Review Article

Impact of geology on hydrogeological and hydrochemical characteristics of groundwater in tropical environments: a narrative review

Abstract

Groundwater is critical in sustaining ecosystems, agriculture, and human livelihoods, particularly in tropical regions where it is often the primary source of freshwater. However, the management of groundwater resources is increasingly threatened by over-extraction, contamination, and the compounding effects of climate change. This review synthesizes critical challenges and future directions in understanding hydrogeology, hydrochemistry, and groundwater management in tropical environments, explicitly focusing on case studies from the Global South. Groundwater quality is shaped by natural geological factors and anthropogenic activities, with trace elements such as arsenic, fluoride, and heavy metals significantly contributing to contamination in several regions. Human-induced pollution, particularly from agricultural practices, mining, and urbanization, further degrades water quality, posing serious public health risks. Through case studies from Bangladesh, East Africa, Latin America, and coastal regions of India, this review explores the diverse ways in which natural and human-induced factors intersect to affect groundwater quality and availability. Each case highlights the complexity of managing groundwater resources in diverse geological and socio-economic contexts. In Bangladesh, the widespread issue of arsenic contamination due to naturally occurring elements mobilized by groundwater extraction has resulted in severe health impacts. High fluoride concentrations in the groundwater of East Africa, exacerbated by volcanic geology, have led to widespread dental and skeletal fluorosis. In Latin America, mining activities have contaminated aquifers with heavy metals, threatening human and agricultural water supplies. In coastal India, excessive groundwater extraction has caused saltwater intrusion, further complicating water security. This review identifies over-extraction, poor water quality, climate change impacts, and weak governance as significant challenges in groundwater management. Future directions include integrating advanced monitoring technologies, interdisciplinary research, community participation, and policy reforms to promote sustainable use and protection of groundwater. Effective management will require a combination of scientific innovation, robust regulatory frameworks, and increased public awareness to ensure long-term water security in tropical regions and beyond.

Keywords: groundwater, hydrogeology, hydrochemistry, tropical environments, global south, over-extraction, contamination, trace elements

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Introduction

Groundwater is one of the most vital resources for human survival, supporting agricultural, domestic, and industrial needs, particularly in tropical environments where surface water resources may be unreliable or limited.[1] In tropical regions, with their varied geological landscapes and climates, groundwater systems are complex and highly dependent on the underlying geological structures. The interaction between groundwater and the geology of an area profoundly influences its hydrological and hydrochemical characteristics.[2] This introduction explores geology's essential roles in determining these features, focusing on tropical environments where high temperatures, seasonal rainfall, and intense weathering create unique groundwater conditions. A region's geology dictates groundwater's distribution, movement, and quality. The rock formations' type, permeability, porosity, and structural characteristics—such as fractures, folds, and faults—determine how water is stored and transmitted underground.[3] In tropical regions, the weathering profiles of rocks are often more intense due to the warm, moist climate, significantly influencing groundwater recharge processes. As a result, groundwater systems in tropical environments are intricately linked with geology, which acts as a natural control for water availability, movement, and quality.

One of the fundamental factors influenced by geology is the aquifer type. Aquifers, the permeable rock formations that store groundwater, vary widely in their capacity to hold and transmit water, depending on the geological materials that compose them.[4] In tropical regions, aquifers may be found in various geological settings, from unconsolidated sediments in river valleys to fractured basement rocks and Karstified Limestones in more complex terrains. The nature of these aquifers is a direct consequence of the underlying geology, and each type exhibits unique hydrological behaviours.[5] For example, alluvial aquifers, often found in valleys and floodplains, are typically associated with high porosity and permeability, allowing for easy recharge and high water yields.

Conversely, aquifers in fractured crystalline basement rocks, common in many tropical regions, may have lower porosity and permeability but can transmit groundwater through fractures and faults. In addition to aquifer type, geological structures such as faults and folds can create conduits or barriers to groundwater flow.[6] These structures often result from tectonic activity in tropical environments, influencing how groundwater moves through the subsurface. Faults, for example, can act as channels for groundwater movement, allowing water to flow between different rock layers or aquifers. On the other hand, they can also act as barriers, blocking water movement and creating localized areas of groundwater accumulation or depletion.[6] This complex interplay between geology and groundwater movement highlights the importance of understanding geological structures when assessing groundwater resources in tropical regions.

Moreover, the hydrochemical characteristics of groundwater are also closely tied to the geology of an area. As groundwater moves through the subsurface, it interacts with the minerals and rocks it encounters, undergoing chemical reactions that alter its composition. These interactions are particularly pronounced in tropical regions where the climate fosters intense weathering.[7] Dissolving minerals from the host rock can lead to elevated concentrations of specific ions in the groundwater, affecting its quality and suitability for various uses. For example, groundwater in areas with limestone or dolomite bedrock may have high concentrations of calcium and magnesium, leading to hard water.[8]

Similarly, groundwater in regions with high concentrations of evaporate minerals, such as gypsum or halite, may contain elevated levels of sulfate or chloride.[9] The intensity of weathering in tropical environments further amplifies the influence of geology on groundwater chemistry. Weathering processes, driven by high temperatures and abundant rainfall, break down rock minerals and release ions into the groundwater.[10] In tropical regions, chemical weathering dominates, forming thick weathering profiles, often referred to as laterites, significantly influencing groundwater recharge and chemistry. The weathering products, such as clays and iron oxides, can affect the movement of water through the subsurface by altering the permeability of the soil and rock layers. Additionally, the leaching of soluble ions from weathered rocks can lead to the development of distinct groundwater chemistries, with elevated concentrations of certain elements depending on the composition of the parent rock.[11]

Geological formations also play a critical role in the spatial distribution of groundwater resources in tropical regions. The variability in rock types and structures across the landscape leads to significant heterogeneity in groundwater availability.[12] In some areas, groundwater may be abundant and easily accessible, while in others, it may be scarce or difficult to extract due to low-permeability rocks or complex geological structures. For instance, groundwater is often found in discrete pockets within fractures and weathered zones in areas underlain by crystalline basement rocks, making its occurrence highly variable.[13] On the other hand, sedimentary basins, with their more homogeneous and permeable rock formations, may offer more consistent and reliable groundwater resources.[14]

The influence of geology on groundwater in tropical environments is not limited to the physical and chemical characteristics of the water itself but also extends to the sustainability and management of groundwater resources.[1] Understanding the geological controls on groundwater flow and recharge is essential for developing sustainable groundwater management strategies, particularly in regions where water resources are under increasing pressure from population growth, agricultural expansion, and climate change. In tropical regions, where rainfall is often seasonal and highly variable, groundwater serves as a crucial buffer against periods of drought and water scarcity.[15] However, the ability of aquifers to recharge and sustain water levels during dry periods heavily depends on the geological conditions that control infiltration and storage.

For example, in areas with highly permeable soils and rock formations, such as alluvial plains or karstic regions, groundwater recharge may be relatively rapid and efficient during the rainy season, allowing aquifers to replenish quickly.[16] Conversely, recharge may be slower and more limited in regions with low-permeability rocks, such as those dominated by crystalline basement formations, making these aquifers more vulnerable to over-extraction and depletion. The geological setting also influences the response of groundwater systems to human activities, such as drilling and pumping, with different aquifer types exhibiting varying degrees of resilience to extraction.[17] In areas where groundwater is extracted from confined aquifers, for example, the depletion of water resources can lead to land subsidence and other long-term environmental impacts.

Furthermore, geology plays a crucial role in determining the vulnerability of groundwater to contamination, which is a significant concern in tropical environments where agricultural and industrial activities are intensifying.[18] The movement of contaminants through the subsurface is controlled by the porosity and permeability of the geological materials, as well as the presence of natural filtration mechanisms, such as clay layers or fractured rock zones.[19] In areas with highly permeable rocks or soils, contaminants can easily infiltrate and spread through the groundwater system, posing a risk to water quality and public health. Conversely, in regions with low-permeability formations, such as clay-rich soils or unfractured crystalline rocks, the movement of contaminants may be slower, allowing for natural attenuation processes to reduce their concentrations before they reach groundwater supplies.[20]

The hydrochemical evolution of groundwater in tropical environments is also influenced by the time groundwater contacts geological materials.[21] This is often called groundwater residence time, which can vary widely depending on the geological setting. In some tropical regions, groundwater may have a short residence time, with rapid recharge and flow through highly permeable rocks or sediments, resulting in relatively young and chemically similar to the recharge water. In other areas, groundwater may have a much longer residence time, particularly in deep or confined aquifers, leading to water that has undergone significant chemical alteration due to prolonged interaction with the surrounding rocks.[22] This can result in elevated dissolved minerals and gases, such as carbon dioxide or methane, affecting the water's quality and suitability.

In a nutshell, the geology of tropical environments plays a fundamental role in shaping groundwater's hydrological and hydrochemical characteristics.[23] From controlling the distribution and movement of groundwater through aquifers to influencing the chemical composition of the water through rock-water interactions, geology acts as a natural determinant of groundwater systems in these regions. Understanding the geological factors that influence groundwater is essential for the sustainable management of this vital resource, particularly in tropical areas where water resources are under increasing pressure from natural and human-induced changes.[24] As climate change and population growth continue to impact water availability in tropical regions, the need for a detailed understanding of the geological controls on groundwater will only become more pressing.[24] By considering the geological context, hydrologists and water resource managers can develop more effective strategies for ensuring groundwater resources' long-term sustainability and quality in tropical environments.

