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Review

Groundwater–Vegetation Interactions in Rangeland Ecosystems: A Review

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Abstract: Water scarcity is a growing global issue, especially in arid and semi-arid rangelands, primarily due to climate change and population growth. Groundwater is a crucial resource for vegetation in these ecosystems, yet its role in supporting plant life is often not fully understood. This review explores the interactions between groundwater and vegetation dynamics in various rangeland types. Groundwater serves as a critical water source that helps sustain plants, but changes in its availability, depth, and quality can significantly impact plant health, biodiversity, and ecosystem stability. Research indicates that groundwater depth affects vegetation types and their distribution, with specific plants thriving at certain groundwater levels. For instance, in grasslands, shallow groundwater can support diverse herbaceous species, while deeper conditions may favor drought-tolerant shrubs and trees. Similarly, in forest ecosystems, extensive root systems access both groundwater and soil moisture, playing a vital role in water regulation. Savanna environments showcase complex interactions, where trees and grasses compete for water, with groundwater potentially benefiting trees during dry seasons. Climate change poses additional challenges by altering rainfall patterns and temperatures, affecting groundwater recharge and availability. As a result, it is crucial to develop effective management strategies that integrate groundwater conservation with vegetation health. Innovative monitoring techniques, including remote sensing, can provide valuable information about groundwater levels and their impact on vegetation, enhancing water resource management. This review emphasizes the importance of understanding groundwater–vegetation interactions to guide sustainable land and water management practices. By enhancing our knowledge of these connections and utilizing advanced technologies, we can promote ecosystem resilience, secure water resources, and support biodiversity in rangeland systems. Collaborative efforts among local communities, scientists, and policymakers are essential to address the pressing issues of water scarcity and to ensure the sustainability of vital ecosystems for future generations.

Keywords: vegetation; groundwater levels; soil moisture; rangelands

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1. Introduction

Water scarcity is becoming an increasing challenge globally, particularly in rangeland systems, due to the dual pressures of climate change and population growth. This scarcity is expected to worsen in areas already struggling with water shortages [1]. In arid and semi-arid rangelands, water is a critical limiting factor for vegetation growth. Vegetation in these areas relies on three main sources of water: surface flow, precipitation, and groundwater [2,3]. As these sources become less reliable due to changing climate conditions and growing demand, it becomes even more challenging to support plant life and maintain healthy rangeland ecosystems. This results in loss of biodiversity, ecological degradation, land desertification, and environmental deterioration, which in turn negatively affect the social and economic development [4].

Groundwater plays a crucial role in sustaining ecosystems, particularly in arid and semi-arid regions where surface water is scarce. It provides a vital water source for vegetation across various rangeland ecosystems globally, as noted by Glanville et al. [5]. However, despite its significance, the extent to which groundwater supports these ecosystems is still not fully understood [6]. This knowledge gap is particularly important because effective rangeland management and planning depend on understanding how different water sources, including groundwater, contribute to ecosystem health [7].

The growing recognition of groundwater's role in sustaining rangeland ecosystems reflects an important shift in ecological research. As highlighted by McLendon et al. and Glanville et al. [2,5], the escalating pressures on rangelands underscore the critical role of groundwater in maintaining vegetation and the broader ecological balance. This emphasis is particularly relevant given the findings of Glanville et al. and Mammola et al. [5,8], which note that our understanding of how groundwater influences vegetation composition, structure, and function has historically been limited. However, with approximately 37% of the world's vegetation relying on groundwater to some extent, recognizing and elucidating this relationship is crucial for effective land management and ecological conservation. This calls for more focused research to better comprehend the role of groundwater across different rangelands to inform sustainable water management practices. Therefore, it is essential to understand the interactions between groundwater and vegetation. As with most studies around the world, attention is paid to sustainable development in arid and semi-arid environments, concerning water allocation between natural and human systems. While much of the global research emphasizes these aspects, studies specifically exploring groundwater–vegetation interactions in rangelands are limited. Notably, Huang et al. [9] synthesized the vegetation response to groundwater depth changes, revealing that factors such as oxygen stress, salinization, and water stress vary in their impact depending on groundwater depth. Complementing this, Le Maitre et al. [10] laid the groundwork by explaining how root systems and vegetation cover influence groundwater systems and hydrological processes. To date, no comprehensive study has explored the influence of groundwater on vegetation across different rangeland ecosystems, including grasslands, savannas, and forests. Therefore, this review aims to bridge that gap by investigating the interactions between groundwater and vegetation dynamics across rangelands, contributing to more informed land and water management practices and sustainable animal production.

2. Groundwater as a Water Source in Rangelands

One of the main functions of rangeland ecosystems is to provide both quality and quantity of water for vegetation and animals, including humans [11]. However, many rangelands are classified as "drylands" (see Figure 1), which means they convert only a small percentage of precipitation into streamflow or groundwater [12]. Mostly, the distribution, quality, and quantity of water are closely linked to how rangeland ecosystems function and are managed, particularly in relation to land-use changes [13]. On the other hand, the vegetation fluctuations within rangelands can significantly impact water interception and, ultimately, groundwater recharge [10,14,15]. According to Kløve et al. [16], groundwater often serves as the primary water source for vegetation in dry rangeland ecosystems, providing essential nutrients, resilience, and stable water temperatures. In particular, certain systems, such as springs, depend directly on groundwater and would not exist without it. The reliance on groundwater may be continuous, seasonal, or occasional, and significant reductions in groundwater supply can lead to observable changes in plant functioning [16].

