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Review Article

Hydrosocial Connectivity and Water Footprint Governance from Andean Headwaters to Coastal Landscapes

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ABSTRACT

Freshwater generated in Andean headwaters regulates ecological processes and sustains rural livelihoods, irrigated agriculture, and expanding coastal cities across western South America. Climate-driven glacier retreat, declining baseflows, land-use intensification, and institutional fragmentation increasingly disrupt this mountain coast hydrological continuum, with severe implications for biodiversity, landscape resilience, and equitable water access. Despite these interconnected pressures, few studies integrate water footprint management with human rights and Indigenous governance perspectives to assess how landscape-scale decisions shape coupled Andean–coastal socio-ecological systems. This review addresses this gap through a structured assessment of scientific literature, hydrological datasets, policy frameworks, and community case studies. Results highlight three dominant drivers of hydrological and ecological degradation: inefficient highland irrigation systems, accelerated cryosphere loss, and governance fragmentation that disconnects upstream users from coastal water security. Traditional Andean infrastructure, including ‘amunas’, terracing, ‘bofedales’, and communal ‘acequias’, emerges as nature-based solutions capable of enhancing infiltration, stabilising flows, and sustaining high-altitude biodiversity. Case studies demonstrate that integrating water footprint management with Indigenous ecological knowledge strengthens ecosystem services, reduces grey-water pollution reaching coastal basins, and operationalises the human right to water. Hybrid governance models that combine remote sensing, hydrological modelling, and water footprint management indicators with community-led water management offer the greatest potential to improve landscape resilience under climate change. Embedding water footprint management into regional land- and water-use policies can protect headwater ecosystems, mitigate salinisation and freshwater decline in coastal aquifers, and promote long-term hydro social sustainability across the Andes coast continuum.

KEYWORDS

Landscape resilience, Indigenous water systems, Nature-based solutions, Environmental flows, Community water governance

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INTRODUCTION

The Andean region, stretching across seven countries from Venezuela to Argentina, is not only a biodiversity hotspot but also a critical socio-hydrological system that supports human life through agriculture, hydropower, and urban water supply [1]. Unlike other mountain regions, the Andes combine fragile high-altitude ecosystems with rapidly growing urban demands, producing some of the most acute rural–urban water tensions in the Global South [2]. Emerging pressures, including mining expansion, hydropower development, and agro-export growth, are intensifying competition for already limited water resources, particularly in semi-arid valleys where upstream-downstream conflicts are escalating. Water footprint management (WFM) provides a comprehensive framework for addressing these challenges by linking water consumption patterns with their ecological and social impacts, moving beyond conventional supply-centred water policies. In the Andean context, WFM is relevant because water scarcity arises not only from physical limitations but also from governance regimes shaped by overlapping customary rights, national regulations, and private sector demands [3]. This situation makes the Andes a strategic setting for examining how ecological sustainability can be balanced with water justice. This perspective highlights the Andes as a testing ground for balancing ecological sustainability with water justice. Despite the growing body of WFM literature, existing studies remain largely fragmented and sectoral, focusing predominantly on agricultural efficiency, industrial water use, or national-scale accounting frameworks [4]. In the Andean region, WFM has not been analysed as an integrated socio-hydrological rule mechanism that simultaneously connects ecological processes, Indigenous water institutions, human rights frameworks, and downstream coastal dependencies. There has been little focus on how Andean headwater water footprints influence hydrosocial connectivity between mountain environments and Pacific urban centres, or how customary governance systems can be effectively harmonised with official WFM indicators in the face of climate change. This issue limits the practical applicability of WFM to water justice, cross-scale governance, and climate adaptation to mountain-coast systems. This gap is filled in this review by synthesising ecological, cultural, governance, and hydrological data to rebrand WFM as a rights-based, cross-scale governance theory of Andean headwaters and coastal downstream systems.

At the same time, international discourses on climate adaptation, biodiversity conservation, and human rights are converging in the region. The recognition of water as a fundamental human right by the United Nations provides a normative framework for aligning WFM with equity goals [5]. Indigenous communities such as the Quechua and Aymara contribute ancestral practices of water regulation, including ritualised allocation and communal governance. These traditions are increasingly studied as models for climate-resilient adaptation [6]. This review synthesises evidence from scientific literature, policy documents, and community-based case studies to evaluate how WFM can strengthen sustainable water governance in the Andes. A structured methodology was applied to identify, screen, and analyse studies published between 2000 and 2025 across databases including Scopus, Web of Science, and Google Scholar. Findings are thematically organised around: (i) the ecological and cultural significance of Andean water systems, (ii) the impacts of climate and socio-economic change, (iii) community and policy responses, and (iv) research gaps for integrating WFM into conservation and governance frameworks.

The hydrological transformations occurring in the Andes are directly linked to coastal water security. Over 60–80% of the freshwater used in Pacific coastal cities from Lima to Trujillo and Arica originates in Andean headwaters. As glaciers retreat, land-use change, and upstream over-extraction reduce dry-season flows, downstream coastal hydrology faces increased salinisation, reduced estuarine dilution capacity, and heightened vulnerability to climate-driven storm surges. Therefore, water footprint management in the Andes is not only a mountain issue but a critical determinant of coastal resilience. This review positions Andean

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WFM within mountain coast hydrological integration to align with the current focus on coastal climate adaptation.

Background on Water Stress and Biodiversity Vulnerability Across the Andes

The Andean zone, which hosts some of the world's greatest biodiversity, is facing rising water scarcity, posing a risk to the region's agricultural potential and environment. The Andes provide a vital freshwater source for approximately 90 million people, with glaciers, rivers, and aquifers across the region collectively sustaining agriculture, hydropower, and domestic water needs [7]. For instance, glaciers contribute around 80% of the dry-season water flow in parts of Peru's Cordillera Blanca [8], while in cities like La Paz, Bolivia, glacier melt accounts for roughly 27% of the water supply during dry periods. Downstream impacts are increasingly visible along Peru's arid coastline, where declining Andean flows reduce freshwater availability for coastal aquifers, intensify seawater intrusion, and destabilise estuarine ecosystems supplying fisheries and mangroves. Thus, Andean water scarcity produces direct consequences for coastal hydrology, creating a coupled system vulnerable to climate change. Nevertheless, the area's water sources are strained by factors such as climate change, inadequate water distribution in agricultural practices, and deforestation. In this context, water scarcity refers to the physical insufficiency of freshwater resources, while water stress reflects the combined effects of limited availability and rising demand, with weak governance structures. One of the most notable impacts of climate change in the Andes has been the widespread retreat of glaciers, which collectively serve as a crucial source of freshwater for human living in the region.

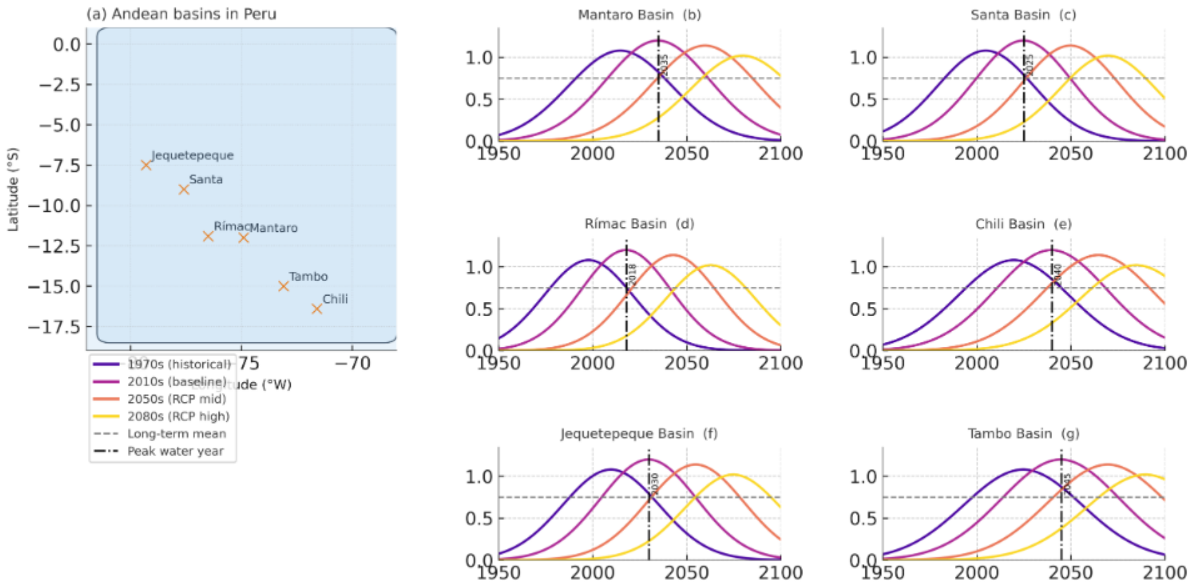

Figure 1. Projected changes in peak water timing and normalised runoff across six Andean basins under historical and future climate periods; figure data adapted from multi-decadal hydrological projections for Peruvian Andes basins [12], [13], and glacier-runoff modelling results [1]

Andean agriculture is highly dependent on irrigation, yet most farm systems still rely on premodern and inefficient methods such as unlined earth canals, gravity-fed flood irrigation, and open-ditch distribution. These systems lose around 30–50% of water through seepage and evaporation, leading to over-extraction of rivers and aquifers, soil salinisation, and reduced crop productivity [9]. Excessive irrigation and other practices, such as limited adoption of water-conservation technologies and poor water management, have caused soil erosion, desertification and the destruction of water sources [10]. Water scarcity is also directly affecting the area's biodiversity. More vulnerable are the ecosystems that rely on stable water sources, as freshwater resources are declining, causing negative effects on plants, fauna, and the overall ecological integrity of the ecosystem. The loss of biodiversity, paired with water scarcity, poses a high risk to the ecological stability of the Andes, affecting the local population, which relies on the natural resources as its primary source of income [11]. Figure 1 illustrates the projected shifts in peak water timing across major Andean basins in Peru, showing a consistent advancement of peak runoff from historical to future climate scenarios. These basin-specific trajectories highlight the accelerating influence of glacier retreat on seasonal water availability throughout the 21st century.

Role of Climate Human Systems Emphasis

The Andean region is one of the regions that rely on water as an essential component of agricultural activities, livelihoods and ecosystems. To local inhabitants, especially native communities such as the Quechua, Aymara, and others, water has become an indispensable element of their cultural identity and way of life. Centuries of use in these communities have led to the development of traditional water management strategies that can be used in their areas to optimise water use in the face of environmental challenges, such as rural irrigation canals, terracing, and water-aring agreements [14]. Nevertheless, these conventional systems are gradually becoming increasingly challenged by population growth and climate change. Not only does water scarcity expose communities to physical health problems arising from a lack of clean drinking water, but it also affects their agricultural activities, including potato farming, organic quinoa and maize cultivation, and quinoa, which are vital sources of food security and income generation [15]. Traditional Andean water harvesting systems further illustrate the socio-ecological resilience of Indigenous practices. The 'amunas' in Peru pre-Inca infiltration canals divert wet-season flows into mountain soils to recharge aquifers, sustaining dry-season water supply. Similarly, 'waru-waru' (raised fields) near Lake Titicaca integrate water channels and elevated plots, buffering crops against frost while creating wetland habitats that support aquatic biodiversity [16]. In Bolivia, 'atajados' (earthen ponds) collect and store rainwater, enhancing both agricultural productivity and ecosystem services in semi-arid zones [17]. These examples show how ancestral technologies continue to provide sustainable water management and reinforce cultural identity.