Groundwater has many uses such as for household, agricultural or industrial purposes in the tropics or where surface water sources might be scarce or seasonal. Still, the conditions and quality of these resources are closely affected by the geology where the aquifers are located, which determines recharge, aquifer characteristics and hydrochemistry water quality. The spatial patterns and processes of weathering, lithological variations and geochemical responses in the tropical zones are responsible for the groundwater flow, storage, and the matrix of pollutants and salinity, including heavy metals. Although the need for maximum sustainable output is apparent, very little activity has been done regarding the relationships between the geology and groundwater in these regions, making it hard to manage water resources effectively. Addressing the interactions between these factors becomes essential in addressing issues of water shortage, water quality and potential health hazards among people who rely on shallow aquifers. This paper reviews the literature on the interplay of geological factors and processes responsible for forming hydrogeological and hydrochemical properties of groundwater in the tropics and suggests integrated solutions to sustain this vital resource.

Description of experimental and/or theoretical methods used in this review

The narrative review approach contributes to synthesizing and integrating existing knowledge to demonstrate how geology interrelates with the hydrogeology and hydrochemistry of groundwater in tropical settings. To this end, a methodology is employed whereby pertinent literature is systematically sought, examined and interpreted to clarify how geological settings determine groundwater properties. The procedure is initiated by conducting a literature survey in a structured form that cuts across relevant academic databases such as Scopus, Web of Science and Google Scholar while using several keywords such as tropical groundwater, geological controls, hydrogeology and hydrochemistry.[25,26] A comprehensive coverage is ensured by including studies published in peer-reviewed journals, technical reports, and relevant book chapters.

Similarly, criteria for inclusion restrict to research completed in tropical regions, with particular attention given to those investigating geological variables including the rock type, structural controls, weathering, and the aquifer system. Articles are selected based on their significance to the study focus, methodology, and general contribution towards explicating the link between geology and groundwater resources regarding quality or quantity. Such studies are excluded with poorly understood geological settings, narrow space and time scope, and areas unrelated to the tropics. Thematically, the review brings together findings and explains the role of geological structure on some hydrogeological characteristics like; porosity, permeability and recharge. The study has also assessed hydrochemical interactions of groundwater with geological materials in explaining the variation of control parameters such as pH, electrical conductivity, major ions and trace elements. The processes unique to the tropics, such as extreme weathering and more significant rainfall amounts, which accelerate mineral leaching and the rate of water-rock interaction, are of particular concern.[27]

To facilitate adequate balance, the review utilises numerical information such as groundwater pollution indices, geostatistics fabrics, and visual and case studying and spatial rhythms to give a more holistic picture of the covered area. This strategy accommodates the complexity of the tropics' groundwater systems and emphasises the geological causes of that complexity. Gaps in the current literature, e.g. absence of data, poor standardisation of approaches and inadequate geography representation, are discussed in depth for possible future studies. This narrative review method allows for nuances in interpreting the effects of geology on tropical groundwater systems, thus synthesising well for academic researchers, policymakers and water resource managers.

Geological framework of tropical environments

Tectonic settings

The region's tectonic settings profoundly influence the geological framework of tropical environments, which play a crucial role in shaping the landscape, soil formation, and groundwater dynamics.[28] Tectonic activity has led to diverse geological features in tropical regions, including mountain ranges, basins, rift valleys, and volcanic plateaus, directly impacting the hydrological systems and environmental conditions. Understanding the tectonic settings of tropical regions is essential for comprehending groundwater resources' spatial distribution and characteristics and predicting natural hazards such as earthquakes, landslides, and volcanic eruptions that could affect water supply and quality.[29,30]

Figure 1 shows the global distribution of tectonic plates and geological provinces, highlighting various tectonic settings and plate boundaries. Key features include cratons (stable ancient crust), passive margins, and active zones such as subduction zones and rift systems. The East African Rift is visible along eastern Africa, where the Somali and African plates diverge.[31,32] This tectonic activity dramatically influences the hydrogeology of sub-Saharan Africa by affecting groundwater recharge, surface water flow, and aquifer distribution. Understanding these tectonic settings is crucial for managing water resources, especially in regions with significant geological features like rift valleys and basins.[33] This diagram also emphasizes the dynamic nature of Earth's crust, with oceanic and continental plates interacting globally across various geological provinces.

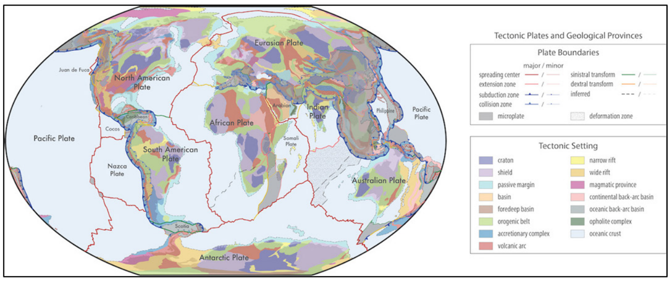

Figure 1 Global Tectonics.[34]

Tectonic settings in tropical regions can be broadly categorized into three primary types: extensional, compressional, and transform regimes.[35] These tectonic regimes generate distinct geological features influencing groundwater availability, movement, and quality. The crust is being pulled apart in extensional tectonic settings, such as rift valleys and grabens, creating deep fault systems and basins that can serve as essential groundwater reservoirs. For example, the East African Rift System is one of the tropical world's most significant extensional tectonic features. In this region, the thinning of the Earth's crust has created deep basins often filled with sediments, forming extensive aquifers.[36,37] The fractures and faults associated with extensional tectonics also enhance groundwater recharge by providing pathways for rainwater to infiltrate the subsurface. However, the complexity of these fault systems can also make groundwater flow highly variable, creating challenges for sustainable management.

In compressional tectonic settings, where tectonic plates are being pushed together, mountain ranges and uplifted plateaus are typical. The Himalayas, the Andes, and the Central African highlands are examples of regions shaped by compressional tectonics.[38,39] In

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these areas, the geological formations are characterised by intense folding, faulting, and metamorphism, significantly influencing the hydrology. However, the steep slopes and rugged terrain associated with compressional tectonics can also lead to rapid runoff, limiting water infiltrating into the subsurface.[40] In addition, the high erosion rates in mountainous areas can lead to sedimentation in nearby rivers and lakes, affecting surface water and groundwater quality.

Transform tectonic settings, characterised by lateral movement along fault lines, also play an essential role in shaping the geology of tropical environments. Transform faults can create highly fractured rock systems, serving as conduits for groundwater movement.[41] These fault systems are often associated with increased seismic activity, positively and negatively affecting groundwater resources. However, the fracturing caused by seismic activity can enhance groundwater recharge by creating new pathways for water to flow into the subsurface. On the other hand, earthquakes and fault movements can also disrupt aquifers, causing groundwater levels to fluctuate and leading to contamination or depletion of water resources in some areas.[42]

Volcanic activity, which is often associated with tectonic settings in tropical regions, also plays a significant role in the geological framework of these environments. Volcanic islands and plateaus, such as those found in the Pacific Ring of Fire or along the East African Rift, are formed by the movement of tectonic plates and the upwelling of magma from the Earth's mantle.[43] Volcanic rocks, such as basalt and andesite, with distinct hydrological properties characterize these volcanic regions. Volcanic rocks can be highly porous and permeable, making them excellent aquifers in some cases. However, volcanic aquifers can also be complex, with highly variable water yields depending on the rock's degree of fracturing and weathering.[44] In addition, volcanic regions are often associated with geothermal activity, which can affect groundwater quality by introducing high concentrations of dissolved minerals, such as sulphur, chloride, and fluoride, into the water.[45]

The tectonic settings of tropical regions also influence the formation of sedimentary basins, which are critical for groundwater storage. Sedimentary basins are typically formed in areas of tectonic subsidence, where the Earth's crust is sinking and creating space for sediments to accumulate over millions of years.[46] These basins are often filled with sand, gravel, clay, and silt layers, which can serve as essential aquifers. The porosity and permeability of these sediments determine the amount of groundwater that can be stored and transmitted within the basin. In tropical regions, sedimentary basins are often found in low-lying areas, such as river valleys and coastal plains, where they can serve as significant groundwater sources for agriculture, drinking water, and industrial use.[47]

Tectonic settings also form karst landscapes, common in tropical regions underlain by limestone or dolomite. Karst landscapes are formed by dissolving soluble rocks, creating features such as sinkholes, caves, and underground rivers.[48] These landscapes are often associated with extensional or compressional tectonic regimes, where fractures and faults enhance the dissolution process by allowing water to flow through the rock. Karst aquifers are typically highly productive, as the dissolved rock creates large underground voids that can store significant amounts of water. However, karst aquifers are also highly vulnerable to contamination, as pollutants can quickly travel through the fractures and voids in the rock, reaching groundwater supplies with little filtration.[49]

The tectonic settings of tropical environments are also closely linked to the region's seismic and volcanic hazards, which can directly impact groundwater resources.[50,51] In areas of active tectonics, such as the Pacific Ring of Fire or the East African Rift, earthquakes and volcanic eruptions can disrupt groundwater systems by causing changes in the permeability of aquifers, triggering landslides that block rivers and alter recharge patterns, or introducing contaminants into groundwater supplies. In volcanic regions, eruptions can release large amounts of ash and gases into the atmosphere, which can be deposited in surface water bodies and eventually seep into the groundwater. The release of volcanic gases, such as sulphur dioxide and carbon dioxide, can also lead to groundwater acidification, affecting its quality and suitability.[52]

Therefore, the tectonic settings of tropical environments play a fundamental role in shaping these regions' geological framework and hydrological systems. From forming aquifers in rift valleys and sedimentary basins to creating karst landscapes and volcanic plateaus, tectonic processes influence groundwater distribution, movement, and quality in tropical areas. Understanding the tectonic context of these regions is essential for the sustainable management of groundwater resources and for predicting and mitigating the impacts of natural hazards on water availability and quality.[53,54] As population growth and climate change continue to place increasing pressure on water resources in tropical regions, the need for a detailed understanding of the geological and tectonic factors that influence groundwater systems will become even more critical.

