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Review Article

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The Impact of Geological Structures on Groundwater Potential Assessment in Volcanic Rocks of the Northwestern Ethiopian Plateau: A Review

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Abstract

This review examines the influence of geological structures on groundwater potential in the volcanic rocks of the Northwestern Ethiopian Plateau. The region's tectonic complexity has shaped fractures, faults and other features that significantly impact groundwater storage and flow. Geological structures, including faults, fractures, folds and lineaments, play a crucial role in groundwater dynamics, particularly in terrains with limited primary porosity, where secondary porosity dominates aquifer characteristics. Faults can act as conduits or barriers, controlling recharge, flow and discharge based on their structural properties and interaction with surrounding rocks. Fractures create secondary porosity, enabling groundwater storage and movement in otherwise impermeable rocks. Lineaments, representing subsurface features such as faults and lithological boundaries, are key indicators of groundwater potential, especially in hard-rock and volcanic terrains. Additionally, folding influences aquifer configuration and flow by creating confined or unconfined groundwater systems through anticlines, synclines and other structures. The review underscores the importance of integrating geological, geophysical and hydrological methods for effective groundwater exploration and management. Volcanic terrains present unique challenges due to their complex lithology and structural heterogeneity. Case studies from various volcanic settings demonstrate how structural features enhance or restrict groundwater movement and highlight the interplay between volcanic lithology and tectonic processes. Recommendations are provided for using a multidisciplinary approach to address these challenges and ensure sustainable groundwater resource management in volcanic regions.

Keywords: Geological structures, Groundwater potential, Volcanic rocks, Ethiopian plateau, Hydrogeology

Introduction

Groundwater is a crucial resource, especially in arid and semi-arid areas where surface water is limited or unreliable [1-3]. In regions with low primary porosity, geological structures like faults, fractures, joints, lineaments and dykes significantly influence groundwater dynamics. These structures can either act as barriers or conduits for groundwater flow, depending on their characteristics such as orientation, density, connectivity and permeability [4]. Faults and fractures often facilitate groundwater flow, while folds and impermeable layers can obstruct it. The interaction between subsurface fluids and faulting is well-documented, making the study of these structures essential for effective groundwater management, particularly in areas where water resources are scarce [5]. In Ethiopia, groundwater is vital, particularly in the arid and semi-arid regions where surface water is unreliable. The Northwestern Ethiopian Plateau, dominated by volcanic rocks formed by Tertiary to Quaternary volcanic activities, is significantly influenced by tectonic processes, particularly those related to the East African Rift System [6-9]. This results in a complex array of fractures, faults and other geological features that govern groundwater movement. Understanding how geological structures influence groundwater is essential for managing this resource effectively. This review evaluates the impact of these structures on groundwater potential in volcanic terrains, focusing on the Northwestern Ethiopian Plateau. Groundwater in volcanic areas is controlled by the physical properties of volcanic rocks and the structural changes caused by tectonic activity. Key factors such as lithological heterogeneity, the degree of fracturing and weathering processes dictate the distribution of groundwater in these regions [10]. In volcanic terrains, faults are particularly significant. These discontinuities in the Earth's crust can either enhance or restrict groundwater flow, depending on their displacement, orientation and associated materials. Faults may serve as conduits for water flow and recharge or act as barriers to groundwater movement. Therefore, understanding fault dynamics is crucial for groundwater management, especially in regions with complex geology [10]. Volcanic rocks are often heterogeneous and anisotropic, making groundwater exploration challenging. The movement and storage of groundwater in these terrains are heavily influenced by geological structures such as faults, fractures, joints and

