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Facultad de Ciencias Agropecuarias

Universidad Nacional de Trujillo

RESEARCH ARTICLE

Sustainable watersheds management in Peru: Challenges and perspectives

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Received: 2 June 2024. Accepted: 8 October 2024. Published: 22 October 2024.

Abstract
Sustainable watershed management stands at the forefront of global efforts to tackle pressing environmental and socio-economic challenges. This study offers a pioneering assessment of the state of research on Peru's watersheds, integrating geographical, environmental, and socio-economic dimensions. By harnessing cutting-edge bibliometric tools, including Bibliometrix and VOSviewer, and adhering to PRISMA guidelines for a systematic review, this work maps the scientific landscape of watershed management in Peru. Utilizing comprehensive databases such as Scopus and Web of Science, the study identifies and analyses key thematic clusters, revealing an escalating focus on the urgent issues of climate change and urbanization, particularly within the critical Rimac River Basin. This basin, vital to the water supply of Lima, the world's second-largest desert city, faces severe threats from pollution and climate instability. Our findings not only chart the evolution of research in this domain but also spotlight emerging opportunities to modernize water management practices through the integration of climate change models, advanced data monitoring, and artificial intelligence. The study makes a compelling case for a collaborative approach, urging stronger alliances among local communities, research institutions, and international stakeholders to foster more resilient and sustainable watershed management strategies in Peru. This paper provides actionable insights, making it an indispensable resource for policymakers and practitioners aiming to secure Peru's water future.

Keywords: Watershed management; Water resources; Sustainability; Peru; Rimac; Climate variability.

DOI: https://doi.org/10.17268/sci.agropecu.2024.043

Cite this article:
Eduardo, K., García-Nauto, N., Laqui-Estaña, J., Vásquez-Senador, M., & Cárdenas-Gaudry, M. (2024). Sustainable watersheds management in Peru: Challenges and perspectives. *Scientia Agropecuaria, 15*(4), 581-592.

1. Introduction

Water is a fundamental resource that underpins both ecological systems and human activities, essential for global sustainability and socio-economic progress. The urgency of effective water management has never been more critical, given the escalating challenges of climate change, pollution, and growing water demand. Research indicates that global agricultural productivity has been significantly impacted by these factors, with a notable 20% reduction since 1970 due to climate change, especially affecting regions like the Near East and North Africa (Kompas et al., 2024). The uncertainty surrounding future water availability is compounded by the expansion of irrigated areas in water-stressed regions, including major food producers such as China, India, Pakistan, and the United States.

In the context of Peru, a country characterized by a diverse and intricate network of watersheds, effective water resource management is of paramount importance. Watersheds, defined by their topographical features and the areas they drain, play a critical role in Peru's water infrastructure (Arai et al., 2010). The sustainable management of these watersheds is vital for ensuring reliable water supplies for agriculture, domestic use, industry, and energy production.

This review provides a detailed examination of current research on watershed management in Peru. It addresses the geographic, environmental, and socio-economic dimensions of watershed management, highlighting the major challenges and proposing potential solutions for sustainable water resource management in the country.

A central case study in this review is the Rimac River Basin, which is crucial for Lima, the second-largest desert city globally. This case study reveals the complexities of managing rapid urbanization, pollution, and the impacts of climate change in a region where water stress is a growing concern (Vega-Jácome et al., 2018). The Rimac River Basin, originating from the Andean highlands and serving as a lifeline for millions, exemplifies the challenges faced by urban watersheds under pressure from population growth and climate variability.

Recent studies underscore the urgency of addressing these challenges through integrated and adaptive management approaches. For instance, Hoefsloot et al. (2024) emphasize the importance of incorporating sustainable urban planning and resilient infrastructure investments to manage urban water resources effectively. Additionally, Caković et al. (2024) highlight the need for robust climate change adaptation strategies and interdisciplinary research to tackle complex water management issues.

The aim of this review is to shed light on the current state of knowledge regarding watershed management in Peru, identifying key challenges and opportunities for improvement. It provides a framework for discussing integrated and sustainable water resource management strategies, with insights aimed at enhancing the effectiveness of watershed management practices in Peru and offering lessons applicable to other regions facing similar issues.

2. Methodology

2.1. Search strategy

The literature search encompassed two primary databases: Web of Science (WOS) and Scopus, utilizing the following keywords: "peruvian" OR "peru" AND "integrated watershed management" OR "hydrographic basins" OR "hydrology". Advanced search functionalities with specific inclusion criteria were employed to target original research papers published in English and Portuguese. On 17 August 2024, the search in Web of Science yielded 301 papers, which were downloaded in RIS format. Similarly, on the same day, data collection in Scopus retrieved 210 documents spanning the period from 1975 to 2024. These documents were downloaded in Microsoft Excel in csv format.

2.2. Data filtering

The articles underwent a blind evaluation process facilitated by the open-access software Rayyan (Ouzzani et al., 2016). Inclusion criteria prioritized hydrological studies conducted within Peruvian basins or transboundary basins shared with neighboring countries like Bolivia, Brazil, Colombia, Chile, and Ecuador. This method encompassed three main phases: removing duplicate entries, screening titles for relevance, and assessing full-text articles.

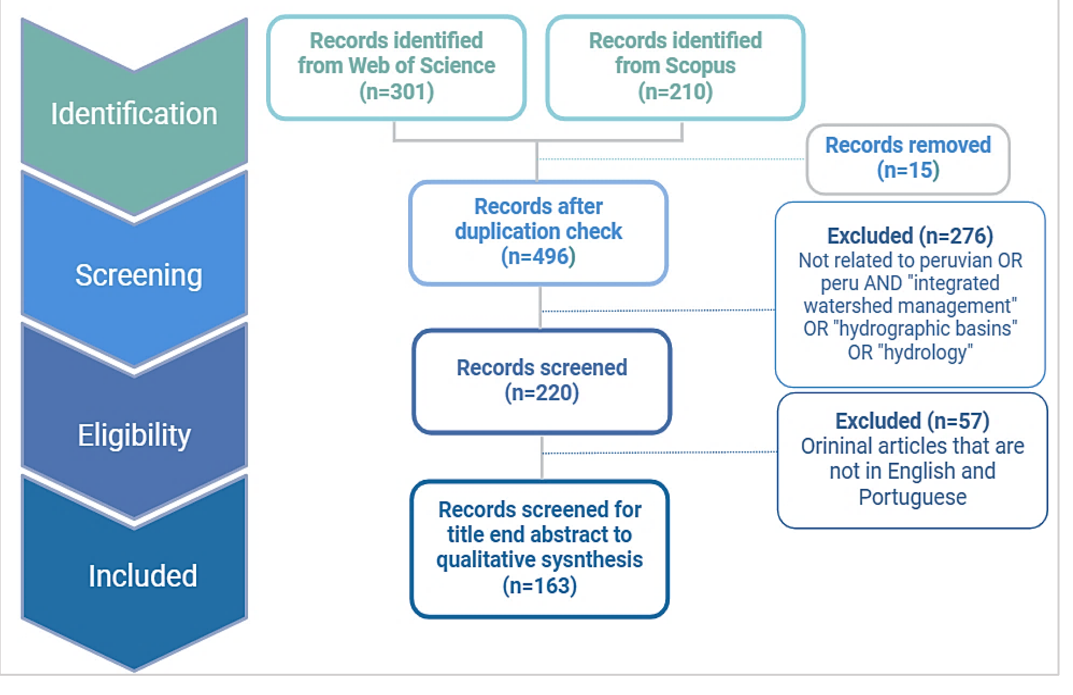

Figure 1. PRISMA selection process flowchart (Page et al., 2021).