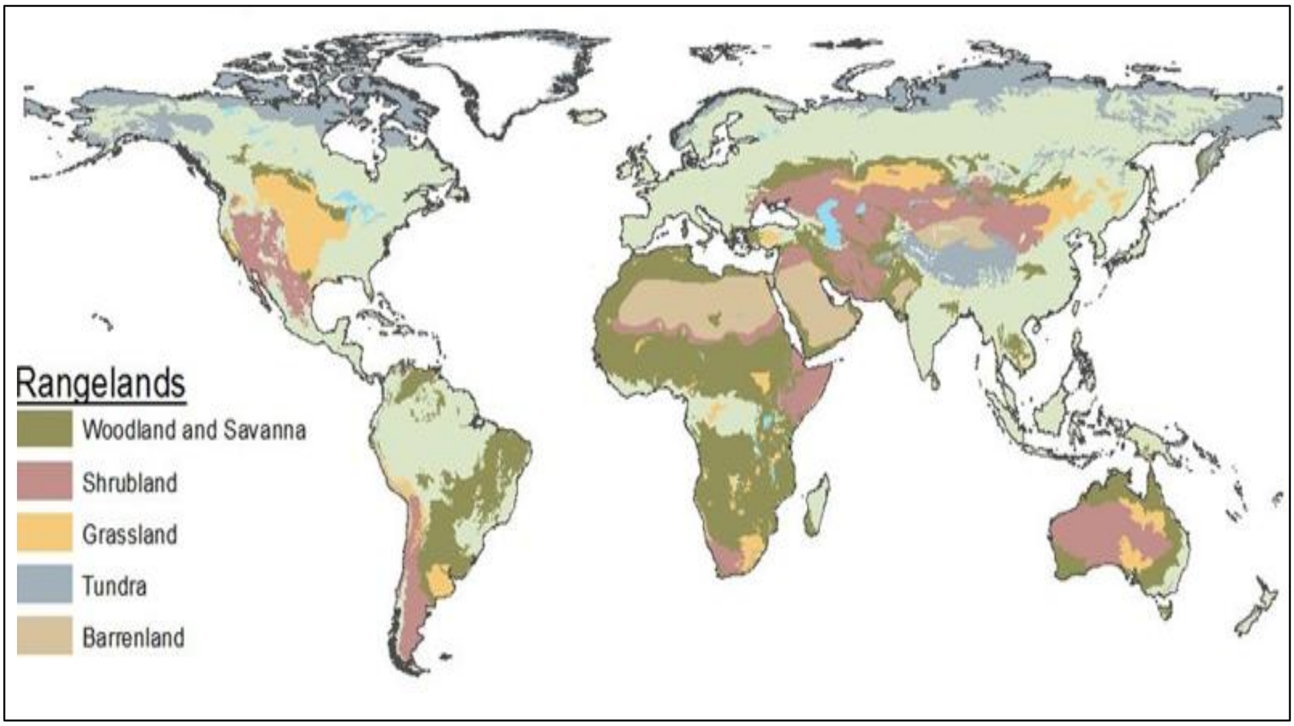

Figure 1. Distribution of rangeland types globally. Source: Rosell et al. [17].

Moreover, the timing and specific characteristics of groundwater can result in varied vegetation responses linked to its availability [18]. For example, a study by Loheide and Booth [19] identified groundwater duration and levels as significant predictors of vegetation composition in riparian grasslands. Additionally, research by Yin et al. [20] demonstrated that groundwater quality also influences vegetation distribution, with the relative importance of different physical, chemical, and biological factors varying according to specific vegetation communities and their locations. Generally, these findings from these studies indicate that groundwater dynamics are essential determinants of vegetation health, composition, and distribution in rangeland ecosystems. Variations in vegetation structure and function significantly influence water interception and groundwater recharge processes, thereby underscoring the reciprocal relationship between vegetation and water resources. Consequently, sustainable management of rangeland ecosystems necessitates a comprehensive understanding of the interaction between groundwater availability and quality and their effects on ecological dynamics.

3. Groundwater Influences on Vegetation Growth Patterns in Rangelands

Vegetation plays a vital role in terrestrial ecosystems like rangelands, contributing significantly to global and regional ecosystem sustainability [21]. It supports essential ecosystem services, including food production and climate stabilization, primarily by absorbing CO_2. In addition to its role in the carbon cycle, vegetation is integral to the hydrological cycle [22]. Water availability is crucial for vegetation growth, but plants also influence local hydrological processes by intercepting precipitation and transpiring water absorbed from the root zone. This interaction is particularly notable in vegetation such trees, which can significantly change water fluxes by returning substantial amounts of water to the atmosphere through transpiration [23]. Consequently, the presence and condition of vegetation, especially in rangelands, are key to maintaining water cycles, ecosystem resilience, and overall environmental stability.

Several studies have explored the impact of groundwater on vegetation status, providing valuable insights into how groundwater depth affects plant communities and soil properties. For instance, Zhao et al. [24] found that groundwater depth significantly influences soil moisture, nutrient availability, and pH levels in sand dune ecosystems. Their research indicates that deeper groundwater is linked to a shift in vegetation structure, where herb species thrive in shallower areas, while tree and shrub species become sparse as groundwater depth increases. The study suggests that, while dominant species like shrubs and trees can adapt to rising groundwater levels, their adaptability has limits beyond a certain depth.

In Denmark, Johansen et al. [25] investigated the dynamics of water levels in groundwater-dependent wetlands across 35 sites, revealing that fluctuations in water levels strongly correlate with the presence of fen vascular plants. They found that bryophytes depend heavily on stable groundwater conditions, and that variability in water levels can significantly restrict species diversity in these wetlands. This highlights the necessity of considering both water level dynamics and nutrient fertility when assessing the quality of habitats in such ecosystems. Similarly, in the Taklamakan Desert of northwest China, Peng et al. [26] characterized the spatial distribution of vegetation and its relationship with environmental factors. Their findings suggest that vegetation is most prevalent in areas with frequent surface water, shallow groundwater, and relatively flat terrain. Optimal vegetation growth was observed when groundwater depths ranged between 3.5 and 4.5 m, underscoring the critical role of groundwater availability in desert ecosystems.

