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Vegetation cover in aquifer recharge: a systematic review

Cobertura vegetal en la recarga de acuíferos: una revisión sistemática

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Abstract

This research analyzes the impact of vegetation cover on groundwater recharge in high Andean regions, where land-use changes and vegetation decline have modified hydrological processes, negatively affecting infiltration capacity and water sustainability. The main objective is to evaluate how vegetation cover affects groundwater recharge processes through a systematic documentary review based on a qualitative approach and the PRISMA methodology. To this end, 27 relevant studies were selected from the Scopus database, prioritizing criteria of relevance, timeliness, and scientific rigor. The results show that dense vegetation cover, especially with native species, promotes water infiltration, reduces runoff, and favors groundwater recharge. In contrast, degraded or deforested areas experience lower water retention capacity and greater surface water losses. Consequently, it is concluded that restoring vegetation cover through ecological management strategies is essential to improve aquifer recharge and ensure the sustainability of water resources in high Andean micro-watersheds. Thus, the conservation and restoration of vegetation not only contributes to the resilience of water systems but also represents a key strategy for addressing the challenges arising from land-use change in these fragile ecosystems.

Keywords: vegetation cover, high Andean micro-watersheds, aquifer recharge.

Resumen

La presente investigación analiza el impacto de la cobertura vegetal sobre la recarga de acuíferos en regiones altoandinas, donde los cambios en el uso del suelo y la disminución de la vegetación han modificado los procesos hidrológicos, afectando negativamente la capacidad de infiltración y la sostenibilidad hídrica. El objetivo principal es evaluar cómo la cobertura vegetal incide en los procesos de recarga subterránea, a través de una revisión documental sistemática basada en el enfoque cualitativo y la metodología PRISMA. Para ello, se seleccionaron 27 estudios relevantes de la base de datos Scopus, priorizando criterios de pertinencia, actualidad y rigor científico. Los resultados evidencian que una cobertura vegetal densa, en especial con especies nativas, promueve la infiltración del agua, disminuye la escorrentía y favorece la recarga de los acuíferos. Por el contrario, las zonas degradadas o deforestadas experimentan menor capacidad de retención hídrica y mayores pérdidas de agua superficial. En consecuencia, se concluye que la restauración de la cobertura vegetal, mediante estrategias de manejo ecológico, resulta fundamental para mejorar la recarga de acuíferos y garantizar la sostenibilidad del recurso hídrico en las microcuencas altoandinas. Así, la conservación y recuperación de la vegetación no solo contribuye a la resiliencia de los sistemas hídricos, sino que también representa una estrategia clave para enfrentar los desafíos derivados del cambio de uso del suelo en estos frágiles ecosistemas.

Palabras clave: cobertura vegetal, microcuencas altoandinas, recarga de acuíferos.

Introduction

In the high Andean regions of Peru, the availability of groundwater is facing a critical situation due to landscape alterations and, above all, the progressive deterioration of vegetation cover. Various factors, such as unplanned agricultural expansion, overgrazing, and deforestation, have profoundly transformed natural infiltration patterns, consequently reducing the recharge capacity of aquifers. A notable case is the Ccasapata Kcucho – Marcaconga – Sangarará micro-basin in the Cusco region, where the Natural Heritage Reserve (REPANA) is currently located. This area has undergone numerous human interventions that have diminished its hydrological resilience and underground storage capacity. Such transformations have led to a decrease in vegetation cover, which has reduced water interception and retention, altered soil structure, and increased surface runoff, directly affecting the balance of the hydrological cycle.

Indeed, recent studies indicate that the loss of vegetation negatively impacts soil hydraulic conductivity, decreases organic matter, and limits moisture retention, significantly reducing aquifer recharge processes (Siddik et al., 2022; Mengistu et al., 2022). Additionally, the presence of plant species adapted to high Andean conditions, as well as the density and spatial distribution of foliage, plays a decisive role in regulating water entry into the subsurface (Song et al., 2021; Salem et al., 2023). However, despite this knowledge, most interventions in micro-basins still do not incorporate comprehensive ecological restoration practices or reforestation strategies with native species, exacerbating the consequences of environmental degradation.

In this context, and considering the marked climate sensitivity of mountain ecosystems, it is crucial to generate context-specific knowledge about the relationship between vegetation cover and aquifer recharge. This research aims to contribute to the design of strategies for sustainable groundwater management in a scenario characterized by increasing anthropogenic pressures and climate change. Furthermore, this work aligns with the Sustainable Development Goals, particularly SDG 6 (clean water and sanitation) and SDG 15 (life on land), promoting an approach that integrates hydrological, ecological, and social dimensions.