2.3. Screening Process

After removing duplicates, 496 studies underwent screening. Following this, 276 papers were excluded due to a lack of relevance to the keywords found in the title, and an additional 57 papers were excluded as their abstracts did not align with the keywords. Ultimately, 163 studies were chosen for qualitative data synthesis, adhering to the criteria outlined in the PRISMA (Page et al., 2021) statement. Figure 1 illustrates the inclusion and exclusion steps of the literature at each stage in accordance with the PRISMA statement.

2.4. Data processing

The comprehensive analysis of scientific mapping, word clouds and origin of articles with the highest number of citations was performed using the "Bibliometrix" package (Aria & Cuccurullo, 2017) in R 4.3.2 software and the RStudio application. For co-occurrence analysis, the software VOSviewer 1.6.20 (Van Eck & Waltman, 2010) was used.

3. Results and discussion

3.1. Descriptive analysis

The analysis of the temporal evolution of publications (Figure 2a) indicates a significant increase in the number of scientific articles over the past few decades, particularly from the year 2000 onwards. This growth reflects a rising awareness and concern for sustainable watershed management in Peru, driven by environmental challenges such as climate change, uncontrolled urbanization, and water pollution. The upward trend suggests a growing interest from the scientific community and an intensification of research efforts to address these issues. Figure 2b shows the distribution of scientific production by author affiliation, reveals the global nature of interest in watershed management in Peru. While Peru leads with 80 articles, indicating strong local commitment, it is notable that researchers affiliated with institutions in the United States, France, Brazil, and Canada have also made significant contributions. This distribution suggests that although the problem is local, the relevance of Peru's watersheds has attracted the attention of the international scientific community. This can be attributed to the unique environmental challenges of Peru, such as water management in a context of high biodiversity and climate variability.

An indicator of an article's influence and significance is the frequency of citations it receives. Table 1 lists the eight most cited articles, highlighting those studies on climate variability, glacier retreat, their impacts on water resources, and human vulnerability have garnered significant scientific attention, particularly in the context of the Andes and the Amazon.

The analysis of keyword clouds highlights a significant evolution in research focus over time. During the period from 1975 to 1999, studies predominantly centered on Peru, with a strong emphasis on topics related to hydrology and streamflow (Figure 3a). This reflects an initial concern with understanding and managing water resources in a more local and specific context.

However, in the subsequent period from 2000 to 2024, a substantial shift in research priorities is observed, with an increasing focus on the Andean region and the impacts of climate change (Figure 3b). This change indicates a response by the scientific community to emerging challenges posed by environmental and climatic changes, reflecting an urgent need to adapt and expand research to address broader and more complex issues affecting the region.

Table 1
Analysis of eight articles with the highest number of citations

Title	Journals	Citations	Authors
Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador)	International Journal of Climatology	407	Espinoza Villar et al., 2009
Glacier recession and water resources in Peru's Cordillera Blanca	Journal of Glaciology	222	Baraer et al., 2012
Isotopic evidence for late Quaternary climatic change in tropical South America	Geology	180	Seltzer et al., 2000
Microbial community composition explains soil respiration responses to changing carbon inputs along an Andes-to-Amazon elevation gradient	Journal of Ecology	164	Whitaker et al., 2014
Modelling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Peru)	Global and Planetary Change	138	Juen et al., 2007
Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru	Climatic Change	138	Bury et al., 2011
The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru	Journal of Hydrology	126	Kaser et al., 2003
Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru	Journal of Glaciology	120	Mark & Seltzer, 2003

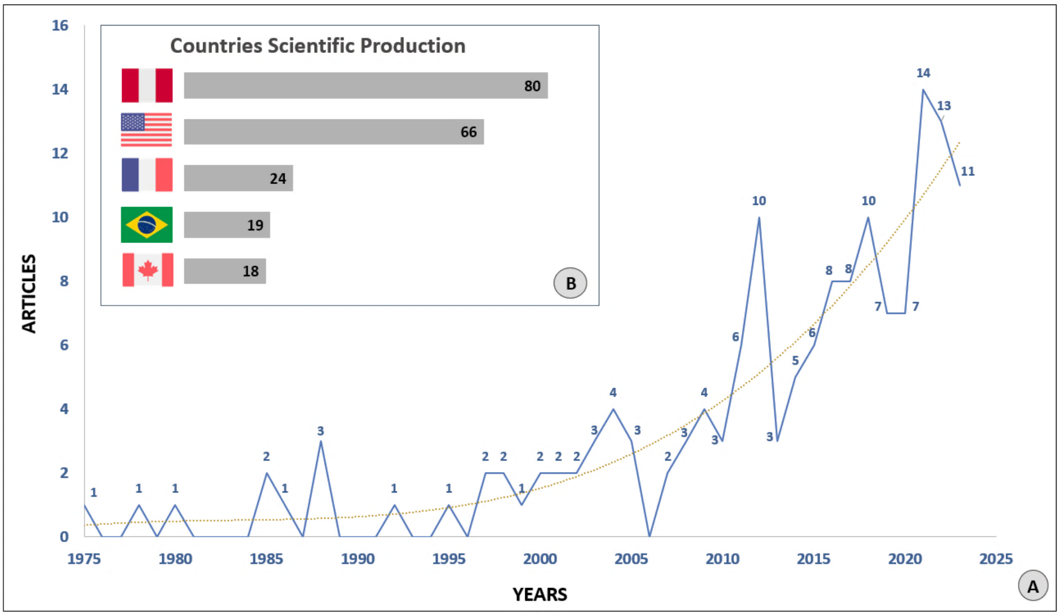

Figure 2. (a) Annual publication count and (b) top five countries with the highest scientific outputs.

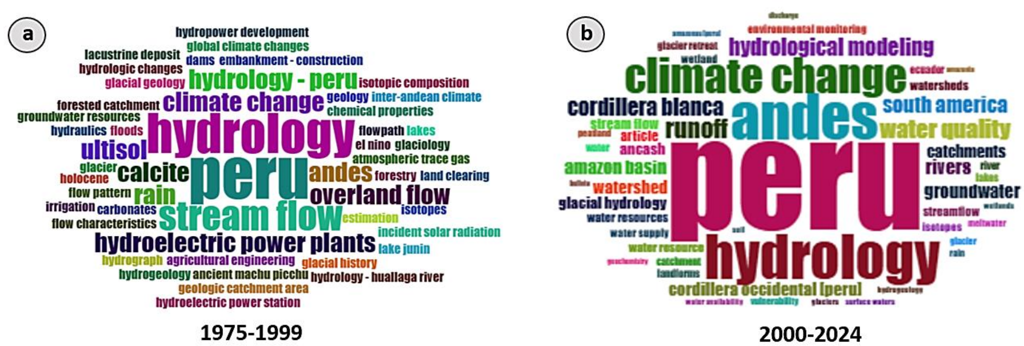

Figure 3. Keyword clouds depicting the periods (a) 1975 to 1999, and (b) 2000 to 2024. Generated using Bibliometrix (data extracted from Scopus and Web of Science).