Additionally, Huang et al. [9] conducted a review of groundwater–vegetation interactions and categorized vegetation responses to groundwater depth changes into monotone and bell-shaped functions. The research highlights that while oxygen stress and salinization are prominent in shallow groundwater conditions, water stress prevails in deeper depths. Their analysis of change rates helped identify limits for groundwater-dependent ecosystems, particularly in arid regions. These studies underscore the necessity for careful management of groundwater resources to support vegetation health and biodiversity, and they highlight the importance of understanding species-specific responses to groundwater dynamics for effective ecological restoration efforts.

3.1. Groundwater in Grassland Rangelands

Grass cover plays a vital role in mitigating the negative effects of raindrop impact on bare soils by preventing erosion and enhancing soil health in rangelands. The incorporation of vegetation residues into the topsoil increases organic matter content, which strengthens soil aggregates, prevents surface seals, and promotes high infiltration rates and hydraulic conductivity [27]. In arid and semiarid rangelands, where precipitation ranges from 200 mm to 400 mm, climatic factors, particularly rainfall, are often considered the primary drivers of grassland dynamics. Groundwater is typically thought to have a minimal impact on the growth of herbaceous plants due to their short root lengths [28]. However, recent studies indicate that groundwater depth (GD) significantly influences grassland vegetation and its distribution [29].

For instance, Loheide and Booth [19] demonstrated that the duration and extent of minimum groundwater levels were often the strongest predictors of vegetation composition in riparian grasslands. This finding underscores the influence of groundwater depth on plant communities, particularly in areas with fluctuating water levels. Froend and Sommer [30] expanded on this by showing that the rate of groundwater decline affects grass species composition, with slower declines leading to a gradual shift towards drought-tolerant species, whereas rapid declines result in significant changes in floristic composition. In a more specific context, You and Liu [31] observed that different species exhibit varied responses to groundwater depth, reflecting species-specific adaptations to groundwater availability. This variability further illustrates the nuanced relationship between groundwater levels and vegetation health.

Additionally, Deng et al. [32] conducted a study in China's Tongliao region, linking the normalized difference vegetation index (NDVI) with groundwater depth. Their findings revealed an optimal groundwater level for vegetation health, and a notable decline in species diversity when GD exceeded 3.5 to 4 m. Similarly, Feng et al. [33] investigated the effects of rapid groundwater decline in the semi-arid, identifying a GD threshold of 4 m where ecosystems transitioned from being groundwater-dependent to precipitation-driven. This shift was associated with significant vegetation degradation. Kim and Jackson [34] highlighted the importance of grasslands in groundwater recharge, noting that croplands contribute the most to recharge rates. This emphasizes the need for effective grassland management to sustain groundwater resources and integrate these ecosystems into broader water balance and climate models. Lastly, while climate and precipitation remain fundamental to grassland health, the influence of groundwater depth is increasingly recognized as a critical factor in shaping vegetation dynamics and species diversity. This underscores the importance of incorporating groundwater considerations into grassland management and conservation strategies to maintain ecosystem resilience and functionality.

3.2. Groundwater in Forest Rangelands

In recent decades, societal demand for freshwater in arid and semi-arid rangelands has sharply increased, and this trend is projected to remain a source of conflict in the future [35]. To alleviate water scarcity, vegetation removal has been employed to boost water yields [36]. However, this practice has contributed to long-term groundwater depletion, with declining water levels largely attributed to the mismanagement of water resources for agricultural, domestic, and industrial uses [37]. At the same time, forest thinning has been utilized as a management tool to mitigate the adverse effects of disturbances, such as prolonged fire suppression, in various regions around the world [35,38–41]. Forests play a crucial role in water regulation, acting as "sponges" that store rainwater and release it gradually, which supports groundwater and stream flow during dry periods [42]. The extensive root systems of woody vegetation, which can extend 5–10 m deep or more, access both soil moisture from the unsaturated zone and groundwater from the saturated and capillary zones through the process of hydraulic lift (as shown in Figure 2) [10,43,44]. Additionally, forests impact atmospheric moisture and rainfall patterns significantly; at least 40% of rainfall over land originates from evapotranspiration, where plants and surfaces release water into the atmosphere [45–47]. Furthermore, salinity–vegetation feedback often links vegetation dynamics to groundwater table changes [48], and while salt accumulation and groundwater salinization are natural processes, they pose serious threats to biodiversity and agriculture, especially when intensified by human activity [49]. This increased salinity has been linked to the loss of woodlands [50,51].

However, while forests or trees are recognized for reducing soil erosion and maintaining nutrient balances, the FAO [52] emphasized that forests can also influence groundwater levels by increasing soil drainage/texture, particularly when the water table is near the surface. In cases where salts accumulate in the upper soil layers, deforestation can cause groundwater levels to rise, leading to the intrusion of salts into the rooting zone of plants. Several studies have noted that forests can reduce groundwater recharge [37,53–55]. For example, a study by Owuor et al. [56] aimed to evaluate the impact of land use and land cover (LULC) changes on groundwater recharge and surface runoff in semi-arid tropical and subtropical regions. Key findings revealed that forests generally exhibited lower groundwater recharge rates and surface runoff compared to other land uses. Specifically, the restoration of bare land to forests decreased groundwater recharge from 42% of precipitation to between 6 and 12%, while converting forests to rangelands increased recharge by 7.8%, and the transition to cropland or grassland resulted in smaller increases of 3.4% and 4.4%, respectively. Additionally, converting forest vegetation to managed LULC increased surface runoff by 1 to 14.1%, whereas converting grassland to forest reduced runoff from 2.5% to 1.1%.