Starting from these considerations, the central question of this study is: How does vegetation cover impact aquifer recharge? Therefore, the general objective is to analyze the impact of vegetation cover on groundwater recharge processes through a systematic literature review aimed at identifying patterns, critical factors, and conservation strategies in similar Andean contexts.

To understand aquifer recharge in high Andean ecosystems, it is essential to adopt an interdisciplinary perspective that articulates the hydrological dynamics of soil, the characteristics of vegetation, and the interactions between land use and climatic factors. Under this view, vegetation cover emerges as a key natural regulator: it facilitates infiltration, reduces runoff, and promotes underground water storage (Castillo et al., 2025). Indeed, mountain micro-basins exhibit high sensitivity to changes in land use, making it fundamental to comprehend the ecological components that influence water recharge to advance towards sustainable resource management (Siddik et al., 2022).

On the other hand, vegetation cover can be defined as the ensemble of species that cover the land surface, whose presence not only contributes to ecological stability but is also fundamental for water regulation (Ivanova et al., 2025). Its structure, density, and conservation status directly influence the soil's capacity to retain moisture and allow percolation to deeper subsurface layers (Yifru et al., 2021). Various authors agree that the loss of vegetation in strategic areas reduces the filtration capacity of soils, promoting compaction, erosion, and loss of organic matter, which diminishes the effective recharge of aquifers (Khalil et al., 2021).

In this regard, one of the key concepts of this study is the recharge rate, understood as the amount of water that enters the underground system over a specified period. This value is conditioned by the soil's texture and topography, evapotranspiration, and the predominant type of vegetation. According to Mengistu et al. (2022), ecosystems with well-conserved shrub or forest cover show higher infiltration rates compared to lands altered by intensive agriculture or degradation. Moreover, the depth of recharge—which indicates how far water penetrates into the subsurface—greatly depends on the geological characteristics of the area and is crucial for the renewal time of aquifers.

Additionally, the quality of recharged water is an essential aspect of aquifer sustainability. The presence of contaminants from agricultural activities or urban runoff can alter the physicochemical properties of infiltrated water, compromising its potability and the health of the subterranean ecosystem (Negese, 2021). It is important to note that the geology of the micro-basin also affects the infiltration process: porous or fractured materials facilitate recharge, while impermeable layers hinder it (Custodio & Llamas, 1996; Freeze & Cherry, 1979; Domenico & Schwartz, 1990). Therefore, characterizing the geological profile of areas like the Ccasapata Kcucho – Marcaconga micro-basin, where REPANA is located, is fundamental for identifying natural recharge mechanisms and promoting effective groundwater management.

The impact of erosion on the soils' recharge capacity should not be underestimated either. The loss of the surface horizon, caused by water or wind and exacerbated by a lack of vegetation, decreases soil porosity and restricts water infiltration into the subsurface (Holz et al., 2015; Al Kaisi, 2000). This, in turn, increases runoff, causes nutrient loss, and leads to greater sedimentation in water bodies, directly affecting water sustainability at a local scale (Kafando et al., 2022).

In summary, the theoretical framework underpinning this research acknowledges that vegetation cover, in its various forms and degrees of conservation, decisively influences aquifer recharge processes. By analyzing variables such as infiltration rate and depth, water quality, terrain geology, ecosystem status, and the role of REPANA, a robust conceptual foundation is established to understand the hydrological functioning of the Ccasapata Kcucho – Marcaconga micro-basin. Such understanding is indispensable for designing territorial management and ecological restoration strategies that ensure water security in vulnerable high Andean areas.

Methodology

This research adopts a qualitative approach aimed at achieving a deep understanding of the relationship between vegetation cover and aquifer recharge processes in high Andean ecosystems. To this end, a methodological design based on a systematic review was employed, allowing for the collection, analysis, and critical interpretation of relevant findings from previous studies. These works address this interaction in geographical and ecological contexts similar to that of the Ccasapata Kcucho – Marcaconga micro-basin, where the Natural Heritage Reserve (REPANA) is located in the Cusco region.