This shift in research focus underscores the importance of aligning scientific agendas with the changing realities of the environment. The transition from a local focus to a more regional and global perspective in water resource research in Peru and the Andean region highlights the growing interconnectedness of environmental challenges and the need for an integrated approach to their management.

3.2. Co-occurrence Analysis

Figure 4a displays clustering and co-occurrence maps of keywords, identifying five distinct research clusters. The first cluster (red) focuses on hydrological and climatic aspects of Peru, with particular emphasis on the Amazon basin and phenomena like the El Niño-Southern Oscillation (ENSO). This cluster highlights the importance of studying how these phenomena impact climate and hydrology in the region. The second cluster (green) centers on climate change in South America, specifically the Cordillera Blanca in Peru, and glacial hydrology. This research examines how glacier retreat affects water resources, which is crucial for understanding future water availability in the region. The third cluster (blue) explores the geography of the Andes and river basins, showing an interest in how geographic features influence water distribution and basin management. The fourth cluster (yellow) focuses on groundwater, hydrogeology, and its interaction with other water resources. This reflects a growing concern about sustainable management of groundwater, an important resource in areas where surface water may be limited or seasonal. The fifth cluster (purple) emphasizes watershed management, water supply, and water quality, key topics for integrated water resource management and ensuring safe water provision. Recent topics focus on hydrology, water flows, precipitation, and risk assessment in river basins. This trend indicates increasing interest in understanding and managing the risks associated with climate variability and water resource management in the context of climate change.

3.3. River Basins in Peru

Peru has a total of 159 river basins, distributed across three main regions (ANA, 2016). The Pacific hydrographic region includes 62 river basins that rely on rainfall in the Sierra and account for only 2.19% of the available freshwater. The Atlantic or Amazon region contains 84 river basins characterized by deep and extensive rivers, holding 97.26% of the country's freshwater. The Titicaca region, comprising 13 river basins, represents 0.56% of the available water.

Among the 163 studies reviewed, 113 focused on specific basins in Peru, while the remaining studies addressed basins that include Peru and neighboring countries. The studies are primarily concentrated in three hydrographic regions (Figure 5): the Atlantic Hydrographic Region (47%), the Pacific Hydrographic Region (46%), and the Titicaca Hydrographic Region (7%).

In the Pacific Hydrographic Region, the Santa River Basin is the most studied, accounting for 21% of the total studies. Research here primarily focuses on the impacts of glacier retreat due to climate change, which has reduced water flow and affected local communities and agriculture (Baraer et al., 2012; Mark et al., 2010). To tackle these challenges, strategies such as water modeling and simulation (Condom et al., 2012) and promoting water literacy have been implemented. Water quality has also been examined, particularly concerning glacial sediments and mining pollution (Magnússon et al., 2020; Rangecroft et al., 2023).

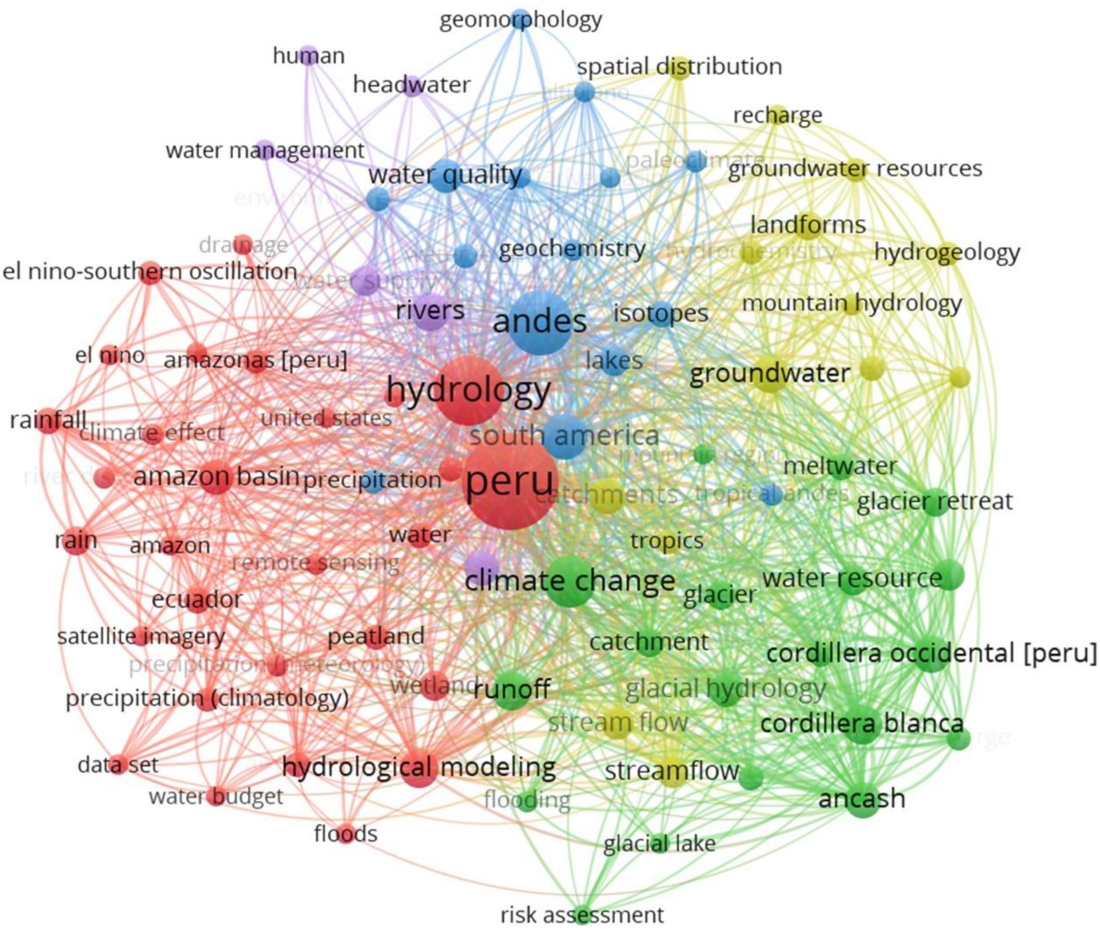

Figure 4. Clustering and co-occurrence maps of keywords obtained using VOSviewer software (Van Eck & Waltman, 2010). Data extracted from Scopus and Web of Science in August 2024.

In the Atlantic Hydrographic Region, the Marañón I, II, III, and IV inter-basins represent 12% of the studies. These studies cover topics like wetland and tuber vegetation, highlighting the diverse ecosystems and the need for their conservation (Kalliola et al., 1991; Lähteenoja & Page, 2011). Research also includes sediment dynamics within the basin (Armijos et al., 2013), satellite technology for sediment load assessment (Espinoza Villar et al., 2012), and hydrological dynamics and flow control (Hill et al., 2018). Additionally, hydrometeorological phenomena for risk mitigation have been explored (Figueroa et al., 2020).

The Ucayali River Basin represents 11% of the studies, focusing on the impact of climate change on basin hydrology, particularly related to El Niño events that affect rainfall patterns and river flow (Lavado Casimiro et al., 2011, 2013). Land use changes and their effects on water availability, including deforestation and agricultural expansion, are also studied (Weng et al., 2018). Recent research has evaluated flood risks due to intense rainfall events, which impact agricultural areas in the basin (Valenzuela et al., 2023).