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lithological contacts. This review aims to provide a deeper understanding of how these structures shape groundwater potential in volcanic regions, particularly in the Northwestern Ethiopian Plateau [1,11]. Fractures, caused by stress in rocks, are essential for groundwater flow in hard-rock terrains. Unlike primary porosity in sedimentary rocks, fractured rocks rely on secondary porosity to store and transmit groundwater. This makes understanding the nature and behavior of fractures critical for groundwater exploration in crystalline and volcanic terrains [13]. Lineaments, visible as linear features on satellite images, often indicate zones of structural weakness, such as fractures and faults, that influence groundwater movement. Identifying and analyzing these lineaments are vital for exploring groundwater resources in areas with complex geological conditions [12]. Folding, another tectonic process common in volcanic regions, leads to the deformation of primary lithological units. The resulting folds can affect the orientation, connectivity and storage capacity of aquifers. In volcanic terrains, folding has significant hydrogeological implications, as it often leads to the creation of confined or semi-confined groundwater systems [14]. The complex interaction between folding and groundwater movement makes it essential to consider this process when assessing groundwater resources in such regions. Thus, understanding the role of geological structures in groundwater dynamics is essential for managing water resources, particularly in volcanic regions like the Northwestern Ethiopian Plateau. Faults, fractures, lineaments and folds all play crucial roles in controlling groundwater flow and storage (Figure 1).

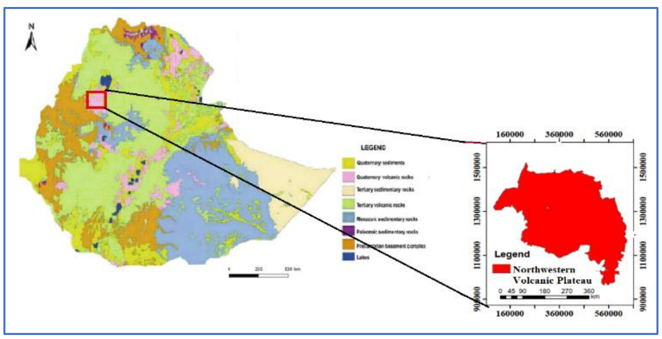

Figure 1: The spatial distribution of geology by Berhanu et al., (on the left side) and the study area (Northwestern Volcanic Plateau) [15].

Methods for Assessing Structural Influence on Groundwater Potential

Assessing groundwater potential in volcanic terrains requires a multi-faceted approach, integrating geological, geophysical, remote sensing, GIS and hydrogeological methods.

Geological mapping

Geological mapping is a crucial tool for understanding the distribution of faults, fractures and folds in volcanic regions. Detailed structural mapping helps identify key areas for groundwater recharge and defines aquifer boundaries [17]. This method allows for the identification of fault zones, fractures and variations in rock types critical to groundwater exploration [18]. Field studies are essential for observing surface fractures and correlating them with groundwater potential. Mapping fracture zones helps to assess their orientation, density and connectivity, which are important for groundwater flow [12,19]. Remote sensing techniques, combined with GIS, enhance lineament detection and analysis. High-resolution satellite images, such as those from Landsat and Sentine-l-2 and Digital Elevation Models (DEMs) help identify and analyze lineaments, while GIS tools assist in calculating lineament density, providing valuable information for groundwater mapping [16].

Geophysical techniques

Geophysical methods, including electrical resistivity, seismic surveys and magnetic techniques, are commonly used to explore subsurface structures and aquifers. These methods are effective in detecting fault zones associated with groundwater movement and in mapping fracture zones within aquifers [12,17]. Electrical resistivity surveys, in particular, are valuable for high-resolution mapping of shallow fractures, helping to delineate areas with significant groundwater potential [20].

Remote sensing and GIS

Remote sensing and GIS are powerful tools for lineament mapping and spatial analysis of groundwater potential. By combining remote sensing data with field observations, these tools have improved the efficiency of groundwater exploration. Satellite imagery, such as from Landsat or Sentinel-2, can be used to map lineaments, revealing fracture patterns that directly correlate with groundwater potential. The integration of GIS allows for spatial analysis that enhances the understanding of groundwater systems and aids in predicting areas of high groundwater yield [21].

