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IMPACT OF UPPER WATERSHED CONSERVATION IN ANDEAN BASINS ON WATER SUPPLY AND CLIMATE RESILIENCE: A COMPARATIVE LITERATURE REVIEW

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1. ABSTRACT

This study aims to comparatively analyze the impact of upper watershed conservation in Andean basins on water supply and climate resilience. Through a literature review, 22 scientific articles published between 2019 and 2022 in the Scopus and Scielo databases were selected, prioritizing applied research in Peru, Bolivia, Ecuador, and Colombia.. Five key thematic axes were identified: integrated watershed management, climate change and water availability, sustainable soil conservation practices, community participation, and hydrological modeling. The results show that upper watershed conservation enhances water regulation, reduces territorial vulnerability, and strengthens adaptive planning. However, challenges remain, such as institutional fragmentation, territorial inequality, and limited integration between scientific knowledge and local practices. It is concluded that an effective strategy requires combining ecological restoration, community engagement, and technological innovation to ensure long-term water sustainability under climate change conditions.

KEYWORDS: Upper watershed conservation, andean basins, water supply, climate resilience, ecosystem management

1. INTRODUCTION

According to UNESCO (2021), water scarcity has become a global crisis that directly threatens human life, food production, and environmental stability. Prolonged droughts, driven by climate change, have resulted in crop failures, livestock deaths, and a reduction in essential water reserves (World Bank, 2025). Millions of people face challenges in accessing potable water, increasing the incidence of disease and death from dehydration or the consumption of contaminated water (World Wildlife Fund, 2025). In many regions, agriculture is severely affected, compromising food security (UNICEF, 2025).

At the global level, the World Bank (2025) reports that the water crisis represents one of the most critical threats of the 21st century. More than 2.2 billion people lack safe access to drinking water, and nearly 4 billion experience severe shortages at least one month per year (UNESCO, 2021). Prolonged droughts and the overexploitation of aquifers have led to crop losses in more than 30% of vulnerable agricultural areas (World Wildlife Fund, 2025). Each year, around 500,000 deaths are associated with diseases transmitted through contaminated water (UNICEF, 2025). Furthermore, climate change intensifies water variability, triggering extreme events that affect food security, public health, and social stability (World Bank, 2025).

According to UNESCO (2025), in Latin America, despite holding approximately 30% of the world's freshwater, distribution remains unequal, and droughts are increasingly recurrent. Over 40% of rural areas lack continuous access to safe water (ECLAC, 2023a). Approximately 35% of agricultural losses in the region are directly linked to water scarcity (World Bank, 2022). Countries such as Mexico, Bolivia, Chile, and Brazil face severe reductions in their aquifer reserves, with direct impacts on agricultural and livestock production (ECLAC, 2023b).

Likewise, UNESCO (2025) emphasizes that Indigenous and peasant populations are particularly vulnerable, with over 50% depending directly on surface sources that have been degraded by pollution, mining, and accelerated glacial melt.

According to the National Water Authority (2024), in Peru, water issues are particularly acute in the high Andean basins, which generate 70% of the nation's water resources. The Environmental Evaluation and Enforcement Agency (2025) notes that the retreat of Andean glaciers has significantly reduced water availability during dry seasons. At least 60% of rural highland communities report growing difficulties in accessing water for drinking and irrigation (National Center for Strategic Planning, 2023). Droughts affect 45% of agricultural lands in the Andean and Altiplano regions, reducing the production of potatoes, quinoa, and barley (World Bank, 2023). Furthermore, subsistence livestock farming is impacted by the loss of pastures and natural water sources (OECD, 2021).

This study is justified by the growing global water crisis, marked by scarcity, prolonged droughts, and the impacts of climate change. This problem severely affects food security, with significant losses in crops and livestock, and causes the death of thousands of people due to lack of access to potable water. In vulnerable regions such as the high Andean basins, the effects are more acute, threatening ecosystems, communities, and ancestral ways of life. Analyzing this situation is key to proposing sustainable and resilient solutions in the face of this water emergency.

The water problem is a global crisis affecting millions of people, with severe consequences for health, agriculture, and economic development. Water scarcity and recurring droughts are causing high mortality rates—both human and animal—due to the lack of access to drinking water and extreme conditions that dehydrate soils. Crops, especially in arid regions, are severely affected, increasing food insecurity. Climate change further exacerbates the situation by altering precipitation patterns and generating extreme weather events such as prolonged droughts and floods. The high Andean basins, vital for supplying water to various regions, are experiencing a decline in their storage capacity due to glacial melt and deforestation, which further worsens the scarcity. This scenario calls for urgent water management policies, conservation strategies, and climate change adaptation to mitigate its devastating effects.

Therefore, the objective of this research is to comparatively analyze the impact of conserving high-altitude areas in Andean watersheds on water supply and climate resilience. In this context, the central research question guiding this review is: How does upper watershed conservation in Andean basins contribute to improving water supply and strengthening climate resilience in the context of climate change?

THEORETICAL FRAMEWORK

According to Callicott (2023), reflection on environmental care has led to the development of theoretical frameworks that guide educational and social action in the face of the global ecological crisis. One of these is the Theory of Environmental or Planetary Conservation, whose main proponent was Aldo Leopold, who in the mid-twentieth century formulated the land ethic as a foundation for a balanced relationship between humans and nature (Meine, 2022). This theory emerged in the context of growing concern over biodiversity loss, ecosystem degradation, and the effects of industrialization on the planet (Callicott, 2022).

Its approach posits that environmental conservation does not merely entail the protection of species or landscapes, but rather a profound transformation of human values toward an ecological understanding of the world (Smith, 2022). This perspective asserts that human decisions should be grounded in ethical principles that recognize the intrinsic rights of all elements of the natural environment, promoting an education focused on ecological responsibility, respect for natural cycles, and harmony between development and environmental conservation (Callicott, 2023).

Yi and Kondolf (2024) argue that from this comprehensive perspective, the Theory of Water Conservation emerges as especially relevant. This theory was conceptually structured by Luna Leopold, a hydrogeologist and the son of Aldo Leopold. It was consolidated in a context of increasing global water scarcity, exacerbated by climate change, pollution of natural sources, and the irrational use of water resources (Smith et al., 2024). It proposes a systemic view of water, not merely as a utilitarian good but as an essential component of ecosystems, whose conservation requires integrated management linking science, policy, and civic participation (Ryan, 2022). Furthermore, Neamtu et al. (2021) point out that the educational approach derived from this theory emphasizes raising awareness among present generations about the rational use of water, the protection of watersheds and aquifers, and innovation in recycling and reuse technologies. Finally, Yi and Kondolf (2024) highlight that the theory also calls on universities to lead water literacy processes and knowledge production aimed at preserving the hydrological cycle.

Ribberink (2023) links the Theory of Sustainability to a holistic view of human development. Its main proponent is Gro Harlem Brundtland, who in 1987 chaired the World Commission on Environment and Development and proposed the most widely cited definition of sustainable development (Tavanti, 2023). In a context marked by the tension between economic growth and environmental degradation, Brundtland (2022) argues that meeting present needs should not compromise the ability of future generations to meet theirs. Sustainability is thus presented as a balanced interrelation between environmental, social, and economic dimensions, grounded in principles of intergenerational equity, environmental justice, and ecological resilience (Singh, 2024). Moreover, Ribberink (2023) contends that, in the university sphere, this theory requires transforming educational models to integrate sustainability into the curriculum, foster applied research on real-world problems, and promote an institutional culture committed to the ethics of care, responsible consumption, and participatory governance. Therefore, the three theories converge on the need to reconfigure higher education as an active agent in the transition toward more sustainable, just, and ecologically aware societies (Tavanti, 2023).

Cotas et al. (2023) define ecosystem services as the direct and indirect benefits that ecosystems provide to society, including food provision, climate regulation, air and water purification, and cultural and recreational values. This concept has gained importance in the face of increasing environmental degradation, as it recognizes that human well-being depends on the integrity of natural systems (Hernández-Blanco et al., 2022). Thus, the analysis of ecosystem services enables functional valuation of ecosystems in both ecological and socioeconomic terms, contributing to more sustainable land management and the design of public policies that integrate environmental conservation with human development (Boerner et al., 2023).