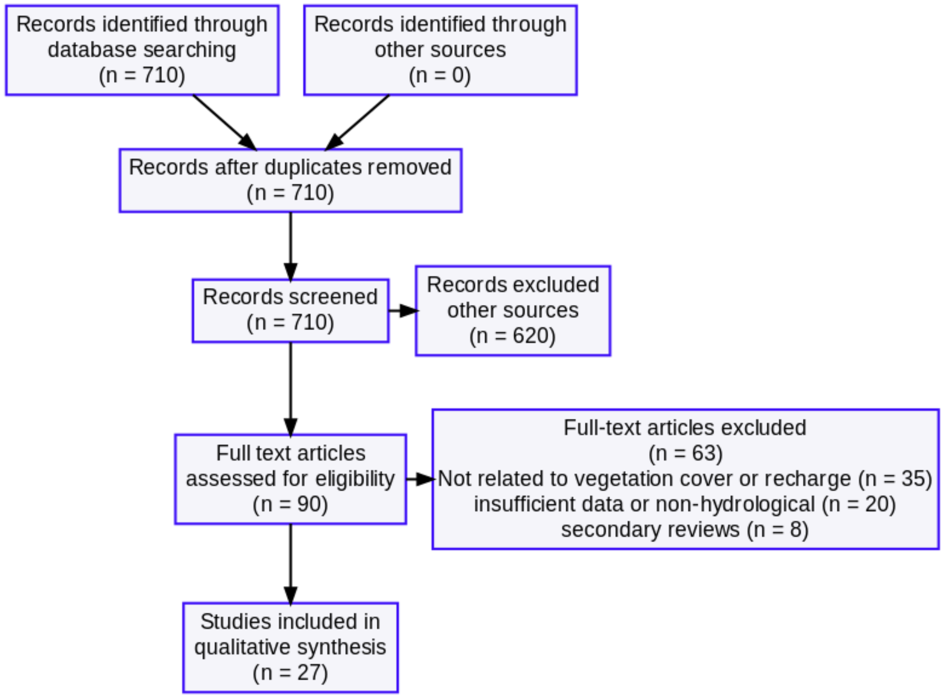
The review process was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol guidelines, which provide a clear framework to ensure transparency and comprehensiveness during the selection and analysis of scientific literature. This protocol was adapted to the specific objectives of the study through the definition of concrete inclusion and exclusion criteria, the design of a planned search strategy, and the use of tools to organize and compare the results obtained.

The document search was carried out between February 2020 and March 2025, using the Scopus database, recognized for its academic reliability. The terms used in the advanced search were: *TITLE-ABS-KEY* ("*vegetation cover*" *OR* "*land use change*" *OR* "*land cover change*") *AND TITLE-ABS-KEY* ("*groundwater recharge*" *OR* "*aquifer recharge*" *OR* "*subsurface infiltration*") *AND TITLE-ABS-KEY* ("*watershed*" *OR* "*catchment*" *OR* "*micro-basin*" *OR* "*mountain basin*") *AND PUBYEAR* > 2018 *AND DOCTYPE* (*ar*) *AND PUBYEAR* > 2019 *AND PUBYEAR* < 2026 *AND* (*LIMIT-TO* (*SUBJAREA*, "*ENVI*")) *AND* (*LIMIT-TO* (*LANGUAGE*, "*English*")) *AND* (*LIMIT-TO* (*EXACTKEYWORD*, "*Land Use*")) *AND* (*LIMIT-TO* (*OA*, "*all*"))

Initially, 736 articles were identified. However, after applying filters related to the thematic area (environmental sciences, hydrology, ecology), recency (last five years), and direct relevance to the topic, a final selection of 27 documents was made that met the established criteria.

To systematize the information, an analysis matrix was designed that included variables such as author and year, country, type of vegetation cover studied, analyzed hydrological indicators, applied methodology, and main findings. This tool facilitated the comparison of common patterns, the identification of divergences, and the generation of relevant emerging categories for discussion. Additionally, special attention was given to those studies that provided data on infiltration rates, quality of recharged water, geological characteristics, and effects of erosion, as these variables are fundamental for interpreting the behavior of aquifers in relation to vegetation landscape.

Figure 1
PRISMA flow diagram of the study selection process



Note. Content generated from https://hollyhartman.shinyapps.io/PRISMAFlowDiagram/

It is important to emphasize that the review also included studies conducted in regions with edaphoclimatic conditions similar to those of Peruvian high Andean ecosystems, such as some areas of the African continent and Central Asia (Doost & Yaseen, 2023; Warku et al., 2021).

To ensure the quality of the selected studies, a qualitative assessment of bias risk was carried out, applying the criteria of the CASP tool for observational research. This assessment considered essential aspects such as clarity in formulating objectives, methodological design, data validity, transparency in presenting results, and coherence in conclusions. Of the 27 studies analyzed, 21 showed a low risk of bias, 5 presented a moderate risk, and only 1 was classified with a high risk. This stage strengthened the analysis and facilitated the more confident identification of relevant trends for the management of REPANA Marcaconga.