Water sources are also important for preserving biodiversity in Andean ecosystems. The area has exceptionally high species richness, with a significant percentage of them being endemic and requiring a steady water supply to exist. Wetlands, high-altitude, and river-based ecosystems are especially prone to fluctuations in water levels. For example, water from glaciers, rivers, and snowmelt supports the growth of unique plant species that flourish in the Andean highlands, including high-altitude grasses and medicinal plants. Furthermore, several species dependent on these ecosystems are listed as threatened in the IUCN Red List. The giant Andean frog (*Telmatobius culeus*), endemic to Lake Titicaca, is Critically Endangered due to declining water quality and habitat loss [18]. High Andean wetlands (bofedales) provide essential breeding habitats for the Andean flamingo (*Phoenicoparrus andinus*) and James's flamingo (*Phoenicoparrus jamesi*), both considered Vulnerable [19]. Likewise, the spectacled bear (*Tremarctos ornatus*), categorised as Vulnerable, relies on montane ecosystems sustained by glacial and wetland water flows. These examples emphasise the interconnectedness of water management, biodiversity protection, and community livelihoods. Table 1 summarises representative Andean species whose survival is closely linked to freshwater availability, highlighting how hydrological stress translates into biodiversity risk.

Table 1. Key Andean species dependent on freshwater systems, associated threats, and conservation status

Species	Ecosystem	Water-related threat	IUCN status	References
Telmatobius culeus (giant Andean frog)	Lake Titicaca	Declining water quality, reduced inflow	Critically Endangered	Muñoz-Saravia *et al.* [20]
Phoenicoparrus andinus (Andean flamingo)	High Andean wetlands (bofedales)	Wetland desiccation, altered hydrology	Vulnerable	Derlindati *et al.* [21]
Phoenicoparrus jamesi (James's flamingo)	Saline lakes and wetlands	Reduced freshwater recharge	Vulnerable	Byju *et al.* [22]
Tremarctos ornatus (spectacled bear)	Montane forests and wetlands	Habitat loss linked to hydrological change	Vulnerable	Bandopadhyay *et al.* [23]
High-Andean grass and medicinal plants	Alpine wetlands	Glacier retreat, soil drying	Regionally Threatened	Veneros *et al.* [24]

The decline in water availability, driven by both natural and anthropogenic processes, causes dramatic consequences on the biodiversity of these ecosystems, and in turn on food webs and communities whose lifestyle is based on these component sources, including fishing and hunting, crop cultivation, and the collection of wild edible plants or harvesting of wild vegetation for subsistence [25]. The stability of these Andean systems directly influences the freshwater inflows to coastal wetlands, deltas, and nearshore marine ecosystems. Reduction in highland baseflows has already been linked to salinisation of coastal agricultural lands and altered nutrient balances in estuarine fish nurseries along Peru's Pacific margin.

Quantitative evidence demonstrates that reductions in Andean headwater flows have measurable downstream consequences. Along Peru's Pacific coast, dry-season river discharge from Andean basins has declined by approximately 20–40% over recent decades [26], contributing to increased salinisation of coastal aquifers at rates of 0.3–1.2 g L^{-1} per decade in Brazil and irrigated valleys of Peru such as Chao, Ica, and Camaná [27]. Reduced freshwater inflows have also lowered estuarine dilution capacity by up to 30% in major river mouths, intensifying nutrient imbalance and affecting fish nursery productivity. These figures confirm that upstream water stress in the Andes directly translates into coastal hydrological and ecological vulnerability.

Objectives of the Review

The primary objective of this review is to examine the role of WFM in addressing water scarcity in the Andean region while protecting biodiversity. WFM, defined as a strategy to reduce water consumption and enhance efficiency in agricultural and community systems [28], offers a framework to ensure that agricultural production is compatible with ecological sustainability. This review evaluates the practical applications of WFM in Andean communities, with particular attention to sustainable agricultural practices and the modernisation of water governance. Furthermore, it explores how WFM supports the realisation of the human right to water, especially in Indigenous Andean communities where access to safe drinking water, sanitation, and irrigation remains severely constrained [29]. The review aims to generate actionable recommendations for policymakers, practitioners, and local communities to ensure equitable access to water resources and long-term ecological sustainability in the Andes and to identify how these strategies support both Andean and coastal ecosystem resilience, particularly in regions where coastal water security depends heavily on mountain hydrology. Considering these objectives, the review seeks to answer the following research questions: What are the primary drivers of water scarcity and water stress in the Andes? How can WFM be applied to strengthen both biodiversity conservation and agricultural sustainability in Andean communities? In what ways do Indigenous practices and knowledge systems contribute to water governance under conditions of scarcity and climate change? How can WFM be integrated into a human rights-based framework to ensure equitable access to water?

MATERIALS AND METHODS

The research adopted a narrative review approach, which is suitable for integrating interdisciplinary evidence across hydrology, water footprint management, biodiversity conservation, Indigenous governance, and human rights. The narrative approach was chosen as the study combines heterogeneous materials such as scientific literature, policy frameworks, and case studies (community-based studies) that cannot be easily compared by methods such as meta-analytical or systematic review methods. The design enables imaginative synthesis and critical analysis of the Andean coastal socio-hydrological continuum.

Data Sources and Literature Search

The scientific databases Scopus, Web of Science, and Google Scholar were searched to conduct a structured literature search. To complement peer-reviewed literature, grey literature from international and regional institutions, such as FAO, UNESCO, UNEP, IPCC, IUCN, and the Peruvian National Water Authority (ANA), was also included. A combination of policy-relevant material on water governance and climate adaptation in the Andes, as well as empirical studies on the same, was chosen through these sources. The presented search included the years 2000–2025, as this is the timeframe during which water footprint evaluation, Indigenous water management, and climate change effects in the Andes have been most active. In the English and Spanish searches, regionalisation was carried out.

Search Terms and Screening Process

Search strings combined thematic keywords related to water management, governance, and ecosystems, including: “water footprint management,” “Andean water governance,” “Indigenous water systems,” “nature-based solutions,” “biodiversity conservation,” “human right to water,” “glacier retreat,” and “Andean–coastal hydrology.” Reference lists of key articles were also screened to identify additional relevant studies. Initial screening was based on titles and abstracts to assess relevance. Full-text screening was conducted to ensure alignment with the study objectives.

Inclusion and Exclusion Criteria

Studies were included if they: (i) focused on the Andean region or Andean-fed coastal basins; (ii) addressed water footprint management, irrigation efficiency, hydrological change, biodiversity, Indigenous water practices, or rights-based governance; and (iii) provided empirical evidence, conceptual frameworks, or documented case studies. Studies were excluded if they: (i) focused solely on non-mountain regions; (ii) addressed water management without relevance to governance, ecosystems, or social dimensions; or (iii) lacked sufficient methodological or contextual detail.

Data Analysis and Synthesis

Selected literature was analyzed using thematic qualitative coding. Studies were grouped into four analytical categories: (1) water footprint management and agricultural practices;

(2) biodiversity and ecosystem services; (3) Indigenous and community-based water governance; and (4) human rights and policy frameworks. Case studies were examined comparatively to identify recurring drivers of hydrological stress, governance challenges, and successful adaptation strategies. Particular attention was given to linkages between upstream Andean water use and downstream coastal impacts. Findings were synthesised to identify synergies, trade-offs, and knowledge gaps relevant to climate-resilient and rights-based water governance.

Methodological Limitations

Being a narrative review, the study lacks quantitative meta-analysis or standardised effect-size comparisons. Nonetheless, the methodology allows for the integrative analysis of disciplines and scales of governance and provides an in-depth understanding of water footprint management in coupled Andean-coastal socio-ecological systems.

RESULTS AND DISCUSSION

The literature review demonstrates that climate change, inefficient irrigation methods, and discontinuous governance structures are joint forces driving water shortages and hydrological instability in the Andes, with severe downstream impacts on the water security of the coast. Findings are likewise consistent in indicating that the traditional Andean water systems, including ‘amunas’, terracing, ‘bofedales’, and communal ‘acequias’, are viable nature-based solutions in that they improve infiltration, control seasonal floods, and sustain biodiversity in high elevations. The combination of water footprint management and an Indigenous governance and rights-based approach can be identified as one of the methods of mitigating blue and grey water footprints, enhancing ecosystem services, and enhancing social equity. Case studies also show that hybrid governance frameworks combining community-led management with remote sensing, hydrological modelling, and water footprint indicators have the greatest potential to increase resilience across the Andean-coastal continuum as climate change intensifies.

Water Footprint Management and Its Significance for Andean Socio-Ecological Systems

As already mentioned, this study’s narrative review approach is particularly well-suited to synthesising knowledge across diverse domains, from water footprint management to biodiversity conservation and human rights. Because more than 70% of the water feeding Peru’s coastal cities and agricultural corridors originates in Andean basins, WFM must be understood as a tool that shapes freshwater availability along the entire mountain coast continuum. Reductions in blue and grey water footprints upstream directly affect coastal aquifer recharge, estuarine water quality, and nearshore ecosystem stability. Unlike systematic reviews, narrative reviews allow for a more flexible integration of conceptual, empirical, and policy-oriented literature to generate thematic insights [30]. To gather relevant literature, searches were conducted in major academic databases including Scopus, Web of Science, and Google Scholar, using keywords such as “water footprint,” “Andean biodiversity,” “human rights to water,” “traditional water management,” and “agriculture in the Andes.” In addition, key reports from international organisations such as FAO, UNESCO, and UNEP were included to capture policy-relevant insights. An iterative reading process was employed, during which studies were thematically coded and grouped according to four emerging categories [31]: traditional and modern water management practices, biodiversity and ecosystem services, socio-political and cultural dimensions of water use, and rights-based approaches to water governance. The identification of knowledge gaps was based on areas where the literature revealed inconsistent findings, under-researched issues, or missing connections [30] among water footprint management, biodiversity, and human rights in the Andean region.