Closely related to this, Raihan et al. (2023) indicate that water supply refers to the natural availability of water resources in a given territory, taking into account factors such as precipitation, runoff, groundwater storage, and water quality. This variable is fundamental to ecological balance and human activities, particularly in regions under high pressure from natural resource use (Ani et al., 2024). The reduction in water supply, resulting from climatic or anthropogenic factors, directly affects water security and water-related ecosystem services (Feng et al., 2025). Therefore, understanding the dynamics of water supply allows for anticipating scarcity scenarios, assessing the sustainability of water use, and designing more resilient management strategies (Adedeji et al., 2022).

In turn, Benitez-Alfonso et al. (2023) explain that climate change manifests as one of the main threats to ecosystems and the stability of water supply. Rising temperatures, variability in precipitation patterns, and extreme weather events significantly alter ecological processes and the availability of natural resources (Shah et al., 2021). This alteration, exacerbated by human activities, undermines the capacity of ecosystems to continue providing essential services (Moore & Schindler, 2022). Consequently, climate change represents not only an environmental transformation but also a multidimensional challenge for sustainable water management and the protection of vulnerable communities (Simonson et al., 2021).

In response to this scenario, climate resilience is defined as the capacity of ecosystems and human societies to anticipate, absorb, adapt to, and recover from the impacts of climate change (Cotas et al., 2023). This resilience is not a static attribute but a process involving scientific knowledge, environmental governance, green infrastructure, and community participation (Hernández-Blanco et al., 2022). Enhancing resilience requires strengthening integrated resource management, promoting nature-based solutions, and reducing social inequalities that increase vulnerability (Boerner et al., 2023).

METODO

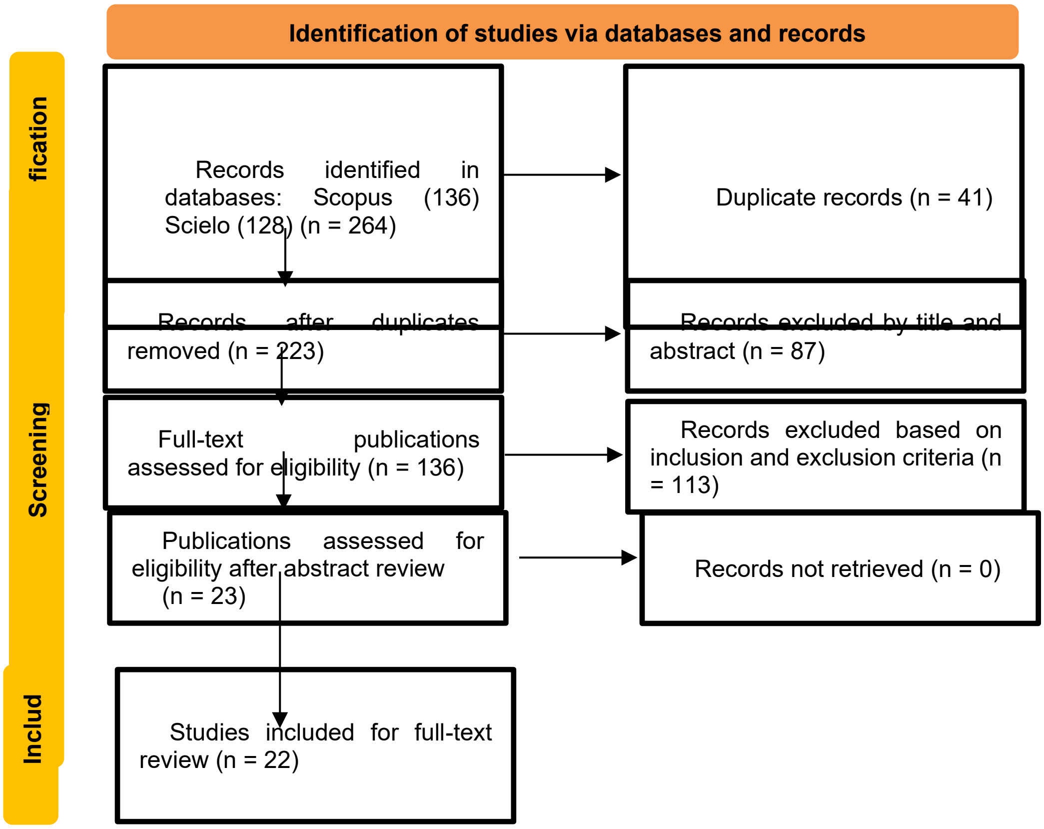
The present study was conducted through a systematic literature review, a methodology that enables the analysis of a specific phenomenon within a defined time frame. Searches were carried out in the Scopus and Scielo databases using the keywords "conservation," "watersheds," and "climate resilience," which yielded a total of 264 scientific articles.

The following inclusion criteria were established for the selection of articles: (a) publications dated between 2019 and 2025, and (b) research studies employing quantitative, qualitative, mixed, or review methodologies. The exclusion criteria included: (a) editorials, book chapters, conference proceedings, and narrative essays; (b) publications unrelated to the research topic; (c) articles that did not focus on the impact of high-altitude watershed conservation on water supply and climate resilience; (d) studies that did not offer a novel contribution; and (e) publications without full-text access. Additionally, Boolean operators such as AND and OR were used to combine the search terms, resulting in the following search strings:

"conservation" AND "watersheds" AND "climate resilience"; "conservation" OR "watersheds" OR "climate resilience"; "conservation" AND "watersheds" AND ("climate resilience"); "conservation" AND "climate resilience" AND ("watersheds"); "watersheds" AND "climate resilience" AND ("conservation"); "watersheds" AND ("conservation" OR "climate resilience").

Figure 1

Scientific Article Selection Flow Diagram



After applying the inclusion criteria, 22 full-text publications were selected for systematic analysis, as shown in Table 1. All the studies included in this review met the predefined inclusion criteria and were considered methodologically relevant for the thematic axes addressed. Although a formal critical appraisal tool such as CASP or AMSTAR was not applied, each article was evaluated based on its relevance to high-altitude watershed conservation, methodological clarity, and empirical or conceptual contributions to water supply and climate resilience. Only those studies that provided substantial evidence and were integrated into the comparative discussion were retained. As such, the final corpus consists of research that directly supports the analytical objectives of this integrative review.

Table 1

Characteristics of the Selected Scientific Articles

N°	Author	Article Title	Methodology	Country	Year	Database
1	Wolka et al. (2023)	The role of integrated watershed	Mixed	Ethiopia	2023	Scopus

		management in climate change adaptation for small farmers in southwestern Ethiopia				
2	Mutanda & Nhamo (2024)	Impact of climate change on major African lakes: a systematic review incorporating pathways to enhance climate resilience	Systematic review	South Africa	2024	Scopus
3	Hargrove et al. (2023)	The future of water in a desert river basin facing climate change and competing demands: a holistic approach to water sustainability in arid and semi-arid regions	Mixed	Mexico	2023	Scopus
4	Girmay et al. (2021)	Assessment of the current and future impact of climate change on the soil loss rate of the Agewmariam watershed, northern Ethiopia	Quantitative	Ethiopia	2021	Scopus
5	Asresu et al. (2025)	Systematic review of climate change impacts on water quality in transitional environments from a multi-hazard perspective	Systematic review	USA	2025	Scopus
6	Stringer et al. (2021)	Climate change impacts on water security in global drylands	Systematic review	Germany	2021	Scopus
7	Jacque et al. (2024)	Implications of water conservation measures in the urban water cycle: a review	Systematic review	Ireland	2024	Scopus
8	Hu et al. (2022)	Evaluation of water conservation function in Tibetan watersheds: modeling the impacts of climate and land use change	Quantitative	China	2022	Scopus
9	Yang et al. (2021)	Hydrological cycle and water	Systematic review	China	2021	Scopus

		resources in a changing world: a review				
10	Křeček et al. (2020)	The role of forests in headwater control in a transforming environment and society	Mixed	Czech Republic	2020	Scopus
11	Osorio et al. (2022)	Projection of climate change impacts on streamflow in the Lurín River basin–Peru, under CMIP5-RCP scenarios	Quantitative	Peru	2022	Scielo
12	Lozano-Povis et al. (2021)	Climate change in the Andes and its impact on agriculture: a systematic review	Systematic review	Peru	2021	Scielo
13	Pacheco & Hernández (2019)	Climate change: some aspects to consider for the survival of living beings. Systematic literature review	Systematic review	Colombia	2019	Scielo
14	Calizaya et al. (2020)	Hydrological foundations for the conservation of natural resources in the Moa Lake basin, Bolivia	Mixed	Bolivia	2020	Scielo
15	Castro & Rajadel (2021)	Another face of the water and climate change issue; two synergistic juxtaposed realities	Systematic review	Cuba	2021	Scielo
16	Sánchez & Peñalver (2025)	Planning and integrated management of water resources in the Ancash region	Qualitative	Peru	2025	Scielo
17	Diaz et al. (2023)	Effects of climate change on mountain ecosystems in the Carabaya Range – Peru	Quantitative	Peru	2023	Scielo
18	Marín-Cabrera (2022)	Characteristics and approaches of climate change projects in Costa Rica from 2011 to 2022	Mixed	Costa Rica	2022	Scielo
19	García-Rengifo &	Climate variability in the Chalpi	Quantitative	Ecuador	2023	Scielo