In the Titicaca Hydrographic Region, which accounts for 7% of the studies, research addresses issues such as climate change impacts on droughts (Zubieta et al., 2021), lake evaporation and water balance (Pillco Zolá et al., 2019), and decreases in precipitation and runoff (Lavado Casimiro et al., 2012). Studies also examine water level fluctuations in Lake Titicaca and the effects of climate variability and human activities on these changes (Lima-Quispe et al., 2021). Paleohydrology studies provide insights into past hydrological and climatic conditions to better understand current and future challenges (Cross et al., 2001; Grove et al., 2003).

Finally, the Piura River Basin, part of the Pacific Hydrographic Region, represents 6% of the studies. Research here addresses groundwater salinization and irrigation management (Kuznetsov et al., 2012; Yakirevich et al., 2013) and explores the relationship between climate and public health, especially concerning diseases like cholera linked to extreme weather events such as El Niño (Ramírez & Grady, 2016). The impact of climate change on watershed hydrology, including variations in temperature and precipitation affecting water availability and runoff patterns, has also been studied (León Ochoa et al., 2019).

The hydrographic regions of Peru, spread across the Pacific, Atlantic, and Titicaca regions, exhibit diverse geographic and climatic characteristics. However, they share common concerns such as climate change, water management, and human impacts like deforestation. Addressing these challenges requires integrated and coordinated approaches to ensure sustainable water resources and the resilience of ecosystems and communities. Ongoing research and the implementation of effective strategies are crucial for tackling these issues and promoting sustainable water management in Peru.

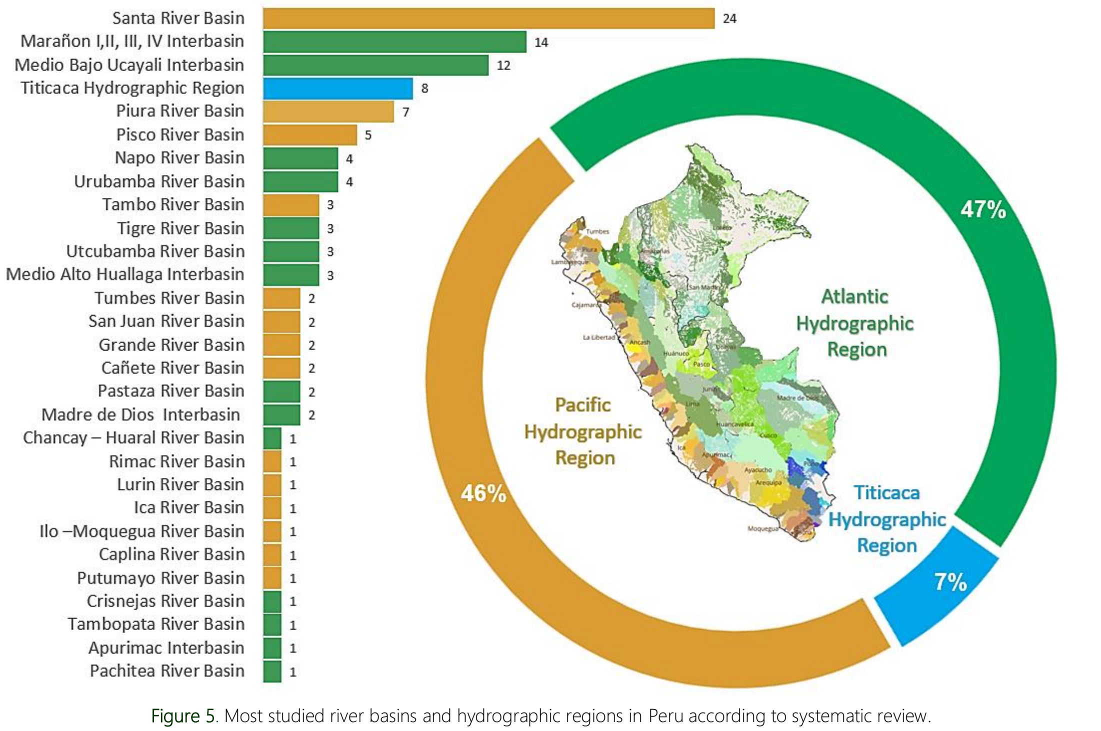

Figure 5. Most studied river basins and hydrographic regions in Peru according to systematic review. The base map was generated using QGIS (3.32).

3.4. A Representative case in Peru's hydrographic basins: Management and challenges in the Rimac River Basin

The Rimac River Basin, located on the central coast of Peru, is crucial due to its role in supplying water to Lima, the world's second-largest megacity situated in a desert environment, following Cairo. With a population exceeding 9,674,755 in 2020, representing around 30% of Peru's total population, Lima depends heavily on the Rimac River Basin for various needs, including domestic, industrial, and agricultural purposes (Vega-Jácome et al., 2018). However, this vital watershed faces numerous complex challenges that threaten its sustainability and health. This section provides a comprehensive analysis of the Rimac River Basin's issues and proposes potential strategies for effective management and conservation.

3.4.1. Geographical and environmental characteristics

The Rimac River Basin covers an area of approximately 3,503.95 km² and features a diverse range of geological and ecological attributes. The river originates at high altitudes in the Andes, with the source located around 4,200 meters above sea level. Approximately 65.7% of the basin's area consists of wet terrain that is crucial for sustaining the river. The Rimac River flows for about 127 km from its origin at the confluence of the Santa Eulalia and San Mateo rivers near Chosica until it reaches the Pacific Ocean. The perimeter of the river's basin is approximately 419.5 km.

Geologically, the basin is characterized by a mix of volcanic, sedimentary, and metamorphic rock formations. The soil varies from fertile in the higher elevations to saline near the coastal desert. The basin's diverse ecological landscape includes high Andean ecosystems, coastal arid forests, paramo ecosystems, and various woodland habitats. Although the Rimac River Basin does not contain glaciers, nearby regions of the Andes have some glaciated areas that contribute to the overall hydrology of the region.

3.4.2. Issues and challenges

The strategic importance of the Rimac River Basin is overshadowed by several pressing challenges:

Impact of the Coastal Niño: The watershed is vulnerable to extreme weather events, such as the 2017 Coastal Niño, which caused severe flash floods and landslides, significantly affecting local communities and infrastructure (Rojas-Portocarrero et al., 2019). The temperature in Peru has increased by 0.8°C since 1960-1980, leading to a 152% rise in premature heat-related deaths among people over 65 between 2000-2004 and 2017-2021 (Carrasco & Barja, 2022). The rising temperatures have also favored the spread of dengue fever, with increased transmission of *Aedes aegypti* and *Aedes albopictus* (Romanello et al., 2022). During the 2023-2024 El Niño event, extreme conditions such as intense rainfall and high temperatures led to significant damage and left over 787,000 people in need (Zevallos, 2024).

Water pollution: Industrial, agricultural, and domestic waste pollution compromises the quality of the Rimac River's water, making it challenging to treat for human consumption and jeopardizing aquatic ecosystems (Pascual et al., 2019). Flooding exacerbates water contamination issues, potentially increasing vector-borne diseases like dengue (Blanco-Villafuerte & Hartinger, 2023).