Water footprint in agricultural practices in the Andes. Agriculture in the Andes is highly dependent on irrigation, yet water conveyance and application methods remain predominantly premodern. Unlined earth canals and gravity-fed flood irrigation dominate the landscape, often resulting in conveyance losses of 20–40% and on-farm application efficiencies of 50–60% [32]. These inefficiencies impose significant pressure on water resources, especially during dry seasons, particularly when demand peaks. Crop choices further compound the challenge: water-intensive staples such as potatoes and maize require sustained irrigation, thereby amplifying the stress created by inefficient conveyance systems [33]. By contrast, native crops like quinoa rely more on green water and demonstrate greater resilience to scarcity, suggesting opportunities to mitigate water pressure through crop diversification [29]. Linking these dynamics to climate change presents an even more urgent scenario: as glacier retreat diminishes dry-season water availability, the persistence of inefficient irrigation and water-intensive cropping systems further amplifies vulnerability. In this context, water footprint accounting (WFA), which disaggregates green, blue, and grey water components, becomes essential for identifying and prioritising interventions that balance agricultural productivity with water conservation. Comparative studies outside the Andes have demonstrated that lining canals and adopting pressurised or micro-irrigation can raise efficiency to over 90%, highlighting the considerable potential for reducing the blue water footprint in Andean farming systems.

Quantitative assessments of crop water footprints further highlight the scale of pressure on Andean water resources. Global and regional studies indicate that potatoes require approximately 287 litres of water per kilogram of production, while maize demands nearly 1,222 L kg^{-1} [33]. By comparison, quinoa averages 1,200–1,500 L kg^{-1}, yet much of this demand is satisfied through green water, making it more resilient under scarcity conditions. These figures illustrate how crop choice directly influences the magnitude of water extraction from rivers and aquifers. Crop selection further shapes the water footprint: potatoes and maize typically require significant irrigation, while quinoa and other native crops exhibit greater resilience to water scarcity through their reliance on green water. Applying WFA, which disaggregates green, blue, and grey components, enables farmers and policymakers to identify which cropping systems impose the heaviest pressure on scarce water resources [34].

Caution must be taken regarding the variability and uncertainty in crop water footprint estimates. The water footprint is highly dependent on local climatic conditions (temperature, precipitation, and evapotranspiration), soil properties (texture, depth, and water-holding capacity), irrigation technology (surface, sprinkler, or drip), and management practices (planting density and fertilisation). In the Andes, the sharp altitudinal gradients and big seasonal differences further increase the spatial heterogeneity of the green, blue and grey components of water. Also, differences in methods across studies, including the selection of evapotranspiration models, the spatial resolution of remote sensing data, and assumptions about effective precipitation, create uncertainty in footprint estimates [35]. The values of the water footprint must therefore be viewed as expected ranges, rather than exact values and as such, site-specific measurements and sensitivity analyses are necessary when applying WFM to Andean agricultural systems.

Water footprint in the local community water use. Beyond agriculture, rural Andean households rely on multi-use community-managed systems that combine domestic supply, livestock watering, and small-scale irrigation. These systems, often administered by local committees, are especially vulnerable during dry seasons when water is contested between urban centres, commercial farms, and Indigenous communities. In places such as La Paz – El Alto, glacier retreat has reduced dry-season water reliability, intensifying competition [36]. Applying WFA at the community scale provides a mechanism to distinguish domestic blue-water needs from agricultural consumption, thereby clarifying conservation and equitable distribution priorities. Traditional recharge infrastructures, particularly the ‘amunas’ in Peru, exemplify nature-based solutions that directly enhance local water security. By diverting wet-season flows into hillslopes, 'amunas' delay runoff and augment dry-season baseflow, with studies documenting median delays of 45 days and average dry-season gains of around 7.5% in Lima's source waters [37]. Recent rehabilitation programs have extended these systems, supporting urban and rural resilience alike. However, despite promising hydrological outcomes, their broader impacts on water quality, equity, and long-term governance remain poorly quantified. Reported baseflow increases of approximately 7.5% associated with 'amunas' are derived primarily from case studies in the central Peruvian Andes, particularly in catchments supplying the Lima metropolitan region [38]. They are highly dependent on local hydrogeology, soil permeability, slope and precipitation regimes, and cannot be directly extrapolated to drier southern Andes or highly fractured volcanic environments. Besides this, hydrological modelling of 'amunas' is subject to uncertainties arising from a lack of long-term monitoring data, assumptions on the direction of movement of underground water, and interannual variability. These values must therefore be understood as indicative rather than universal, with emphasis on the need for a site-specific evaluation before replication.

In the Andes, Indigenous water governance is highly diverse and local rather than universal. For example, Quechua communities in the central and southern regions of the Peruvian Andes tend to coordinate irrigation through communal 'acequias' organised by rotating assemblies, known as 'faenas' [39]. In contrast, Aymara systems of the Peruvian Altiplano rely on 'ayllu' leadership and collective regulations related to pastoralism and wetland administration. In the páramo areas of Ecuador, water governance is often a synthesis of community councils and water-user associations, both legally established and representing various historical and institutional pathways. By recognising this diversity, Indigenous water governance is not treated as a single model, underscoring the need to integrate WFM into the context.

Although most of the old Andean water systems are adaptive and resilient, not all are sustainable under the current climate pressures. Occurrence of amoebas, 'bofedales' management and rotational grazing practices tend to increase infiltration and ecosystem stability, but other practices like ungulates surface diversion or increased flood irrigation are more likely to increase water stress in response to reduced glacier melting and changed rainfall regimes [40]. Therefore, certain conventional systems need to be adjusted by introducing refined allocation regulations, hydrological monitoring, or additional efficiency measures to survive in the face of mounting climate change. To implement WFM effectively and in a culturally appropriate manner, certain practices must be identified as resilient and adaptation-dependent.

<u>Measuring and monitoring water footprints in the Andean context.</u> Accurate water footprint measurement in the Andes is complicated by steep topography, rapidly changing glacier dynamics, and sparse hydrological records. Traditional gauging networks are insufficient for capturing the high temporal and spatial variability of water flows, prompting interest in remote sensing and IoT-based monitoring of evapotranspiration, soil moisture, and streamflow. Integrating these technologies into WFA can provide basin-scale visibility of consumptive use while tracking green, blue, and grey water footprints across agricultural and community sectors [41]. Recent applications of remote sensing and hydrological modelling have advanced the estimation of crop- and basin-scale water footprints. For instance, Feng *et al.* [42] derived regional maize water footprints using MOD16 evapotranspiration (ET) products in combination with the data from Global Land Data Assimilation System (GLDAS). Similarly, Sun *et al.* [43] produced high-resolution maps of green and blue agricultural water footprints at the pixel level through remote-sensing ET datasets. The Food and Agriculture Organisation's WaPOR database has supported multiple case studies that apply satellite-based ET to water auditing from basin to irrigation scheme scales [44]. The WA+ framework has been used for basin-wide water accounting with remote-sensing ET in regions such as the Indus. In the

western United States, the OpenET platform now provides validated field-scale ET estimates that enable water managers to perform depletion accounting.

Likewise, studies using the SWAT model, such as in the Ceyhan Basin, have demonstrated the integration of hydrologic modelling to refine estimates of effective precipitation and partition green and blue water footprints [45]. Standardised indicators to link footprint reductions with biodiversity outcomes are absent, and wetlands monitoring remains fragmented across agencies. Without such integration, WFA risks remaining a technical exercise divorced from ecological realities, limiting its value for long-term adaptation strategies in the Andes. The WFM is typically assessed through three complementary components: green, blue, and grey water footprints. Grey-water footprint assessment is particularly relevant in mining-impacted Andean catchments, where water-quality degradation represents a major driver of ecological and social risk. In regions such as Cajamarca, Cerro de Pasco, and the Santa River basin, elevated concentrations of heavy metals, including arsenic, cadmium, and mercury, have been documented downstream of mining operations [46]. These pollutants substantially increase the grey-water footprint by requiring large volumes of freshwater to dilute contaminant loads to acceptable environmental standards. In such contexts, grey-water footprints often exceed blue-water footprints, underscoring that pollution, rather than abstraction alone, is a dominant constraint on water availability. Incorporating grey-water indicators into WFM, therefore, provides a critical lens for evaluating trade-offs between extractive activities, ecosystem health, and downstream water security in the Andes. The green water footprint represents the volume of rainwater consumed by crops and vegetation through evapotranspiration; the blue water footprint accounts for surface and groundwater withdrawn for irrigation, domestic use, and industry; and the grey water footprint measures the volume of freshwater required to assimilate pollutants, such as fertilisers or pesticides, to meet water quality standards [41]. These indicators, expressed in cubic metres per tonne of product (m^3 t^{-1}) or litres per kilogram (L kg^{-1}), provide a standardised way to compare water-use efficiency across crops, households, and basins. In the Andean context, quantifying all three components is essential: green water dominates rainfed quinoa systems, blue water drives irrigation-dependent maize and potato production, and grey water reflects pollution loads from fertilisers, mining, and wastewater. Integrating these metrics allows WFM to move beyond generalised notions of scarcity and instead target specific levers for reducing pressure on ecosystems while safeguarding community needs [45].

Despite their analytical potential, remote sensing and Internet of Things (IoT) based monitoring systems face significant feasibility barriers in rural Andean contexts. High upfront costs for sensors, data loggers, and maintenance limit adoption among smallholder communities and local water-user associations. Technical capacity constraints, including limited training in data interpretation and system maintenance, further restrict effective use. Connectivity challenges are particularly acute in high-altitude regions, where unreliable electricity supply and weak mobile or internet coverage hinder real-time data transmission [47]. In addition, institutional fragmentation and short project cycles often result in pilot initiatives that lack long-term support and integration into local governance structures. Addressing these barriers requires low-cost monitoring technologies, capacity-building programs, offline-capable data platforms, and sustained institutional partnerships to ensure that digital WFM tools are both accessible and locally actionable.

<u>Integration of water footprint into local water management systems.</u> The process of incorporating water footprint management into local water governance systems in the Andes has several major research gaps that must be addressed to achieve sustainable water use in the region. Among the key gaps is the poor understanding of the implications of water footprint management for local communities, particularly marginalised populations, such as Indigenous people and smallholder farmers. Although the latter is gradually being applied, water footprint management practices have yet to receive ample studies on their socio-economic impacts in

such communities. Research is recommended to investigate the social and economic effects of conservation measures, focusing on the livelihoods of local communities and the convergence of these measures with traditional water rights. A study by Hailegnaw *et al*. [48] highlights the need to explore the domains of socio-economic influences in greater depth, particularly the interests of marginalised populations and the mutually beneficial relations between them and contemporary forms of governance. Also, Leroy *et al.* [49] emphasise the importance of accounting for local socio-political processes in implementing the strategy for managing the water footprint. Community engagement in WFM can be operationalised through concrete mechanisms rather than general participation. One promising avenue is citizen science, where farmers and households collect data on rainfall, soil moisture, or irrigation timing using low-cost sensors or mobile applications. Such data can feed into basin-level observatories, improving the resolution of hydrological monitoring while empowering communities with actionable knowledge.