	Durán-Ballén (2023)	Grande River basin in Napo–Ecuador				
20	Alonso et al. (2024)	Sustainable development and its implications for the Peruvian Amazon. A systematic review	Qualitative	Peru	2024	Scielo
21	García Dueñas et al. (2022)	Study of socio-ecological resilience to climate change in coastal communities: an initiative from the province of Cienfuegos	Mixed	Cuba	2022	Scielo
22	Núñez-Rodríguez & Carvajal-Rodríguez (2021)	Educating in times of climate change for human resilience and environmental regeneration	Systematic review	Costa Rica	2021	Scielo

RESULTS AND DISCUSSION

According to the systematic review conducted, the following themes are addressed: the impact of high-altitude watershed conservation on water supply and climate resilience.

Table 2

Scientific Articles on Watershed Conservation and Climate Change

Authors	Article Objective	Article Contributions	Article Conclusions
Wolka et al. (2023)	Evaluate climate variability, farmers' adaptation strategies to climate change, and the role of integrated watershed management in climate change adaptation across different agroecologies of smallholder farmers in southwestern Ethiopia.	Integrated watershed management includes physical measures such as terraces, trenches, stone walls, and tree plantations that reduce erosion, enhance water retention, and improve agricultural productivity. These practices mitigate climate impacts, improve soil moisture, reduce runoff, and increase crop productivity, thereby strengthening climate resilience and water security. Farmer participation improves adaptive capacity and reduces vulnerabilities associated with poverty and low response capacity. Rising temperatures and droughts affect the physical, biological, and chemical parameters of lakes, impacting water availability. There is a need for sustainable water resource management in the face of climate	Most farmers perceive climate variability (irregular rainfall and rising temperatures). Integrated watershed management positively influences adaptation and agricultural productivity. Socioeconomic factors (farm size, gender, education, experience) influence adaptation decisions. It is recommended to consider watershed management as a key strategy. It is necessary to broaden studies and experimentally quantify impacts.

		variability. Climate- and human-induced changes affect both water quality and quantity. The importance of integrating conservation and adaptation into watershed management policies is emphasized.	
Mutanda & Nhamo (2024)	Conduct a systematic review on the impact of climate change on Africa's major lakes, incorporating pathways to enhance climate resilience in these ecosystems and the dependent communities.	The importance of cross-border cooperation and stakeholder participation in water management is highlighted. Integrating models of water quantity and quality (including salinity) in the context of drought and climate change is recommended. Suggested strategies include water savings in urban and agricultural sectors, alternative sources (desalination, reuse), and flexible policies for efficient allocation. An adaptive management approach with broad participation and interdisciplinary training is proposed to enhance resilience.	The article concludes the urgent need to strengthen the climate resilience of African lakes against climate change. It highlights the complexity of managing water resources in contexts of uncertainty and conflicting projections. It emphasizes integrated and evidence-based policies to conserve and manage these ecosystems.
Hargrove et al. (2023)	Demonstrate and test a holistic approach for future water sustainability in a region experiencing increasing water scarcity, considering both the quantity and quality of surface and groundwater, as well as different sectors and political jurisdictions.	Rainfall erosivity is projected to increase due to climate change, leading to higher rates of soil loss. Mitigation is suggested through the improvement of the C factor (vegetation cover) and P factor (conservation practices). These measures help restore degraded land, maintain water supply, and increase climate resilience through sustainable land-use policies.	The holistic and interdisciplinary approach, combined with the participation of multiple stakeholders and integrated models, allows for a coherent vision of the regional future. Despite a lack of consensus, transboundary collaboration, integrated surface and groundwater management, and a joint approach to water quantity and quality are essential for sustainability and resilience to climate change.
Girmay et al. (2021)	Evaluate the current and future impact of climate scenarios on soil loss rates in the Agewmariam watershed, using a climate model, USLE, and GIS.	It provides insights into how physiological adaptations, such as selective brain cooling, allowed artiodactyls to survive in arid environments. Although it does not directly address watershed conservation or current water management, it has indirect implications for resilience in water-limited environments.	Future soil loss rates will increase with growing rainfall erosivity. These losses can be mitigated through vegetation cover and soil conservation. Sustainable soil use policies and prevention of land-use change in agricultural areas are vital.
Asresu et al. (2025)	Review the state of the art of knowledge and research on the impacts of climate change on water quality in transitional environments from a multi-hazard perspective.	It proposes an integrated approach to equitable watershed and water resource management; adaptive governance that considers quality, reuse, agricultural productivity, and health; climate-adapted policies with multisectoral participation and transboundary management.	It is concluded that current approaches are dominated by observational analysis, but high-resolution technologies and integrated models (physical + AI) are needed to improve understanding and support adaptation decisions.

Stringer et al. (2021)	Examine observed and projected impacts of climate change on water security in arid landscapes up to 2100; emphasize efficient water management and integrated, equitable policies.	Water conservation in buildings reduces urban demand, eases pressure on watersheds, and delays infrastructure investment; it enhances urban climate resilience. A systemic approach is needed to avoid negative effects on water system operations.	Water security challenges will increase; traditional knowledge must be integrated with innovation and integrated policies. There is a pressing need to address the social and political dimensions of water.
Jacque et al. (2024)	Provide a global and holistic overview of the opportunities, challenges, and implications of water conservation within the urban water cycle.	Climate change, land use, and vegetation cover determine the capacity for water conservation and regulation. Models allow mapping and evaluating key ecosystem functions; they contribute to watershed resilience strategies.	Conservation measures are effective in saving water, energy, and costs; they outperform supply-side solutions. However, their adoption depends on technical, social, economic, and political factors and may have side effects on water quality and system operation; more long-term studies are needed.
Hu et al. (2022)	Evaluate the water conservation function in watersheds considering climate change, land use, and vegetation cover through hydrological models to understand spatial-temporal variation.	The need for an integrated hydro-biogeochemical model for watershed management is highlighted, considering the co-evolution of human and water systems. Emphasis is placed on understanding interactions between soil and atmosphere, especially in areas such as alpine zones with cryosphere, which are key to the hydrological cycle and its variability. For climate resilience, it is proposed to improve predictions of changes in water resources at regional and watershed levels, as well as the capacity to prevent and mitigate water-related disasters by adapting to climate change through appropriate policies.	Water conservation is a complex process influenced by multiple factors; climate change and land use significantly affect this function. Hydrological models are effective for assessing and predicting changes, key to sustainable management.
Yang et al. (2021)	The objective of the article is to summarize current research and highlight future directions in water science from four perspectives: the water cycle, hydrological processes, coupled natural and social water systems, and integrated watershed management. It emphasizes the need to understand the combined impacts of climate change	The article points out that water management must balance the quantity and quality of resources for life, production, and ecology, and integrate adaptive mechanisms considering uncertainty and user behavior.	Research on the water cycle and water resources has driven socioeconomic and technological development. Currently, the water cycle system is rapidly changing due to climate change and human activity, showing problems such as extreme events, groundwater depletion, desertification, and water scarcity. These global and regional problems require decisions based on science and terrestrial system analysis. It is crucial to protect water resources and strengthen the prevention and mitigation of disasters by adapting water policies to social, productive, and ecological needs in the context of climate change.