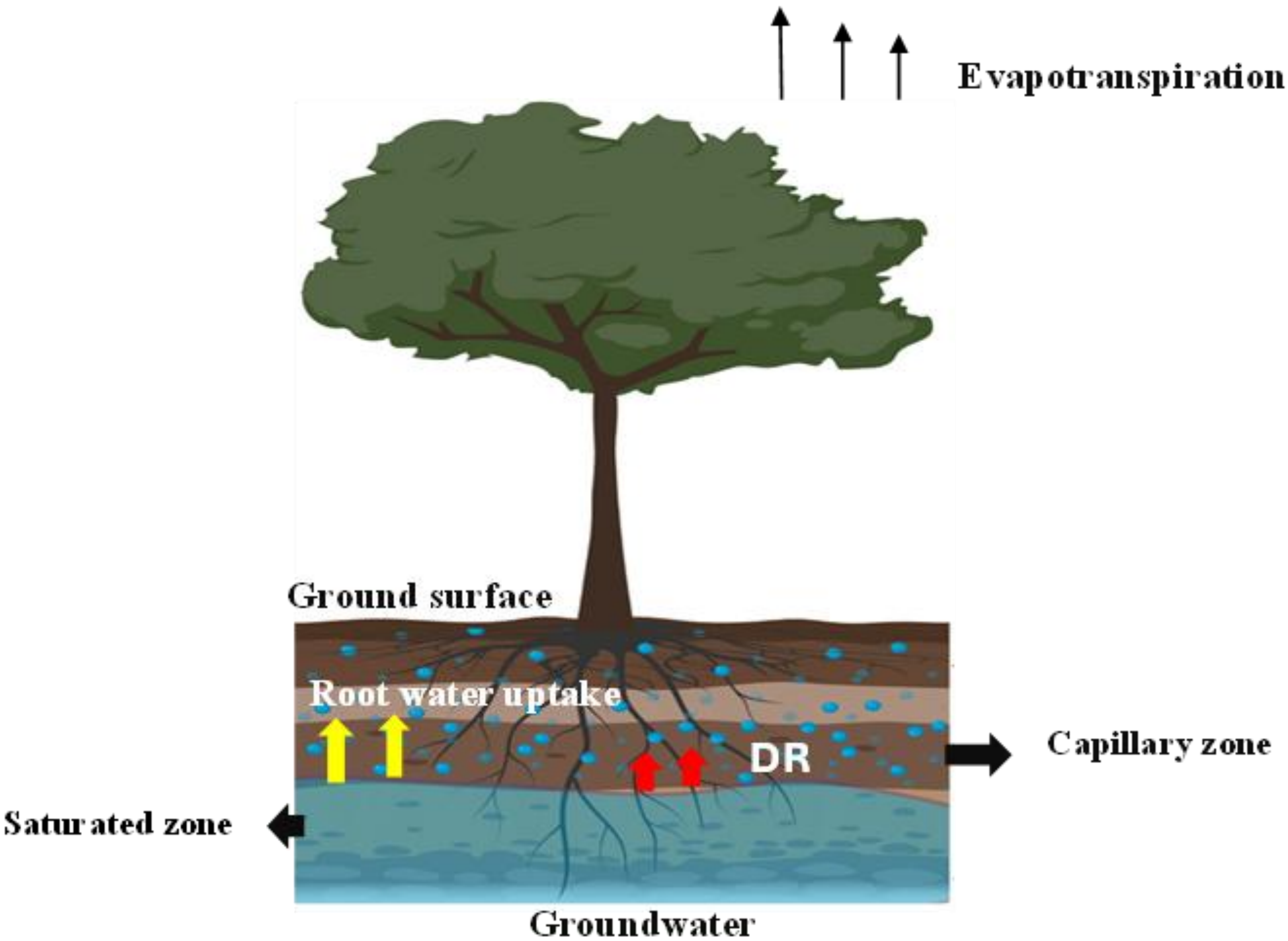

Figure 2. The movement of water from groundwater through tree root systems. Deep-rooted (**DR**) the soil water contents beneath deep-rooted vegetation.

The study by Le Maitre et al. [10] and Acharya et al. [54] explain how shifts in vegetation, such as the transition from grasslands to forests, impact groundwater recharge and the water balance. It finds that root systems often extend beyond traditional depths, with deep roots in woody plants extracting significant water volumes, and that changes in vegetation, particularly from grassland to taller vegetation, can drastically alter groundwater levels. Meanwhile, Ilstedt et al. [57] demonstrate that groundwater recharge is maximized at intermediate tree densities, where moderate tree cover can enhance groundwater recharge, challenging the belief that tree planting reduces water availability and suggesting benefits for widespread tree establishment in seasonally dry tropical regions. Lastly, a study by Tuswa et al. [58] reveals that commercial plantation forests, such as those with Pinus elliotii and Pinus radiata, have higher transpiration rates compared to indigenous forests like the Groenkop forest, leading to reduced deep drainage and groundwater recharge. Additionally, groundwater recharge is more influenced by the intensity and frequency of individual rainfall events rather than by annual rainfall averages. These findings highlight the need to consider both transpiration losses and rainfall patterns in groundwater recharge assessments and management.

In comparison, Allen and Chapman [59] identified two key impacts of afforestation on Ireland's groundwater systems. First, afforestation significantly reduces groundwater recharge due to increased soil moisture uptake by trees and the higher water-holding capacity of forest soils, lowering recharge rates to as little as one-tenth of those observed under grassland or heathland. Second, afforestation adversely affects groundwater quality by promoting acidification and nitrification, driven by the scavenging of atmospheric pollutants by forest canopies and the deposition of acidic leaf litter. Together, these findings highlight the complex relationship between forestry practices and groundwater resources, reinforcing the need for strategic management of tree cover to balance water availability and quality.

These studies underscore that shifts in land use, particularly the conversion of forests to rangelands or croplands, have significant implications for groundwater recharge and surface runoff dynamics. Generally, forests tend to reduce groundwater recharge while increasing runoff when altered for other agricultural uses, presenting considerable challenges for effective water resource management. Furthermore, while forests are essential in regulating hydrological processes by storing and gradually releasing rainwater, their effects on groundwater levels exhibit considerable complexity; they can either hinder recharge or contribute to raising groundwater levels in areas characterized by high salt accumulation. Interestingly, evidence suggests that a moderate presence of trees can enhance groundwater recharge, particularly in dry tropical regions, highlighting the importance of strategic tree management practices to optimize water resources.