Another approach is the creation of local water observatories, participatory platforms where community members, municipal officials, and researchers jointly review water footprint indicators and negotiate allocation priorities. These observatories can function as early-warning systems for scarcity and biodiversity risks, while also strengthening accountability in water governance. In addition, co-management agreements that formally integrate Indigenous water-sharing traditions (e.g., 'amunas' or communal canals) with modern WFM tools create institutional spaces where local knowledge informs basin planning [3]. Together, these mechanisms move participation beyond symbolic involvement toward structured roles that ensure communities actively shape data generation, decision-making, and policy implementation.

Traditional methods include irrigation canals and terracing in Andean regions, practices that have been sustained for centuries as integral components of community-based water governance. There has, however, been minimal research on the issues and successes of combining these practices with modern methods such as drip irrigation and micro-sprinklers. The study should examine the compatibility of existing systems, the problems encountered during integration, and what led to more sustainable water consumption. According to Ghorbanpour *et al*. [50], additional empirical studies are required to evaluate the possibilities of combining the traditional and new water management techniques. Similarly, Hoogesteger *et al.* [51] posit that the decentralised interaction methodology between these systems should be understood to achieve effective water conservation and social acceptability. Future research could also examine how hybrid systems, where ancestral techniques are supplemented by sensor-based irrigation scheduling, perform under conditions of seasonal water stress. As shown in **Table 2**, these traditional practices illustrate how Indigenous knowledge contributes to sustainable water governance and ecosystem protection in Andean agricultural systems. The other gaps that have not been fully exploited are equity in water footprint management, especially between big agribusiness and small farms. Increasing water consumption in industrial-scale agriculture may intensify preexisting water access shortages, particularly impacting the local population. Socio-economic differences in water access should be researched to identify ways to ensure that vulnerable groups are not disproportionately affected by water footprint management.

Table 2. Traditional and Indigenous water management infrastructures in the Andes

Practice	Hydrological function	Ecological benefits	Documented effect	Ref.
'Amunas'	Infiltration canals (aquifer recharge)	Dry-season flow; erosion control	+7.5% flow; 30–45 d delay	[48]
'Waru-waru'	Moisture retention; frost buffering	Soil moisture; yield stability	+25–50% yield; −15–30% ET	[16]

Practice	Hydrological function	Ecological benefits	Documented effect	Ref.
Terracing	Runoff/erosion control	Slope stability; infiltration	+40% WUE; −50% erosion	[2]
'Atajados'	Rainwater storage	Dry-season supply	+10–20% water availability	[52]
'Acequias'	Communal water distribution	Equity; efficiency	↓conflicts; ↑efficiency	[53]
'Bofedales'	Natural water storage	Baseflow; biodiversity	Sustained baseflow	[54]
'Qochas'	Rainwater harvesting	Livestock; microclimate	+20% soil moisture; ↓runoff	[55]
'Pukios'	Subsurface flow channels	Perennial supply	Stable year-round flow	[56]
'Waru' ponds	Water retention/recycling	Soil–groundwater balance	↑groundwater stability	[57]
'Camellones'	Drainage regulation	Aeration; productivity	+15–35% yield	[58]
'Pallares'	Sediment filtering	Water quality	−20–35% sediment	[54]
Fog catchers	Fog condensation	Supplemental irrigation	4–7 L m^{-2} d^{-1}	[59]
'Ayllu'systems	Collective governance	Equity; cooperation	−60% conflicts	[60]
Pasture rotation	Grazing control	Wetland recovery	+30% vegetation; +18% retention	[54]

Uhlenbrook *et al.* [61] consider the fair distribution of water a critical form of sustainability and warn that massive agricultural activities should not distract from the interests of the local population. The authors note that participatory water management plays a significant role in empowering marginalised groups by including them in decision-making, a crucial step for attaining equality in water distribution [62]. However, little is known about how gender dynamics, migration, and intergenerational knowledge transfer influence equitable participation in water governance, representing a significant research gap. For community-based water governance models, more research is needed in this aspect as well. Although the community-based governance system has been introduced in some parts of the Andes, there is insufficient research on its contribution to the effectiveness of water footprint management. Evaluating how participatory decision-making, water-sharing agreements, and community-led initiatives can be integrated with modern water management practices is important. Bos and Brown [63] outline the potential of local governance to promote water conservation, yet more studies are required to elucidate which processes ensure its effectiveness. Decentralised management may foster water conservation, but it needs investigation to determine its capacity to support water footprint management.

<ins>Implications of gaps.</ins> The absence of detailed knowledge on these gaps has significant implications for both policy and practice in the Andes. Without evidence on the socio-economic impacts of WFM on smallholders and Indigenous groups, conservation policies risk reinforcing existing inequalities by favouring commercial agriculture over subsistence farming [3]. Similarly, the lack of studies on hybrid systems combining ancestral techniques with modern technologies hinders the design of context-appropriate irrigation programs, leading to low adoption rates or the erosion of traditional governance structures [64]. Weak monitoring frameworks and real-time indicators limit governments' ability to anticipate

water shortages, undermining adaptive planning under accelerating glacier retreat [65]. Finally, insufficient research on equity dimensions such as gender, migration, and generational knowledge transfer means that water governance reforms may overlook key drivers of participation and exclusion [62]. In practice, addressing these gaps is not only a matter of academic rigour but a prerequisite for crafting policies that are socially equitable, technologically viable, and ecologically sustainable in Andean communities. Given the Andean coastal connectivity, WFM integration must extend beyond local governance to basin-to-coast frameworks that align highland community systems with coastal water demand management.

Biodiversity Conservation and The Role of Water in Andean Ecosystems

To structure the discussion on biodiversity, this review adopts the ecosystem services framework as a guiding lens. Within this model, water supports multiple categories of ecosystem services that are directly relevant to Andean communities. As a provisioning service, water supports agriculture, drinking supply, fisheries, and hydropower [1]. As a regulating service, it stabilises flows, buffers floods, and maintains water quality in highland wetlands and rivers [66]. As a cultural service, water underpins ritual practices, spiritual identity, and Indigenous worldviews that see rivers and glaciers as living beings [67]. Finally, as a supporting service, water sustains soil fertility, nutrient cycling, and habitats essential for endemic species. Framing biodiversity-water linkages in this way clarifies how water footprint management interventions affect not only ecological integrity but also human well-being [68]. It also highlights where synergies or trade-offs emerge, for example, when irrigation efficiency improves provisioning services but risks reducing environmental flows needed for regulating services and biodiversity protection. Using this framework ensures that the following subsections explicitly link ecological significance, threats, and conservation strategies to the diverse services water provides in the Andes. Degraded Andean hydrology also affects coastal biodiversity, especially migratory bird species, coastal wetlands, and nursery grounds dependent on freshwater inflows from the Andes. Reduced environmental flows have been linked to mangrove stress in northern Peru and altered salinity gradients in Pacific estuaries.

<u>Ecological significance of the Andes: unique species and habitats.</u> The Andes is considered among the most biodiverse regions in the world, with an abundance unmatched by any other region, and many species and ecosystems that differ drastically with altitude and geography. The area has a variety of ecosystems, such as cloud forests, high-altitude wetlands, temperate rainforests, and parched deserts. Ecosystems do not just harbour unique plant and animal species; they are also ecologically critical for regulating hydrology and biodiversity across South America [69]. Biodiversity is especially high in cloud forests located in the lower and mid-altitude Andes. The forests are also marked by an abundance of mist and moisture, creating a distinct microclimate that supports numerous plant species, mosses, and epiphytes. These ecosystems support rare and emblematic species, including the Andean (spectacled) bear (*Tremarctos ornatus*) and the endangered mountain tapir, as well as a rich diversity of birds, amphibians, and reptiles [70]. For example, Sangay National Park in Ecuador, one of the most ecologically intact Andean reserves, harbours over 430 bird species, 107 mammals, 33 amphibians, and 14 reptiles, making it a critical biodiversity stronghold [71]. These wetlands provide a critical water source and play a pivotal role in regulating the hydrological cycle by storing and gradually releasing flows into rivers. They constitute essential habitat for endemic species such as the Andean flamingo, the vicuña, and various species of high-altitude plants that grow in nutrient-poor soils. Ecosystems also help regulate water quality, making them crucial to biodiversity and human water consumption. As illustrated in **Figure 2**, these ecosystems are closely linked to water availability, and disturbances to water resources pose a direct threat to the existence of these species and ecosystems [72].

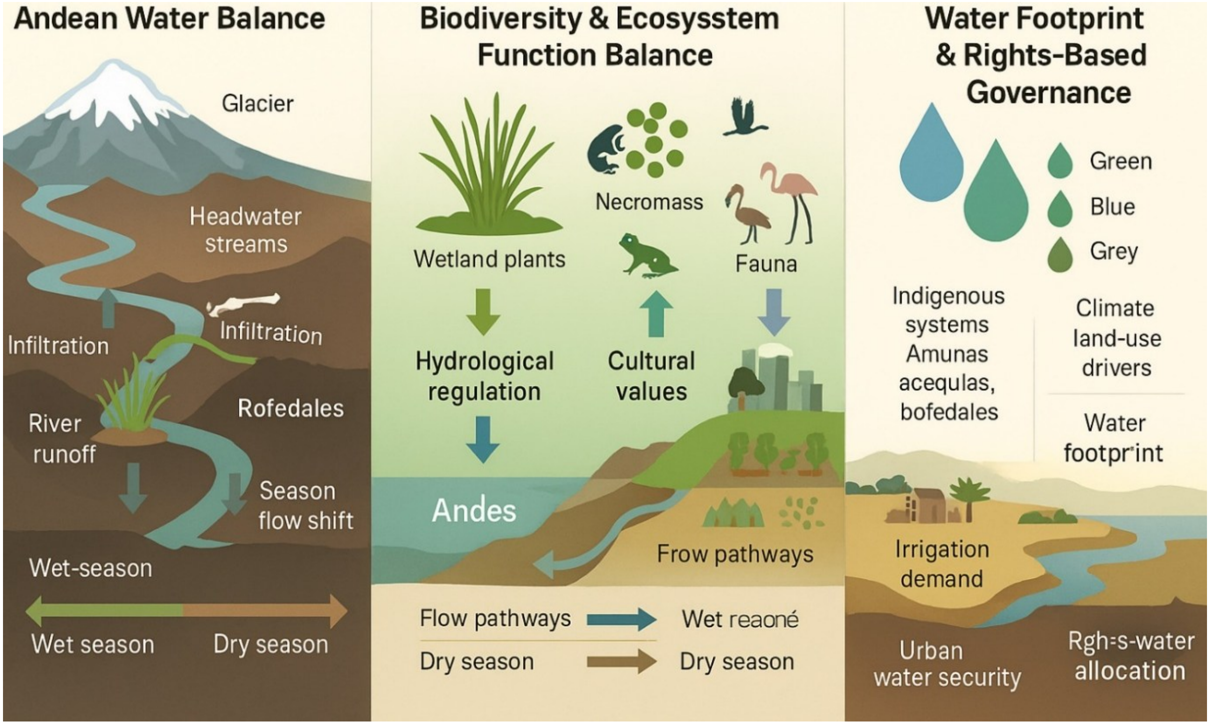

Figure 2. Functional linkages between water balance and biodiversity balance in Andean ecosystems

Water resources as key drivers of Andean biodiversity. Water is a cornerstone of biodiversity in the Andes, where ecosystems depend on both the availability and quality of freshwater resources. Glaciers, rivers, lakes, and aquifers provide continuous inputs that sustain agriculture, wetlands, and habitats. Still, unlike in many temperate regions, water distribution here is highly seasonal and strongly influenced by glacier melt. Seasonal meltwater from glaciers and snowpacks regulates not only river discharge but also soil moisture, allowing high-altitude grasslands, shrublands, and mosses to persist in otherwise nutrient-poor soils. These vegetation systems form the foundation of Andean food webs. Such plants stabilise soils and supply forage to herbivores such as the vicuña (*Vicugna vicugna*). Beyond their ecological role, vicuñas also hold deep cultural and economic significance in Andean societies, valued since pre-Inca times for their exceptionally fine wool, which remains one of the most expensive natural fibres worldwide and contributes to rural livelihoods today.