	and human activities on hydrological processes and water resources across various temporal and spatial scales for sustainable development.		
Křeček et al. (2020)	Evaluate the impacts of environmental and social change on forest functions in a headwater watershed in the Jizera Mountains (Czech Republic) during the period 1850–2100.	Forests in the Jizera Mountains have played a key role in protecting water resources and biodiversity, evolving from spruce plantations to a more native composition that enhances ecosystem stability. Atmospheric acid deposition damaged water quality until the 1980s, but emission reductions and forestry practices such as clear-cutting spruces supported the progressive recovery of water bodies and aquatic ecosystems.	Over two centuries, forests have changed in composition, initially favoring exotic conifers resistant to pollution and now moving toward restoring native species. The recovery from water acidification in the experimental watershed is due to both sulfur emission reductions and specific forestry practices. Projected environmental change will not significantly affect water recharge capacity or recent recovery from acidification, preserving key forest protective functions.
Osorio et al. (2022)	Evaluate the likely impacts of climate change on the flow of the Lurín River using outputs from six Global Climate Models (GCMs) under three different Representative Concentration Pathways (RCP 2.6, 4.5, and 8.5), in order to inform policymakers and water resource managers in the watershed.	Models for 2071–2100 predict increases in temperature, decreases in flow, and changes in flow dynamics, but they will not significantly compromise water recharge, water quality recovery, or biodiversity, demonstrating a degree of resilience.	Significant flow reduction is projected toward the end of the 21st century. Less runoff will be available due to decreased precipitation and increased evapotranspiration. These are essential findings for watershed water management planning.
Lozano-Povis et al. (2021)	Understand and analyze the impacts of climate change in the Andean region of South America, focusing on glaciers, soil erosion, water resources, food security, and ecosystem conservation.	Detailed projections of climate change impact on the water supply of the Lurín River. It considers the spatial and temporal dynamics of climate change for sustainable management. It reports the need to strengthen climate resilience through adaptive management.	Climate change affects hydrological and ecological dynamics in the Andes. Glacier retreat and erosion require an integrated approach that includes social, political, and economic factors. Adaptation is key for watersheds, water, and food security.
Pacheco & Hernández (2019)	Provide consolidated and updated information on climate change to support decision-making regarding its impact on life on	Landscape, erosion, and climate relationship; watershed conservation. Impact of glacial retreat on hydrology and water management. Need for effective and adaptive public policies for food security.	Climate change caused by human greenhouse gas emissions requires mitigation. Impacts affect human health and migrations. Geopolitical problems arise from asymmetric power relations.

	Earth and the development of environmental plans and policies.		
Calizaya et al. (2020)	Evaluate water resources in the Moa Lake basin, Bolivia, to ensure sustainable development and conservation in the Tacana indigenous region, considering climate change scenarios.	Incentives and penalties for efficient water use. Improve water infrastructure. Reduce nutrients in rivers and promote integrated management. Limit paved surfaces. Reduce energy demand and switch energy sources. CO_2 capture.	There is a need to evaluate and protect water supply. Promote IWRM and climate resilience. Encourage sustainable productive activities as a means of conservation and development.
Castro & Rajadel (2021)	Analyze, from the state of the art, the elements that characterize the water situation and the effects of climate change on its quality and availability.	Use of WEAP and SWAT models to analyze water supply. Declare watersheds as protected areas. Promote a culture of climate resilience and IWRM. Diversify sustainable activities (tourism, beekeeping, agroforestry).	The relationship between water quality and availability and climate change worsens social inequalities. Coherent public policies that prioritize social well-being are needed.
Sánchez & Peñalver (2025)	Analyze the planning and integrated management of water resources in Ancash, Peru, focusing on agriculture, human subsistence, and environmental conservation in a context of climate variability.	Importance of water sources with adequate quality and quantity. Climate change conditions water availability and quality. Integrated approaches are required for water resilience. Integrated and sustainable management adapted to climate change. Strengthen water infrastructure and sustainable agricultural practices. Intervene in watersheds to reduce pollution. Reservoir strategies to harness lost water.	A specialized body should be created to monitor water projects. The Regional Agricultural Directorate should lead coordination. Ensure water rights. Involve user boards. Promote a water and reservoir culture as a sustainability strategy.
Diaz et al. (2023)	Evaluate the effects of climate change on mountain ecosystems in the Carabaya mountain range, Peru, for the years 2050 and 2070 under climate scenarios RCP-4.5 and RCP-8.5 using the Holdridge life zone model (HLZ) to analyze spatial and altitudinal changes in life zones due to climate change.	The article highlights that climate change significantly reduces ecosystems such as glaciers, tundras, and páramos, which are essential for water regulation and supply in the Andes. Since more than 85% of the Peruvian population depends directly or indirectly on mountain ecosystems for water, energy, and food, understanding these changes is key to developing comprehensive adaptation strategies that improve climate resilience and watershed conservation.	There is great similarity between HLZ and the ecosystems in the Carabaya range, making HLZ a valid reference for evaluating climate change impacts. Nine HLZs were identified, with the Subtropical Montane Humid Forest, Andean Subtropical Pluvial Tundra, and Very Humid Subtropical Páramo being the most extensive. Under climate change scenarios, dramatic changes are projected, especially the near-total loss of the Nival, Tundra, and Páramo zones by 2070, while the Montane Humid Forest will expand significantly, displacing other ecosystems to higher altitudes.
Marín-Cabrera	Contribute to better decision-making to address climate change through the analysis of 43	Projects focused on the protection and restoration of ecosystems, including watershed and spring management. Water resources were a cross-cutting issue in the projects,	The predominant focus is on capacity building, ecosystem protection, and water resource management, while food security is less prioritized. Most projects are led by NGOs with budgets

(2022)	climate change projects in Costa Rica, identifying priorities, themes, and challenges to improve investments and reduce climate vulnerabilities.	although only 1% specifically addressed the distribution and efficient use of water.	managed by international organizations, with greater investment in coastal provinces.
García-Rengifo & Durán-Ballén (2023)	Characterize climate variability in the Chalpi Grande River watershed based on environmental variables of precipitation, temperature, and streamflow. It also has specific objectives related to the compilation and systematization of 31 years of climate data and verification through specialized remote sensors on time and climate.	The protection of water resources affects water availability and is closely linked to safety and resilience to climate risks, due to its impact on social conflict, well-being, and poverty. The need to increase efforts and investments in the management and efficient use of water resources for sustainability and climate change adaptation is emphasized.	Five key challenges to increase impact are: strengthen local capacity and governance; increase community participation; prioritize food security; include risk management in strategic planning; and enhance monitoring based on scientific evidence. Greater attention to water resources is required due to their intersection with multiple social and climatic issues.
Alonso et al. (2024)	Analyze the relevance of sustainable development and its implications in the Peruvian Amazon, proposing a conceptual framework that facilitates understanding and appropriately addresses its impact in the region, with the aim of achieving harmony between the environment, economic growth, and social well-being.	The document does not provide detailed contributions regarding watershed conservation, water supply, or climate resilience explicitly in the analyzed text. However, it highlights the importance of the environmental dimension within sustainable development and the challenges in the Peruvian Amazon, which include environmental threats such as deforestation and poor forest management, indirectly affecting climate resilience and water resources in the region.	Climate variability between 1985 and 2015 in the Chalpi Grande River basin showed slight variations in temperature, precipitation, and flow, with extreme events present. These changes could cause increasing impacts in the economic, health, and social sectors if observed trends continue. Precipitation variations are closely linked to flow rates, enabling hydrological model evaluations to predict potential impacts on the watershed.
García Dueñas et al. (2022)	Promote and strengthen socio-ecological resilience to the effects of climate change in coastal communities of the province of Cienfuegos, Cuba, given the low social perception of environmental risk.	The project engages in the integrated management of coastal ecosystems and watersheds, ensuring the conservation and rational use of natural resources for sustainable development. It seeks to improve indicators of the ecological health of these ecosystems, promoting relevance, awareness, and sustainable use in response to climate change and adaptation and	In the Peruvian Amazon, sustainable development has not yet been achieved. Despite economic growth, extreme poverty and social disparity persist, creating socioecological conflicts. The region faces severe environmental threats such as deforestation, illegal activity, and poor forest governance, leading to significant environmental problems. The need for long-term, sustainable,

	To this end, the study proposes to conceptually and methodologically ground social perception and resilience, characterize coastal communities from a sociocultural perspective, conduct studies on socio-ecological resilience, and develop mechanisms for science communication that foster greater public participation.	mitigation processes. It contributes to environmentally friendly, sustainable, and inclusive local economic management to confront the negative effects of climate change.	and integrated measures is emphasized to promote sustainable growth in the region.
Núñez-Rodríguez & Carvajal-Rodríguez (2021)	Make available to teaching staff the implications of the constructs of human resilience and environmental regeneration for the education of future generations who must adapt to and mitigate the negative effects of climate change, promoting their appreciation and integration into the educational field.	The article contributes to the importance of fostering biological, cognitive, and emotional processes in schools related to resilience, to confront complex and vulnerable environments affected by climate change. This involves education for environmental regeneration that contributes to the recovery of natural systems, indirectly supporting watershed conservation and water supply, thus enhancing climate resilience.	Although the document does not include an explicit conclusion section, it is inferred that strengthening connections between social and natural systems through interdisciplinary studies and participatory strategies significantly improves socio-ecological resilience in vulnerable communities. It highlights the importance of science communication, civic participation, and appreciation of communal resources to face the challenges of climate change and to improve quality of life and social cohesion.