Geological formations

The geological framework of tropical environments is a crucial determinant of the hydrogeological processes that govern groundwater storage, flow, and quality.[55] Tropical environments encompass vast and geologically diverse regions with high temperatures and significant rainfall. In conjunction with the unique geological formations, these climatic conditions lead to distinct patterns of weathering, rock-water interactions, and aquifer development. The geology of tropical regions is shaped by various formations that have evolved over millions of years through tectonic activity, volcanic processes, sediment deposition, and extensive weathering.[56,57] Understanding these formations and their hydrogeological significance is essential for groundwater exploration, water resource management, and addressing water scarcity, contamination, and sustainability challenges in these regions.

One of the tropical regions' most prominent geological formations is the crystalline basement, which comprises ancient igneous and metamorphic rocks such as granites, gneisses, and schists.[58] These basement rocks, dating back to the Precambrian era, are found across large areas of tropical Africa, South America, and Asia. The primary characteristic of these formations is their low porosity and permeability, which limits the amount of water they can store in their primary pore spaces. However, weathering and tectonic forces over time create fractures and faults within these rocks, enhancing their secondary porosity and forming fractured crystalline aquifers.59 These aquifers, though low-yielding, can provide sustainable water supplies, particularly in rural areas of tropical regions where demand is lower.

The intense chemical weathering in tropical climates further modifies crystalline basement rocks. High temperatures and abundant rainfall lead to deep weathering profiles extending tens of meters below the surface.[60] This weathering process produces thick layers of

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saprolite (a clay-rich, weathered rock) and lateritic soils. Saprolites, while typically low in permeability, can store significant quantities of water in their pore spaces, especially in regions where they overlie fractured bedrock. Lateritic soils, rich in iron and aluminium oxides, form a hardened layer at the surface that can impede infiltration and promote surface runoff, reducing groundwater recharge rates in some areas.[61]

Sedimentary formations also play a significant role in the geology of tropical environments. These formations include sandstones, limestones, and shales deposited in ancient marine, fluvial, and lacustrine environments.[62] Due to their higher primary porosity and permeability than crystalline basement rocks, Sedimentary basins in parts of Africa, South America, and Southeast Asia are some of the most productive aquifers in tropical regions. Sandstone aquifers, for example, can store large volumes of groundwater and often yield higher quantities of water, making them essential sources for urban water supply and agricultural irrigation.[63] However, the permeability of sedimentary rocks varies depending on the degree of cementation, grain size, and sorting. Well-sorted, coarse-grained sandstones generally exhibit higher permeability and better groundwater flow, while poorly sorted, fine-grained sediments, such as shales, act as aquicludes or confining layers, restricting groundwater movement.[64]

Limestone formations, common in tropical karst regions, present unique hydrogeological challenges. Karst aquifers, formed through the dissolution of carbonate rocks like limestone and dolomite, develop extensive networks of caves, sinkholes, and underground rivers.[65] These karst features create highly irregular and unpredictable groundwater flow patterns, with water scurrying through conduits and fractures. While karst aquifers can provide large volumes of water, they are highly susceptible to contamination due to their rapid flow and direct connection to surface water. Pollutants from agriculture, industry, and sewage can quickly infiltrate these aquifers, making water quality management a significant concern. Karst regions, such as those in Southeast Asia, the Caribbean, and parts of Central America, require careful monitoring and protection to ensure the sustainability of groundwater resources.[66]

Volcanic formations, especially in tropical regions with active or recently active volcanoes, also contribute to the hydrogeological framework. Volcanic rocks, such as basalts and andesites, can form productive aquifers due to their high porosity and permeability.[67] Basaltic lava flows, for example, often contain vesicles (gas bubbles) and fractures that enhance water storage and movement. In regions like the East African Rift Valley, volcanic aquifers provide water for rural and urban populations. However, volcanic aquifers are often associated with geothermal activity, which can introduce elevated levels of dissolved minerals, including sulfur and metals, into groundwater, posing challenges to water quality.[68] Additionally, the tectonic activity associated with volcanic regions can cause frequent changes in groundwater flow patterns and water table levels.

In tropical coastal areas, sedimentary formations often extend offshore, and groundwater in these regions is subject to additional geological influences, particularly the interaction between freshwater and seawater.[69] Coastal aquifers, typically composed of unconsolidated sediments such as sands and gravel, are prone to saltwater intrusion, especially in areas where groundwater is overexploited. The geology of coastal zones, including impermeable confining layers or paleo channels (ancient riverbeds), can either enhance or inhibit seawater intrusion into freshwater aquifers.[70] Managing coastal groundwater resources in tropical environments requires a detailed understanding of the geological framework to prevent salinization and ensure a sustainable water supply.[71]

Tectonic activity also plays a significant role in the geological framework of tropical environments. Regions such as the East African Rift, the Andes, and the Philippines are located along active tectonic plate boundaries, where the movement of the Earth's crust creates fractures, faults, and rift valleys.[72] These tectonic features can enhance groundwater storage and flow by increasing the permeability of rock formations, but they also pose challenges, such as the potential for earthquakes and volcanic eruptions, which can disrupt groundwater systems. In addition, the geothermal activity associated with tectonic zones can lead to elevated groundwater temperatures and the presence of geothermal springs, which may influence local water chemistry.[73,74]

Overall, the geological framework of tropical environments is diverse and complex, with a wide range of formations that control groundwater availability, movement, and quality.[75] Crystalline basement rocks, sedimentary basins, volcanic formations, and karst systems each present unique hydrogeological characteristics that must be considered when developing water management strategies in tropical regions. The interplay between geology, climate, and human activities further complicates groundwater systems in these areas, making it essential to integrate geological knowledge into sustainable water resource management practices.[24] Thus, understanding the geological context of tropical aquifers is crucial for addressing current and future challenges related to water scarcity, contamination, and the impacts of climate change.

Hydrogeological properties of groundwater

Aquifer types

Hydrogeological properties of groundwater are primarily determined by the types of aquifers that store and transmit water through geological formations. Aquifers, broadly categorized into unconfined, confined, and semi-confined types, are formed within various geological environments, such as fractured rocks, sedimentary basins, and volcanic formations.[76] Understanding the nature of these aquifer types is crucial for groundwater management, as each possesses unique characteristics regarding storage capacity, recharge potential, water flow, and overall water quality.[77] These properties are deeply influenced by rock permeability, porosity, and the degree of geological structure development, including fractures and faults. This discussion delves into the main types of aquifers and how their geological settings dictate their hydrogeological properties.

Unconfined aquifers are typically found in sedimentary basins or weathered rock zones and are the most accessible for groundwater extraction.[78] These aquifers are directly recharged by precipitation and surface water infiltration since an impermeable layer does not cap them. The water table in unconfined aquifers fluctuates depending on the rate of recharge and extraction, making them particularly sensitive to seasonal variations in rainfall.[79] Their storage capacity and permeability depend mainly on the sediment type: sandy or gravelly aquifers have high porosity and permeability, allowing for significant groundwater flow. In contrast, aquifers of finer sediments like silt and clay exhibit lower permeability and are more prone to water retention. The ease of recharge and extraction makes unconfined aquifers a vital water source in many regions, but they are also more vulnerable to contamination from surface pollutants.[80]

Figure 2 illustrates groundwater flow in a volcanic basaltic aquifer system, showcasing the influence of topography, fractures, and perched aquifers. Groundwater recharge occurs via rainfall, infiltrating through fractures in the basaltic lava flows. Springs are formed where groundwater intersects the surface, typically near fractures or fault zones.[81] Productive wells and boreholes (A and C) are located where permeable fractures and faults enhance groundwater flow, while unproductive sites (B and D) are due to low permeability in the basalt layers. Groundwater flow is directed toward lower elevations, with faults influencing water's vertical and lateral movement across different strata.[81]

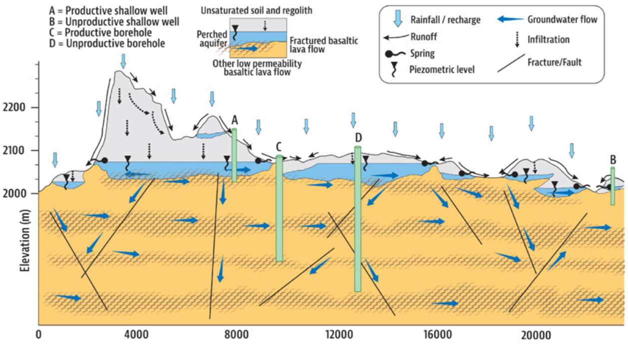

Figure 2 The hydrogeological theoretical model shows vertical characteristics of elevation of the area (m) and horizontal characteristics of distances (m).[81]

Unconfined aquifers are often found in lateritic soils or weathered crystalline rocks in tropical environments. These aquifers form due to intense weathering, leading to thick, porous saprolite layers that store and transmit water.[82] The hydrogeological properties of such aquifers depend on the weathered zone's thickness and the degree of fracturing in the underlying bedrock. The recharge rates in these aquifers are generally high, but due to the shallow nature of the aquifer, the water stored is highly susceptible to evaporation and contamination from surface activities.[83] Additionally, over-extraction in regions dependent on unconfined aquifers can cause a decline in the water table, reducing groundwater availability during dry periods.