Other emblematic species tied to water availability include the Andean (spectacled) bear (*Tremarctos ornatus*), Andean condor (*Vultur gryphus*), mountain tapir (*Tapirus pinchaque*), Andean flamingo (*Phoenicoparrus andinus*), and giant coot (*Fulica gigantea*). By consistently identifying both common and taxonomic names, biodiversity assessments in this region can better bridge ecological and conservation discourses. Water also underpins the functioning of soil microbial communities. Microorganisms in the Andes decompose organic matter, recycle nutrients, and maintain soil fertility. For example, nitrifying bacteria (*Nitrosomonas* spp.) regulate nitrogen availability, while arbuscular mycorrhizal fungi facilitate nutrient uptake by plants under water-limited conditions [73]. When water availability decreases, these microbial processes slow dramatically, cascading effects on vegetation productivity and carbon cycling. It highlights that water scarcity is not only a problem for visible flora and fauna, but also for the hidden microbial networks that sustain ecosystem health. In addition, water quality degradation has emerged as a key stressor. Agricultural runoff, untreated wastewater, and industrial effluents reduce oxygen levels, alter microbial assemblages, and impair aquatic biodiversity. Studies from Ecuador and Peru show that native fish populations decline sharply in streams exposed to fertiliser and pesticide contamination, disrupting food webs that extend to birds and mammals [74]. These stressors compound the impacts of glacier retreat, further threatening Andean biodiversity. Given the high dependence of ecosystems on freshwater, sustainable water management is essential. Traditional approaches such as irrigation canals and communal water-sharing systems have long helped buffer communities and ecosystems against scarcity. Recent studies emphasise that integrating these practices with modern hydrological tools, such as remote sensing and watershed modelling, can enhance monitoring of water availability and guide adaptive conservation policies [75]. This hybrid approach is urgently needed to balance agricultural use with biodiversity protection across the Andes.

Threats to biodiversity: unsustainable water use and climate change. Unsustainable water practices in the Andes are placing ecosystems under severe strain. Traditional surface irrigation, still dominant in many agricultural valleys, results in greater inefficiencies. More than half of diverted water is lost through conveyance before reaching the fields, creating shortages for downstream wetlands and aquatic habitats [76]. New hydrological surveys in Ecuador and northern Peru indicate that water losses in unlined canals range between 45−65%, with the greatest deficits recorded during the dry season when ecological demand is highest [77]. This situation not only reduces water availability but also intensifies competition between communities, agriculture, and biodiversity. Beyond quantity, water quality deterioration represents an equally critical threat. In Andean catchments with intensive potato and maize production, elevated nitrate and phosphate levels have been linked to algal blooms and oxygen depletion in high-altitude lakes, resulting in fish mortality and reduced aquatic invertebrate diversity.

Similarly, mining effluents containing heavy metals continue to contaminate rivers in Bolivia, Chile, and southern Peru, with cadmium and lead concentrations frequently exceeding international safety standards. These contaminants bioaccumulate through food webs, undermining amphibian survival and reducing reproductive success in aquatic birds. Climate variability further compounds these risks. Recent analyses show that the tropical Andes have experienced a 20% increase in extreme rainfall events over the last three decades, alongside prolonged seasonal droughts [78]. Such variability destabilises wetland hydrology and accelerates soil erosion on steep slopes, reducing the resilience of ecosystems to support plant and animal life. Unlike glacier retreat (already discussed in earlier sections), these shifts in rainfall regimes highlight a different dimension of climate pressure on biodiversity. At the species level, altered hydrology has caused population stress in endemic amphibians such as *Telmatobius marmoratus*, whose tadpoles depend on stable stream flows, and in aquatic birds like the Andean goose (*Chloephaga melanoptera*), which requires persistent wetlands for feeding and breeding [79]. These impacts illustrate the cascading nature of water-related stressors on trophic networks and community stability. The combined pressures of water mismanagement and climate change thus expose Andean ecosystems to unprecedented vulnerability. A major research gap remains in linking hydrological disturbance with biodiversity decline through long-term monitoring. While there is substantial hydrological modelling of glacier retreat, far fewer studies integrate socio-hydrological dynamics (irrigation governance, water rights) with biodiversity outcomes. Future work should prioritise interdisciplinary approaches that merge hydrology, ecology, and local governance to predict and mitigate biodiversity losses.

Case studies of water-related impacts on biodiversity. To enhance comparability across case studies, each example is presented using a standardised analytical structure comprising: (i) geographic location and hydrological setting; (ii) primary water-related problem or driver of change; (iii) relevant WFM governance, or policy intervention (where applicable); and (iv) documented ecological and social outcomes. This structure facilitates cross-case comparison and highlights how different combinations of climatic pressures, human activities, and governance responses shape water-related impacts across the Andes.

Water-related pressures on Andean ecosystems manifest in concrete regional case studies, providing insight into how unsustainable practices and environmental change interact with biodiversity decline. These examples highlight the ecological consequences of poor water management, agricultural intensification, and industrial activity. This review used case studies from 2000–2025 to examine links between water footprint management, biodiversity, and Indigenous rights in the Andes. Fifteen studies were selected for geographic relevance, documentation quality, and focus on water use and governance. A thematic analysis captured ecological settings, biodiversity impacts, and management strategies, enabling cross-country comparisons and identification of regional gaps.

One striking example comes from the Bolivian 'altiplano', where irrigation withdrawals from Lake Poopó caused the near-total collapse of the ecosystem in 2015. The lake, once covering more than 3,000 km², shrank to less than 10% of its historic size due to upstream diversion and mining effluents [80]. This development led to the decline of fish populations and the displacement of migratory bird species, including the Andean flamingo (*Phoenicoparrus andinus*) and the Andean avocet (*Recurvirostra andina*). The collapse of Lake Poopó reflects the interaction of both climatic variability and human water extraction rather than a single causal factor. Prolonged drought conditions and increased evapotranspiration associated with climate change reduced inflows and heightened the lake's sensitivity to disturbance. However, these climatic stresses were compounded by extensive upstream water withdrawals for irrigation and mining, as well as channel modifications that diverted inflows away from the lake. Evidence indicates that while climate variability acted as a triggering stressor, sustained human extraction and governance failures were the dominant drivers that transformed episodic low-water conditions into a systemic collapse. This interaction underscores the importance of integrating climate risk with controls on consumptive and grey-water footprints in endorheic Andean basins.

In southern Peru's high-altitude wetlands (bofedales), intensification of camelid grazing has been linked to vegetation loss, soil compaction, and reduced wetland hydrological capacity [81]. These alterations decrease wetlands' resilience to seasonal drought and reduce habitat availability for endemic amphibians, particularly *Telmatobius* species, many of which are already threatened by chytrid fungus. Another case comes from the Cajamarca mining region of northern Peru, where open-pit gold extraction has altered water quality and hydrology. Elevated levels of arsenic and mercury have been recorded in rivers adjacent to mining zones, impacting aquatic macroinvertebrates and fish communities that form the base of the food web. The standardised case studies demonstrate that hydrological collapse and biodiversity loss in the Andes typically emerge from coupled climate and governance pressures, reinforcing the need for basin-scale WFM rather than sector-specific interventions. The key examples illustrating these governance approaches are presented in **Table 3** and commented on.

Table 3. Representative case studies linking water management and governance in the Andes

Location	Primary driver of change	Ecological impact	Community response	Outcome	Reference
Lake Poopó (Bolivia)	Irrigation + mining	Ecosystem collapse	Basin mobilisation	Governance reform needed	[80]
Cajamarca (Peru)	Gold mining	Biota decline	Community protest	Conflict persists	[60]
Páramos (Ecuador)	Agriculture	↓Baseflow; biodiv. loss	Rewetting	Recovery observed	[82]
Mendoza Basin (Argentina)	Groundwater overuse	Wetland loss	Allocation reform	Recharge stabilised	[83]
S. Peru	Overgrazing	↓Wetland	Restoration	↑Resilience	[54]

Location	Primary driver of change	Ecological impact	Community response	Outcome	Reference
Bofedales		function			
Cotopaxi (Ecuador)	Water diversion	Irrigation shortage	Legal action	Water rights secured	[84]
Santa River (Peru)	Glacier loss	↓Flow; habitat loss	Reservoir adaptation	Trade-offs identified	[12]
Vilcanota Basin (Peru)	Climate + tourism	Pollution; wetland loss	Co-management	Policy inclusion	[85]
Altiplano Lakes	Mining + ET	Habitat decline	Cross-border monitoring	Governance gaps exposed	[86]
Cordillera Blanca (Peru)	Glacier retreat	Species shifts	Adaptation plans	Resilience improved	[87]
Huancavelica (Peru)	Deforestation + mining	↓Water quality	Reforestation	Service recovery	[88]
Cochabamba Valley	Urban + irrigation	Aquifer depletion	User committees	Allocation improved	[76]
Santa Elena (Ecuador)	Drought + infrastructure	Crop loss	Irrigation projects	+25% efficiency	[89]
Tarija Basin (Bolivia)	Privatisation	Access inequality	Social movement	Legal limits set	[2]
Arequipa Valley (Peru)	Agro-industry	River depletion	Basin dialogue	Integrated planning	[88]

<u>Strategies for using water footprint management to enhance biodiversity conservation.</u> The WFM provides a structured framework for linking water-use efficiency with biodiversity conservation in the Andes. Instead of repeating previously mentioned practices, this section consolidates and critically evaluates both traditional and modern strategies, highlighting their trade-offs, synergies, and research gaps. One of the most effective strategies is improving irrigation efficiency by adopting drip and deficit irrigation systems. These practices significantly reduce water losses compared to surface irrigation, thereby alleviating pressure on rivers and wetlands. However, while drip irrigation lowers water extraction, it may still promote intensive monocultures that reduce habitat heterogeneity and, in turn, biodiversity. A balance must be achieved between water-saving efficiency and ecological diversity. Agroecological practices, such as crop rotation, intercropping, agroforestry, and organic farming, not only lower the agricultural water footprint but also increase soil fertility, enhance pollinator diversity, and reduce chemical runoff [90]. These methods strengthen ecological resilience but often face scaling limitations due to labour intensity and market barriers. This gap requires policies and incentives to make biodiversity-friendly farming economically viable for Andean communities.