Key Strategies to Strengthen Water Resilience through High-Altitude Conservation

Integrated Watershed Management

Integrated watershed management (IWM) has emerged across the literature as a strategic framework to address the multiple and intersecting pressures affecting water resources, particularly in climate-sensitive regions. Sánchez and Peñalver (2025) emphasize the value of inter-institutional and territorial coordination in facilitating more efficient infrastructure planning; however, this claim reveals a recurring assumption in the literature: that institutional coordination is achievable without addressing underlying power asymmetries or resource inequalities. Similarly, while models such as SWAT and WEAP have demonstrated capacity to simulate land use and climate scenarios to improve decision-making (Calizaya et al., 2020), their effective implementation is often limited by data gaps and the lack of technical expertise in rural contexts—an issue not adequately addressed in most case studies.

A consistent pattern identified across studies is the emphasis on combining surface and groundwater management with multisectoral engagement to improve long-term sustainability in arid regions (Hargrove et al., 2023). Yet, there is limited comparative evidence on how these integrative models perform in diverse governance regimes. Most examples, such as those in Hargrove et al. (2023), remain situated in specific political ecologies without extrapolation to more fragile or conflict-affected basins.

Interestingly, local experiences from sub-Saharan Africa present compelling insights on the potential for community-based IWM practices to scale up into broader governance reforms (Wolka et al., 2023). However, the literature still lacks clarity on the mechanisms that facilitate such scalability. Is the transition driven by institutional support, social capital, or external funding? The absence of comparative frameworks to assess such trajectories constitutes a significant gap.

Yang et al. (2021) advocate for an integrated systems approach that balances ecological and human needs, recognizing the dynamic complexity of the hydrological cycle. Nonetheless, this theoretical proposition is rarely operationalized with robust indicators or implementation metrics, limiting its utility for adaptive planning in data-scarce territories.

Moreover, the literature highlights the role of protected water corridors in preserving streamflow regulation (Calizaya et al., 2020), yet fails to adequately explore how such conservation efforts interface with land tenure regimes or local economic pressures. International cooperation is frequently cited as a facilitator of cross-jurisdictional integration (Hargrove et al., 2023), but its effectiveness appears contingent on shared technical foundations—a condition not often met in heterogeneous Andean governance landscapes.

The integration of biophysical practices such as trenches, terraces, and reforestation is reported to enhance water recharge and stabilize agricultural outputs (Wolka et al., 2023). However, these findings largely stem from pilot studies, with minimal discussion of long-term ecological feedbacks or maintenance challenges. The coupling of spatial data and social dynamics is increasingly recognized as crucial for adaptive planning (Yang et al., 2021), yet few studies rigorously quantify the co-benefits of this integration.

Finally, the recurring call for participatory modeling—praised for aligning community goals with technical scenarios (Calizaya et al., 2020)—raises concerns regarding representativeness and decision-making authority. Many of these models remain expert-driven and technocratic, potentially sidelining indigenous epistemologies or traditional management systems.

In summary, while integrated watershed management is widely endorsed as a holistic and scalable strategy, the literature reveals notable inconsistencies regarding its practical feasibility, especially in socio-politically fragmented and ecologically fragile regions. Future research should focus on empirically validating the long-term outcomes of IWM practices, particularly through longitudinal, interdisciplinary studies that bridge hydrological modeling, governance dynamics, and local agency.

Climate Change and Future Water Supply

Climate change has significantly altered hydrological dynamics in mountain systems, particularly in regions highly dependent on seasonal precipitation. In this context, Osorio et al. (2022) identify a sustained decline in projected streamflow in the Lurín River basin, associated with increased evapotranspiration. Additionally, the accelerated retreat of Andean glaciers has been cited as a factor undermining interannual water stability (Mutanda & Nhamo, 2024). Based on the Holdridge life zone model, it has been projected that the altitudinal shift of ecosystems will significantly reduce snow-covered and páramo areas by 2070 (Diaz et al., 2023). Furthermore, extreme rainfall and drought events recorded in Ecuador demonstrate increasing flow variability, impacting both potable water supply and the agricultural cycle (García-Rengifo & Durán-Ballén, 2023).

Through a regional approach, Castro and Rajadel (2021) warn that anthropogenic and climatic pressure on water resources has heightened the vulnerability of social systems. In this context, the use of high-resolution climate projections allows for risk anticipation and the planning of hydrological adaptation measures (Osorio et al., 2022). Moreover, the observed reduction of cold zones in the Carabaya mountain range is expected to shift water recharge areas to more limited altitudes (Diaz et al., 2023). In addition, changes in temperature and precipitation are correlated with the decline in water quality, imposing further challenges on treatment systems (Castro & Rajadel, 2021).

Using satellite data, García-Rengifo and Durán-Ballén (2023) reveal a trend toward shorter hydrological cycles, with direct implications for urban and rural planning. At the same time, the reduction in glacial volume projected under RCP 8.5 scenarios suggests a structural loss of water supply by the end of the century (Osorio et al., 2022). Furthermore, Mutanda and Nhamo (2024) emphasize that the degradation of lacustrine ecosystems limits the ecological resilience of watersheds in the face of climate disturbances. Lastly, it has been shown that combined alterations in climate and land use contribute to the simultaneous degradation of streamflows, vegetation cover, and ecosystem services (Diaz et al., 2023).

Climate Change and Future Water Supply

Climate change has profoundly reshaped hydrological dynamics in mountain ecosystems, particularly those reliant on seasonal precipitation regimes. Osorio et al. (2022) document a persistent decrease in projected streamflow in the Lurín River basin, linked to elevated evapotranspiration. This finding aligns with broader evidence on glacial retreat across the Andes, identified by Mutanda and Nhamo (2024) as a major contributor to destabilized interannual water availability. Diaz et al. (2023), employing the Holdridge life zone model, project substantial losses in snow and páramo ecosystems by 2070, indicating an ecological shift that jeopardizes critical recharge zones. However, while these studies present strong climate modeling, they rarely address socio-political constraints on adaptation implementation.

Flow variability patterns further exacerbate water insecurity. In Ecuador, extreme rainfall and drought cycles disrupt both drinking water access and agricultural planning (García-Rengifo & Durán-Ballén, 2023). Castro and Rajadel (2021) expand this discussion, highlighting that combined anthropogenic and climatic stressors intensify systemic vulnerability. Yet, most research lacks a multi-hazard integration framework to understand cumulative impacts. While high-resolution climate models enable early risk identification (Osorio et al., 2022), they often exclude the governance dimension needed for actionable hydrological planning.

The literature also points to structural transformations in water cycles. Satellite-based studies by García-Rengifo and Durán-Ballén (2023) suggest shorter hydrological cycles, requiring adaptive infrastructure. Meanwhile, the decline of glacial mass under RCP 8.5 scenarios (Osorio et al., 2022) signals long-term supply instability. Mutanda and Nhamo (2024) emphasize ecosystem degradation as a limit to watershed resilience, yet fail to offer specific governance pathways to reverse this trend. Diaz et al. (2023) identify the intersection of land use change and climate as a major driver of degraded streamflows and loss of ecosystem services, but empirical studies quantifying these synergies are still scarce.

Sustainable Soil Conservation Practices

Soil degradation remains a critical barrier to watershed functionality and water regulation. Wolka et al. (2023) analyze physical conservation methods such as terraces and trenches, showing their role in enhancing infiltration and stabilizing terrain. However, while these measures are proven effective in smallholder settings, their scalability remains poorly documented. Girmay et al. (2021) project increased soil loss under future rainfall erosivity scenarios, yet the operational challenges of implementing vegetative cover at scale are underexplored.

The transition to native species in headwater zones has restored hydrological and ecological functions (Křeček et al., 2020), but long-term monitoring is needed to confirm permanence. Historical land use analysis by Alonso et al. (2024) reveals how deforestation and agricultural intensification in the Peruvian Amazon diminished soil infiltration, underscoring the need to integrate landscape history into conservation planning. Although Wolka et al. (2023) reaffirm the benefits of slope stabilization, more systematic evaluations of cost-efficiency are required.