Finally, the interpretation of the results was approached from a hermeneutic-descriptive perspective, aiming to understand the implicit meanings in qualitative data and generate reflections applicable to territorial management in the Peruvian context. This approach enabled not only the recognition of conceptual patterns but also the proposal of guidelines for sustainable management of the groundwater resource, based on the restoration and proper management of vegetation cover.

Results of the systematic review

The systematic analysis of 27 studies confirms that vegetation cover is a key hydrological factor for aquifer recharge, as it regulates infiltration into the saturated zones of the subsurface. In the context of climate change, this ecological function becomes even more relevant, especially in high Andean systems characterized by steep slopes, seasonal rainfall patterns, and increasing water stress. Variables such as soil structure, land cover, and the temporal distribution of precipitation condition the effectiveness of the recharge process. Although most evidence comes from regions like East Africa, South Asia, and Latin America, the limited representation of high Andean micro-basins in scientific literature reveals a significant knowledge gap regarding climate vulnerability scenarios.

Among the hydrological indicators most frequently analyzed are the recharge rate, surface runoff, underground storage, and the quality of infiltrated water. The methodologies most commonly used include hydrological models such as SWAT, spatial analyses using geographic information systems (GIS), and ecohydrological simulations. This methodological variety allowed for the identification of how variables such as vegetation density, type of cover, and conservation status influence the soil's infiltration capacity. In particular, it was found that loamy-sandy and silty soils with good structure exhibit higher infiltration rates, especially when covered by dense forest vegetation or agroforestry systems. Conversely, compacted or eroded soils—often associated with degraded grasslands or areas of intensive agriculture—showed a significant reduction in infiltration and an increase in surface runoff.

The results highlight that the loss of vegetation cover, especially in areas with steep slopes, decreases effective recharge. For example, some studies report reductions of up to 45% in recharge in deforested areas (Ware et al., 2024) and increases in runoff exceeding 35%. In contrast, reforestation with native species or the implementation of agroforestry systems has been shown to improve infiltration by more than 25%. Similarly, intensive agricultural practices and urban expansion significantly contribute to soil sealing, reducing the natural recharge capacity by up to 30%, depending on local hydrological and geomorphological conditions.

Based on the analysis of the selected studies, the following comparative matrix was developed, summarizing the main findings related to the relationship between vegetation cover and aquifer recharge:

Table 1

Analysis matrix of studies on vegetation cover and aquifer recharge

Author and Year	Hydrological Indicators	Applied Methodology	Key Conclusion
Anand et al. (2025)	NDVI, LST, SAVI	Post-classification in ArcMap	17% reduction in vegetation in peri-urban areas, no connection to recharge.
Agbelade (2025)	NDVI, LST	NDVI Calculation	Urban cover <30% not linked to recharge.
Mohammed & Scholz (2024)	Permeability, recharge zones	AHP + GIS	Optimal areas with >60% permeability; vegetation weighted up to 0.5.
Blevins et al. (2024)	Water balance	Economic modeling + hydrological simulation	Recharge >80 mm/year in conserved soils; reduced seasonal deficit (23%).
Luo et al. (2024)	Water storage	Ecohydrological monitoring	Dense vegetation retained up to 40% more water during droughts.
Kumar et al. (2024)	Water balance components	SWAT Calibration	Forest cover reduced runoff by 35% and increased recharge by 25%.
Faunt et al. (2024)	Recharge, subsidence	Groundwater flow modeling	Natural vegetation reduces subsidence (<5cm vs. 28cm in degraded areas).
Han et al. (2024)	Runoff, artificial recharge	Hydrological model + infiltration module	Recharge infrastructure increased infiltration by 30-45%.
Zarei et al. (2024)	Water balance, runoff	Spatiotemporal GIS	Loss of vegetation reduced water balance by up to 22%.
Ware et al. (2024)	Hydrological response	SWAT	Deforestation increased runoff by 45% and reduced recharge by 30%.
Feng et al. (2024)	Aquifer depletion	Irrigation simulation	Efficient irrigation reduced pressure on aquifer by 37%.
Arsiso & Mengistu (2023)	Runoff, supply	Hydrological simulation	Savannas increased retention in reservoirs by up to 15% in the dry season.
Kambombe et al. (2023)	Flow regime	Impact + time series	Base flow decreased by 26% due to vegetation degradation.