Hydrogeological studies

Hydrogeological studies, including aquifer tests, tracer studies and water table monitoring, are essential for understanding aquifer properties and groundwater movement. These studies provide insights into recharge rates, flow mechanisms and the dynamics of fractured aquifers. Hydraulic tests, such as pumping and slug tests, help quantify key parameters like hydraulic conductivity and transmissivity in fractured aquifers [10]. The results are vital for assessing the productivity of groundwater systems influenced by geological structures. Areas with dense lineament patterns often correlate with high-yield groundwater wells, particularly where lineament intersections occur, as they enhance permeability and groundwater flow [18]. Combining lineament analysis with other hydrogeological data provides a comprehensive understanding of groundwater potential, especially in arid and semi-arid regions, where groundwater is a vital resource [21].

Role of Geological Structures in Groundwater potential

Geological structures are critical in influencing groundwater dynamics in volcanic terrains.

Faults and their role in groundwater systems

Faults play a significant role in shaping groundwater potential by creating pathways for water flow or acting as barriers. Normal faults often facilitate groundwater recharge, while reverse faults can restrict flow due to compression and low permeability. The hydraulic conductivity of fault zones varies depending on the infilling material; materials like clay or gouge reduce permeability, while open fractures enhance it, allowing for easier water movement. In cases where faults are filled with low-permeability materials, such as clay or calcite, they may act as barriers, disrupting groundwater flow and forming perched water tables or isolated groundwater systems [17]. Faults can enhance groundwater movement in volcanic terrains, particularly where fracturing and brecciation have occurred. These fractures and fault planes create preferential pathways for water, linking aquifers and increasing recharge. In volcanic regions, fault zones often correspond with high-yielding wells due to the secondary porosity they create. Faults are also associated with springs, where groundwater rises to the surface through fault intersections with aquifers. These springs serve as important indicators of subsurface hydrogeology and are commonly utilized as drinking water sources in fault-prone areas [10]. However, faults filled with impermeable materials such as clay or silica can reduce permeability and restrict groundwater flow, making them barriers. The permeability of fault zones is influenced by factors like fault orientation, the stress field and the direction of groundwater flow. Vertical faults generally promote vertical water flow, while horizontal or shallow faults can act as barriers [12]. The width of the fault zone also affects its ability to facilitate water flow; narrow, well-fractured faults tend to enhance flow, while wider zones filled with gouge material may impede it [22]. The surrounding lithology further influences fault behavior, with faults in basaltic rock typically enhancing flow due to the rock's fractured nature, while those in pyroclastic material may have more variable effects, depending on consolidation and weathering [18,22].

Fractures and secondary porosity

Fractures play a crucial role in enhancing secondary porosity, which significantly influences groundwater storage and movement in consolidated rocks. In highly fractured zones, groundwater yields tend to be higher due to increased permeability and connectivity. In volcanic terrains, for instance, fractured basalts act as primary aquifers, while unfractured basalts typically serve as aquitards [18]. Fractures allow surface water to penetrate deeper into the subsurface, enhancing recharge in areas with dense fracturing, which often results in higher groundwater potential [22]. The effectiveness of fractures as groundwater conduits largely depends on their connectivity. Well-connected fractures form extensive networks that facilitate both lateral and vertical water flow, whereas isolated fractures may restrict groundwater movement [20]. In hard rocks, like basalt, granite and gneiss, groundwater storage is almost entirely dependent on the presence of fractures, as these rocks generally have low primary porosity. The aperture or width of fractures also plays a significant role in their hydraulic conductivity. Wider fractures allow for greater water flow, while narrow fractures may impede movement. Fractures infilled with materials such as clay or calcite can reduce hydraulic conductivity and limit water movement [12]. Additionally, the orientation of fractures relative to the regional stress field and topography influences groundwater flow. Fractures aligned with the hydraulic gradient promote flow, whereas those oriented perpendicular to it may hinder movement [10]. Higher fracture density is generally associated with increased groundwater storage and flow, although excessive fracturing can lead to water loss due to rapid drainage into deeper zones [17].