Geospatial modeling has enhanced precision in erosion risk identification (Girmay et al., 2021), though such tools remain inaccessible to many rural stakeholders. Agroforestry practices have shown promise in reversing soil structure degradation (Křeček et al., 2020), but adoption hinges on cultural acceptance and institutional incentives. Additionally, Alonso et al. (2024) report that deep-rooted vegetation is superior for slope control, yet few programs prioritize native species reintroduction over commercial plantations.

Wolka et al. (2023) emphasize that community uptake of conservation strategies depends on local perceptions and governance support. This reflects a broader gap in understanding the social dimensions of soil restoration. Moreover, evidence from Křeček et al. (2020) suggests that forest recovery post-acidification can hasten water quality improvements, but little attention has been given to replicability in Andean contexts.

Climate Resilience in Rural Areas

The literature increasingly affirms that rural climate resilience is contingent on the interface between local adaptive capacities and ecosystem robustness. Wolka et al. (2023) highlight that conservation practices employed by smallholder farmers mitigate rainfall unpredictability and buffer production shocks. Nonetheless, few studies unpack the enabling conditions for sustained practice adoption.

Lozano et al. (2021) and Marín (2022) converge in stressing that climate financing disproportionately targets high-exposure rural regions. However, the design of these investments often overlooks the agency of local actors. The role of education in fostering resilience is advanced by Núñez and Carvajal (2021), who argue for emotional and ecological learning as early-stage adaptation mechanisms. Yet, such proposals are rarely operationalized in national adaptation frameworks.

García et al. (2022) identify the synergy between community cohesion and environmental stewardship as a foundation for collective adaptation. This insight remains underexplored in policy-oriented literature. Wolka et al. (2023) further report that adaptive farmers incur fewer losses, but longitudinal evidence is lacking. Marín (2022) and Núñez & Carvajal (2021) affirm that schools serve as key spaces for environmental awareness, yet their institutional constraints are rarely discussed.

Science communication emerges as a recurring theme. García et al. (2022) suggest that improved climate risk perception enhances decision-making, but the tools and methods to achieve this shift are unclear. Integrated educational and ecological programs (Lozano et al., 2021) show long-term promise, yet require stable funding. Green infrastructure initiatives have demonstrably reduced rural flood risks (Marín, 2022), although issues of maintenance and equity in benefit distribution remain understudied. Lastly, the alignment of local capacities with national climate policies (Wolka et al., 2023) offers an avenue for institutional resilience, but more research is needed to examine its feasibility.

Hydrological Modeling for Adaptive Planning

Hydrological modeling has become central to forecasting climate-induced stress on water systems, yet significant disparities exist in model application and integration. Calizaya et al. (2020) promote the use of WEAP and SWAT in evaluating high-Andean watershed interventions, but do not assess their institutional adoption across different governance levels. Hu et al. (2022) demonstrate that seasonal variability in steep terrains can be reliably modeled, though model calibration often depends on data quality not universally available. Hargrove et al. (2023) advocate for the inclusion of salinity and demand variables in arid region modeling to increase simulation coherence. However, the trade-offs between model complexity and usability for local stakeholders are insufficiently addressed. García & Durán (2023) show how historical data and remote sensing validate precipitation-runoff correlations, yet few frameworks integrate real-time feedback loops.

Jacque et al. (2024) argue that urban conservation modeling reduces infrastructure stress, but rural applications of such logic remain underexplored. Calizaya et al. (2020) note that supply-demand scenarios help prioritize investments, but do not resolve power asymmetries that influence allocation. Predictive models in mountain environments (Hu et al., 2022) demonstrate accuracy, yet often exclude institutional and social dynamics.

Importantly, Hargrove et al. (2023) stress that participatory modeling builds legitimacy, but few studies critically examine who participates and under what conditions. Jacque et al. (2024) suggest institutional feedback loops improve model performance, yet scalability beyond pilot projects remains uncertain. García & Durán (2023) underscore that including social variables enhances vulnerability assessments, but integrated models are rarely used in decision-making processes. Calizaya et al. (2020) and Hu et al. (2022) propose evolutionary algorithms to refine model sensitivity, though the implications for policy uptake are still unclear.

Community Participation and Water Governance

Participatory water governance has garnered growing support as a counterpoint to top-down policy prescriptions, particularly under climate stress conditions. Sánchez and Peñalver (2025) contend that the early involvement of Water User Boards strengthens infrastructure implementation. While promising, this position overlooks cases where user boards are politically co-opted or under-resourced.

Wolka et al. (2023) report that collective rural practices buffer climatic extremes, but lack comparative data to identify replicable governance conditions. Cross-border collaboration, as documented by Hargrove et al. (2023), enhances legitimacy, though the durability of such agreements remains tenuous in volatile political climates. Marín (2022) affirms that participatory designs improve local relevance, yet most studies stop short of assessing impact.

Stringer et al. (2021) reinforce the need for adaptive, inclusive processes in water-insecure regions, but offer limited methodological guidance. Sánchez and Peñalver (2025) note that co-management improves sustainability, though tensions between technical and community knowledge persist. Evidence from Wolka et al. (2023) suggests that participatory frameworks can enhance allocation efficiency, yet often lack formal institutional recognition.

Marín (2022) links co-designed conservation strategies to institutional continuity, but long-term evaluations are sparse. Hargrove et al. (2023) advocate for decentralized, flexible regulation that recognizes local arrangements, but fail to address enforcement capacity. Stringer et al. (2021) highlight the role of collective learning, but few systems include iterative feedback. Multi-stakeholder platforms (Sánchez & Peñalver, 2025) appear crucial, yet their representativeness and decision-making power warrant scrutiny. Finally, Wolka et al. (2023) assert that combining local and technical knowledge leads to more effective interventions, but the balance of power in these exchanges is often implicit rather than critically examined.

Comparative Analysis of High-Altitude Watershed Conservation in Relation to Water Supply and Climate Resilience in Andean Countries: Peru, Bolivia, Ecuador, and Colombia

In the Andean region, the conservation of high-altitude watersheds has become central to climate adaptation and water security. However, divergent national trajectories reveal significant disparities in governance, community engagement, scientific integration, and policy coherence. In Peru, Payment for Ecosystem Services (MRSE) initiatives, backed by ANA and the Ministry of Environment, have reportedly mitigated glacier loss and improved recharge (Lozano-Povis et al., 2021), yet long-term institutional alignment remains fragile.

Bolivia's approach, as detailed by Calizaya et al. (2020), integrates indigenous governance in Moa Lake, using hydrological modeling combined with traditional knowledge. Nevertheless, weak institutional scaffolding at the national level limits upscaling potential. Ecuador's Integrated Water Resource Management Systems (García-Rengifo & Durán-Ballén, 2023) reflect growing technological sophistication, but face sustainability issues linked to political turnover and urban-rural tensions.

In Colombia, the Páramo Law aims to protect strategic ecosystems (Pacheco & Hernández, 2019), yet conservation remains disconnected from broader territorial planning. Extractive conflicts persist, undermining resilience. While Peru and Bolivia advance community-based conservation, Ecuador and Colombia favor regulatory and technological mechanisms.

Despite distinct institutional pathways, all four countries face recurring barriers: institutional fragmentation, unstable financing, and territorial inequality. Effective models share three pillars: ecological restoration, predictive technologies, and participatory governance. However, comprehensive evaluations remain limited, and few programs have achieved long-term resilience outcomes. Future strategies must focus on multiscale integration, equitable resource distribution, and institutional durability to consolidate climate-resilient watershed systems in the Andes.

Although prior studies have addressed watershed conservation in isolation, few have examined the intersection between hydrological modeling and community governance in the Andean region. This review highlights the lack of multiscale studies that integrate traditional knowledge systems with predictive tools in fragile highland basins. Addressing this gap is essential to designing truly context-sensitive and resilient water management strategies in the Andes.

CONCLUSION

The synthesis of the twenty-three reviewed articles confirms that high-altitude watershed conservation is intrinsically linked to water supply regulation and climate resilience in Andean regions. Comparative evidence demonstrates that integrated watershed management, community engagement, and the use of hydrological modeling tools constitute effective responses to water stress and climate-related threats. These strategies not only enhance local adaptive capacities but also support long-term ecological stability and the continuity of water-related ecosystem services.