Segura-Millán & Pérez (2023)	Water conservation	Ecosystem services assessment	PSE conserved 12,000 ha with a 19% increase in vegetation cover.
Andualem et al. (2023)	NDVI, infiltration	Remote sensing	Infiltration increased by 34% after comprehensive micro-basin management.
Mengistu et al. (2022)	Recharge, runoff	SWAT + GIS	Deforestation raised runoff by 39%, reduced recharge by 28%.
Ashraf et al. (2022)	Recharge, base runoff	Land use - climate model	Intensive agriculture reduced recharge by 30%.
Abraham et al. (2022)	Recharge sensitivity	Hydrology with emphasis on wetlands	Wetlands increased infiltration by up to 120 mm/year.
Rivas-Tabares et al. (2022)	Hydrological dynamics	Participatory mapping	Community prioritized high recharge areas, without quantitative data.
Bremer et al. (2021)	Priority recharge areas	Spatial planning	Identified areas with recharge >300 mm/year under native forest.
Oke & Alowo (2021)	Aquifer sustainability	Predictive modeling	Aquifer projected to deplete in 25 years without tree cover.
Afzal et al. (2021)	Water availability	Climate scenarios	Loss of vegetation could reduce recharge by 15-30% (2050-2080).
Barua et al. (2021)	Recharge	Modeling + tracers	Forest cover maintained recharge >120 mm/year; deforestation dropped to <80 mm/year.
Cristiano et al. (2020)	Urban runoff	Urban ecohydrological model	Urban vegetation reduced runoff by 35% and increased infiltration by 18%.
Dibaba et al. (2020)	Basin response	SWAT + land use change	Runoff increased by 41%; infiltration fell by 32% due to deforestation.
Larbi et al. (2020)	Water balance	Coverage change simulation	Vegetation loss reduced water balance by 25-40%.

Results analysis

The analysis of 27 studies reveals a direct and significant relationship between vegetation cover and aquifer recharge. The loss of vegetation is associated with increases in surface runoff ranging from 30% to 45%, while restoration can increase recharge by up to 35%. Infiltration rates exceeding 100 mm/year are recorded in forest soils, compared to less than 60 mm/year in degraded areas. Vegetation covers with complex structures, such as native forests and agroforestry systems, promote deep percolation, in contrast to degraded landscapes. In the Ccasapata Kcucho – Marcaconga micro-basin, within REPANA, these dynamics are clearly reflected: reforestation with native species has contributed to stabilizing the local water balance. Although hydrological models like SWAT and remote sensing tools such as NDVI have allowed for the identification of critical recharge areas, a significant gap persists in the integration of sociocultural factors, limiting the application of holistic approaches to water management in high Andean micro-basins.

Discussion and local implications

The reviewed studies agree that dense vegetation covers, such as native and agroforestry forests, enhance aquifer recharge by favoring infiltration and reducing surface runoff (Kumar et al., 2024; Luo et al., 2024; Ware et al., 2024). Conversely, vegetation degradation and intensive land use increase runoff by up to 45% and decrease effective recharge by more than 30% (Mengistu et al., 2022; Ashraf et al., 2022; Dibaba et al., 2020). Tools such as the SWAT model, geographic information systems, and NDVI analysis have proven useful for evaluating critical recharge areas (Zarei et al., 2024; Cristiano et al., 2020). Additionally, the importance of combining ecohydrological approaches with community participation to promote sustainable water management is highlighted (Segura-Millán & Pérez-Verdín, 2023; Rivas-Tabares et al., 2022). These findings are particularly relevant for high Andean micro-basins like Ccasapata – Marcaconga, whose ecological and geomorphological structure aligns with areas studied in East Africa and Latin America.

Located in the Cusco region at over 3,800 meters above sea level, the Ccasapata Kcucho – Marcaconga micro-basin features sandy-loam soils, slopes exceeding 15%, and vegetation cover dominated by grasslands and subsistence crops. These characteristics are similar to other mountainous areas in Latin America and East Africa, where a close relationship between vegetation cover degradation and reduced recharge has been demonstrated (Dibaba et al., 2020; Mengistu et al., 2022). In REPANA, a recent improvement in infiltration processes and water stability has been observed, attributed to restoration actions, underscoring the importance of promoting strategies based on reforestation with native species, sustainable land management, and monitoring with tools such as GIS and NDVI (Cristiano et al., 2020; Segura-Millán & Pérez-Verdín, 2023).

Study limitations

Although this systematic review provides valuable evidence regarding the relationship between vegetation cover and aquifer recharge, it presents certain limitations. Firstly, most of the consulted studies primarily come from Africa and Asia, with limited representation of high Andean ecosystems similar to the Peruvian case, which restricts the direct and generalizable application of the results. Secondly, there is significant methodological heterogeneity among the studies, particularly regarding the hydrological models used and the methods of measuring recharge, complicating precise quantitative comparison between studies. Finally, no local research with primary data on the Ccasapata Kcucho – Marcaconga micro-basin was identified, limiting the possibility of validating or directly contrasting global findings with empirical evidence specific to the area of interest.