Lineaments and groundwater potential

Lineaments, which are surface expressions of subsurface geological structures, play a crucial role in groundwater exploration. Studies using remote sensing and GIS have shown that areas with high lineament density tend to have higher groundwater yields. These linear features often mark zones of increased permeability and recharge potential. Lineaments provide direct pathways for surface water to infiltrate into the subsurface, enhancing recharge in regions where primary porosity is limited. Areas with dense lineaments generally exhibit improved groundwater potential due to the enhanced connectivity between fractures. Lineaments serve as conduits for groundwater flow, particularly in terrains lacking significant primary porosity. Their orientation and connectivity are critical in determining regional groundwater flow patterns [10]. In hard-rock and volcanic terrains, lineaments often define areas with increased secondary porosity, which can enhance aquifer storage capacity. These regions are commonly targeted for high-yield wells [18]. The effectiveness of lineaments in influencing groundwater dynamics depends on their depth, width and the degree of weathering of the underlying rocks [21,22].

Folding and its impact on aquifer systems

Folds, especially anticlines, can create confined aquifers by trapping water between impermeable layers. Synclines, which are trough-like folds with layers dipping towards the center, can serve as groundwater reservoirs when composed of permeable materials like fractured basalts. The impermeable layers at the edges of synclines can prevent lateral water flow, enhancing storage [10]. In volcanic terrains, synclines may act as groundwater reservoirs depending on their lithology and structural configuration [22]. Anticlines, arch-like folds where layers dip away from the crest, can trap groundwater beneath impermeable layers, forming confined aquifers that are often under artesian pressure. These aquifers are significant groundwater resources [12]. Recharge zones are typically located along the flanks of anticlines where fractures and faults intersect the surface. Volcanic rocks, with their alternating layers of permeable (e.g., fractured basalt) and impermeable (e.g., volcanic ash) materials, can create complex aquifer systems through folding. Tightly folded volcanic sequences can lead to compartmentalization of groundwater flow, complicating recharge and extraction processes [18]. Folding also generates secondary porosity through fractures formed along fold axes and limbs, which enhances permeability and facilitates groundwater flow. In volcanic terrains, the orientation and density of these fractures are key factors in determining the hydraulic conductivity of folded structures [20].

Case Studies

Northwestern Ethiopian Plateau

The Northwestern Ethiopian Plateau, part of the larger Ethiopian Highlands, is a significant region for groundwater resources, providing water for both rural and urban populations [23]. The plateau features a complex geological setting, with basaltic volcanic rocks, faulting and sedimentary layers, all of which affect groundwater availability and movement. This case study examines the geological, hydrological and environmental factors that influence groundwater potential in the Northwestern Ethiopian Plateau [24,25]. Groundwater potential in the volcanic regions of the Northwestern Ethiopian Plateau is significantly influenced by geological structures and lithology. In this area, fractured basalts and fault zones act as primary aquifers, while interbedded pyroclastic deposits often serve as aquitards [26]. Geophysical surveys and lineament mapping have been effectively utilized to identify areas with high groundwater yields, contributing to the efficient management of water resources in the region [18]. These techniques have proven particularly useful in locating high-yielding wells, which are often found near major lineaments, highlighting their critical role in groundwater exploration and development [21]. The Northwestern Ethiopian Plateau lies within the Northern Main Ethiopian Rift (NMER) of the East African Rift System (EARS), which trends NE-SW and connects with the Afar Triple Junction. This region is characterized by active tectonic extension and volcanism [6,7]. The NMER region also exhibits significant Quaternary faulting and a complex geomorphological landscape, which further influences groundwater availability [4]. Thus, The Northwestern Ethiopian Plateau has significant groundwater potential due to its unique geological structures, such as volcanic rocks, fault zones and sedimentary layers. However, this potential is threatened by over-extraction, environmental degradation and climate change. Sustainable groundwater management strategies, including mapping geological structures, land conservation and reforestation, are essential to ensure the long-term availability of water for both agricultural and urban needs.