Moreover, the review reveals that soil conservation, spatial monitoring, social inclusion, and multiscalar governance are critical dimensions of comprehensive water planning. Since headwater ecosystems play a pivotal role in regulating hydrological flows, interventions must combine scientific knowledge, local experience, and ecological restoration to maximize effectiveness. Addressing water resilience, therefore, requires not only technical solutions but also sociopolitical coordination, particularly in vulnerable and institutionally fragmented highland territories. This review contributes relevant insights for policy design in the context of climate change. First, it underscores the urgent need to implement decentralized and participatory governance frameworks that bridge scientific expertise with indigenous and peasant knowledge systems. Second, it recommends prioritizing conservation interventions in headwater zones through schemes that integrate green infrastructure, ecosystem-based adaptation, and legal recognition of strategic ecosystems. These actions must be supported by sustained investments in high-resolution hydrological monitoring and climate modeling to enable predictive, evidence-based decision-making. From a legal and institutional perspective, more flexible and nested regulatory frameworks are needed to account for the ecological and sociocultural heterogeneity of Andean watersheds. Inter-institutional coordination platforms should link environmental, agricultural, and water sectors, promoting a systemic vision of water security. It is also essential to integrate water equity and climate justice principles into decision-making, ensuring that conservation and adaptation strategies reduce—not exacerbate—territorial inequalities.

In terms of research implications, this study identifies three critical gaps in the current literature. First, future research should develop context-specific resilience metrics tailored to high-altitude Andean basins, where hydrological variability is closely tied to glacial retreat and land use change. Second, there is a notable lack of empirical validation of participatory modeling in watershed planning, particularly in rural and Indigenous territories where local governance plays a key role. Third, ecosystem service frameworks remain underutilized in Andean water governance, despite their potential to integrate ecological, economic, and cultural values into planning processes. This review is limited by its reliance on secondary sources and the exclusion of grey literature or policy evaluations. Additionally, the geographic concentration of case studies may constrain the generalizability of findings to non-Andean regions. Future research should prioritize longitudinal studies that assess the durability of conservation outcomes, explore multilevel governance interactions, and develop integrated indicators that capture both biophysical dynamics and sociopolitical processes.

REFERENCES

Adedeji, K. B., Ponnle, A. A., Abu-Mahfouz, A. M., & Kurien, A. M. (2022). Towards digitalization of water supply systems for sustainable smart city development—Water 4.0. *Applied Sciences, 12*(18), 9174. https://doi.org/10.3390/app12189174

Alonso, R. C., Cano, J. L., Quispe, R., & Santa Cruz, K. S. (2024). Sustainable development and its implications for the Peruvian Amazon: A systematic review. *Aula Virtual, 5*(12), e298. https://doi.org/10.5281/zenodo.11301897

Ani, E. C., Olajiga, O. K., Sikhakane, Z. Q., & Olatunde, T. M. (2024). Renewable energy integration for water supply: A comparative review of African and U.S. initiatives. *Engineering Science & Technology Journal, 5*(3), 1086–1096. https://doi.org/10.51594/estj/v5i3.972

Asresu, A. T., Furlan, E., Horneman, F., Zennaro, F., Nguyen, N. D., Torresan, S., Critto, A., & Marcomini, A. (2025). A systematic review of climate change impacts on water quality in transitional environments from a multi-hazard perspective. *Estuarine, Coastal and Shelf Science*, 109194. https://doi.org/10.1016/j.ecss.2025.109194

Benitez-Alfonso, Y., Soanes, B. K., Zimba, S., Boesch, C., Daszkowska-Golec, A., & Foyer, C. H. (2023). Enhancing climate change resilience in agricultural crops. *Current Biology, 33*(23), R1246–R1261. https://doi.org/10.1016/j.cub.2023.10.028

Boerner, T. J., Deems, S., Furlani, T. R., Knuth, S. L., & Towns, J. (2023). ACCESS: Advancing innovation: NSF's advanced cyberinfrastructure coordination ecosystem: Services & support. In *Proceedings of PEARC '23: Practice and Experience in Advanced Research Computing 2023: Computing for the Common Good* (pp. 173–176). https://doi.org/10.1145/3569951.3597559

Brundtland, G. H. (2022). Public financing for primary health care is the key to universal health coverage and strengthening health security. *The Lancet Global Health, 10*(5), e602–e603. https://doi.org/10.1016/S2214-109X(22)00166-8

Calizaya, A., Mendoza, J., & Copa, M. (2020). Hydrological bases for the conservation of natural resources in the Moa Lake Basin, Bolivia. *Revista de Investigación e Innovación Agropecuaria y de Recursos Naturales, 7*(2), 30–45. http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S2409-16182020000200006

Callicott, J. B. (2022). Three project ideas to fill research gaps in Aldo-Leopold scholarship. *Socio-Ecological Practice Research, 4*, 11–16. https://doi.org/10.1007/s42532-021-00102-6

Callicott, J. B. (2023). Aldo Leopold as educator: His legacy for field environmental philosophy. In R. Rozzi et al. (Eds.), *Field environmental philosophy* (Vol. 5). Springer. https://doi.org/10.1007/978-3-031-23368-5_16

Castro, N. A., & Rajadel, O. N. (2021). Another face of the water and climate change problem: Two synergistic and juxtaposed realities. *Revista Universidad y Sociedad, 13*(4), 351–360. http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S2218-36202021000400351
Cotas, J., Gomes, L., Pacheco, D., & Pereira, L. (2023). Ecosystem services provided by seaweeds. *Hydrobiology, 2*(1), 75–96. https://doi.org/10.3390/hydrobiology2010006
Díaz, R. D., Machaca, A. D., Belizario, G., & Lujano, E. (2023). Effects of climate change on mountain ecosystems in the Carabaya Range, Peru. *Revista Brasileira de Meteorologia, 38*. https://doi.org/10.1590/0102-778638230088
Economic Commission for Latin America and the Caribbean (ECLAC). (2023a). *Report on the regional process of Latin America and the Caribbean to accelerate SDG 6 compliance*. ECLAC. https://www.cepal.org/sites/default/files/events/files/informe_del_proceso_regional_de_america_latina_y_el_caribe_para_la_aceleracion_del_cumplimiento_del_ods_6_.pdf
Economic Commission for Latin America and the Caribbean (ECLAC). (2023b). *2023 Regional Water Dialogues in Latin America and the Caribbean: Towards the United Nations Water Conference*. ECLAC. https://www.cepal.org/sites/default/files/events/files/informe_dialogos_2may2023_ns.pdf
Environmental Evaluation and Oversight Agency (OEFA). (2025). *Results of water environmental component monitoring in early environmental assessments*. https://www.datosabiertos.gob.pe/dataset/resultados-de-los-monitoreos-del-componente-ambiental-agua-en-las-evaluaciones-ambientales-1
Feng, F., Zhang, Y., Chen, Z., Ni, J., Feng, Y., Xie, Y., & Zhang, C. (2025). Machine learning to assess and support safe drinking water supply: A systematic review. *Journal of Environmental Chemical Engineering, 13*(1), 114481. https://doi.org/10.1016/j.jece.2024.114481
García, R. Y., Soler, S. D., Mirabal, Y., & Agüero, F. C. (2022). Socioecological resilience to climate change in coastal communities: An approach from the province of Cienfuegos. *Conrado, 18*(87), 44–54. http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S1990-86442022000400044
García-Rengifo, C., & Durán-Ballén, S. (2023). Climate variability in the Chalpi Grande River Basin in Napo-Ecuador. *Enfoque UTE, 14*(1), 1–17. https://doi.org/10.29019/enfoqueute.872
Girmay, G., Moges, A., & Muluneh, A. (2021b). Assessment of current and future climate change impact on soil loss rate of Agewmariam Watershed, Northern Ethiopia. *Air, Soil and Water Research, 14*. https://doi.org/10.1177/1178622121995847
Hargrove, W., Heyman, J., Mayer, A., Mirchi, A., Granados-Olivas, A., Ganjegunte, G., Gutzler, D., Pennington, D., Ward, F., Chavira, L. G., Sheng, Z., Kumar, S., Villanueva-Rosales, N., & Walker, W. (2023). The future of water in a desert river basin facing climate change and competing demands: A holistic approach to water sustainability in arid and semi-arid regions. *Journal of Hydrology: Regional Studies, 46*, 101336. https://doi.org/10.1016/j.ejrh.2023.101336
Hernández-Blanco, M., Costanza, R., Chen, H., de Groot, D., Jarvis, D., Kubiszewski, I., Montoya, J., Sangha, K., Stoeckl, N., Turner, K., & van 't Hoff, V. (2022). Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. *Global Change Biology*. https://doi.org/10.1111/gcb.16281
Hu, W., Li, G., & Gao, Z. (2022). Assessment of water conservation function in Tibetan Plateau catchments: Modelling impacts of climate and land use change. *Journal of Hydrology: Regional Studies, 41*, 101064. https://doi.org/10.1016/j.ejrh.2022.101064
Jacque, H., Mozafari, B., Dereli, R. K., & Cotterill, S. (2024). Implications of water conservation measures on urban water cycle: A review. *Sustainable Production and Consumption, 50*, 571–586. https://doi.org/10.1016/j.spc.2023.11.003
Křeček, J., Nováková, J., Palán, L., Pažourková, E., & Stuchlík, E. (2020). Role of forests in headwater control with changing environment and society. *International Soil and Water Conservation Research, 9*(1), 143–157. https://doi.org/10.1016/j.iswcr.2020.11.002
Lozano, A., Alvarez, C. E., & Moggiano, N. (2021). Climate change in the Andes and its impact on agriculture: A systematic review. *Scientia Agropecuaria, 12*(1), 101–108. https://doi.org/10.17268/sci.agropecu.2021.012
Marín-Cabrera, M. (2022). Characteristics and approaches of climate change projects in Costa Rica from 2011 to 2022. *Revista Tecnología en Marcha, 35*(3), 35–47. https://doi.org/10.18845/tm.v35i3.5750
Meine, C. (2022). Land, ethics, justice, and Aldo Leopold. *Socio-Ecological Practice Research, 4*, 167–187. https://doi.org/10.1007/s42532-022-00117-7
Moore, J. W., & Schindler, D. E. (2022). Getting ahead of climate change for ecological adaptation and resilience. *Science, 376*(6600), 1421–1426. https://doi.org/10.1126/science.abo3608
Mutanda, G. W., & Nhamo, G. (2024). Impact of climate change on Africa's major lakes: A systematic review incorporating pathways of enhancing climate resilience. *Frontiers in Water, 6*, 1443989. https://doi.org/10.3389/frwa.2024.1443989
National Center for Strategic Planning (CEPLAN). (2023). *Foresight study on water stress and food insecurity in Peru*. https://cdn.www.gob.pe/uploads/document/file/5511475/4909702-estudio-prospectivo-de-estres-hidrico-e-inseguridad-alimentaria-ceplan.pdf
National Water Authority (ANA). (2024). *Institutional Report 2023*. https://www.ana.gob.pe/sites/default/files/file_content/Memoria%20Anual%202023.pdf