Urban pressure and accelerated development: Rapid urbanization around Lima exerts immense pressure on natural resources, leading to heightened water demand and conflicts among stakeholders (Hommes & Boelens, 2018). This urban expansion degrades aquatic ecosystems, alters the hydrological cycle, and increases water pollution due to population growth and industrial activities. Integrating social and ecohydrological factors into urban planning is crucial, yet there is limited guidance on applying these concepts effectively (Hansen & Pauleit, 2014).

Water risk and scarcity: Extreme weather events and climate change exacerbates droughts and floods, increasing community vulnerability and impacting water availability (Bell, 2022). Water scarcity is part of broader urban issues, including poor housing quality, inadequate public investment, and exclusion from decision-making (Ioris, 2012). Lima's water stress is compounded by outdated infrastructure and a centralized wastewater management system (Torre et al., 2024). Addressing water scarcity globally involves innovative management models and integration of resources (Caković et al., 2024). Effective risk management, infrastructure resilience, and disaster response are critical (Ramírez & Briones, 2017; Zevallos, 2024).

3.4.3. Future perspectives and sustainable management

3.4.3.1. Sustainable urban planning

Sustainable urban planning is crucial for mitigating environmental impacts and optimizing water resource utilization in rapidly growing urban areas. Effective urban planning practices include:

Land use management: Strategically managing land use to prevent overdevelopment and protect critical water sources. This involves zoning regulations that prioritize green spaces and limit industrial encroachment on sensitive areas.

Green infrastructure: Implementing green infrastructure such as rain gardens, permeable pavements, and green roofs helps manage stormwater, reduce runoff, and enhance water infiltration. These measures improve water quality by filtering pollutants and reducing the burden on traditional water treatment systems (Lara-Valencia et al., 2022).

Preservation of green areas: Protecting and expanding urban green areas and natural habitats is essential for maintaining ecological balance and supporting biodiversity. These areas also play a critical role in regulating local climate and improving air and water quality.

Integration of water governance practices: Lima's Water and Sewerage Service (SEDAPAL) is increasingly adopting practices like "siembra y cosecha de agua" (water harvesting) to enhance urban water security. These practices involve capturing and storing rainwater for later use, reducing reliance on external water sources, and mitigating the impacts of urbanization (Hoefsloot et al., 2024).

3.4.3.2. Infrastructure improvement

Strategic investments in infrastructure are pivotal for addressing water pollution and improving water quality. Key approaches include:

Resilient infrastructure: Developing infrastructure that can withstand extreme weather events and adapt to changing climatic conditions. This includes constructing flood defenses, reinforcing riverbanks, and upgrading drainage systems to handle increased rainfall and reduce flood risks.

Efficient water treatment systems: Investing in advanced water treatment technologies to enhance the ability to purify contaminated water. This includes the construction and maintenance of small-scale treatment facilities, such as the "amunas" in San Pedro de Casta, which manage rainwater runoff and prevent contamination of the river (Hoefsloot et al., 2024).

Maintenance and upgrades: Regular maintenance and upgrades to existing infrastructure are essential to ensure the continued functionality and effectiveness of water management systems. This involves monitoring infrastructure conditions, addressing wear and tear, and integrating new technologies as they become available.

3.4.3.3. Climate change adaptation

Formulating and implementing robust climate change adaptation strategies are crucial for enhancing community resilience and ensuring water security. Effective strategies include:

Integrated Watershed Management (IWM): Adopting IWM approaches to manage watersheds holistically, considering all aspects of the ecosystem, including land use, water resources, and biodiversity (Caković et al., 2024). Studies have shown that IWM can improve agricultural production and soil quality, as seen in Uganda's Karamoja Region and Ethiopia's Miyo-Hadi watershed (Barakagira & Ndungo, 2023; Mekonnen et al., 2021).

Adaptive management practices: Developing flexible management strategies that can be adjusted based on changing conditions and new information. This involves continuous monitoring of environmental indicators, forecasting potential impacts, and adjusting management practices accordingly.

Community-based adaptation: Engaging local communities in the development and implementation of adaptation strategies to ensure that measures are relevant and effective. Local knowledge and practices can provide valuable insights into managing climate risks and adapting to environmental changes.

3.4.3.4. Community participation

Fostering active community participation in watershed management and conservation is essential for sustainable outcomes. Key elements include:

Engagement and empowerment: Involving local communities in decision-making processes and recognizing their traditional knowledge and practices. This includes creating platforms for dialogue, incorporating community feedback, and ensuring equitable access to water resources (Miranda Sara et al., 2016).

Education and awareness: Promoting environmental education and raising awareness about the importance of watershed conservation. Educating communities about sustainable practices and the impacts of environmental changes can foster greater participation and commitment to conservation efforts.

Strengthening disaster risk management: Improving disaster risk management systems to better respond to extreme weather events and other emergencies. This involves enhancing early warning systems, improving infrastructure resilience, and coordinating response efforts across different sectors (Torres Mallma, 2021).

Ongoing research and governance: Supporting continued research on watershed management and conservation to inform policy and practice. Effective governance structures are necessary to ensure that research findings are translated into actionable policies and management strategies (Beveridge et al., 2024).

The Rimac River Basin faces significant challenges that demand coordinated and sustained efforts to ensure its long-term sustainability. By adopting integrated and participatory approaches, combining advanced technology with community engagement, and emphasizing adaptive management, it is possible to achieve a balance between human development and environmental preservation in this critical Peruvian region.

3.5. Future perspectives

The ongoing and future challenges in sustainable watershed management in Peru necessitate a multifaceted approach to ensure the resilience and adaptability of water resources amid climatic and anthropogenic pressures. Drawing on the extensive review and analysis presented in this study, the following future perspectives emerge as critical areas for advancing the field:

a. Integrated climate change adaptation strategies: The urgency to address the impacts of climate change on water resources is increasingly apparent. The growing frequency and severity of climatic events, such as glacier retreat in the Andes and shifting precipitation patterns, underscore the need for comprehensive climate adaptation strategies. Future research should focus on integrating climate models with watershed management practices to enhance predictive capabilities and inform adaptive measures. Caković et al. (2024) emphasize the importance of interdisciplinary approaches that incorporate climate projections into water management plans. It is crucial to develop robust strategies for climate change adaptation and mitigation, including ecosystem restoration, reforestation, and sustainable water management practices.

b. Enhanced urban and rural water management: As urbanization accelerates, particularly in water-stressed regions such as Lima, there is an urgent need for innovative solutions to manage urban water resources effectively. Sustainable urban planning and investments in resilient infrastructure are critical to addressing these challenges, as highlighted by Hoefsloot et al. (2024). Urban strategies should focus on managing stormwater, reducing pollution, and mitigating the adverse effects of urbanization on watersheds. Simultaneously, rural areas, which rely heavily on traditional water management practices, need modernization to cope with increasing water demand and variability. Technological advancements and improved methods are essential for enhancing water management in these regions. Integrating sustainable urban planning with advancements in rural water management will contribute to a more comprehensive and effective approach to water resource management across both urban and rural contexts.