3.3. Groundwater in Savanna Rangelands

Savanna rangelands are characterized by open, mixed woodlands and grasslands, where biomass dynamics are shaped by factors such as rainfall patterns, soil properties, herbivory, and wildfire. These rangelands typically receive around 650 mm of rainfall annually, which restricts their spread in comparison to more densely wooded environments [60]. In savannas, ecological water processes have been explained through the interactions between trees and grasses, which contribute to the spatial variability across the rangeland. Trees and grasses respond differently to rainfall and soil conditions; deep sandy soils tend to support tree growth, while grasses thrive in shallow soils with higher clay content [60,61]. However, there remains an ongoing debate regarding their water consumption patterns in savanna ecosystems. This includes examining the competition for water between trees and grasses across different ecological settings and understanding the implications of bush encroachment on water balances, particularly groundwater recharge [62].

Further complicating this dynamic is the rooting depth of different plant types within savanna ecosystems. According to Stone and Kalisz [63], most savanna trees possess deep root systems, with certain legumes extending their roots between 3 and 20 m deep, and in rare instances even exceeding 53 m. In contrast, herbaceous plants typically exhibit shallower rooting systems, with annuals having roots less than 0.3 m and perennials usually extending less than 1.5 m. Notably, some herbaceous species can develop root systems that reach depths of up to 10 m. This variation in root depth not only reflects the adaptive strategies of these vegetations to maximize water uptake from groundwater but also underscores the complexity of interactions within savanna ecosystems and their responses to ecological stressors (Figure 3). Several studies have explored the role of groundwater in savanna vegetation, highlighting its significance for tree water use.

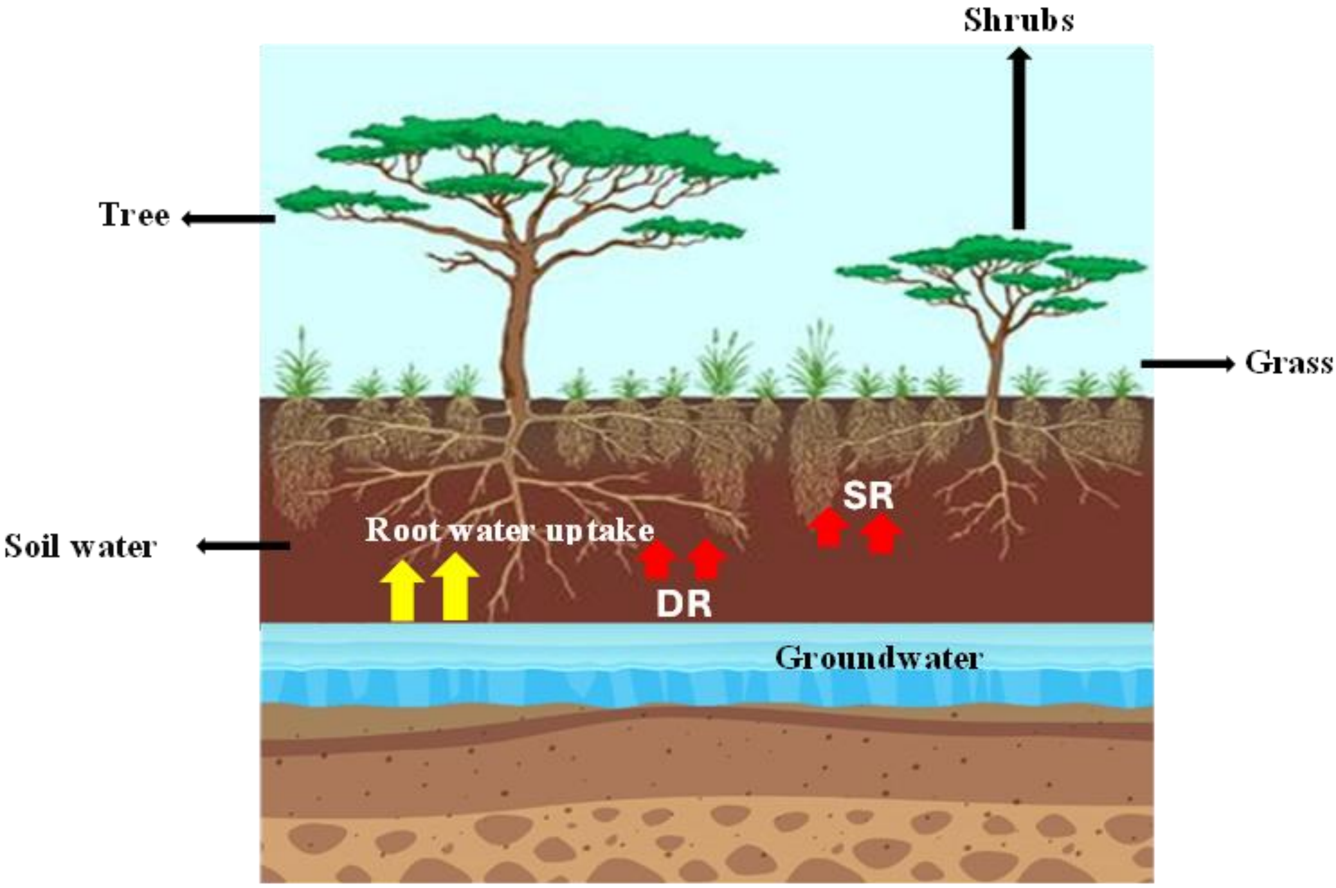

Figure 3. The movement of water from groundwater through root systems of different vegetation in savanna rangelands. **SR** and **DR** are the soil water contents beneath shallow-rooted and deep-rooted vegetation, respectively. Adopted from Smith [64] and White and Smith [65].