Conclusions

The systematic review confirms that vegetation cover plays a fundamental role in aquifer recharge in high Andean ecosystems, such as the Ccasapata Kcucho – Marcaconga micro-basin. Dense and well-conserved covers, such as native forests and agroforestry systems, significantly enhance water infiltration and reduce surface runoff. Conversely, vegetation degradation linked to practices such as intensive agriculture and overgrazing can decrease recharge by up to 45%. However, interventions aimed at vegetation restoration have shown increases in infiltration exceeding 35%.

Despite the frequent application of hydrological models like SWAT, the use of remote sensors, and analyses through geographic information systems, there remains a significant gap in integrating social variables and traditional knowledge into these investigations. In this regard, it is recommended to promote interdisciplinary approaches that integrate ecological restoration, sustainable land management, and active community participation as key elements within integrated strategies for the sustainable management of water resources in vulnerable basins.

References

Abraham, T., Muluneh, A., Girma, R., Hartmann, A., & Tekleab, S. (2022). Quantifying sensitivity of groundwater recharge to land use and land cover changes by improving model performance on the wetland dominated Tikur Wuha Watershed, Ethiopia. *Water Cycle*, *3*, 112-125. https://doi.org/10.1016/j.watcyc.2022.08.002

Afzal, M., Vavlas, N., & Ragab, R. (2021). Modelling study to quantify the impact of future climate and land use changes on water resources availability at catchment scale. *Journal of Water and Climate Change, 12*(2), 339–361. https://doi.org/10.2166/wcc.2020.117

Agbelade, A. D. (2025). Analyzing the influence of urban vegetation cover on land surface temperature in Southwestern Nigeria. *Discov Environ, 3*, 10. https://doi.org/10.1007/s44274-025-00186-x

Al Kaisi, M. (2000). Soil erosion: An agricultural production challenge. En *Integrated Crop Management Encyclopedia*. Iowa State University. https://dr.lib.iastate.edu/entities/publication/f3279abb-1439-4c44-a5eb-454018e0db68

Anand, S., Kumar, H., Kumar, P., Kumar, M., & Kumar, S. (2025). Analyzing landscape changes and their relationship with land surface temperature and vegetation indices using remote sensing and AI techniques. *Geoscience Letters, 12*(1), 7. https://doi.org/10.1186/s40562-024-00372-4

Andualem, Z. A., Meshesha, D. T., & Hassen, E. E. (2023). Impacts of watershed management on land use/cover changes and landscape greenness in Yezat Watershed, North West, Ethiopia. *Environmental Science and Pollution Research, 30*, 64377–64398. https://doi.org/10.1007/s11356-023-26798-5

Arsiso, B. K., & Mengistu Tsidu, G. (2023). Land use and land cover change modulates hydrological flows and water supply to Gaborone Dam Catchment, Botswana. *Water, 15*(19), 3364. https://doi.org/10.3390/w15193364

Ashraf, S., Ali, M., Shrestha, S., Hafeez, M. A., Moiz, A., & Sheikh, Z. A. (2022). Impacts of climate and land-use change on groundwater recharge in the semi-arid lower Ravi River basin, Pakistan. *Groundwater for Sustainable Development, 17*, 100743. https://doi.org/10.1016/j.gsd.2022.100743

Barua, S., Cartwright, I., Dresel, P. E., & Daly, E. (2021). Using multiple methods to investigate the effects of land-use changes on groundwater recharge in a semi-arid area. *Hydrology and Earth System Sciences, 25*(1), 89–104. https://doi.org/10.5194/hess-25-89-2021

Blevins, S., Hansen, K. M., Paige, G. B., MacKinnon, A., & Bastian, C. T. (2024). Economic evaluation of water management alternatives in the Upper Green River Basin of Wyoming. *Water, 16*(12), 1685. https://doi.org/10.3390/w16121685

Bremer, L. L., DeMaagd, N., Wada, C. A., & Burnett, K. M. (2021). Priority watershed management areas for groundwater recharge and drinking water protection: A case study from Hawai'i Island. *Journal of Environmental Management, 286*, 111622. https://doi.org/10.1016/j.jenvman.2020.111622

Castillo, P., Castrellón, J., Caballer, C., & Rodríguez, S. (2025). Análisis de la influencia de la cobertura vegetal en la producción de sedimentos en laderas. *I+D Tecnológico, 21*(1). https://revistas.utp.ac.pa/index.php/id-tecnologico/article/view/4130

Cristiano, E., Deidda, R., & Viola, F. (2020). EHSMu: A new ecohydrological streamflow model to estimate runoff in urban areas. *Water Resources Management, 34*, 4865–4879. https://doi.org/10.1007/s11269-020-02696-0

Custodio, E., & Llamas, M. R. (1996). *Hidrología subterránea* (Tomo I y II). Ediciones Omega.