Traditional water management practices, including irrigation canals (acequias), terracing, and community-based water-sharing agreements, have sustained Andean livelihoods for centuries. Their strength lies in fostering collective governance and social cohesion, ensuring equitable water distribution even under scarcity. Yet these systems are increasingly vulnerable to glacier retreat and altered rainfall patterns, necessitating complementing them with scientific monitoring and adaptive planning. Recent technological advances, such as remote sensing, hydrological modelling, and water accounting frameworks, allow more precise measurement of water footprints at farms and watershed scales. For example, satellite-based evapotranspiration mapping in Peruvian catchments has improved monitoring of water use efficiency and biodiversity impacts [91]. However, these tools demand technical expertise and reliable data access, which are often lacking in rural Andean regions. Bridging this digital divide is a pressing research and policy challenge. Ultimately, the most promising path lies in hybrid approaches that integrate traditional governance with modern WFM tools.

Human rights-based approach to water management in Andean communities. In this study, human rights to water are understood as the universal entitlement to safe, sufficient, acceptable, physically accessible, and affordable water for personal and domestic use, as articulated in UN General Assembly Resolution 64/292 [5] and CESCR General Comment No. 15 (2002). Social equity refers to the fair and inclusive distribution of water across regions, communities, genders, and generations. Justice refers to governance frameworks that integrate human rights and equity while safeguarding ecosystems and cultural values [92]. International law now recognises water as a human right. In 2010, the United Nations Human Rights Council adopted a resolution recognising the right to water and sanitation as a human right in the General Assembly. This resolution says that every individual is entitled to adequate, safe, acceptable, physically accessible, and affordable water to meet their personal and domestic needs. It is not only a health and hygiene privilege; it also plays a fundamental role in the well-being of individuals and communities. The human right to water in coastal cities such as Lima, Ilo, Chancay, and Trujillo is increasingly compromised by declining Andean inflows, requiring integrated, rights-based governance between mountains and coasts.

Enforcement of the human right to water in Andean states faces persistent implementation constraints. Common challenges include fragmented mandates among national water authorities, environmental regulators, and subnational governments; limited budgets and technical capacity for monitoring and compliance; and weak sanctioning power when influential actors (e.g., mining, hydropower, agro-export) violate allocation rules or exceed discharge limits. Policy contradictions also emerge when constitutional or statutory recognition of water rights and environmental protections coexist with development policies that prioritise extractive concessions, large-scale irrigation expansion, or inter-basin transfers, creating gaps between rights "on paper" and realised access in practice. Empirical evidence shows that rights-based approaches can improve equity when they are coupled with enforceable institutional mechanisms. For example, in Ecuador, constitutional recognition of the rights of nature and water as a strategic public resource has supported community and Indigenous claims in páramo-fed watersheds, strengthening protections for communal drinking-water systems and upstream ecosystems [93]. In Peru's Santa River basin, water conflicts linked to glacier retreat, mining pressures, and hydropower demand have motivated legal and institutional reforms focused on allocation rules and environmental oversight, illustrating both the potential and limits of rights-based governance in contested basins. These cases demonstrate that equity gains are most visible where legal recognition is matched with participatory enforcement, transparent allocation, and effective regulation of pollution.

Gender, migration, and intergenerational influences also shape equity outcomes in rights-based governance. Women are often the main providers of household water and community health, but are under-represented in formal water-user bodies and negotiation arenas; gender-inclusive governance thus influences both procedural equity (voice) and distributional equity (allocation). It may be weakened by migration, often driven by climatic stress, and by economic changes, where labour for community maintenance ('faenas') is eroded, along with disrupted local knowledge of water. Simultaneously, the outmigration of youth might accelerate intergenerational loss of knowledge in activities such as 'amunas' maintenance, 'bofedales' management, and rotational allocation, thereby lowering adaptive capacity in the long run [94]. Rights-based frameworks are thus reinforced by actions that enhance decision-making among women, flexible involvement of mobile households and intergenerational transfer based on local training and documentation and co-management.

For indigenous peoples of the Andes, water is not only a survival resource but also carries spiritual, cultural, and communal significance [92]. However, these worldviews are diverse and evolving. For example, Quechua groups in Cusco maintain ritual ties with springs (puquios) [95] and wetlands, while Aymara communities in Bolivia emphasise collective irrigation governance through 'ayllu'-based systems [96]. Recognising this plurality avoids essentialising Indigenous perspectives and instead highlights how their practices adapt under shifting political, economic, and climatic pressures [2]. The constitutional treatment of the rights to water and their consideration as Indigenous rights have been controversial issues in prospective countries like Peru, Bolivia, Ecuador, and Colombia. Although notable contributions are being made in some countries and to some water bodies, such as in 2008 in Ecuador, where a constitution was adopted that establishes the rights of nature and Indigenous peoples concerning their territories, the implementation of these rights remains tenuous. In Peru, Indigenous water rights have received partial legal recognition; however, these rights are frequently undermined by national water policies that prioritise commercial interests such as large-scale mining and industrial agriculture, often at the expense of local and native communities [53]. The water management systems and traditional knowledge of Indigenous peoples developed over several centuries also form part of the ethical considerations in Indigenous water rights. These systems include irrigation canal management and community water-sharing agreements, grounded in Indigenous worldviews that treat water as a communal resource to be cared for and shared, rather than a commodity to be exploited. The realisation and recognition of native rights to water can diminish the unsustainability in fair water treatment in the Andes, enabling people to govern their water resources and safeguard their cultural universes.

Distributing water fairly is a major issue in the Andes, especially in remote and rural settlements. Such societies are sometimes prone to inaccessible clean water due to geographic inaccessibility, lack of infrastructure, and inability to fortify monumentally. Although urban populations can usually access water piping systems, rural and Indigenous populations in the Andean highlands often have limited or poor access to water supplies, e.g., rivers, streams or well water, which are often contaminated or simply inadequate to their demands. Rights-based approaches in the Andes have produced both successes and shortcomings. The human rights approach in the Andes requires the state and international organisations to cooperate not only to provide access to water, but also to make it accessible, affordable and safe. The Andean region faces persistent challenges, including political instability, lack of coordination among government institutions, and limited investment in infrastructure, all of which hinder universal access to clean water. Inadequate sanitation and poor water quality contribute to waterborne diseases, disproportionately affecting Indigenous populations and deepening health disparities. International organisations such as the United Nations, along with NGOs, play a critical role in supporting the right to water and advancing equitable distribution in remote areas. They assist in awareness creation and resource mobilisation and collaborate with the local community to develop and prescribe sustainable water solutions.

Water Footprint Management as a Tool for Sustainable Agriculture and Ecosystem Protection

Water footprint management is the systematic assessment and regulation of water consumption across agricultural production systems to ensure the efficient use of freshwater resources. By quantifying the volumes of blue, green, and grey water used in crop cultivation and food production, this approach enables the identification of opportunities to optimise water use. Implementing water footprint strategies in agriculture promotes resource-efficient irrigation practices, reduces water pollution from agrochemicals, and supports long-term ecosystem resilience. Consequently, water footprint management serves as an important tool for advancing sustainable agriculture while protecting aquatic ecosystems, maintaining watershed balance, and ensuring water security for future generations.

<u>Efficient water use in agriculture: role of irrigation technologies.</u> In this study, eco-efficient practices are defined as water-saving measures such as drip irrigation or

pre-Incan 'amunas' that maximise productivity per unit of water [97], [98]. Sustainable methods include practices like rotational grazing in high-altitude 'bofedales', which maintain forage production while preserving hydrological functions [99]. Better management practices refer to strategies such as lining canals to reduce seepage losses or crop rotations that minimise evapotranspiration [98]. These distinctions help clarify how WFM translates into concrete interventions in the Andean region. New irrigation methods, such as drip irrigation and spray irrigation, are becoming instrumental in saving water and improving water efficiency [100]. Drip irrigation, in which water is delivered to the plant roots, reduces actual water loss because there is less evaporation of water and runoff. In this system, crops receive exactly the amount of water they require, thereby minimising waste and improving productivity. Another important water-saving technology is sprinkler irrigation, which can be applied in areas where drip irrigation is less feasible due to land characteristics or crop types. These systems distribute water uniformly across larger areas, reducing the total irrigation demand compared to conventional flood irrigation. Such technologies have been particularly valuable in the highland agricultural regions of the Andes that frequently face water scarcity. For example, in Peru, the successful adoption of drip irrigation in quinoa cultivation has enabled farmers to achieve higher yields while using less water. Beyond improving water-use efficiency, these technologies have also enhanced resilience by allowing farmers to sustain production during dry spells. Effective case studies can illustrate how water-efficient irrigation systems can transform the current way of farming in the Andes, not only sustaining farmers in their way of life but also ensuring that ecosystems within which these water bodies are located remain healthy [101].

However, high-efficiency irrigation systems also entail important trade-offs. While drip and sprinkler technologies reduce field-level water losses, they may decrease return flows that traditionally recharge downstream aquifers and wetlands. In closed or semi-arid Andean basins, reduced percolation can lower groundwater recharge, potentially affecting baseflows that sustain bofedales and coastal aquifers. Moreover, improved efficiency can incentivise agricultural expansion or intensification (the so-called "rebound effect"), whereby saved water is used to cultivate additional land or higher-value crops, thereby offsetting conservation gains. Stiffened monocultural systems can also decrease habitat heterogeneity and increase the use of agrochemicals, enhancing grey water footprints and ecological pressures [102]. For these reasons, modernisation of irrigation should be incorporated into basin-level allocation regulations and environmental water protection, so that the efficiency gains are translated into actual water savings and biodiversity gains.

<u>Crop selection and water footprint reduction in Andean farming.</u> Another important method for reducing the water footprint of agriculture in the Andes is selecting water-efficient crops. Less water is used to grow crops such as quinoa, known to grow better in high-altitude areas than conventional crops like maize and potatoes. Farmers can also minimise their water use by adopting drought-resistant varieties, thereby ensuring food security. In the Cordillera Blanca of Peru, the restoration of ancient 'amunas' has increased groundwater recharge and sustained dry season flows, supporting both agriculture and aquatic ecosystems [97]. Similarly, in Puno, community-managed 'bofedales' with rotational grazing regulate water flows while maintaining biodiversity and carbon storage. These examples show how WFM strategies grounded in both traditional and modern practices can generate tangible ecological and livelihood benefits. Moreover, reduced water consumption benefits not only by lowering irrigation costs but also by supporting local biodiversity, as native and climate-resilient crops are typically better suited to Andean environments.