For instance, Lamontagne et al. [66] demonstrated that groundwater is a major water source for trees in the Daly River riparian zone, contributing over 50% of the water used for transpiration. They also noted variability in groundwater reliance among species, with some like *Melaleuca argentea* and *Barringtonia acutangula* depending more on groundwater, while others, such as *Cathorium umbellatum* and *Acacia auriculiformis*, relied more on soil water, particularly at higher elevations. Salazar and Goldstein [67] observed that groundwater levels fluctuated along topographic gradients in central Brazil's fire-protected savannas, with greater variations at lower elevations where tree density and diversity decreased due to waterlogging. Le Maitre et al. [10], Alshehri and Mohamed [68], and Szabó et al. [69] investigated how changes in vegetation types, such as from grasslands to forests, impact groundwater recharge, noting that root systems can extend well beyond 1 m and significantly influence groundwater extraction. Their research highlights the need for further investigation into vegetation–groundwater interactions, especially in semi-arid savannas and coastal plains.

In a related study, Miller et al. [70] focused on *blue oak trees (Quercus douglasii)* in a California oak savanna, finding that during the dry season these trees rely heavily on groundwater, with uptake rates between 4 and 25 mm month^{-1} and about 80% of total evapotranspiration coming from groundwater. This reliance provides short-term survival benefits but does not support sustained growth, particularly under prolonged drought or human consumption pressures. Most studies have focused on the interaction between trees and groundwater in savanna rangelands. However, research that includes other vegetation, such as grasses and forbs, often explores competition rather than relationships.

For instance, Donzelli et al. [71] investigated tree–grass coexistence in dry savannas by using a dynamical resource-competition model. Their findings highlighted that the trees are superior competitors for nitrogen, whereas grasses excel in competing for water. Krebs et al. [72] found that variations in groundwater nutrient levels (N, P, and K) were influenced by groundwater levels, hydrological events, vegetation types, and agricultural practices. Their study demonstrated the efficiency of nutrient retention in different plant–soil ecosystem compartments and showed that the wettest meadow, with a tall forbs formation, had lower nutrient levels due to higher groundwater rather than vegetation type. Based on these findings, it can be assumed that the presence of forbs in rangelands may contribute to increased groundwater levels. Forbs, known for their drought-tolerant traits, often thrive under dry conditions better than grasses [73]. Additionally, Clegg and O'Connor [74] observed that forbs and grasses exhibit inverse water use efficiencies, particularly in clayey soils. Despite these insights, there remains a lack of comprehensive scientific research on the interaction between forbs and groundwater.

4. Climate Change and Its Impact on Groundwater–Vegetation Interactions

Climate change is the long-term shift in weather patterns, mainly caused by the buildup of greenhouse gases like carbon dioxide (CO_2) in the atmosphere. This impacts the water cycle by changing how water evaporates, falls as rain, and moves through the environment. As a result, water availability in ecosystems is altered, affecting life on Earth [75]. One of the most vulnerable water sources is groundwater, which many people and ecosystems rely on. The Intergovernmental Panel on Climate Change (IPCC) [76] has identified climate change as a serious threat to groundwater sustainability. It is evident that changing weather patterns have significant implications for groundwater recharge, with varying regional effects depending on shifts in precipitation and temperature. Rainfall intensity, duration, and frequency are key drivers influencing groundwater replenishment, where increased precipitation may enhance recharge in some areas, while prolonged droughts can lead to reduced infiltration and depletion of groundwater reserves [76–79]. Additionally, although rising temperatures generally increase evapotranspiration, their influence on groundwater is not uniform. In winter, higher temperatures can enhance infiltration and percolation by shifting precipitation from snow to rain, reducing snow storage and spring snowmelt while allowing for more direct recharge during periods of low evapotranspiration [80–84]. Conversely, in warmer seasons, elevated temperatures intensify capillary rise, drawing moisture from the water table to meet atmospheric demand, which may contribute to groundwater depletion [85,86]. These interactions highlight the complexity of climate-induced groundwater dynamics, necessitating region-specific assessments to understand the balance between precipitation-driven recharge and temperature-driven losses. Hence, several studies have been done around the world as shown in Table 1.

Evidently, climate change is affecting groundwater in many regions, making it crucial to manage water resources wisely. In Asia and Africa, rising temperatures, unpredictable rainfall, and growing populations are causing groundwater levels to drop, highlighting the need for better monitoring and management. Meanwhile, in America and Europe, changes in temperature and rainfall impact on groundwater differently, emphasizing the need for region-specific approaches to water storage, recharge, and contamination risks. Therefore, protecting groundwater is more important than ever as climate change continues to alter the water cycle [85].

Table 1. Some global research on the impact of climate change on groundwater in ecosystems.

Region	Key Findings	Climate Change Indicators	Source
America	These studies found that significant increases in groundwater recharge (GWR) occur with precipitation increases above specific thresholds, and GWR decreases if changes are below these thresholds. Temperature changes exceeding +2 °C also significantly affect GWR, with increases limited to +30 mm/year if temperatures rise more than +4.5 °C. As climate change is expected to increase global temperatures, disrupt the hydrological cycle, and cause varying impacts on groundwater storage, larger basins are predicted to experience more storage.	Temperature and rainfall	[87,88]
Asia	These studies highlight that groundwater is vital for vegetation growth during droughts, with declining groundwater tables threatening plant survival, especially in prolonged droughts. Climate change is expected to reduce recharge capacity, increase contamination, and cause variability in surface water availability, making groundwater unsuitable or insufficient in vulnerable areas, particularly in low-elevation coastal zones.	Floods, drought	[89,90]
Europe	These studies show that historical land use and land cover changes in Europe, especially after the collapse of the Soviet Union and EU formation, increased cloud cover and reduced shortwave radiation, affecting energy and water balances with varying impacts on drought and heat. Climate change is also causing significant impacts on groundwater resources in Southeast Europe, particularly in the Pannonian Basin, Romania, Bulgaria, Greece, and Turkey, while the Dinaric and Alps Mountains experience lower effects, with half the region facing drought conditions.	Drought and heat	[91,92]
Africa	These works highlighted that climate change may impact groundwater resources, but the combined effects of population growth, urbanization, and rising food demands on water resources are likely to be more significant. They also emphasized the importance of land use planning, improved monitoring, and integrated management to optimize water resources and mitigate contamination from extreme rainfall events.	Industrialization and rain	[93,94]