Neamtu, R., Sluser, B., Plavan, O., & al. (2021). Environmental monitoring and impact assessment of Prut River cross-border pollution. *Environmental Monitoring and Assessment, 193*, 340. https://doi.org/10.1007/s10661-021-09110-1
Núñez, J. J., & Carvajal, J. C. (2021). Educating in times of climate change for human resilience and environmental regeneration. *Revista Electrónica Educare, 25*(2), 542–550. https://doi.org/10.15359/ree.25-2.30
Organisation for Economic Co-operation and Development (OECD). (2021). *Water governance in Peru*. https://www.oecd.org/content/dam/oecd/es/publications/reports/2021/03/water-governance-in-peru_0980e96a/f826f55f-es.pdf
Osorio, K. J., Ramos, L., & Velásquez, T. (2022). Projection of climate change impacts on the streamflow of the Lurín River Basin–Peru, under CMIP5-RCP scenarios. *Idesia (Arica), 40*(1), 101–114. https://doi.org/10.4067/S0718-34292022000100101
Pacheco, G. A., & Hernández, R. (2019). Climate change: Some aspects to consider for the survival of living beings—A systematic literature review. *Revista Cuidarte, 10*(3), e664. https://doi.org/10.15649/cuidarte.v10i3.664
Raihan, A., Pereira, J. J., Begum, R. A., & Rasiah, R. (2023). The economic impact of water supply disruption from the Selangor River, Malaysia. *Blue-Green Systems, 5*(2), 102–120. https://doi.org/10.2166/bgs.2023.031
Ribberink, A. (2023). Gro Harlem Brundtland. In R. Brinkmann (Ed.), *The Palgrave handbook of global sustainability*. Palgrave Macmillan. https://doi.org/10.1007/978-3-031-01949-4_154
Ryan, J. C. (2022). Hydropoetics: The rewor(l)ding of rivers. *River Research and Applications, 38*(3), 486–493. https://doi.org/10.1002/rra.3844
Sánchez, M. P., & Peñalver, M. J. (2025). Integrated planning and management of water resources in the Ancash region. *Revista InveCom, 5*(2), e502006. https://doi.org/10.5281/zenodo.12738450
Shah, A., Nazari, M., Antar, M., Msimbira, L. A., Naamala, J., Lyu, D., Rabileh, M., Zajonc, J., & Smith, D. L. (2021). PGPR in agriculture: A sustainable approach to increasing climate change resilience. *Frontiers in Sustainable Food Systems, 5*. https://doi.org/10.3389/fsufs.2021.667546
Simonson, W. D., Miller, E., Jones, A., García-Rangel, S., Thornton, H., & McOwen, C. (2021). Enhancing climate change resilience of ecological restoration—A framework for action. *Perspectives in Ecology and Conservation, 19*(3), 300–310. https://doi.org/10.1016/j.pecon.2021.05.002
Singh, V. (2024). Environment, development, and sustainability. In *Textbook of environment and ecology*. Springer. https://doi.org/10.1007/978-981-99-8846-4_23
Smith, J. A., Vimal, S., Baeck, M. L., & Miller, A. J. (2024). Cloudbursts and the upper tail of short-duration rainfall: Hortonian perspectives. *Hydrological Sciences Journal, 69*(16), 2337–2355. https://doi.org/10.1080/02626667.2024.2404712
Smith, L. (2022). 'On this sand farm in Wisconsin': Aldo Leopold, the Leopold Shack, and the Aldo Leopold Foundation. In *Ecological restoration and the U.S. nature and environmental writing tradition*. Palgrave Macmillan. https://doi.org/10.1007/978-3-030-86148-3_4
Stringer, L. C., Mirzabaev, A., Benjaminsen, T. A., Harris, R. M. B., Jafari, M., Lissner, T. K., Stevens, N., & Tirado-von der Pahlen, C. (2021). Climate change impacts on water security in global drylands. *One Earth, 4*(6), 856–873. https://doi.org/10.1016/j.oneear.2021.05.010
Tavanti, M. (2023). Higher purpose in sustainability leaders. In *Developing sustainability in organizations* (Sustainable Development Goals series). Palgrave Macmillan. https://doi.org/10.1007/978-3-031-36907-0_3
UNESCO. (2021). *United Nations World Water Development Report 2021: The value of water*. World Water Assessment Programme (WWAP). https://www.unesco.org/reports/wwdr/2021/es
UNESCO. (2025). *World Water Development Report 2025: Mountains and glaciers – Water towers (Executive summary)*. https://reliefweb.int/report/world/informe-mundial-sobre-el-desarrollo-de-los-recursos-hidricos-2025-de-las-naciones-unidas-montanas-y-glaciares-torres-de-agua-resumen-ejecutivo
UNICEF. (2025). *Water scarcity*. https://www.unicef.org/wash/water-scarcity
Wolka, K., Uma, T., & Tofu, D. A. (2023). The role of integrated watershed management in climate change adaptation for small-scale farmers in Southwest Ethiopia. *Environmental and Sustainability Indicators, 19*, 100260. https://doi.org/10.1016/j.indic.2023.100260
World Bank. (2022). *The climate crisis in Latin America also entails a water crisis: What's next?* https://blogs.worldbank.org/es/latinamerica/la-crisis-climatica-en-america-latina-tambien-entrana-una-crisis-del-agua-como
World Bank. (2023). *Peru: Strategic actions for water security. Water security diagnostic*. https://documents1.worldbank.org/curated/en/099062023100531967/pdf/P17363602652300490a20b067e3b55cf68d.pdf
World Bank. (2025). *Water overview: News on development, research, and data*. https://www.worldbank.org/en/topic/water/overview
World Wildlife Fund. (2025). *Water scarcity*. https://www.worldwildlife.org/threats/water-scarcity
Yang, D., Yang, Y., & Xia, J. (2021). Hydrological cycle and water resources in a changing world: A review. *Geography and Sustainability, 2*(2), 115–122. https://doi.org/10.1016/j.geosus.2021.05.003
Yi, S., & Kondolf, G. M. (2024). Environmental planning and the evolution of inter-basin water transfers in the United States. *Frontiers in Environmental Science, 12*, 1489917. https://doi.org/10.3389/fenvs.2024.1489917