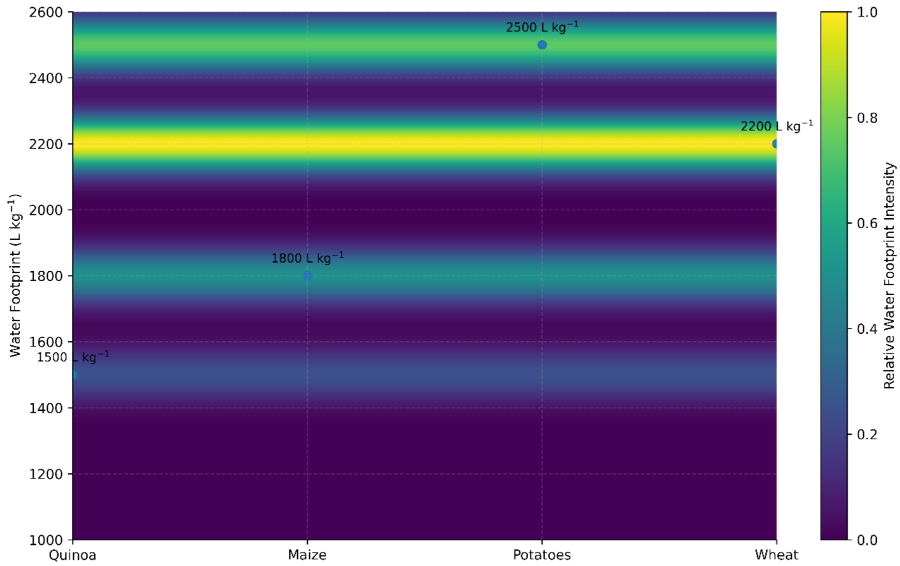

Figure 3. Comparative water footprint intensity of major crops cultivated in Andean and Andean-fed agricultural systems; figure data from Arjen et al. [41], values represent approximate total water footprints

Beyond crop selection, crop rotation remains a cornerstone of Andean farming systems, playing a vital role in water conservation. Rotating crops with different water and nutrient requirements helps maintain soil fertility, reduce reliance on artificial irrigation, and improve long-term soil water retention, as shown in Figure 3. The heatmap-style visualisation reflects relative differences in total water demand, integrating green and blue water components reported in the literature; higher colour intensity indicates greater water consumption per unit of yield, highlighting crop-dependent differences relevant for water footprint management and irrigation planning. Quinoa exhibits the lowest footprint (≈1500 L kg^{-1}), largely due to its reliance on green water and physiological tolerance to water stress; maize (≈1800 L kg^{-1}), wheat (≈2200 L kg^{-1}), and potatoes (≈2500 L kg^{-1}) show progressively higher water demands associated with irrigation dependence and climatic sensitivity. By contrasting these crops, Figure 3 supports the argument that crop selection is a critical lever for reducing agricultural water footprints in the Andes, particularly under conditions of declining dry-season water availability driven by glacier retreat and climate variability. Additionally, soil management practices such as mulching and organic manure application contribute to water conservation by reducing evaporation losses, increasing soil moisture content, and improving soil structure. The combination of all these practices enables streamlining water consumption, preserving soil quality, and minimising the overall water footprint of agriculture in the area [103].

Community-led water conservation practices: integrating traditional knowledge. The practice of water conservation among Andean communities has existed for several decades. Techniques such as terracing, canal irrigation, and aqueducts have enabled these people to manage their water resources efficiently, ensuring constant availability of water for both domestic use and agricultural activities. These practices are fundamental strategies for sustaining livelihoods under conditions of scarcity. A closer examination reveals that Indigenous practices and technical conservation approaches often share common objectives, even if expressed through different methods. For example, Andean terracing reduces runoff and soil erosion, mirroring modern soil and water conservation engineering that promotes slope stabilisation and moisture retention [104]. Similarly, communal irrigation canals (acequias) function not only as cultural institutions but also as decentralised systems of equitable water allocation and demand management, aligning with contemporary goals of participatory governance and environmental flow protection [92]. Ritualised water-sharing assemblies echo principles of adaptive co-management, ensuring seasonal adjustment of water allocations, much resembling scientific recommendations for dynamic allocation in the face of climate variability [92], [96]. By explicitly recognising these overlaps, WFM can be reframed as a hybrid system, where ancestral techniques provide legitimacy and social cohesion, while technical innovations such as drip irrigation, hydrological modelling, or remote sensing strengthen efficiency and monitoring [75], [98].

Bridging these two knowledge domains highlights that conservation goals such as soil fertility, biodiversity protection, and equitable access are already embedded in Indigenous systems and can be reinforced rather than replaced by modern science [2]. An illustrative example is terracing, widely practised in the Andean highlands, which mitigates soil erosion and surface runoff while retaining soil moisture and nutrients. Similarly, controlled canal irrigation systems, often built with local materials, channel water from nearby rivers and streams to agricultural fields [105]. When such ancestral practices are combined with modern technologies like drip irrigation and water-efficient crop management, they can substantially reduce the water footprint and enhance the sustainability of Andean agriculture. For instance, in several Andean regions, the integration of modern irrigation tools within existing community-based water rights systems has promoted more equitable water distribution and improved efficiency [106].

<u>Water recycling and wastewater treatment systems for sustainable water use.</u> Reuse of treated wastewater is a new phenomenon in sustainable water use, especially in areas with water scarcity, such as the Andean highlands. Despite these benefits, wastewater reuse faces major barriers in the Andes. Infrastructure costs for treatment plants remain prohibitively high for many municipalities, and social acceptance is often low due to contamination concerns. In addition, national frameworks such as Peru's Guidelines for Reuse of Treated Wastewater exist but are unevenly implemented. Digital technologies can support this strategy by integrating IoT-enabled water-quality sensors and predictive analytics to optimise reuse scheduling, ensuring treated water is applied when most needed during dry seasons. Linking recycling systems to digital monitoring platforms could also reassure communities by providing transparent data on water safety.

There are various situations in which treated wastewater may be utilised for non-edible purposes, such as crop production or landscaping, where water quality is not particularly strict. For example, in the Andean region, treated wastewater can be applied to cultivate fodder crops or to expand agricultural areas where drinking-water quality standards are not required [107]. This practice also reduces pressure on freshwater resources, providing farmers with a more reliable water supply during dry seasons. Nonetheless, wastewater treatment systems must meet strict health and environmental standards to prevent soil and water pollution and ensure long-term sustainability. Khan *et al.* [108] demonstrated that, with proper monitoring, treated wastewater can be safely reused in agriculture, supporting sustainable landscapes and reducing negative environmental impacts. The adoption of water recycling and treatment technologies not only curbs excessive freshwater use but also enhances water-use efficiency and reduces farming costs.

Artificial Intelligence and Machine Learning for Precision Irrigation Management

To be operationally meaningful, emerging digital technologies must be explicitly linked to WFM metrics and decision-making frameworks. AI and ML applications can translate remote-sensing and sensor data into actionable indicators by estimating green, blue, and grey water footprints at field, community, and basin scales. For example, machine-learning models that integrate evapotranspiration, soil moisture, and crop growth data [109] can inform allocation decisions by identifying periods and locations of excessive blue-water use or elevated grey-water loads [110]. When embedded within basin-scale planning tools and water accounting frameworks (e.g., WFA and WA+), these technologies support scenario analysis, intervention prioritisation, and transparent stakeholder negotiation, rather than functioning solely as technical monitoring tools [50].

These technologies enable the creation of smart water distribution systems that integrate real-time weather data, crop health indicators, and climate conditions to determine irrigation needs. By analysing large datasets, AI models can optimise irrigation schedules to minimise water waste while maximising yields. For example, AI-enabled systems combine soil moisture levels, weather station data, and satellite imagery to make immediate decisions about water allocation and infrastructure use [111]. Such systems can determine when to irrigate, how much water to apply, and at what intervals, thereby reducing irrigation inefficiencies. In addition, integrating deep learning and predictive analytics enables tailored irrigation strategies for specific crops and regions, further enhancing water efficiency and sustainability.

A significant innovation for water resource governance is the adoption of blockchain technology. Blockchain can enhance the traceability and transparency of water consumption data, ensuring equitable and responsible use of resources. It creates secure, tamper-proof records of water exchanges, allowing communities and agricultural stakeholders to monitor distribution and consumption patterns. Furthermore, blockchain systems could introduce water credits or decentralised trading of water rights, encouraging cooperative and sustainable practices. Embedded smart contracts could automatically enforce agreed conditions for water allocation, ensuring fair and efficient distribution of resources.

Another important ethical and equity issue associated with the implementation of digital technologies in Andean water governance concerns their deployment. Issues with data privacy arise when hydrological, agricultural, or household water-use data are collected without explicit approval or protection, especially on Indigenous lands. Digital divides in connectivity, literacy, and hardware availability can leave marginalised communities unable to enjoy the same benefits as those who have access to an AI-enabled decision-making system [49]. Additionally, the visualisation of value judgments in algorithmic decision-making models may reinforce status quo power inequity when outputs are perceived as objective or fair. To prevent these threats, transparency, free prior informed consent, domestic data ownership, and participatory model interpretation should be the rules in the realm of digital WFM, meaning that technology, not community-led governance, should be supported.

Remote Sensing and Drones for Water Footprint Monitoring

The application of remote sensing and drone technologies is transforming real-time monitoring of water use and agricultural productivity. Multispectral and thermal imaging sensors mounted on drones provide detailed information on crop health, soil moisture levels, and overall water consumption. These tools provide farmers with unprecedented accuracy in assessing crop requirements, enabling precision farming practices. At a broader scale, satellite-based remote sensing is increasingly used to detect critical water footprints at the regional level. Satellites are particularly effective for monitoring vegetation health, water availability, and environmental conditions, generating large datasets that support optimised water use across entire farming systems. Together, these technologies simplify water resource monitoring and management, thereby enhancing agricultural sustainability and preserving favourable environmental conditions [112].

Vertical farming in high-altitude or urban environments has strong potential to reduce the agricultural water footprint. Vertical farming and GM drought-tolerant crops have the potential to save water but have yet to be tested in remote Andean highland locations [113]. Vertical farming also requires a stable electricity supply, climate-managed infrastructure, technical skills, and access to capital, which are not usually available to rural Andean populations. Likewise, GM crops have also been introduced amid regulatory challenges, seed cost limitations, cultural acceptability and the problem of dependence on external inputs that may be incompatible with Indigenous seed sovereignty and pre-modern cropping. As a result, the technologies will be more feasible in the peri-urban or coastal systems than in the high-altitude rural areas. They must be viewed as complementary and situational, but not central in the WFM strategies in the Andes, where low-input, culturally appropriate and locally available solutions are prioritised.