Table 1. *Cont.*

Region	Key Findings	Climate Change Indicators	Source
Australia	These studies outlined that climate change is altering groundwater ecosystems by shifting microbial communities, reducing groundwater levels, and impacting river flows and food webs. These changes threaten biodiversity and highlight the need for better data, integrated models, and adaptive policies to protect vulnerable systems.	Floods and high temperatures	[95,96]
South America	These studies highlighted that climate change will significantly reduce aquifer recharge, increasing reliance on groundwater, and will also alter groundwater–surface water interactions, affecting water balance and the timing of wet and dry periods.	Floods and heatwaves	[97,98]
Global	These studies highlight the significant impacts of global climate change on groundwater systems, with altered evapotranspiration and reduced snowmelt affecting groundwater storage and surface–groundwater interactions. Over-pumping, combined with climate effects, is depleting groundwater resources, threatening groundwater-dependent ecosystems and essential services like irrigation during droughts. To address these challenges, long-term monitoring, strategic management, and integrated approaches across diverse geochemical environments are crucial for safeguarding water quality, ecosystem health, and human wellbeing.	Drought and heat	[99–103]

5. Management Practices for Optimizing Groundwater–Vegetation Interactions

5.1. Sustainable Water Management Strategies

Over recent decades, global groundwater levels have experienced significant declines, driven by the intensive extraction of this resource for irrigation, domestic water supply, and the compounded effects of climate change [104,105]. This trend of groundwater depletion, which has accelerated since the 1960s, is projected to intensify in the coming years [106,107]. Vegetation and groundwater exhibit a complex interdependence that informs the spatial variability of groundwater discharge zones. For example, the removal of trees and shrubs has been associated with a 20-m rise in the water table over a 30-year period [10,14]. These hydrological shifts can cause unfavorable environmental impacts, including biodiversity loss, ecological degradation, land desertification, and wider ecological deterioration, all of which can affect social and economic development [108].

Given these challenges, groundwater management has gained increasing importance within the fields of water and ecology. Sustainable management of groundwater-dependent ecosystems (GDEs) is essential, as these systems play a pivotal role in ecological functioning and biodiversity conservation [109,110]. Over recent decades, advancements in systematic methodologies, computational tools, and novel optimization and simulation models have significantly enhanced the capacity to manage groundwater resources effectively [104]. These developments are crucial for mitigating the escalating impacts of groundwater depletion and ensuring sustainable water management in the face of growing ecological pressures. According to Chandio et al. [111], groundwater predictive models are also a significant part of groundwater management and modeling since they provide informative knowledge about the behavior of groundwater flow systems. These advances were successfully applied in different studies to manage groundwater for ecosystem health.

For instance, Eamus et al. [112] categorize groundwater-dependent ecosystems (GDEs) into three major classes and identify various techniques for locating these ecosystems, emphasizing the use of inferential methodologies and remote sensing methods. The study also highlights contemporary threats to GDEs, noting that human activities, such as groundwater extraction, disrupt the natural hydrological attributes essential for their persistence. Norouzi-Khatiri et al. [104] highlight the significance of simulation and surrogate models as central groundwater predictive tools, offering a thorough examination of both quantitative and qualitative groundwater models. Additionally, the study emphasizes the importance of uncertainty analysis techniques in groundwater modeling, identifying them as essential analytical tools that delineate the most relevant research areas within the field. These findings contribute to a deeper understanding of effective groundwater management and allocation strategies. A study by Orellana et al. [113] aimed to synthesize knowledge on groundwater-dependent vegetation by integrating insights from ecology, plant physiology, environmental engineering, hydrology, and geoscience. They emphasize that the physiological characteristics of these plants significantly influence their composition and distribution, highlighting the critical role of groundwater availability in natural ecosystems. Additionally, they call for improved methodologies to quantify transpiration partitioning between unsaturated and saturated zones and advocate for the development of integrated models that link hydrology, ecology, and geomorphology.

Furthermore, theories and frameworks have also been developed to help in managing groundwater for healthy ecosystems. A study by Zhanga et al. [114] examined the relationship between groundwater depth (GWD) and vegetation distribution in arid regions, utilizing Tsallis entropy theory to establish a functional relationship based on empirical data. The study finds a strong correlation between shallow GWD and higher vegetation coverage, with normalized difference vegetation index (NDVI) values increasing until an optimal depth of approximately 10 m, beyond which coverage declines, and demonstrates high correlation coefficients (exceeding 0.9, $p < 0.01$) in the Ejina, Qaidam, and Hailiutu basins. Moreover, Kath et al. [115] introduce the Framework for Assessing Ecological Responses to Groundwater Regime Alteration (FERGRA), which facilitates the examination of how changes in groundwater regimes impact the timing, variability, duration, frequency, and magnitude of groundwater connections to various groundwater-dependent ecosystems (GDEs), thereby influencing their ecological processes and the provision of ecosystem services. This framework allows for the concurrent assessment of multiple GDEs, enhancing the identification of commonalities and knowledge gaps in existing research, enabling the formulation of hypotheses to quantify ecological responses, and facilitating evaluations of trade-offs between the benefits of groundwater extraction and the conservation of GDEs to safeguard ecosystem services. Jakeman et al. [110] emphasize the importance of integrated groundwater management (IGM) as a framework that encompasses not only the management of groundwater resources but also their interconnectedness with surface water and other environmental factors. They highlight that effective IGM is essential for ensuring the sustainability of groundwater systems while addressing the socioeconomic and environmental impacts of water use. Their work advocates for a collaborative approach that involves stakeholders and considers the complex interactions within water systems, aiming to achieve more resilient and sustainable outcomes for both communities and ecosystems.