Confined aquifers, on the other hand, are trapped beneath an impermeable or semi-permeable layer, typically composed of clay, shale, or dense rock formations. These aquifers are pressurized, and water is under more pressure than unconfined aquifers.[84] When a well penetrates the confining layer, the pressure can cause the water to rise above the aquifer's level, creating an artesian well. Confined aquifers are usually recharged in areas where the confining layer is absent or where fractures in the rock allow water to seep into the aquifer.[85] Recharge rates for confined aquifers are slower than unconfined aquifers due to the protective layer limiting direct infiltration, but their water is generally less susceptible to contamination.

The hydrogeological properties of confined aquifers are often influenced by the type of material forming the confining layers and the region's geological history. Confined aquifers can store vast amounts of water in sedimentary basins, where layers of sandstone, limestones, or other porous rocks are interbedded with less permeable clays and shales.[86] Such aquifers are common in large sedimentary basins in parts of Africa, Asia, and the Americas. The pressure within confined aquifers often leads to greater yields when tapped, making them essential water sources for municipal and agricultural use. However, due to their isolation, over-extraction from confined aquifers can lead to problems such as land subsidence and long-term depletion, as recharge rates are insufficient to maintain the balance of extraction.[87,88]

In tropical environments, confined aquifers are less common than unconfined ones but can be found in regions where tectonic activity has formed faulted and folded rock layers. These aquifers often contain ancient, fossil water recharged under different climatic conditions and may be less renewable.[89] These aquifers' long water residence time typically leads to higher mineralization levels, resulting in water with unique hydrochemical characteristics. In regions where confined aquifers are heavily exploited, such as parts of India and the Sahel region in Africa, careful management is needed to avoid over-extraction and depletion.[90]

Fractured rock aquifers represent a distinct category, primarily found in crystalline rocks, volcanic formations, and areas with significant tectonic activity. In these aquifers, water is stored and transmitted through fractures, joints, and faults within otherwise impermeable rock formations.[91] The hydrogeological properties of fractured rock aquifers are highly variable and depend on the extent and connectivity of the fracture network. In some cases, the fractures are well-developed and interconnected, allowing for rapid groundwater movement and high yields.[92] In other instances, the fractures may be poorly developed or filled with minerals, limiting water flow.

In tropical regions, fractured rock aquifers are significant in areas with crystalline basement rocks, such as sub-Saharan Africa. The weathering of these rocks creates a saprolite layer, which acts as a reservoir for water, while deeper fractures within the bedrock allow for groundwater movement.[93] The hydrogeological behaviour of these aquifers is highly dependent on local geological conditions, including the degree of weathering and fracturing.[94] In general, fractured rock aquifers tend to have lower storage capacity than sedimentary aquifers, but they can still provide reliable water sources in areas where other aquifers are absent. However, these aquifers are often challenging to manage due to their heterogeneity and difficulty locating productive fractures.[95]

Volcanic aquifers, typically found in regions with recent or historical volcanic activity, are another critical aquifer type. These aquifers form in porous volcanic rocks, such as basalt, which can store large volumes of water in their vesicles and fractures.[96,97] Volcanic aquifers often have high permeability due to the interconnected nature of the pores and fractures, allowing for rapid groundwater movement. However, the hydrogeological properties of volcanic aquifers can vary greatly depending on the age and composition of the volcanic rock. Younger volcanic rocks tend to have higher permeability, while older rocks may have undergone mineralization or weathering, reducing their ability to transmit water.[98]

In tropical volcanic regions, such as parts of East Africa and Central America, volcanic aquifers provide a significant water source. The permeability of these aquifers allows for quick recharge during rainy seasons, making them an essential resource in areas with variable rainfall.[99] However, volcanic aquifers are also vulnerable to contamination from surface pollutants and volcanic gases, affecting groundwater quality. Additionally, the complex geology of volcanic terrains, with multiple layers of lava flows and ash deposits, can make it challenging to predict aquifer behaviour and manage groundwater resources effectively.[100]

Thus, the hydrogeological properties of groundwater are intimately linked to the geological characteristics of aquifers. Unconfined aquifers, confined aquifers, fractured rock aquifers, and volcanic aquifers have unique storage capacities, recharge potentials, and water quality characteristics that influence their usability.[101,102] Understanding the geology of these aquifers is essential for effective groundwater management, particularly in tropical environments where water resources are under increasing pressure due to population growth, climate change, and economic development. Each aquifer type presents distinct challenges and opportunities for sustainable water use, highlighting the need for tailored management strategies considering local geological conditions.[103]

Groundwater flow mechanisms

Groundwater flow mechanisms are intricately linked to the hydrogeological properties of aquifers, which dictate how water is stored, transmitted, and distributed in subsurface environments.[104] Understanding groundwater flow requires a thorough examination of the physical properties of aquifers, such as porosity, permeability, hydraulic conductivity, and the natural gradients driving the movement of water. These flow mechanisms are essential for water resource management, especially in regions dependent on groundwater for domestic, agricultural, and industrial purposes. The movement of groundwater is primarily governed by Darcy's Law, a principle that describes the flow of fluid through porous media.[105,106] This fundamental equation states that groundwater flow is directly proportional to the hydraulic gradient (the difference in water pressure between two points) and the hydraulic conductivity (the ability of the subsurface material to transmit water). Therefore, the rate at which groundwater flows depends on the permeability of the geological formations and the pressure driving the water movement (Figure 3).

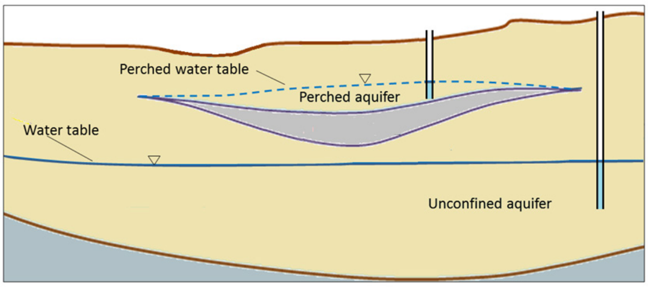

Figure 3 Groundwater flow.

The properties of the subsurface materials are central to understanding groundwater flow mechanisms. Porosity refers to the percentage of void spaces within a rock or sediment that can hold water, while permeability is the ability of those pores to transmit water.[107,108] High porosity does not always equate to high permeability, as pore spaces must be interconnected for water to flow through them. For instance, clay-rich materials can have high porosity but very low permeability, resulting in minimal water movement.[109] Aquifers are typically classified based on their porosity and permeability. Unconsolidated sediments such as sands and gravels often have high porosity and high permeability, making them excellent conduits for groundwater.[110] On the other hand, fractured rocks, like basalt or limestone, depend on secondary porosity (fractures, joints, and faults) for groundwater movement. In such systems, the hydraulic properties of the fractures dominate flow patterns, creating a highly anisotropic environment where water movement is significantly more efficient through these fractures than through the surrounding matrix.[111]

Hydraulic Conductivity Hydraulic conductivity is a crucial parameter that describes how easily water can move through a material's pore spaces or fractures.[112] It is influenced by the intrinsic properties of the rock or sediment (permeability) and the viscosity and density of the fluid. Hydraulic conductivity can vary by magnitude across different geological materials, from coarse gravel, which facilitates rapid flow, to clay, where water movement is exceedingly slow. The nature of the aquifer also impacts groundwater flow mechanisms. In confined aquifers, water is stored under pressure between layers of low-permeability materials (aquicludes), and the flow can be slower but more directed compared to unconfined aquifers, where the hydraulic gradient and the permeability of the aquifer material predominantly govern water movement.[113] In unconfined aquifers, water typically flows downward to recharge zones and laterally toward discharge areas like rivers, lakes, or wells.

The unconfined, confined, or semi-confined aquifer plays a significant role in groundwater flow. Unconfined aquifers are those where the water table forms the upper boundary, and the aquifer is directly recharged by surface water or precipitation.[114] Groundwater flow in these aquifers follows the land's topography, moving from areas of higher elevation (recharge zones) to lower elevation (discharge zones). The flow in unconfined aquifers tends to be relatively shallow, and the water levels fluctuate seasonally with changes in recharge and discharge.[115] Confined aquifers, in contrast, are bounded above and below by impermeable layers, which prevent direct recharge from above but may allow recharge from distant areas where the aquifer is exposed. In confined aquifers, groundwater is under pressure, leading to artesian conditions where water naturally rises above the aquifer's level when tapped by a well.[116] The flow in confined aquifers is usually more stable and less influenced by surface conditions, but recharge can be slower due to the limited areas where water can infiltrate into the aquifer.