c. Strengthening data and monitoring systems: Effective watershed management relies on robust data and monitoring systems. The review identified significant gaps in the availability and integration of hydrological data across different regions of Peru. Future efforts should focus on enhancing data collection, employing remote sensing technologies, and developing comprehensive databases to support real-time monitoring and decision-making. The integration of emerging technologies, such as artificial intelligence (AI), can significantly enhance these systems, thereby helping to better understand watershed dynamics and improving resource allocation.

d. Fostering regional and international collaboration: Watershed management in transboundary basins requires cooperation between neighboring countries. The review indicates that studies addressing shared river basins are limited. Future research should emphasize strengthening regional collaboration to address cross-border water management challenges, share best practices, and develop joint strategies for sustainable resource use.

e. Promoting water literacy and strengthening community and institutional collaboration: The successful implementation of water management strategies depends on active community involvement and heightened public awareness. Promoting water literacy is essential, as it empowers local communities to participate meaningfully in watershed management initiatives. Educational programs and participatory approaches should be developed to ensure communities are well-informed and actively engaged in conservation efforts and the adoption of sustainable practices. Moreover, strengthening collaboration among institutions, government agencies, and local communities, including indigenous peoples and local stakeholders, is crucial. By fostering these partnerships, water management practices can become more equitable, inclusive, and effective, ultimately leading to more resilient and sustainable outcomes.

f. Addressing knowledge gaps and research priorities: The evolution of research focus from local hydrology to broader regional and global issues reflects the changing landscape of water management. Future research should address identified knowledge gaps, particularly in the areas of groundwater management, the impact of land use changes on hydrology, and the integration of socio-economic factors into watershed management strategies. Prioritizing these research areas will contribute to a more holistic understanding of water resource challenges and solutions.
g. Investment in scientific research and technological innovation: Increased investment in research and technology to address water-related challenges, supporting interdisciplinary research and professional training. This is essential for developing innovative solutions that ensure the sustainability of water resources amidst evolving environmental and socio-economic conditions.

By addressing these future perspectives, stakeholders can advance the field of watershed management in Peru, ensuring the sustainability of water resources amidst evolving environmental and socio-economic conditions.

4. Conclusions

This comprehensive review of sustainable watershed management in Peru underscores the complexity and urgency of addressing water resource challenges in the face of rapid environmental changes and socio-economic development. Peru, blessed with abundant water resources across its Pacific, Atlantic, and Titicaca hydrographic regions, faces significant threats from water contamination, deforestation, biodiversity loss, and the escalating impacts of climate change, such as glacial retreat, shifting precipitation patterns, and disrupted hydrological cycles. These challenges necessitate the integration of climate change adaptation strategies, the modernization of urban and rural water management systems, and the enhancement of data and monitoring infrastructures through the strategic use of emerging technologies like artificial intelligence.

The case of the Rimac River, a vital water source for Lima, vividly illustrates the pressures faced by Peru's watersheds, including urbanization, pollution, and climate variability. To effectively address these issues, this study emphasizes the critical importance of integrated water planning, riparian ecosystem conservation, and the adoption of innovative technologies for enhanced water resource monitoring and management.

Collaboration emerges as a central theme throughout this review. The success of watershed management in Peru hinges on strong partnerships between local communities, governmental agencies, and international stakeholders. Promoting water literacy and actively engaging communities in conservation efforts are crucial steps toward fostering a sense of ownership and responsibility for sustainable water use. Additionally, addressing knowledge gaps through focused research on groundwater management, land use changes, and the socio-economic dimensions of water management will lay the groundwork for informed decision-making and policy development.

Moving forward, substantial investment in scientific research and technological innovation, coupled with a commitment to interdisciplinary approaches that integrate environmental, social, and economic considerations, will be essential. Only through collaborative, multidisciplinary efforts can Peru meet the evolving challenges posed by climate change and development pressures. By embracing these future perspectives, Peru can enhance the resilience of its watersheds, ensuring the sustainability of water resources for future generations. This holistic approach will not only safeguard the environment but also support the well-being and prosperity of communities across the nation, securing water availability and quality for generations to come.

Acknowledgements

We are grateful to the Universidad Nacional de Moquegua for funding the Article Processing Charge for this article.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

K. Eduardo: Conceptualization, Formal analysis, Investigation, Writing-review & editing. N. Garcia-Nauto: Conceptualization, Investigation, Methodology, Writing-review & editing. Trial. J. Laqui-Estaña: Conceptualization, Investigation, Resources, Writing-review & editing. M. Vásquez-Senador: Investigation, Methodology. M. Cárdenas-Gaudry: Formal analysis, Investigation, Supervision, Visualization, Writing-review & editing, Project administration.

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References

ANA Autoridad Nacional del Agua. (2016). Priorización de Cuencas para la Gestión de los Recursos Hídricos. Ediciones ANA.

Arai, F. K., Pereira, S. B., & Gonçalves, G. G. G. (2010). Characterization of water availability in a hydrographic basin. *Engenharia Agricola*, *32*(3), 591–601. https://doi.org/10.1590/S0100-69162012000300018

Aria, M., & Cuccurullo, C. (2017). Bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Armijos, E., Crave, A., Vauchel, P., Fraizy, P., Santini, W., Moquet, J.-S., Arevalo, N., Carranza, J., & Guyot, J. L. (2013). Suspended sediment dynamics in the Amazon River of Peru. *Journal of South American Earth Sciences*, *44*, 75–84. https://doi.org/10.1016/j.jsames.2012.09.002

Baraer, M., Mark, B. G., McKenzie, J. M., Condom, T., Bury, J., Huh, K.-I., Portocarrero, C., Gómez, J., & Rathay, S. (2012). Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, *58*(207), 134–150. https://doi.org/10.3189/2012JoG11J186

Barakagira, A., & Ndungo, I. (2023). Watershed management and climate change adaptation mechanisms used by people living in dryland areas of Lokere catchment in Karamoja, Uganda. *Environmental and Socio-Economic Studies*, *11*(1), 45–57. https://doi.org/10.2478/ENVIRON-2023-0004

Bell, M. G. (2022). Overlooked legacies: Climate vulnerability and risk as incrementally constructed in the municipal drinking water system of Lima, Peru (1578–2017). *Geoforum*, *132*, 205-218. https://doi.org/10.1016/j.geoforum.2021.02.016

Beveridge, C. F., Espinoza, J. C., Athayde, S., Correa, S. B., Couto, T. B. A., Heilpern, S. A., Jenkins, C. N., Piland, N. C., Utsunomiya, R., Wongchuig, S., & Anderson, E. P. (2024). The Andes-Amazon-Atlantic pathway: A foundational hydroclimate system for social-ecological system sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(22). https://doi.org/10.1073/PNAS.2306229121

Blanco-Villafuerte, L., & Hartinger, S. M. (2023). Impact of climate change on the health of Peruvians: challenges and strategies for a comprehensive response. *Revista Peruana de Medicina Experimental y Salud Publica*, *40*(2), 130. https://doi.org/10.17843/RPMESP.2023.402.12998

Bury, J. T., Mark, B. G., McKenzie, J. M., French, A., Baraer, M., Huh, K. I., Zapata Luyo, M. A., & Gómez López, R. J. (2011). Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change*, *105*(1), 179–206. https://doi.org/10.1007/s10584-010-9870-1

Caković, M., Dragović, N., Jovanović, N., Rončević, V., Živanović, N., Zlatić, M., & Vasić, F. (2024). Current Trends and Future Perspectives of Integrated Watershed Management. *South-East European Forestry*, *15*(1). https://doi.org/10.15177/SEEFOR.24-12