5.2. Monitoring and Remote Sensing for Sustainable Groundwater Management

Understanding the dynamics of groundwater storage is crucial in hydrology because it influences the availability, quality, and sustainability of this vital resource. Given the increasing impacts of human activities and climate change, accurately assessing variations in groundwater storage is essential for effective water management and climate adaptation strategies [116,117]. Various methods have been employed to monitor groundwater dynamics worldwide. Traditional techniques, such as wells and boreholes, are commonly drilled to access groundwater [118,119], and manual measurements, like electric sounders, are also used [120,121]. However, these methods face challenges, including time consumption and the need for physical installation at specific locations. These limitations hinder the creation of comprehensive groundwater assessments that account for variations over an extensive area [122].

Furthermore, according to Wehbe and Temimi [123], addressing the limitations and challenges in groundwater monitoring requires innovative and advanced technological approaches. In recent years, advancements in remote sensing tools have provided cost-efficient and innovative solutions for assessing and monitoring groundwater [122,124]. Various remote sensing techniques have played a crucial role in understanding subsurface conditions and dynamics, offering valuable data for groundwater assessment and monitoring. For instance, a study in South Africa by Ndou et al. [125] utilized Landsat images (Landsat-5 TM for 1995 and 2005, and Landsat-8 OLI for 2015) to model groundwater depth. This study identified a significant relationship between evapotranspiration (ETp) and groundwater levels. Similarly, another study employing multispectral remote sensing data (Landsat-8 and Sentinel-2) successfully monitored the spatial distribution of groundwater-dependent vegetation (GDV), achieving up to 97% accuracy with GDV coverage ranging between 2.34% and 2.60%. Additionally, other studies [126–129] have demonstrated the effectiveness of the Moderate Resolution Imaging Spectroradiometer (MODIS) in estimating groundwater recharge. These studies found that groundwater recharge is primarily constrained by precipitation, and while remote sensing data effectively estimate water availability and groundwater levels (with a correlation of 0.868 compared to measured data), ground-based monitoring remains essential for accurate water resource management. Beyond MODIS, airborne and commercial sensors, such as WorldView, have been employed in groundwater assessment and monitoring [130–132]. These studies highlight that satellite data effectively monitor the impact of groundwater salinity on vegetation, as vegetation indices/spectral variables values are closely correlated with salinity levels. Additionally, topographic features have been shown to predict groundwater discharge with up to 93% accuracy, even in regions with limited geological data.

Furthermore, the Gravity Recovery and Climate Experiment (GRACE) mission has significantly advanced the monitoring of groundwater in ecosystems, as demonstrated by numerous studies [68,133–136]. These studies highlight the use of GRACE/GLDAS satellite data to estimate groundwater levels, which supports sustainable water management by revealing spatial variations and identifying over-exploited areas. GRACE's capabilities, coupled with InSAR technologies, provide a comprehensive assessment of groundwater storage changes, especially in regions where in situ data is limited. These advancements in remote sensing technologies continue to enhance groundwater monitoring, offering valuable insights for sustainable water resource management while complementing traditional ground-based approaches.

6. Conclusions

Water scarcity, especially in arid and semi-arid rangeland systems, is rapidly becoming a significant global challenge. This issue is driven by climate change, rising populations, and changes in land use, making it even more essential to better understand the relationship between groundwater and vegetation. Groundwater serves as a vital resource for plants in these ecosystems, influencing their health, diversity, and resilience. As traditional sources of water become increasingly unreliable, protecting and managing groundwater resources is crucial for both ecological sustainability and agricultural productivity. The interaction between vegetation and groundwater is complex and intertwined. Plants not only rely on groundwater for hydration but also play a critical role in the groundwater cycle itself. Their roots help absorb and stabilize the soil, which impacts how water seeps into the ground. As groundwater levels fluctuate, they can dramatically affect plant growth, composition, and overall ecosystem health. Studies show that factors like groundwater depth and quality significantly influence vegetation dynamics. For example, certain plant species thrive at specific groundwater levels, while others may struggle or decline. Understanding these specific needs can guide better land management practices. The impact of climate change is also a crucial factor in groundwater dynamics. As weather patterns shift, they affect how much water replenishes groundwater sources. Increased rainfall may boost groundwater in some areas, while prolonged droughts can severely deplete it. Effective management strategies must consider these climatic changes to ensure sustainable water supplies. Notably, this understanding is vital in rangeland ecosystems, where fluctuations in vegetation depend heavily on groundwater availability. Moreover, the need for improved monitoring and management practices is paramount. Traditional methods of measuring groundwater often come with limitations, such as being time-consuming or geographically restricted. However, the adoption of advanced technologies like remote sensing can provide more comprehensive insights into groundwater levels and their impact on vegetation. These innovative approaches allow for better management of both water resources and vegetation, promoting a healthier ecosystem overall. Lastly, integrated groundwater management that considers the complex interplay between groundwater and vegetation offers promising avenues for conservation and sustainability. Collaborative approaches involving local communities, scientists, and policymakers are crucial for developing effective strategies that balance human and ecological needs. By advancing our understanding of groundwater–vegetation interactions and utilizing new technologies for monitoring, we can work towards more sustainable rangeland systems that support biodiversity, enhance resilience against climate change, and secure water resources for future generations. Ultimately, the pursuit of sustainable management practices will help us address the pressing challenges of water scarcity while protecting vital ecosystems essential for life on Earth.

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