Semi-confined or leaky aquifers occur where a lower permeability (aquitard) layer above the principal aquifer allows some vertical water leakage. This type of aquifer introduces more complexity into groundwater flow, as water can move both laterally within the aquifer and vertically through the aquitard, depending on the hydraulic gradient between adjacent aquifers or layers.[117] In fractured aquifers, groundwater flow is governed by fractures, joints, or faults in the rock. These fractures can create highly variable flow patterns depending on their orientation, connectivity, and aperture size. Fractured aquifers are often found in crystalline rocks such as granite or metamorphic formations where primary porosity is low, and groundwater flow is primarily restricted to the fractures.[118,119] The flow in such systems can be rapid, particularly along major fault lines, but may also be highly localized, with limited interconnection between different fracture networks.

Karst aquifers, formed in soluble rocks like limestone or dolomite, present another unique groundwater flow mechanism. Over time, the dissolution of the rock creates underground channels and caverns, allowing for very rapid groundwater flow through conduits.[120] This type of aquifer is characterised by significant variability in flow rates, ranging from slow movement through minor fractures and pores to fast flow through large, open conduits. Karst systems are highly vulnerable to contamination because pollutants can quickly travel through the conduits with minimal filtration by the surrounding rock. Coastal aquifers present additional complexity due to the interface between fresh groundwater and saline seawater. In these environments, groundwater flow mechanisms are influenced by the balance between freshwater inflow from recharge areas and the intrusion of saltwater from the ocean.[121,122] A critical factor in these systems is the hydraulic gradient, which must remain high enough to prevent the encroachment of saline water into freshwater aquifers. Over-extraction of groundwater in coastal areas can lead to saltwater intrusion, significantly impacting groundwater quality.

Alluvial aquifers, commonly found in river valleys and floodplains, are typically composed of unconsolidated sands, gravels, and silts.[123] These materials allow for high hydraulic conductivity and relatively rapid groundwater flow. In alluvial systems, groundwater is closely linked to surface water, and river stages, seasonal flooding, and sediment deposition can influence flow patterns. Recharge often occurs directly from rivers and streams, and groundwater can discharge back into surface water bodies during low-flow conditions, creating a dynamic exchange between groundwater and surface water systems. Human activities such as groundwater extraction, land use changes, and artificial recharge influence groundwater flow mechanisms.[124,125] Excessive pumping from wells can lower the water table, alter the natural flow patterns, and induce downward migration of pollutants from the surface. Large-scale groundwater extraction can sometimes lead to land subsidence or changes in the groundwater flow direction, affecting neighbouring wells and ecosystems.[126]

Artificial recharge techniques, including recharge basins, injection wells, and managed aquifer recharge (MAR) projects, are increasingly used to enhance groundwater storage and mitigate over-extraction impacts.[127] These activities can modify the natural groundwater flow regime by increasing the recharge rate in targeted areas, thereby altering the distribution and movement of groundwater. In summary, groundwater flow mechanisms are determined by a combination of geological factors, aquifer characteristics, and external pressures. Understanding these flow patterns is essential for effective water resource management, particularly in regions where groundwater is critical for human and environmental needs.[128,129] The interplay between natural hydrogeological properties and human interventions presents ongoing challenges and opportunities for sustaining groundwater resources.

Hydrochemical properties of groundwater

Major Ions

The hydrochemical properties of groundwater are primarily defined by the composition of dissolved ions, which reflect the complex interplay between geological formations, hydrological processes, and anthropogenic influences.[130] Groundwater chemistry is shaped by the type of rock through which the water moves, the residence time of water within the aquifer, and the chemical reactions between water and minerals. Among these chemical components, significant ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), chloride (Cl^-), and nitrate (NO_3^-) are the most significant contributors to groundwater's chemical composition.[131]

Calcium and magnesium

Calcium and magnesium are critical contributors to water hardness, often derived from the dissolution of carbonate minerals such as calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$).[132] In regions dominated by sedimentary rocks, such as limestone and dolomites, these ions are typically found in high concentrations in groundwater. The weathering of silicate minerals also contributes to calcium and magnesium levels, though to a lesser extent.[133] Calcium and magnesium levels are influenced by the degree of water-rock interaction and CO_2 in groundwater. CO_2 from the atmosphere or soil zones dissolves in water, forming carbonic acid (H_2CO_3), enhancing carbonate minerals' dissolution. This process is widespread in regions with limestone bedrock, leading to relatively high concentrations of these ions.[134] Their presence in groundwater is crucial for maintaining the chemical equilibrium with aquifer minerals, as they buffer the pH of groundwater and contribute to the overall geochemical balance.

Sodium and potassium

Sodium and potassium are alkali metals commonly found in groundwater due to the weathering of silicate minerals such as feldspars and micas. Sodium is typically more abundant than potassium in natural waters, as it is more soluble and tends to remain in solution for extended periods. Both ions are also introduced into groundwater from anthropogenic sources, such as agricultural runoff (fertilizers) and industrial waste.[135] Sodium concentrations in groundwater can also be elevated due to the ion exchange process, where calcium or magnesium in the aquifer matrix is replaced by sodium.[136] This process is widespread in clays and other fine-grained sediments that contain exchangeable cations. Sodium levels are further enhanced in coastal areas through seawater intrusion, a significant concern in many coastal aquifers worldwide. Elevated sodium levels can affect the suitability of groundwater for drinking and irrigation, as high concentrations of sodium can lead to soil degradation and plant stress.[137] Though less abundant, potassium is critical in plant nutrition and soil health. It is less mobile than sodium, often adsorbed onto clay particles or incorporated into the structure of secondary minerals such as clays.[138,139] As a result, groundwater in regions dominated by clayey sediments tends to have lower potassium concentrations. However, where intense chemical weathering of potassium-bearing minerals occurs, especially in tropical environments, potassium can contribute significantly to the groundwater's chemical makeup.

Bicarbonate

Bicarbonate is one of the most common anions in groundwater and is primarily derived from the dissolution of carbonate minerals, particularly in carbonate rock aquifers. It forms when carbon dioxide (CO_2) reacts with water, producing carbonic acid dissociating into bicarbonate ions (HCO_3^-). This process plays a crucial role in controlling the pH of groundwater, typically resulting in mildly alkaline conditions.[140] Bicarbonate concentrations are indicative of the extent of water-rock interaction. Bicarbonate concentrations tend to be higher in groundwater systems with a long residence time, where water has had sufficient time to equilibrate with carbonate minerals.[141] Additionally, bicarbonate buffers groundwater against significant pH changes, maintaining chemical stability and influencing the solubility of other ions, such as calcium and magnesium. In karst regions, where groundwater flows through extensive carbonate rock formations, bicarbonate levels are exceptionally high, contributing to phenomena such as the formation of caves and sinkholes through karstification.[142]

Sulfate

Sulfate in groundwater originates primarily from the dissolution of sulfate-bearing minerals such as gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$).[143] It is also introduced into groundwater systems through the oxidation of sulfide minerals, particularly in areas with extensive mining activities or regions with abundant pyrite (FeS_2). In sedimentary basins, sulfate concentrations tend to be high where evaporite deposits are present. Sulfate is a conservative ion, meaning it does not readily precipitate or react with other minerals, allowing it to persist in groundwater for extended periods.[144] Elevated sulfate levels can lead to issues such as scaling in water distribution systems and contribute to a slightly acidic pH in groundwater, mainly when sulfide oxidation occurs. In some cases, high sulfate levels are associated with undesirable taste and laxative effects in drinking water, making it an important parameter in water quality assessments.[145]

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Chloride

Chloride is a highly soluble and conservative ion in groundwater, primarily derived from the dissolution of halite (NaCl) or seawater intrusion in coastal aquifers.[146] It can also enter groundwater through atmospheric deposition, agricultural activities, and industrial pollution. Due to its conservative nature, chloride is a valuable tracer for understanding groundwater flow patterns and mixing processes. In coastal regions, elevated chloride levels are a crucial indicator of seawater intrusion, a significant concern in overexploited aquifers.[147,148] Chloride contamination from anthropogenic sources, such as road salt or wastewater effluent, can also be significant in urban areas. High chloride concentrations can render groundwater unsuitable for drinking and irrigation, contributing to soil salinization and plant stress.

Nitrate

Nitrate is a nutrient ion that plays a critical role in ecosystems, but in groundwater, high concentrations are often associated with contamination from agricultural runoff, septic systems, and industrial waste.[149] Nitrate levels in natural groundwater systems are typically low, as nitrogen fixation from the atmosphere is limited. However, excessive use of nitrogen-based fertilizers in agricultural regions has led to widespread nitrate contamination in groundwater, particularly in shallow, unconfined aquifers. Elevated nitrate concentrations pose significant risks to human health, particularly in infants, where it can lead to conditions such as methemoglobinemia (blue baby syndrome).[150] Nitrate is also a key indicator of anthropogenic influence on groundwater systems, and its presence often correlates with other contaminants, such as pesticides and heavy metals. The major ions in groundwater—calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate—are fundamental to understanding groundwater systems' chemical properties and quality.[151] These ions reflect the aquifer's geological conditions and provide insight into anthropogenic influences and potential water quality concerns. Understanding the hydrochemical characteristics of groundwater is essential for sustainable water management, ensuring safe drinking water and the protection of ecosystems.

Trace elements

Groundwater is an essential resource for drinking water, irrigation, and industrial processes, and its hydrochemical properties, including the presence of trace elements, significantly influence its quality.[152] Trace elements, present in minute quantities (typically less than 0.01% by weight), play crucial roles in various biochemical processes and can have profound implications for human health, agricultural productivity, and environmental sustainability. Understanding the sources, behaviours, and effects of trace elements in groundwater is vital for effective water resource management, particularly in regions experiencing anthropogenic pressures and natural geochemical variability.[153] Trace elements in groundwater can originate from both natural and anthropogenic sources. Natural sources include weathering of rocks and minerals, volcanic activity, and biological processes. For example, arsenic, selenium, and fluoride can leach into groundwater from mineral deposits or through the dissolution of soil and sedimentary materials.[154] The geochemical environment, including pH, redox potential, and mineralogy, significantly affects the solubility and mobility of these trace elements. For instance, in reducing conditions, arsenic can be mobilized from iron oxides, leading to elevated concentrations in groundwater.