Dibaba, W. T., Demissie, T. A., & Miegel, K. (2020). Watershed hydrological response to combined land use/land cover and climate change in highland Ethiopia: Finchaa Catchment. *Water, 12*(6), 1801. https://doi.org/10.3390/w12061801

Domenico, P. A., & Schwartz, F. W. (1990). *Physical and chemical hydrogeology*. John Wiley & Sons.

Doost, Z. H., & Yaseen, Z. M. (2023). The impact of land use and land cover on groundwater fluctuations using remote sensing and geographical information system: Representative case study in Afghanistan. *Environment, Development and Sustainability, 27*, 9515–9538. https://doi.org/10.1007/s10668-023-03111-2

Faunt, C. C., Traum, J. A., Boyce, S. E., Seymour, W. A., Jachens, E. R., Brandt, J. T., Sneed, M., Bond, S., & Marcelli, M. F. (2024). Groundwater sustainability and land subsidence in California's Central Valley. *Water, 16*(8), 1189. https://doi.org/10.3390/w16081189

Feng, G., Jin, W., Ouyang, Y., & Huang, Y. (2024). The role of changing land use and irrigation scheduling in groundwater depletion mitigation in a humid region. *Agricultural Water Management, 291*, 108606. https://doi.org/10.1016/j.agwat.2023.108606

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice-Hall.

Han, Q., Qi, T., & Khanaum, M. M. (2024). Evaluation of the offsets of artificial recharge on the extra run-off induced by urbanization and extreme storms based on an enhanced semi-distributed hydrologic model with an infiltration basin module. *Water, 16*(7), 1032. https://doi.org/10.3390/w16071032

Holz, D. J., Williard, K. W. J., Edwards, P. J., & Schoonover, J. E. (2015). Soil erosion in humid regions: A review. *Journal of Contemporary Water Research & Education, 154*, 48–59. https://doi.org/10.1111/j.1936-704X.2015.03187.x

Ivanova, Y., Lugo, V. D. H., & Herrera, M. F. P. (2025). Incidencia del cambio de coberturas vegetales sobre la capacidad de regulación hídrica en la Cuenca del Río Cuja, Colombia. *Revista EIA, 22*(43), 4327. https://revistabme.eia.edu.co/index.php/reveia/article/view/1793

Kafando, M. B., Koita, M., Zouré, C. O., Yonaba, R., & Niang, D. (2022). Quantification of soil deep drainage and aquifer recharge dynamics according to land use and land cover in the basement zone of Burkina Faso in West Africa. *Sustainability, 14*(22), 14855. https://doi.org/10.3390/su142214855

Kambombe, O., Ngongondo, C., Monjerezi, M., & others. (2023). Investigating human-induced threat to hydrological regime of Lake Chilwa Basin, Malawi. *Applied Water Science, 13*, 161. https://doi.org/10.1007/s13201-023-01965-8

Khalil, M. M., Tokunaga, T., Heggy, E., & Abotalib, A. (2021). Groundwater mixing in shallow aquifers stressed by land cover/land use changes under hyper-arid conditions. *Journal of Hydrology, 598*, 126428. https://doi.org/10.1016/j.jhydrol.2021.126428

Kumar, S. B., Mishra, A., & Dash, S. S. (2024). Response of climate change and land use land cover change on catchment-scale water balance components: A multi-site calibration approach. *Journal of Water and Climate Change, 15*(4), 1750–1771. https://doi.org/10.2166/wcc.2024.581

Larbi, I., Obuobie, E., Verhoef, A., Julich, S., Feger, K. H., Bossa, A. Y., & Macdonald, D. (2020). Water balance components estimation under scenarios of land cover change in the Vea catchment, West Africa. *Hydrological Sciences Journal, 65*(13), 2196–2209. https://doi.org/10.1080/02626667.2020.1802467

Luo, S., Tetzlaff, D., Smith, A., & Soulsby, C. (2024). Assessing impacts of alternative land use strategies on water partitioning, storage and ages in drought-sensitive lowland catchments using tracer-aided ecohydrological modelling. *Hydrological Processes, 38*(4), e15126. https://doi.org/10.1002/hyp.15126

Mengistu, T. D., Chung, I.-M., Kim, M.-G., Chang, S. W., & Lee, J. E. (2022). Impacts and implications of land use land cover dynamics on groundwater recharge and surface runoff in East African Watershed. *Water, 14*(13), 2068. https://doi.org/10.3390/w14132068