Carrasco, G., & Barja, A. (2022). Warming Stripes para las 24 regiones del Perú. https://healthinnovation.github.io/WarmingStripes4PE

Condom, T., Escobar, M., Purkey, D., Pouget, J. C., Suarez, W., Ramos, C., Apaestegui, J., Tacsi, A., & Gomez, J. (2012). Simulating the implications of glaciers' retreat for water management: A case study in the Rio Santa basin, Peru. *Water International*, *37*(4), 442–459. https://doi.org/10.1080/02508060.2012.706773

Cross, S. L., Baker, P. A., Seltzer, G. O., Fritz, S. C., & Dunbar, R. B. (2001). Late Quaternary Climate and Hydrology of Tropical South America Inferred from an Isotopic and Chemical Model of Lake Titicaca, Bolivia and Peru. *Quaternary Research*, *56*(1), 1–9. https://doi.org/10.1006/qres.2001.2244

Espinoza Villar, J. C., Ronchail, J., Guyot, J. L., Cochonneau, G., Naziano, F., Lavado, W., De Oliveira, E., Pombosa, R., & Vauchel, P. (2009). Spatio-temporal rainfall variability in the Amazon basin countries (Brazil, Peru, Bolivia, Colombia, and Ecuador). *International Journal of Climatology*, *29*(11), 1574–1594. https://doi.org/10.1002/joc.1791

Figueroa, M., Armijos, E., Espinoza, J. C., Ronchail, J., & Fraizy, P. (2020). On the relationship between reversal of the river stage (repiquetes), rainfall and low-level wind regimes over the western Amazon basin. Journal of Hydrology: *Regional Studies*, *32*, 100752. https://doi.org/10.1016/j.ejrh.2020.100752

Grove, M. J., Baker, P. A., Cross, S. L., Rigsby, C. A., & Seltzer, G. O. (2003). Application of strontium isotopes to understanding the hydrology and paleohydrology of the Altiplano, Bolivia–Peru. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *194*(1), 281–297. https://doi.org/10.1016/S0031-0182(03)00282-7

Hansen, R., & Pauleit, S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *Ambio*, *43*(4), 516–529. https://doi.org/10.1007/S13280-014-0510-2

Hill, A. F., Stallard, R. F., & Rittger, K. (2018). Clarifying regional hydrologic controls of the Marañón River, Peru through rapid assessment to inform system-wide basin planning approaches. *Elementa: Science of the Anthropocene*, *6*, 37. https://doi.org/10.1525/elementa.290

Hoefsloot, F. I., Martínez, J., & Pfeffer, K. (2024). An emerging knowledge system for future water governance: sowing water for Lima. *Territory, Politics, Governance*, *12*(6), 825–845. https://doi.org/10.1080/21622671.2021.2023365

Hommes, L., & Boelens, R. (2018). From natural flow to 'working river': Hydropower development, modernity and socio-territorial transformations in Lima's Rimac watershed. *Journal of Historical Geography*, *62*, 85-95. https://doi.org/10.1016/j.jhg.2018.04.001

Ioris, A. A. R. (2012). The geography of multiple scarcities: Urban development and water problems in Lima, Peru. *Geoforum*, *43*(3), 612–622. https://doi.org/10.1016/J.GEOFORUM.2011.12.005

Juen, I., Kaser, G., & Georges, C. (2007). Modelling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Perú). *Global and Planetary Change*, *59*(1), 37–48. https://doi.org/10.1016/j.gloplacha.2006.11.038

Kalliola, R., Puhakka, M., Salo, J., Tuomisto, H., & Ruokolainen, K. (1991). The dynamics, distribution and classification of swamp vegetation in Peruvian Amazonia. *Annales Botanici Fennici*, *28*(3), 225–239. http://www.jstor.org/stable/23725332

Kaser, G., Juen, I., Georges, C., Gómez, J., & Tamayo, W. (2003). The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Perú. *Journal of Hydrology*, *282*(1), 130–144. https://doi.org/10.1016/S0022-1694(03)00259-2

Kompas, T., Che, T. N., & Grafton, R. Q. (2024). Global impacts of heat and water stress on food production and severe food insecurity. *Scientific Reports*, *14*(1), 14398. https://doi.org/10.1038/s41598-024-65274-z

Kuznetsov, M., Yakirevich, A., Pachepsky, Y. A., Sorek, S., & Weisbrod, N. (2012). Quasi 3D modeling of water flow in vadose zone and groundwater. *Journal of Hydrology*, *450–451*, 140–149. https://doi.org/10.1016/j.jhydrol.2012.05.025

Lähteenoja, O., & Page, S. (2011). High diversity of tropical peatland ecosystem types in the Pastaza-Marañón basin, Peruvian Amazonia. *Journal of Geophysical Research: Biogeosciences*, *116*(G2). https://doi.org/10.1029/2010JG001508

Lara-Valencia, F., Garcia, M., Norman, L. M., Anides Morales, A., & Castellanos-Rubio, E. E. (2022). Integrating Urban Planning and Water Management Through Green Infrastructure in the United States-Mexico Border. *Frontiers in Water*, *4*, 782922. https://doi.org/10.3389/FRWA.2022.782922/BIBTEX

Lavado Casimiro, W. S., Labat, D., Guyot, J. L., & Ardoin-Bardin, S. (2011). Assessment of climate change impacts on the hydrology of the Peruvian Amazon–Andes basin. *Hydrological Processes*, *25*(24), 3721–3734. https://doi.org/10.1002/hyp.8097

Lavado Casimiro, W. S., Labat, D., Ronchail, J., Espinoza, J. C., & Guyot, J. L. (2013). Trends in rainfall and temperature in the Peruvian Amazon–Andes basin over the last 40 years (1965–2007). *Hydrological Processes*, *27*(20), 2944–2957. https://doi.org/10.1002/hyp.9418

Lavado Casimiro, W. S., Ronchail, J., Labat, D., Espinoza, J. C., & Guyot, J. L. (2012). Analyse de la pluie et de l'écoulement au Pérou (1969–2004): Bassins versants du Pacifique, du Lac Titicaca et de l'Amazone. *Hydrological Sciences Journal*, *57*(4), 625–642. https://doi.org/10.1080/02626667.2012.672985

León Ochoa, R. F., Portuguez Maurtua, D. M., & Chávarri Velarde, E. A. (2019). Modelación de la disponibilidad hídrica del rio Piura - Perú, considerando la incidencia del cambio climático. *Journal of High Andean Research*, 21(3), 182–193. https://doi.org/10.18271/ria.2019.476

Lima-Quispe, N., Escobar, M., Wickel, A. J., von Kaenel, M., & Purkey, D. (2021). Untangling the effects of climate variability and irrigation management on water levels in Lakes Titicaca and Poopó. *Journal of Hydrology: Regional Studies*, *37*, 100927. https://doi.org/10.1016/j.ejrh.2021.100927

Magnússon, R., Cammeraat, E., Lücke, A., Jansen, B., Zimmer, A., & Recharte, J. (2020). Influence of glacial sediments on the chemical quality of surface water in the Ulta valley, Cordillera Blanca, Peru. *Journal of Hydrology*, *587*, 125027. https://doi.org/10.1016/j.jhydrol.2020.125027