Anthropogenic sources of trace elements include industrial activities, agricultural runoff, wastewater discharge, and mining operations. Heavy metals such as lead, cadmium, mercury, and chromium often enter groundwater through industrial effluents and contaminated surface runoff.[155] Pesticides and fertilizers used in agriculture can also introduce trace elements like copper, zinc, and selenium into groundwater. Urbanization, characterised by increased impervious surfaces and altered hydrology, can exacerbate the leaching of trace elements into aquifers, making it essential to assess the impacts of land-use changes on groundwater quality.[156] The concentrations of trace elements influence groundwater's hydrochemical properties, which can serve as indicators of water quality and potential health risks. For instance, elevated levels of arsenic in groundwater are a significant public health concern, especially in regions such as Bangladesh, West Bengal, and parts of Mexico, where millions of people rely on groundwater for drinking.[157] Chronic exposure to arsenic is associated with various health issues, including skin lesions, internal cancers, cardiovascular disease, and developmental effects in children. The World Health Organization (WHO) has established a guideline value of 0.01 mg/L for arsenic in drinking water, highlighting the need for effective monitoring and mitigation strategies.[158]

Similarly, fluoride, a trace element beneficial at low concentrations for dental health, can become a health hazard when present in excess.[159] High fluoride concentrations in groundwater can lead to dental and skeletal fluorosis, which affects teeth and bones. Fluoride levels are influenced by geological formations, particularly in volcanic and sedimentary rocks, where natural sources can result in elevated concentrations in groundwater.[160] Regions with high fluoride levels often face challenges in providing safe drinking water, necessitating interventions such as defluoridation or alternative water sources. Heavy metals in groundwater pose another significant challenge to water quality. Often introduced through corroded plumbing and industrial discharges, lead can leach into groundwater and contaminate drinking water supplies.[161] Exposure to lead is particularly harmful to children, causing developmental delays, cognitive deficits, and various health problems. Regulatory measures, such as the U.S. Environmental Protection Agency (EPA) Lead and Copper Rule, aim to control lead concentrations in drinking water, but challenges remain in ensuring compliance and protecting vulnerable populations.[162,163]

Selenium, an essential trace element for human health, can also be toxic at elevated concentrations.[164] It typically enters groundwater through the weathering of splendiferous minerals and agricultural runoff. Excessive selenium exposure can lead to sclerosis, characterised by symptoms such as hair loss, gastrointestinal distress, and neurological effects. Monitoring selenium levels in groundwater is critical in agricultural areas where its accumulation may occur due to irrigation practices.[165] Biogeochemical processes, including adsorption, desorption, precipitation, and complexation, also influence the behaviour of trace elements in groundwater systems.[166,167] For instance, trace elements can adsorb onto mineral surfaces in aquifers, influencing their mobility and bioavailability. The presence of organic matter, microbial activity, and changes in environmental conditions can further alter these processes, affecting the fate of trace elements in groundwater. Understanding these complex interactions is essential for predicting the transport and transformation of trace elements in aquifer systems.[168]

Water quality management in areas affected by trace elements requires a multifaceted approach that considers the geological,

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hydrological, and anthropogenic influences on groundwater.[169] Regular monitoring of trace element concentrations, alongside comprehensive assessments of land-use practices, can help identify pollution sources and assess the effectiveness of mitigation strategies.[170] In addition, community engagement and education are crucial for raising awareness about the potential risks associated with trace elements in groundwater and promoting safe water practices. Thus, trace elements in groundwater play a significant role in determining water quality and potential health risks.[171,172] A complex interplay of natural processes and human activities influences their presence and behaviour. As groundwater remains a critical resource for millions worldwide, understanding trace elements' hydrochemical properties is essential for ensuring safe drinking water, protecting public health, and promoting sustainable water management practices. Future research should focus on developing innovative monitoring techniques, enhancing treatment methods, and implementing policies to safeguard groundwater resources from contamination by trace elements.

Interactions between geology, hydrogeology, and hydrochemistry

The interactions between geology, hydrogeology, and hydrochemistry form a complex framework that governs groundwater systems and their characteristics. Understanding these interactions is crucial for effective water resource management, mainly where groundwater is a primary water supply.[173,174] Geology provides aquifers' foundational materials and structure, influencing their physical properties, while hydrogeology describes the movement and distribution of groundwater within these geological frameworks. Hydrochemistry, on the other hand, examines the chemical composition of groundwater and the processes that affect its quality.[175] Analyzing how these three components interact allows a more holistic understanding of groundwater systems and their responses to natural and anthropogenic influences.

Geology plays a fundamental role in determining the hydrogeological characteristics of an area. The lithological composition of rocks and sediments directly affects porosity and permeability, critical factors in aquifer behaviour.[176,177] For instance, consolidated rocks such as granite and basalt typically exhibit low permeability, leading to confined aquifers with limited water movement. In contrast, sedimentary formations, such as sandstones and gravels, often have higher porosity and permeability, facilitating the movement and storage of groundwater. This disparity in geological formations creates diverse aquifer types, including unconfined aquifers, confined aquifers, and fractured rock aquifers, each with unique hydraulic characteristics.[178] Figure 4 depicts major hydrochemical processes in the soil zone of recharge areas.

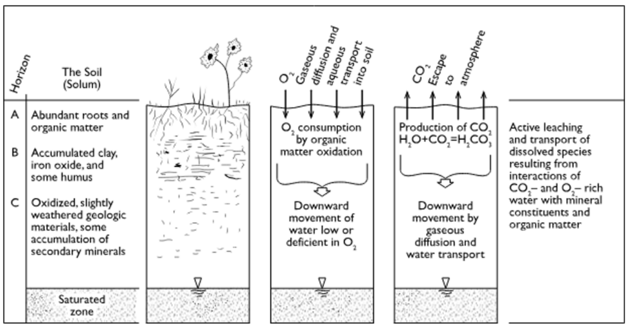

Figure 4 Graphic depiction of major hydrochemical processes in the soil zone of recharge areas.

Geochemically, the most important acid produced in the soil zone is H_2CO_3, derived from the reaction of CO_2 and H_2O. The CO_2 is generated by the decay of organic matter and by the respiration of plant roots. Organic-matter decay is the main source and can be represented by the reaction

$$O_2\ (g) + CH_2O = CO_2(g) + H_2O \quad (1)$$

where the simple carbohydrate CH_2O is used to designate organic matter. Other organic compounds can also be used in oxidation equations to represent CO_2 production. Anaerobic reactions, such as reducing sulfate and nitrate, also generate CO_2. These processes, however, make only minor contributions to the CO_2 budget of the soil atmosphere.[179]

The structural geology of an area, including faults, fractures, and folds, further influences groundwater flow patterns and availability.[6,180] Fractures can significantly enhance the permeability of otherwise impermeable rocks, creating pathways for water movement. This is particularly evident in crystalline rock aquifers, where the degree and orientation of fracturing can determine the availability and flow of groundwater. Tectonic activity can also lead to the forming new fractures or altering existing ones, impacting groundwater systems over time. For example, groundwater flow can be redirected in regions experiencing tectonic uplift or subsidence, leading to changes in water table levels and aquifer recharge rates.[181]

Hydrogeology encompasses the study of groundwater movement, recharge, and discharge, all heavily influenced by geological factors.[182] Recharge areas, where precipitation infiltrates the ground to replenish aquifers, are often located in areas with high permeability, such as sandy soils or fractured rock. Conversely, discharge areas where groundwater flows to the surface (e.g., springs or wetlands) are typically associated with low-lying regions or geological features that impede water movement, such as clay-rich formations. Understanding these dynamics is essential for managing groundwater resources, particularly in water scarcity and competing water-use demands.[183] The hydrochemical characteristics of groundwater are intrinsically linked to the geological setting and hydrogeological processes. As groundwater moves through geological formations, it interacts with minerals and organic materials, resulting in various chemical reactions that alter its composition.[184] For example, groundwater in limestone aquifers often exhibits higher concentrations of calcium and bicarbonate due to the dissolution of calcite, a common mineral in these formations. This process, known as carbonation, can lead to the formation of karst landscapes characterised by features such as sinkholes and caves, which further influence groundwater movement and storage.[185]

Similarly, the weathering of silicate minerals in igneous and metamorphic rocks can release nutrients such as potassium, sodium, and magnesium into groundwater, impacting its hydrochemical properties.[186] The chemical composition of groundwater can also be affected by anthropogenic influences, such as agricultural runoff, industrial discharges, and wastewater infiltration. The presence of fertilizers and pesticides can lead to increased concentrations of nitrate and other trace elements, posing risks to water quality and human health.[187] Redox conditions, which describe the balance between oxidation and reduction processes in groundwater, are another critical aspect of the interactions between geology, hydrogeology, and hydrochemistry.188 The geochemical environment, including factors such as pH, temperature, and organic matter content, influences the redox state of groundwater, impacting the mobility of various trace elements and contaminants. For instance, in reducing conditions,

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certain metals like iron and manganese can become more soluble, leading to higher concentrations in groundwater.[189] Conversely, oxidizing conditions can precipitate these metals, leading to lower concentrations.