East African rift system

The East African Rift System (EARS) is one of the most significant geological features in the world, stretching from the Red Sea in the north to Mozambique in the south. This tectonic plate boundary is characterized by faulting, volcanic activity and the formation of deep rift valleys. The geological structures in the EARS such as faults, fractures, volcanic rocks and sedimentary deposits play a crucial role in groundwater storage and flow. Understanding the hydrogeology of the region is essential for assessing the groundwater potential, especially in areas where surface water resources are scarce or unreliable. A study by Kebede et al., explored the groundwater potential of the East African Rift System by examining the hydrogeological properties of the region, including geological mapping, borehole data and geophysical surveys [27]. The East African Rift System (EARS) serves as a key example of how tectonic processes influence groundwater potential in volcanic regions. In this system, faults and fractures enhance secondary porosity, leading to the development of extensive aquifer systems. However, the complex variability in volcanic lithology can present challenges in groundwater exploration. Fault zones in the EARS play a crucial role in groundwater dynamics by acting as recharge pathways, while impermeable volcanic layers limit lateral water flow. Fractures associated with tectonic activity in the rift are particularly important for groundwater recharge and storage. Normal faults, along with the fractures they generate, facilitate recharge and support the storage of water in rift valley aquifers, which is essential for supplying water to arid regions. Additionally, lineaments formed by faults further enhance recharge and water storage in fractured aquifers, making them critical sources of groundwater in these drought-prone areas. Folding in volcanic terrains along the EARS creates alternating layers of permeable and impermeable materials. Recharge primarily occurs along the flanks of anticlines, while synclinal troughs act as natural storage zones. These folded structures are vital for regional water supply, especially in arid zones where surface water is scarce [17]. In Ethiopia, groundwater is a major source of fresh water for domestic, industrial and agricultural needs, particularly in the absence of reliable surface water. Ethiopia, often referred to as the "Water Tower of Northeast Africa," is home to numerous rivers that flow from the highlands to lowland areas and neighboring countries [1]. Given the critical role of groundwater, it is essential to ensure its year-round availability by conducting detailed field investigations, incorporating satellite imagery and assessing the region's geological structures and geomorphological features [28,29]. Thus, the East African Rift System offers significant groundwater potential due to its complex geological structures, including volcanic rocks, fault zones and sedimentary basins. However, this potential varies greatly across the region and careful management is required to prevent over-extraction and degradation. Integrated geological and structural mapping practices, enhanced groundwater recharge and proper monitoring are essential to ensure the sustainability of groundwater resources in this critical region.

Challenges and Opportunities

Challenges and limitations

Groundwater exploration in the volcanic terrains of the Northwestern Ethiopian Plateau faces several challenges:

Data scarcity: A major limitation is the lack of high-resolution geological and geophysical data, which hinders a thorough understanding of the structural controls on groundwater potential. Additionally, the resolution of remote sensing data may not be sufficient to accurately map lineaments, which are critical for groundwater exploration.

Structural complexity: The variation in fault orientations, fracture densities and lithological diversity complicates the prediction of groundwater flow paths. The anisotropic nature of fractured and folded aquifers further complicates flow modeling and groundwater movement predictions.

Climate variability: Unpredictable rainfall patterns impact recharge rates and groundwater availability. Changes in precipitation due to climate fluctuations affect the reliability of structurally controlled aquifers, especially in regions with complex geological structures. Variations in recharge rates can undermine the consistency of groundwater resources, especially in folded aquifer systems where recharge mechanisms are less predictable.

Complex flow paths: In volcanic regions, groundwater movement often follows intricate and unpredictable flow paths, exacerbating difficulties in estimating groundwater availability and potential. The interactions between structural features, such as faults and fractures, with surface and subsurface conditions are not easily modeled.

Opportunities

Advanced mapping techniques: Remote sensing and Geographic Information Systems (GIS) offer valuable tools for mapping and characterizing geological structures like folds, faults and fractures in volcanic terrains. These technologies enable more accurate identification of groundwater recharge zones and flow pathways. Furthermore, advancements in geophysical techniques, such as electrical resistivity and seismic surveys, allow for better mapping of fault zones and aquifer systems.

Integrated approaches: Combining geological, geophysical and hydrogeological data is a promising strategy for improving groundwater management, especially in complex volcanic regions. Integrated approaches allow for a more comprehensive understanding of the dynamics of fault-controlled aquifers and fractured groundwater systems. By synthesizing multiple datasets, more accurate predictions of groundwater availability and sustainable management strategies can be developed.