Mensah, J. K., Ofosu, E. A., Yidana, S. M., Akpoti, K., & Kabo-bah, A. T. (2022). Integrated modeling of hydrological processes and groundwater recharge based on land use land cover, and climate changes: A systematic review. *Environmental Advances, 8*, 100240. https://doi.org/10.1016/j.envadv.2022.100240

Mohammed, R., & Scholz, M. (2024). Groundwater potential zone delineation through analytical hierarchy process: Diyala River Basin, Iraq. *Water, 16*(20), 2891. https://doi.org/10.3390/w16202891

Negese, A. (2021). Impacts of land use and land cover change on soil erosion and hydrological responses in Ethiopia. *Applied and Environmental Soil Science, 2021*, 1–14. https://doi.org/10.1155/2021/5558816

Oke, S. A., & Alowo, R. (2021). Groundwater of the Modder River Catchment of South Africa: A sustainability prediction. *Water, 13*(7), 936. https://doi.org/10.3390/w13070936

Rivas-Tabares, D., Tarquis, A. M., De Miguel, Á., Gobin, A., & Willaarts, B. (2022). Enhancing LULC scenarios impact assessment in hydrological dynamics using participatory mapping protocols in semiarid regions. *Science of the Total Environment, 803*, 149906. https://doi.org/10.1016/j.scitotenv.2021.149906

Salem, A., Abduljaleel, Y., Dezsó, J., & Lóczy, D. (2023). Integrated assessment of the impact of land use changes on groundwater recharge and groundwater level in the Drava floodplain, Hungary. *Scientific Reports, 13*, 10457. https://doi.org/10.1038/s41598-023-37782-2

Segura-Millán, K., & Pérez-Verdín, G. (2023). The effect of payments for ecosystem services on forest cover, land use, and capacity building in northern Mexico. *Trees, Forests and People, 11*, 100387. https://doi.org/10.1016/j.tfp.2023.100387

Shuler, C., Brewington, L., & El-Kadi, A. I. (2021). A participatory approach to assessing groundwater recharge under future climate and land-cover scenarios, Tutuila, American Samoa. *Journal of Hydrology: Regional Studies, 34*, 100796. https://doi.org/10.1016/j.ejrh.2021.100796

Siddik, S., Tulip, S. S., Rahman, A., Islam, N., Haghighi, A. T., & Touhidul, S. (2022). Impact of vegetation cover on aquifer recharge. *Journal of Environmental Management, 315*, 115096. https://doi.org/10.1016/j.jenvman.2022.115096

Song, G., Huang, J., Ning, B., Wang, J., & Zeng, L. (2021). Effects of groundwater level on vegetation in the arid area of western China. *China Geology, 4*(3), 527–535. https://doi.org/10.31035/cg2021027

Ware, H. H., Chang, S. W., Lee, J. E., & Chung, I.-M. (2024). Assessment of hydrological responses to land use and land cover changes in forest-dominated watershed using SWAT model. *Water, 16*(4), 528. https://doi.org/10.3390/w16040528

Warku, F., Korme, T., & Nedow, D. (2021). Impacts of land use/cover change and climate variability on groundwater recharge for Upper Gibe Watershed, Ethiopia. *Sustainable Water Resources Management, 8*(2), 45. https://doi.org/10.1007/s40899-021-00560-y

Yifru, B., Chung, M., Kim, M., & Chang, S. (2021). Assessing the effect of land use/land cover and climate change on water yield and groundwater recharge in East African Rift Valley using integrated model. *Journal of Hydrology: Regional Studies, 37*, 100918. https://doi.org/10.1016/j.ejrh.2021.100918

Zarei, M., Ghazavi, R., Abdollahi, K., Ranzi, R., Teegavarapu, R. S. V., & Barontini, S. (2024). Spatiotemporal variation of water balance components in Mashhad catchment, Iran: Investigating the impact of changes in climatic data and land use. *Water Supply, 24*(2), 397–415. https://doi.org/10.2166/ws.2024.018

Zhou, Z., & Yaseen, Z. M. (2023). Evaluating the influence of land cover on groundwater fluctuations using RS and GIS: Case study in Afghanistan. *Environment, Development and Sustainability, 27*, 9515–9538. https://doi.org/10.1007/s10668-023-03111-2

Zhou, Z. H., & Zeng, L. (2021). Groundwater interactions in land cover dynamics under arid conditions. *China Geology, 4*(3), 544–555. https://doi.org/10.31035/cg2021032