The relationship between groundwater and surface water is also crucial to these interactions. Groundwater can influence surface water quality through base flow, where groundwater discharges into rivers, lakes, and wetlands, providing a source of nutrients and minerals.[190] Conversely, surface water can recharge groundwater aquifers, particularly in water bodies above the water table. However, this interaction can also lead to groundwater contamination, particularly in urban or agricultural settings where surface runoff may carry pollutants into aquifers.[191] Climate change and land-use changes increasingly impact the interactions between geology, hydrogeology, and hydrochemistry.[192] Changes in precipitation patterns, temperature, and evapotranspiration can alter groundwater recharge rates and flow patterns, affecting water availability. For instance, prolonged droughts can reduce aquifer recharge, leading to declining water levels and increased reliance on groundwater for irrigation and domestic use. In urban areas, land-use changes, such as increased impervious surfaces, can disrupt natural hydrological cycles, leading to altered recharge rates and increased surface runoff.[193]

Effective groundwater management requires an integrated approach that considers the interactions between geology, hydrogeology, and hydrochemistry.[194] This includes implementing monitoring programs to assess groundwater quality, regularly analyzing hydrochemical data to identify trends and potential contamination sources, and developing land-use policies that protect recharge areas and promote sustainable water use. Additionally, public education and community engagement are essential for raising awareness about the importance of groundwater resources and the need for conservation efforts.[195] The interactions between geology, hydrogeology, and hydrochemistry are complex and multifaceted, playing a critical role in determining groundwater availability, movement, and quality. Understanding these interactions is essential for effective water resource management, particularly amid increasing demands and environmental changes.[196] A comprehensive approach that integrates geological, hydrological, and chemical data can facilitate sustainable groundwater management practices, ensuring the protection and availability of this vital resource for future generations.

Case studies and applications

The study of groundwater hydrochemistry and its trace elements is crucial for understanding the quality and sustainability of this vital resource,[197] especially in regions heavily dependent on groundwater for drinking, irrigation, and industrial purposes. By analyzing case studies from various geographical and climatic settings, we can observe how geological factors, land use, and human activities affect groundwater characteristics, providing insights into effective management strategies. These case studies highlight the application of hydrochemical principles and trace element monitoring in addressing water quality challenges.

One prominent case study is the well-documented arsenic contamination in Bangladesh, which serves as an example of natural hydrochemical processes leading to widespread public health issues.[198] Groundwater in the Ganges-Brahmaputra delta, where millions rely on wells for drinking water, contains high concentrations of arsenic, primarily from the weathering of arsenic-bearing minerals in sediments.[199] The deltaic sediments, coupled with reducing conditions in the aquifer, enhance the mobilization of arsenic into groundwater.[200] Despite significant global attention and mitigation efforts, including installing deep wells and water treatment technologies, arsenic exposure continues to affect large populations. This case emphasizes the importance of geological understanding and the challenges in providing safe water in regions where natural geochemical processes dictate groundwater quality. Furthermore, it demonstrates how local geological settings—such as sediment composition and aquifer redox conditions—can interact to create widespread contamination issues that require multifaceted solutions, including social, economic, and technological interventions.

Another case study comes from Central America, where volcanic terrains present unique hydrochemical challenges. In Nicaragua and El Salvador, groundwater from volcanic aquifers often exhibits elevated levels of fluoride, a naturally occurring trace element that becomes problematic in excessive concentrations.[201,202] In regions with high fluoride, prolonged groundwater consumption leads to fluorosis, particularly in rural areas with limited alternative water sources. The fluoride contamination stems from the dissolution of fluoride-rich minerals present in volcanic rocks. These case studies highlight the need for region-specific groundwater monitoring programs that account for local geological characteristics. Additionally, they underscore the necessity of affordable treatment technologies, such as reverse osmosis or locally appropriate filtration systems, to remove fluoride from drinking water. Importantly, they also point to the challenges in rural water management, where communities may lack the resources or knowledge to address long-term health risks posed by natural contaminants.

In sub-Saharan Africa, case studies on groundwater contamination frequently emphasize the role of agricultural and mining activities in altering hydrochemical properties. For example, in Zambia's Copper belt region, extensive mining activities have contaminated groundwater with heavy metals, including copper, lead, and cadmium.[203,204] Mining waste, tailings, and acid mine drainage are primary sources of these pollutants, which leach into aquifers and surface water systems. This contamination affects the availability of clean drinking water and poses risks to agricultural productivity, as irrigation with contaminated groundwater can accumulate heavy metals in crops. The Zambia case study illustrates the direct link between industrial activities and groundwater quality degradation, showing the need for robust environmental regulations, effective waste management, and regular groundwater monitoring in mining regions.205 Furthermore, it demonstrates the intersection of environmental and economic issues, as mining remains a critical economic activity, and balancing resource extraction with water quality protection is a significant challenge for policymakers.

In India, the over-extraction of groundwater for agricultural irrigation has led to hydrochemical changes, particularly the increase in salinity and nitrate contamination in regions such as Punjab and Haryana.[206,207]

Intensive agricultural practices, including the overuse of fertilizers, contribute to nitrate leaching into groundwater, while excessive pumping lowers the water table, causing the upward migration of saline water from deeper layers. These regions are now facing dual water quality issues: nitrate contamination, which poses health risks such as methemoglobinemia ("blue baby syndrome"), and salinization, which reduces the productivity of agricultural land. India's agricultural groundwater use case study underscores the importance of integrated water management strategies that balance groundwater extraction with replenishment. It also highlights the role of agronomic practices in influencing groundwater quality, suggesting the need for more sustainable irrigation practices, soil health management, and reducing chemical inputs to protect water and food security.

In Europe, the long-term impacts of industrialization on groundwater quality are well-exemplified in regions such as the Ruhr Basin in Germany, where decades of coal mining and industrial activity have severely impacted groundwater hydrochemistry. The Ruhr Basin, once a major coal mining centre, experienced significant groundwater contamination due to mining-related acidification and the release of heavy metals into aquifers.[208,209] Although mining activities have ceased mainly, the legacy of contamination persists, requiring continuous management efforts to mitigate the environmental damage. This case study demonstrates the long-lasting impacts of industrial activities on groundwater systems, where even after the cessation of the polluting activities, water quality issues remain due to the slow movement of groundwater and the continued leaching of contaminants from mine residues. It also highlights the importance of environmental remediation and long-term groundwater monitoring in post-industrial regions, emphasizing the need for sustainable decommissioning practices and pollution control measures.

In contrast, Australia provides a case study on sustainable groundwater management in the face of climatic variability. The Great Artesian Basin, one of the largest aquifer systems in the world, spans much of inland Australia and supports agriculture and rural communities in otherwise arid regions.[210,211] Over time, groundwater extraction, particularly for livestock watering, has led to the decline of water pressure in the artesian wells. However, through coordinated management efforts, including the capping of free-flowing wells and the development of water-saving infrastructure, Australia has managed to stabilize water pressure and ensure the long-term sustainability of this vital resource. The case of the Great Artesian Basin demonstrates how effective groundwater management practices, informed by hydrogeological research,[212,213] can mitigate over-extraction and ensure the continued availability of groundwater in regions where surface water resources are limited. It also illustrates the critical role of governance, community participation, and technological innovation in achieving sustainable water use.

These case studies, spanning different regions and hydrogeological contexts, emphasize the diverse factors influencing groundwater hydrochemistry and trace element distribution. They reveal the complex interactions between geology, human activities, and environmental processes in shaping groundwater quality. Whether dealing with naturally occurring contaminants like arsenic and fluoride or anthropogenic pollutants such as heavy metals and nitrates, these examples illustrate the need for comprehensive, region-specific groundwater management strategies that account for local geological conditions, land use, and socio-economic factors. Collectively, these case studies offer valuable lessons for groundwater management worldwide. They demonstrate that addressing groundwater quality requires a holistic approach integrating scientific understanding of hydrochemical processes with sustainable water use, pollution control, and resource governance practices. As groundwater continues to be a critical resource in the face of population growth, industrialization, and climate change, the insights from these case studies can inform future efforts to safeguard groundwater quality and ensure its sustainable use for future generations.

Challenges and future directions

Groundwater resources, particularly in tropical environments, face challenges threatening their sustainability and quality. As populations grow, economies expand, and climate change intensifies, groundwater systems are under increasing pressure.[214,215] Several challenges have emerged, highlighting the need for more integrated and effective management strategies. Understanding these challenges and anticipating future directions in groundwater research and policy development are essential for safeguarding water resources for future generations.

One of the most pressing challenges is over-extraction. Groundwater is often perceived as an abundant and easily accessible resource, particularly in regions where surface water is scarce or unreliable.[216,217] This perception has led to excessive groundwater pumping, particularly for agriculture and urban water supply, which depletes aquifers faster than they can be naturally replenished. In many cases, the result significantly lowers the water table in northern India, parts of the Middle East, and Mexico City. Over-extraction can lead to various problems, including land subsidence, saltwater intrusion in coastal areas, and the degradation of water-dependent ecosystems. Addressing this challenge requires a shift in managing groundwater, moving toward more sustainable extraction practices. This includes implementing regulatory frameworks that limit pumping, promoting water-efficient technologies in agriculture and industry, and encouraging the recharge of aquifers through methods like rainwater harvesting and managed aquifer recharge.