In the vertical farming system, crop production occurs in stacked layers within controlled indoor environments, allowing precise regulation of water use to achieve maximum efficiency. Such systems typically rely on hydroponics, aeroponics, or aquaponics, which consume significantly less water compared to traditional soil-based cultivation. Moreover, vertical farms employ closed-loop water-recycling technologies that further reduce waste and optimise reuse. Importantly, vertical farming offers a promising solution for environmentally sensitive regions with limited arable land, such as the Andean highlands, by providing a sustainable, long-term alternative for food production that places less pressure on already scarce natural water resources.

Genetic Modification for Drought-Resistant Crops

Among the most innovative strategies to reduce the agricultural water footprint is the development of GM drought-tolerant crops. These crops are specifically designed to thrive under water-limited conditions by using less water or enduring temporary drought stress. For instance, ongoing initiatives to cultivate drought-resistant wheat and maize aim to reduce dependence on irrigation. When combined with precision farming techniques, genetic modification can further optimise water use while safeguarding food security. Such innovations are particularly critical in the Andean region, where agricultural systems are highly vulnerable to prolonged dry periods and water scarcity.

The density-based correlation plots highlight the complex interactions among ecological, hydrological, and socio-economic variables within Andean socio-hydrological systems. The visualisation reveals clusters of strong associations between water availability, ecosystem stability, and agricultural practices, indicating that water governance and land-use decisions are closely interconnected with ecosystem functioning. These patterns illustrate how changes in water management practices can influence both environmental resilience and community livelihoods in mountain regions. The relationships among these variables are illustrated in Figure 4. In the density-based correlation plots shown in this figure, each subplot shows a two-dimensional kernel density distribution (heatmap) overlaid with scatter points (coloured dots) and a 1:1 reference line (white dashed diagonal). The convention for colour scales is that warmer colours indicate higher data density.

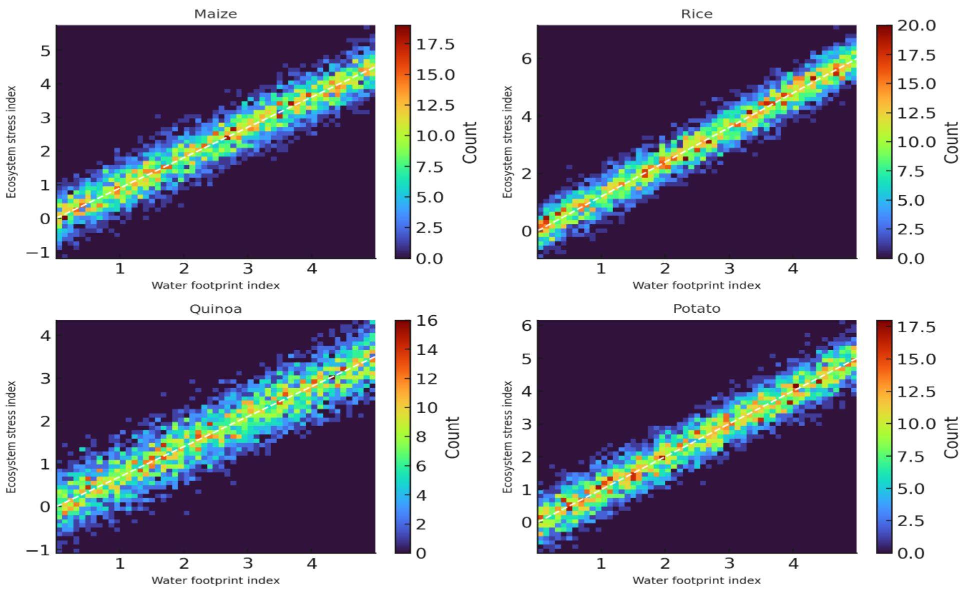

Figure 4. Density-based correlation plots illustrating key water ecosystem relationships between Andean socio-hydrological systems; figure data from Hamidov et al. [114]

Desalination and Water Recycling for Agriculture

Desalination technology, which converts seawater into freshwater, is emerging as a promising solution for water-scarce agricultural regions. When combined with water recycling systems, desalination can provide a more stable water supply for farming activities. Modern desalination techniques have made the process more energy-efficient and effective, enabling its adoption in areas with abundant seawater but limited freshwater resources.

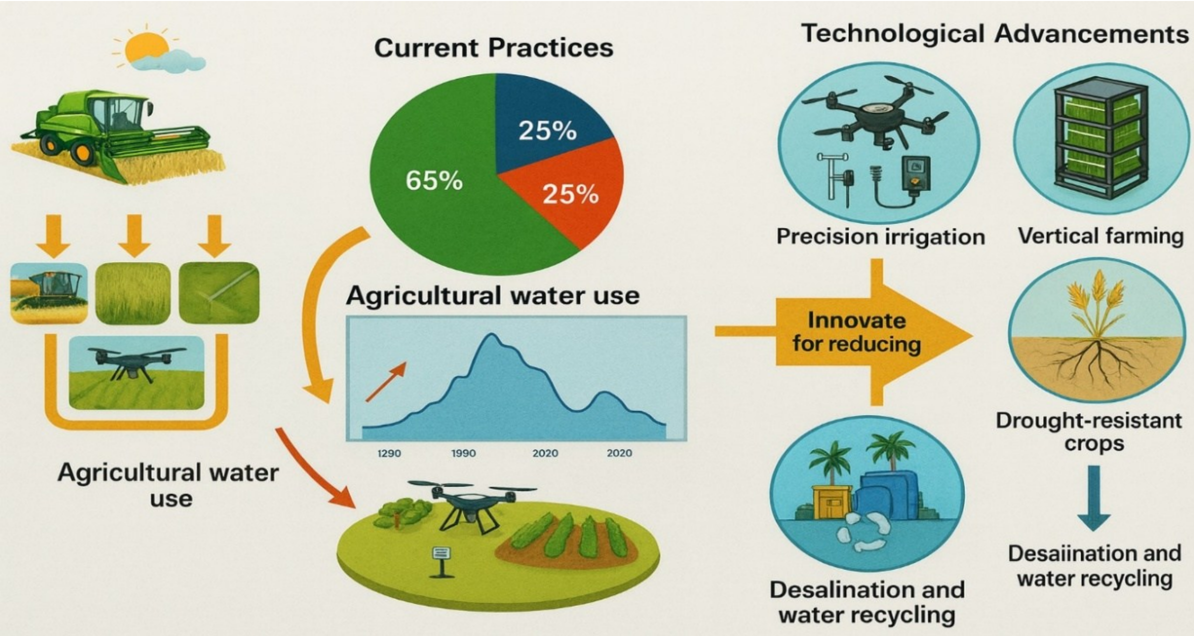

Figure 5. Conceptual framework of artificial intelligence and technological innovations for precision irrigation and water footprint optimisation in Andean agriculture

As shown in **Figure 5**, combining desalination technologies with innovative water treatment systems could significantly reduce reliance on traditional freshwater sources in the Andean coastal areas, ensuring a more reliable water supply for agriculture even during drought periods. The concept of the water-energy nexus, an emerging field of research, emphasises the interconnections between water and energy use in farming. Recent advances in solar-powered irrigation systems and high-efficiency water pumps have reduced energy demand for extracting and distributing water. These developments enable the adoption of sustainable water management strategies in agriculture, helping to reduce both environmental impacts and the carbon footprint of irrigation practices. In remote Andean regions, where irrigation often relies on costly pumping, renewable energy sources such as solar and wind offer practical, economically viable alternatives to fossil fuels and advance long-term sustainability **[115]**.

CONCLUSIONS

Water scarcity, biodiversity decline, and hydrological instability in the Andes create profound and multifaceted downstream consequences for coastal hydrology, coastal food systems, and the long-term resilience of low-lying coastal communities. As demonstrated throughout this review, WFM, when grounded simultaneously in Indigenous knowledge and human rights frameworks, offers a robust and strategic pathway to safeguard hydrological connectivity along the entire mountain-to-coast continuum. This connectivity is essential for sustaining freshwater flows from high-mountain wetlands, páramos, glaciers, and bofedales to the rivers, aquifers, estuaries, and coastal ecosystems that depend on them.

Strengthening WFM requires hybrid governance approaches that blend ancestral Andean practices (such as amunas, terracing, and communal irrigation systems) with modern technological innovations, environmental-flow protections, and rights-based water policies. Such integrated governance is indispensable for reducing upstream pressures of over-extraction, land-use intensification, cryosphere loss, and pollution that exacerbate coastal salinisation, water insecurity, and climate-related risks. These risks not only threaten agricultural productivity and biodiversity but also undermine the stability of coastal aquifers, estuarine dilution capacity, fisheries, and the overall socio-ecological resilience of coastal regions. By linking WFM to Indigenous ecological knowledge, hydrological science, and human rights, Andean communities gain the tools needed to adapt to rapid environmental change, restore degraded ecosystems, and ensure equitable water access across generations.

The evidence presented here underscores that enhancing WFM in Andean highlands represents far more than a localised adaptation measure: it is a cornerstone of regional sustainability and a critical foundation for coastal climate resilience throughout western South America. Ensuring the long-term security of coastal populations ultimately depends on protecting, restoring, and equitably managing water resources in the Andean headwaters.

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AUTHORS CONTRIBUTIONS

Franklin Ore Areche and Russbelt Yaulilahua-Huacho contributed to the data curation, statistical analysis, and drafting of the manuscript. Luis-Donato Araujo Reyes was responsible for the conceptualisation, methodology, data analysis, and manuscript writing. Percy Cesar Estrada-Ayre handled the data collection, literature review, and editing of the manuscript. Percy Eduardo Basualdo-Garcia contributed to the development of the methodology and data interpretation. Anthony Enriquez-Ochoa wrote the original draft, managed the project, and supervised the research. Syntia Porras-Sarmiento was involved in the investigation, data analysis, and revision of the manuscript. Miriam Liz Palacios-Mucha provided supervision, secured funding, and reviewed the final manuscript.

NOMENCLATURE

Abbreviations

AI	Artificial intelligence
ANA	Autoridad Nacional del Agua (Peru)
CESCR	Committee on Economic, Social and Cultural Rights
ET	Evapotranspiration
FAO	Food and Agriculture Organisation of the United Nations
GM	Genetically modified
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
SDGs	Sustainable Development Goals
SWAT	Soil and Water Assessment Tool
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WA+	Water Accounting Plus
WaPOR	FAO Water Productivity through Open Access of Remotely Sensed Data

WFA Water Footprint Assessment
WFM Water Footprint Management

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