological modeling provides valuable insights into the practical application of these techniques for safeguarding underground water sources during energy extraction. These examples highlight successful implementations, lessons learned, and comparisons of various energy extraction methods.

6.1. Successful Implementations of Hydrogeological Modeling

The Marcellus Shale Region, USA, The Marcellus Shale is a major natural gas field in the northeastern United States, spanning several states including Pennsylvania, New York, and West Virginia. The region has seen extensive hydraulic fracturing (fracking) activities to extract natural gas from shale formations. Objective, To assess and manage the impacts of fracking on groundwater resources, including potential contamination from fracking fluids and methane migration. A comprehensive hydrogeological model was developed incorporating geological, hydrological, and chemical data. The model simulated groundwater flow, contaminant transport, and methane migration pathways. The model helped identify critical areas at risk of contamination and informed the implementation of monitoring and mitigation measures. As a result, groundwater quality has been effectively monitored and managed, with early detection systems in place to address potential contamination incidents.

The Great Artesian Basin, Australia, The Great Artesian Basin (GAB) is one of the largest artesian groundwater basins in the world, covering 1.7 million square kilometers. It supports various activities, including coal seam gas (CSG) extraction. Objective, To understand the impacts of CSG extraction on the groundwater levels and pressure within the GAB. A regional-scale numerical groundwater model was developed to simulate the impacts of water extraction for CSG activities on the basin's aquifers. The model provided critical insights into the cumulative impacts of multiple CSG projects on groundwater resources. It guided regulatory decisions, ensuring sustainable extraction rates and effective management of groundwater pressure levels, preventing significant declines and maintaining the basin's ecological and economic value.

Geothermal Energy in Iceland, Iceland extensively utilizes geothermal energy for heating and electricity generation, capitalizing on its abundant geothermal resources. Objective, To optimize geothermal resource extraction while protecting groundwater quality and preventing land subsidence. Detailed hydrogeological models were developed for major geothermal fields, incorporating thermal, hydrological, and geological data. These models simulated the impacts of geothermal fluid extraction on subsurface temperatures, pressure, and groundwater flow. The models have been instrumental in designing sustainable extraction schemes that balance energy production with groundwater protection. They have also helped identify optimal reinjection sites to maintain reservoir pressure and prevent subsidence.

6.2. Lessons Learned from Past Projects

Successful hydrogeological modeling requires the integration of multidisciplinary data, including geological, hydrological, chemical, and land use information. Collaborative efforts among geologists, hydrologists, engineers, and environmental scientists enhance model accuracy and reliability. In the Marcellus Shale project, integrating chemical data on fracking fluids with geological and hydrological information was crucial for accurately predicting contaminant migration pathways (Onwuka and Adu, 2024). Continuous monitoring and data collection are essential for validating models and adapting management strategies. Real-time data collection and remote sensing technologies provide valuable information for ongoing model calibration and adjustment (Adama et al., 2024). The Great Artesian Basin project demonstrated the importance of maintaining a network of monitoring wells to track changes in groundwater pressure and levels, ensuring that the model remained accurate and relevant over time (Onwuka and Adu, 2024). Adaptive management approaches allow for flexibility in response to new data and changing conditions. This iterative process involves updating models and management strategies based on monitoring results and new scientific knowledge. In Iceland's geothermal energy projects, adaptive management has been key to optimizing resource extraction while minimizing environmental impacts. Regular updates to the hydrogeological models based on monitoring data have ensured sustainable geothermal energy production (Akinsanya et al., 2024). Engaging local communities and stakeholders in the modeling and decision-making processes enhances transparency and builds trust (Onwuka and Adu, 2024). Incorporating local knowledge and addressing stakeholder concerns can lead to more effective and accepted management strategies. The Marcellus Shale project involved extensive stakeholder engagement, including public meetings and consultations with local communities. This approach helped address concerns about groundwater contamination and ensured that the management strategies had broad support.

Case studies of hydrogeological modeling in various energy extraction contexts demonstrate the critical role these models play in safeguarding groundwater resources. Successful implementations highlight the importance of multidisciplinary data integration, continuous monitoring, adaptive management, and stakeholder engagement (Adama and Okeke, 2024). Lessons learned from past projects underscore the need for flexibility and community involvement. Comparing different energy extraction methods reveals the unique challenges and modeling requirements associated with each, emphasizing the tailored approaches necessary to effectively manage and mitigate their impacts on underground water sources (Popoola et al., 2024).

7. Conclusion

The exploration of hydrogeological modeling in the context of safeguarding underground water sources during energy extraction has illuminated several key findings, Hydrogeological modeling serves as a powerful tool for assessing and managing the impacts of energy extraction activities on groundwater resources. By integrating geological, hydrological, and chemical data, models can simulate groundwater flow, contaminant transport, and subsurface changes, enabling informed decision-making and the development of targeted mitigation measures. Case studies from diverse regions and energy extraction methods have demonstrated the successful application of hydrogeological modeling. These examples have showcased the importance of multidisciplinary data integration, continuous monitoring, and stakeholder engagement in achieving sustainable resource management outcomes. Lessons from past projects underscore the importance of adaptive management and flexibility in responding to evolving conditions and new scientific knowledge. Continuous monitoring, data collection, and stakeholder involvement are essential for refining models and management strategies over time.

Continuous monitoring and adaptive management emerge as critical components of effective groundwater management strategies. Real-time data collection, remote sensing technologies, and monitoring networks provide essential information for validating models, detecting changes in groundwater conditions, and identifying emerging risks. This continuous feedback loop enables stakeholders to respond promptly to evolving conditions and implement timely interventions. Adaptive management approaches allow for flexibility in adjusting management strategies based on new information and changing circumstances. By regularly updating hydrogeological models and management plans in response to monitoring data and stakeholder input, decision-makers can optimize resource management outcomes and minimize negative impacts on underground water sources.

As hydrogeological modeling continues to evolve, several avenues for future research and development emerge, Enhancing the integration of multidisciplinary data sources, including advancements in remote sensing technologies and data analytics, can enhance the accuracy and reliability of hydrogeological models. Further research into quantifying model uncertainty and conducting sensitivity analyses will improve our understanding of model limitations and enhance the robustness of modeling results. Exploring advanced modeling techniques, such as coupled hydrogeological and geomechanical models, can provide a more comprehensive understanding of subsurface processes and their interactions. Developing decision support systems that incorporate stakeholder preferences, risk tolerances, and socioeconomic factors can facilitate more informed and transparent decision-making processes. Integrating climate change scenarios into hydrogeological models will be crucial for assessing future impacts on groundwater resources and developing adaptation strategies to mitigate potential risks. Fostering collaboration and knowledge sharing among researchers, practitioners, and policymakers globally can accelerate advancements in hydrogeological modeling and promote best practices for sustainable groundwater management. In conclusion, hydrogeological modeling plays a pivotal role in safeguarding underground water sources during energy extraction activities. By integrating scientific data, stakeholder input, and adaptive management strategies, hydrogeological models can inform sustainable resource management practices and contribute to the protection of groundwater for current and future generations. Continued research and development efforts will be essential for advancing the field of hydrogeological modeling and addressing emerging challenges in groundwater management.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest exists among the Authors.

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