Innovative tools and algorithms: The use of advanced algorithms to automate the detection and analysis of lineaments and other geological structures can significantly enhance the accuracy and efficiency of groundwater exploration. These innovations also allow for improved mapping of fracture-controlled aquifers, which are critical in volcanic terrains where primary porosity is often absent [30-33].

Conclusion

Geological structures are fundamental in determining groundwater dynamics in the volcanic rocks of the Northwestern Ethiopian Plateau. This review synthesizes existing research, emphasizing the critical role of faults, fractures and lithological variations in groundwater potential assessments. The integration of advanced techniques and addressing data gaps will be vital for ensuring sustainable groundwater resource management in the region. Faults have a dual impact on groundwater potential, acting both as conduits and barriers, depending on their structural features and the materials that fill them. A comprehensive understanding of the hydrogeological behavior of faults is essential for effective groundwater exploration and management. Advances in mapping technologies, geophysics and remote sensing are increasingly enhancing our ability to assess fault-controlled aquifers and develop sustainable groundwater systems. Fractures are a key component in groundwater systems, particularly in hard-rock and volcanic terrains where primary porosity is often minimal. Their effectiveness as groundwater conduits and storage zones is determined by factors such as orientation, density and connectivity. Advances in geophysical methods, remote sensing and hydrogeological studies have significantly improved our understanding of fracture-controlled aquifers, which are vital in many volcanic regions. Lineaments are crucial for exploring groundwater systems, particularly in areas with low primary porosity. These structural features serve as conduits for recharge and groundwater flow, making them prime targets for high-yielding wells and sustainable water resource management. The development of remote sensing, GIS and geophysical tools has greatly enhanced lineament analysis, providing new opportunities for groundwater exploration in complex geological environments. Folding, particularly in volcanic rocks, significantly impacts aquifer systems by influencing groundwater storage, flow and recharge. Anticlines and synclines, along with their associated fractures, shape groundwater dynamics, making an understanding of folded volcanic terrains essential for effective exploration. The complexity of these folded systems highlights the importance of integrating structural and lithological data for successful groundwater management. Thus, by integrating multidisciplinary approaches-combining geology, geophysics, hydrogeology, remote sensing and GIS—is crucial for improving groundwater resource management in the volcanic terrains of the Northwestern Ethiopian Plateau and similar regions. Addressing current challenges and leveraging new technologies will enable the development of sustainable groundwater resources to meet the needs of growing populations in such areas.

Recommendations and Future Directions

To enhance groundwater potential assessment in the Northwestern Ethiopian Plateau, the following steps are recommended:

Integrated approaches: Combining geological, geophysical and hydrological techniques for comprehensive groundwater assessments is crucial. A multidisciplinary approach will provide a more holistic understanding of the region's groundwater systems and improve the accuracy of potential zones identification.

High-resolution mapping: The use of advanced remote sensing and GIS technologies is essential for improving the identification of groundwater potential zones. High-resolution imagery, coupled with GIS tools, will help delineate fault zones, fractures and other structural features that influence groundwater availability, leading to more accurate and efficient exploration efforts.

Long-term monitoring: Establishing monitoring networks across key regions will allow for the ongoing assessment of groundwater systems, particularly to track the impact of climatic fluctuations and structural changes on groundwater recharge and flow patterns. Long-term data will help in predicting future groundwater trends and guide sustainable resource management.

Develop robust models: Future research should focus on developing advanced models that integrate structural geology, hydrological and climatic data. These models would provide a dynamic and predictive understanding of groundwater systems, enabling more effective and sustainable groundwater management. Simulating various scenarios, such as climate change or land-use modifications, will be essential for ensuring the long-term viability of groundwater resources in volcanic terrains.

Data Availability Statement

The data supporting the findings of this study are provided within the manuscript.

Author Contributions

Bishaw Mihret: Conceptualized the study, designed the methodology, experimented and performed data analysis. Ajebush Wuletaw: Contributed to writing the manuscript, provided supervision, reviewed the manuscript and contributed to critical revisions. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare that they have no competing interests.

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