Mark, B. G., Bury, J., McKenzie, J. M., French, A., & Baraer, M. (2010). Climate Change and Tropical Andean Glacier Recession: Evaluating Hydrologic Changes and Livelihood Vulnerability in the Cordillera Blanca, Peru. *Annals of the Association of American Geographers*, *100*(4), 794–805. https://doi.org/10.1080/00045608.2010.497369

Mark, B. G., & Seltzer, G. O. (2003). Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru. *Journal of Glaciology*, *49*(165), 271–281. https://doi.org/DOI: 10.3189/172756503781830746

Mekonnen, M., Abeje, T., & Addisu, S. (2021). Integrated watershed management on soil quality, crop productivity and climate change adaptation, dry highland of Northeast Ethiopia. *Agricultural Systems*, *186*, 102964. https://doi.org/10.1016/J.AGSY.2020.102964

Miranda Sara, L., Jameson, S., Pfeffer, K., & Baud, I. (2016). Risk perception: The social construction of spatial knowledge around climate change-related scenarios in Lima. *Habitat International*, *54*, 136149. https://doi.org/10.1016/j.habitatint.2015.12.025

Ouzzani, M., Hammady, H., Fedorowicz, Z. et al. (2016). Rayyan - a web and mobile app for systematic reviews. *Syst Rev*, *5*, 210. https://doi.org/10.1186/s13643-016-03844.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *International Journal of Surgery*, *88*, 105906. https://doi.org/10.1016/j.ijsu.2021.105906

Pascual, G., Iannacone, J., & Alvariño, L. (2019). Benthic macroinvertebrates and toxicological tests for assessing water and sediment quality of the Rimac River, Lima, Peru. *Revista de Investigaciones Veterinarias del Perú*, *30*(4), 1421-1442. https://doi.org/10.15381/rivep.v30i4.17164

Pillco Zolá, R., Bengtsson, L., Berndtsson, R., Martí-Cardona, B., Satgé, F., Timouk, F., Bonnet, M.-P., Mollericon, L., Gamarra, C., & Pasapera, J. (2019). Modelling Lake Titicaca's daily and monthly evaporation. *Hydrology and Earth System Sciences*, *23*(2), 657–668. https://doi.org/10.5194/hess-23-657-2019

Ramírez, I. J., & Briones, F. (2017). Understanding the El Niño Costero of 2017: The Definition Problem and Challenges of Climate Forecasting and Disaster Responses. *International Journal of Disaster Risk Science*, *8*(4), 489–492. https://doi.org/10.1007/S13753-017-0151-8

Ramírez, I. J., & Grady, S. C. (2016). El niño, climate, and cholera associations in Piura, Peru, 1991-2001: A wavelet analysis. *EcoHealth*, *13*(1), 83–99. https://doi.org/10.1007/s10393-015-1095-3

Rangecroft, S., Dextre, R. M., Richter, I., Grados Bueno, C. V, Kelly, C., Turin, C., Fuentealba, B., Hernandez, M. C., Morera, S., Martin, J., Guy, A., & Clason, C. (2023). Unravelling and understanding local perceptions of water quality in the Santa basin, Peru. *Journal of Hydrology*, *625*, 129949. https://doi.org/10.1016/j.jhydrol.2023.129949

Rojas-Portocarrero, W. K., Hidalgo-Egocheaga, B., Moya-Durand, C. A., Castro-Pérez, F., & Barboza-Palomino, M. (2019). Percepción de riesgo ante las inundaciones en personas que habitan en zonas vulnerables de Lima, Perú. *Revista Cubana de Salud Pública*, *45*, e1190.

Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P., Scamman, D., Arnell, N., Ayeb-Karlsson, S., Ford, L. B., Belesova, K., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., van Daalen, K. R., Dalin, C., Dasandi, N., Costello, A. (2022). The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. *The Lancet*, *400*(10363), 1619–1654. https://doi.org/10.1016/S0140-6736(22)01540-9

Seltzer, G., Rodbell, D., & Burns, S. (2000). Isotopic evidence for late Quaternary climatic change in tropical South America. *Geology*, *28*(1), 35–38. https://doi.org/10.1130/0091-7613(2000)28<35:IEFLQC>2.0.CO;2

Torre, A., Vázquez-Rowe, I., Parodi, E., & Kahhat, R. (2024). A multi-criteria decision framework for circular wastewater systems in emerging megacities of the Global South. *Science of The Total Environment*, *912*, 169085. https://doi.org/10.1016/J.SCITOTENV.2023.169085

Torres Mallma, S. F. (2021). Mainstreaming land use planning into disaster risk management: Trends in Lima, Peru. International *Journal of Disaster Risk Reduction*, *62*, 102404. https://doi.org/10.1016/j.ijdrr.2021.102404

Valenzuela, J., Figueroa, M., Armijos, E., Espinoza, J.-C., Wongchuig, S., & Ramirez-Avila, J. J. (2023). Flooding risk of cropland areas by repiquetes in the western Amazon basin: A case study of Peruvian Tamshiyacu City. *Journal of Hydrology: Regional Studies*, *47*, 101428. https://doi.org/10.1016/j.ejrh.2023.101428

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Vega-Jácome, F., Lavado-Casimiro, W. S., & Felipe-Obando, O. G. (2018). Assessing hydrological changes in a regulated river system over the last 90 years in Rimac Basin (Peru). *Theoretical and Applied Climatology*, *132*(1-2), 347-362. https://doi.org/10.1007/s00704-017-2084-y

Weng, W., Luedeke, M. K. B., Zemp, D. C., Lakes, T., & Kropp, J. P. (2018). Aerial and surface rivers: downwind impacts on water availability from land use changes in Amazonia. *Hydrology and Earth System Sciences*, *22*(1), 911–927. https://doi.org/10.5194/hess-22-911-2018

Whitaker, J., Ostle, N., Nottingham, A. T., Ccahuana, A., Salinas, N., Bardgett, R. D., Meir, P., & McNamara, N. P. (2014). Microbial community composition explains soil respiration responses to changing carbon inputs along an Andes-to-Amazon elevation gradient. *Journal of Ecology*, *102(*4), 1058–1071. https://doi.org/10.1111/1365-2745.12247

Yakirevich, A., Weisbrod, N., Kuznetsov, M., Rivera Villarreyes, C. A., Benavent, I., Chavez, A. M., & Ferrando, D. (2013). Modeling the impact of solute recycling on groundwater salinization under irrigated lands: A study of the Alto Piura aquifer, Peru. *Journal of Hydrology*, *482*, 25–39. https://doi.org/10.1016/j.jhydrol.2012.12.029

Zevallos, R. (2024). El Niño Costero 2023-2024 was the most intense in the last 20 years in Western South America | Regional Climate Center. https://crc-osa.ciifen.org/en/2024/06/17/el-nino-costero-2023-2024-fue-el-mas-intenso-de-los-ultimos-20-anos-en-el-oeste-de-sudamerica/

Zubieta, R., Molina-Carpio, J., Laqui, W., Sulca, J., & Ilbay, M. (2021). Comparative analysis of climate change impacts on meteorological, hydrological, and agricultural droughts in the Lake Titicaca basin. *Water (Switzerland)*, *13*(2). https://doi.org/10.3390/w13020175