Water quality is another critical challenge. Groundwater contamination from natural and anthropogenic sources continues to affect many regions, particularly in the Global South, where groundwater is the primary source of drinking water.[218,219] Natural contaminants, such as arsenic, fluoride, and radon, pose severe health risks, while anthropogenic pollutants, including nitrates from agricultural runoff, heavy metals from mining and industrial activities, and untreated wastewater, degrade groundwater quality. In many developing regions, groundwater monitoring is insufficient or non-existent, meaning contamination often goes undetected until public health crises emerge. The complexity of groundwater systems and limited financial and technical resources make addressing water quality issues particularly difficult.[190,220] Solutions must include better monitoring systems, affordable water treatment technologies, and more vigorous enforcement of environmental regulations. In addition, public awareness campaigns and community involvement can play a critical role in promoting water quality protection.

Climate change represents an increasingly significant challenge to groundwater sustainability. Rising global temperatures and shifting precipitation patterns alter the hydrological cycle, affecting groundwater recharge rates and availability.[221,222] In tropical environments, where many regions already experience high variability in rainfall, climate change is expected to exacerbate droughts and reduce surface water availability, further increasing reliance on groundwater. Additionally, sea-level rise caused by climate change threatens coastal aquifers with saltwater intrusion, particularly in low-lying islands and coastal cities.[223,224] In the future, groundwater management must incorporate climate adaptation strategies, such as developing resilient water infrastructure, improved forecasting models for groundwater availability, and policies prioritising sustainable water use in the face of changing climatic conditions.

Institutional and governance challenges also hinder effective groundwater management. In many countries, groundwater governance frameworks are weak or fragmented, with unclear responsibilities and limited coordination between different levels of government.[225,226]

Groundwater is often managed separately from surface water despite the close hydrological connection between the two. Furthermore, groundwater is commonly treated as an open-access resource, leading to the "tragedy of the commons," where individual users extract as much water as possible without considering long-term sustainability. Addressing governance challenges will require reforming institutional frameworks to integrate groundwater and surface water management better, establish clear rights and responsibilities for groundwater use, and improve stakeholder participation. Additionally, there is a need for more robust data collection, transparent sharing of information, and the development of policies that align with local socio-economic conditions.

A significant challenge in groundwater management is economic development and environmental protection tension. In many regions, groundwater extraction is critical for agricultural production, industrial development, and economic growth.[227,228] However, these activities often conflict with the need to protect groundwater resources for future generations. For example, large-scale agriculture, mining, and urbanization can degrade groundwater quality and reduce availability, mainly due to unregulated water use. Balancing economic interests with sustainable water management requires innovative solutions that reconcile short-term economic gains with long-term environmental sustainability. Economic incentives, such as pricing mechanisms for groundwater use, subsidies for water-efficient technologies, and penalties for pollution, could help create a more sustainable balance between development and conservation.[229]

Given these challenges, several future directions emerge for groundwater management and research. One key area is the integration of advanced technologies into groundwater monitoring and management systems. Remote sensing, geospatial analysis, and artificial intelligence can provide valuable data on groundwater levels, quality, and recharge rates, allowing for more accurate predictions and better decision-making.[230] Innovations in water treatment technologies, such as low-cost filters for removing contaminants like arsenic and fluoride, can also play a crucial role in improving water quality, particularly in low-income regions.[231,232] These technological advances must be combined with capacity-building initiatives to ensure local water managers and communities have the skills and resources to implement and maintain them.

Interdisciplinary research is another important direction for future groundwater studies. Groundwater systems are inherently complex, involving interactions between geology, hydrology, biology, and human activities.[233,234] Future research must integrate these disciplines to fully understand groundwater dynamics and develop effective management strategies. This includes exploring the socio-economic dimensions of groundwater use, such as how water access and quality impact livelihoods, food security, and public health. Researchers must also engage with local communities, policymakers, and stakeholders to ensure that scientific findings are translated into actionable solutions that reflect the needs and priorities of those most affected by groundwater issues.

Community involvement will be essential in addressing groundwater challenges moving forward. Top-down approaches to groundwater management often fail to account for local knowledge, needs, and behaviours, particularly in rural areas where groundwater use is decentralized.[235,236] Participatory approaches that involve communities in water management decisions, groundwater monitoring, and conservation efforts can foster a sense of ownership and responsibility. For example, community-led initiatives to monitor borehole levels or protect recharge areas have succeeded in some regions. Empowering communities through education and capacity-building can help ensure the long-term sustainability of groundwater resources.

Policy reform is also a critical future direction. Groundwater management policies must evolve to reflect the growing pressures on water resources, particularly in climate change and population growth.[237,238] Governments must create comprehensive groundwater management plans that include clear regulations on extraction, pollution control, and recharge activities. Policies that integrate groundwater and surface water management, regulate transboundary aquifers, and promote the equitable sharing of water resources will be crucial. Additionally, there needs to be more vigorous enforcement of existing regulations, supported by adequate funding and institutional capacity.[239]

Addressing groundwater's challenges in tropical and other environments requires a holistic, integrated approach that combines scientific research, technological innovation, community participation, and policy reform (Figure 5). As the demand for freshwater continues to rise and the impacts of climate change become more pronounced, the future of groundwater management will depend on our ability to adapt and develop sustainable solutions that protect this essential resource for future generations. The hierarchical diagram illustrates a structured framework for sustainable water resource management in tropical environments. It begins with introducing the context highlighting the geological and sustainability aspects. The framework then delves into geology and hydrogeological characteristics, exploring the role of aquifers, structural geology, and topography in groundwater distribution. Hydrochemical characteristics such as geochemical processes and water quality are vital components that follow.

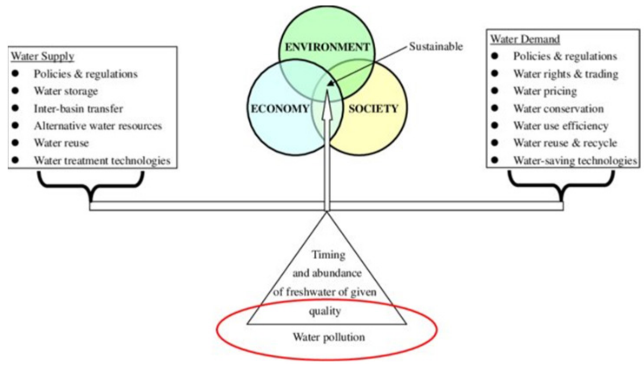

Figure 5 Framework for sustainable water resources management.

Figure 5 depicts a comprehensive framework for sustainable water management, emphasizing the interconnectedness of environmental, economic, and social factors. It visualizes the delicate balance required to ensure the availability and quality of water resources for present and future generations. At the core of the framework lies the concept of sustainability. This encompasses the three pillars of environmental, economic, and social dimensions. A circle represents each pillar, and their overlapping areas indicate their synergies and trade-offs. The environmental pillar focuses on the ecological aspects of water management. It includes water supply, storage, inter-basin transfer, alternative water resources, reuse, and treatment technologies. These components are crucial for maintaining the natural balance of water ecosystems and preserving biodiversity. The economic pillar emphasizes the economic value of water and its role in various sectors, including agriculture, industry, and domestic use. It highlights the importance of policies and regulations, water rights and trading, water pricing, and water conservation measures to ensure efficient and equitable water allocation.

The social pillar recognizes the social and cultural dimensions of water. It encompasses water demand, rights and trading, conservation, use efficiency, reuse and recycling, and water-saving technologies. These components are essential for meeting the needs of society, promoting social equity, and fostering sustainable water use practices. Likewise, Figure 5 underscores the critical role of timing and abundance of freshwater of given quality in water management. This element serves as the foundation upon which the three pillars rest. It highlights the importance of considering the temporal and spatial variations in water availability and the quality of water resources. Furthermore, Figure 5 highlights the issue of water pollution as a significant threat to water sustainability. Water pollution can degrade water quality, harm ecosystems, and impact human health. Addressing water pollution requires concerted efforts to reduce pollution sources, implement effective treatment technologies, and promote sustainable water use practices. Figure 5 offers a valuable framework for understanding the complex interplay between environmental, economic, and social factors in water management. By recognizing the interconnectedness of these dimensions and addressing the challenges of water scarcity, pollution, and climate change, we can work towards a more sustainable and equitable future for water resources.

Conclusion

In conclusion, the sustainable management of groundwater resources in tropical environments is imperative for ensuring water security and ecological health in the face of growing challenges. This framework emphasizes the intricate relationships between geology, hydrogeology, and hydrochemistry, illustrating how these factors influence groundwater availability and quality. Recognizing the diverse geological settings within tropical regions is crucial for developing tailored management strategies considering local conditions and needs. Human activities, including land use changes, urbanization, and climate change, pose significant threats to groundwater systems. Thus, adopting an integrated water resource management (IWRM) approach that involves stakeholder participation, effective governance, and adaptive management practices is essential. Sustainable practices such as groundwater recharge enhancement, pollution control, and monitoring programs can significantly mitigate these threats and promote long-term water security. Furthermore, the case studies presented in this review underscore the practical applications of these strategies in various contexts, providing valuable insights for policymakers and practitioners. As we progress, prioritising research, community engagement, and policy development will be vital for fostering resilience in groundwater systems. By addressing the complex interplay between geological and anthropogenic factors, we can create a sustainable future for water resources in tropical environments, benefiting people and ecosystems.

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Conflicts of interest

The author declares there is no conflict of interest.

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