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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 infrastructures including amunas, terracing, bofedales, and communal acequias emerge as nature-based solutions capable of enhancing infiltration, stabilizing 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 operationalizes 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 salinization 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

INTRODUCTION

The Andean region, stretching across seven countries from Venezuela to Argentina, represents not only a biodiversity hotspot but also a critical socio-hydrological system supporting 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 holds relevance 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 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 as well as downstream coastal dependencies. There has been little focus on the way Andean headwater water footprints influence hydrosocial connectivity between mountain environments and Pacific urban centers, or how customary governance systems can be effectively harmonized with official WFM indicators in the face of climate change. This issue limits the practical applicability of WFM to the issues of water justice, cross-scale governance, and climate adaptation to mountain -coast systems. This gap is filled in this review by synthesizing ecological, cultural, governance, and hydrological data to rebrand WFM as a right-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 ritualized allocation and communal governance. These traditions are increasingly studied as models for climate-resilient adaptation [6]. This review synthesizes 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 analyze studies published between 2000 and 2025 across databases including Scopus, Web of Science, and Google Scholar. Findings are thematically organized 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 freshwater used in Pacific coastal cities from Lima to Trujillo and Arica originates in Andean headwater. As glacier retreat, land-use change, and upstream over-extraction reduce dry-season flows, downstream coastal hydrology faces increased salinization, 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 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

Andean zone where one finds some of the widest biodiversity of life in the world is the issue of rising scarcity of water, which is posing a risk to the agriculture potential in addition to the environment of the region. The Andes serve as 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 represents roughly 27% of 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 destabilize 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 water sources in the area become strained because of a set of factors such as climate change, inadequate distribution of water in agricultural practice and deforestation. In this context, water scarcity refers to the physical insufficiency of freshwater resources, while water stress reflects both limited availability and rising demand combined 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. 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 between 30-50% of water through seepage and evaporation, leading to over-extraction of rivers and aquifers, soil salinization, and reduced crop productivity [9]. Excessive irrigation of water and other practices such as the limited adoption of water conservation technologies as well as management of water have caused soil erosion, desertification and destruction of water sources [10]. Water shortage is also influencing the biodiversity of the area directly. More vulnerable are the risky ecosystems that rely on stable water sources, as freshwater resources are losing their supply, causing negative effects on the plants, the fauna, and the overall ecological integrity of ecosystem. The loss of biodiversity paired with the lack of water poses with high risks to the ecological stability of the Andes, which affects the local population, who use the natural resources as the 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.

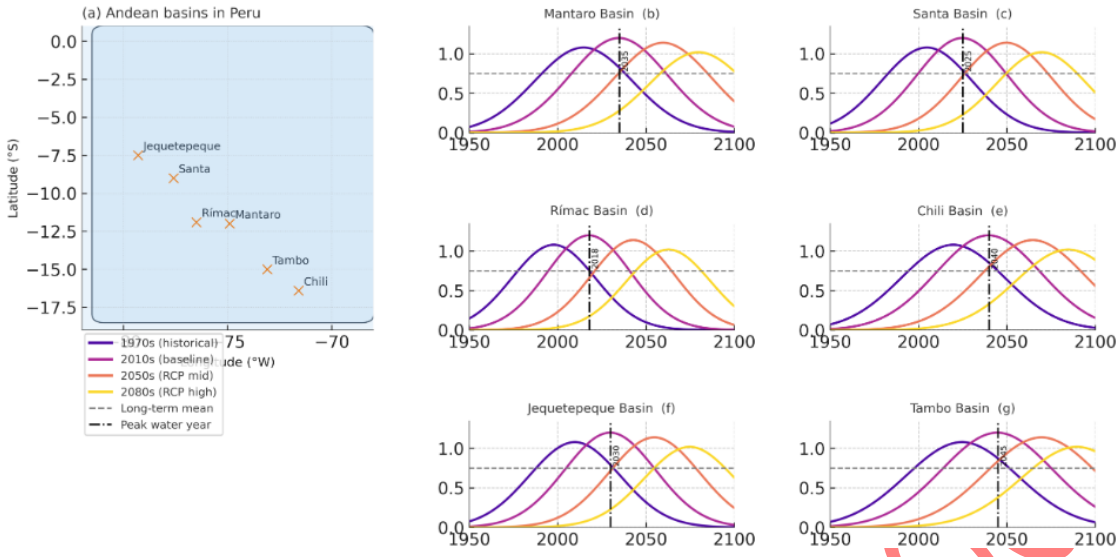

Figure 1: Projected changes in peak water timing and normalized runoff across six Andean basins under historical and future climate periods

Note: The figure data were adapted from multi-decadal hydrological projections for Peruvian Andes basins reported by *ANA (Autoridad Nacional del Agua, [12]*, AntarcticGlaciers.org [13] and the glacier-runoff modelling results synthesized in *Vuille et al. [1]*.

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 the local inhabitants, especially native communities like the Quechua, the Aymara, and others, water has become an indispensable element of their cultural identity and way of life. Centuries of usage in these communities have led to the development of the traditional water management strategies that can be used in their areas to optimize water usage in the face of challenges in the environmental conditions like Rural irrigation canal, terracing and water sharing agreements [14]. Nevertheless, these conventional systems are gradually becoming increasingly challenged by population growth and climate change. Not only does water scarcity expose the communities to physical health problems arising due to a dearth of clean drinking water, but it also affects their agricultural activities, including potato farming, organic quinoa and maize cultivation, and quinoa, the vital food security and income generation sources [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 in preservation of biodiversity in Andean ecosystems. The area has an exceptionally high species richness with a significant percentage of them being endemic and depending on steady sources of water to exist. The wetlands, high-altitude and river-based ecosystems are especially prone to water fluctuations. As an illustration, water that is availed by glaciers, rivers, and snowmelt facilitates growth of unique species of plants which flourish at the Andean highlands; these include plants such as 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*), categorized as *Vulnerable*, relies on montane ecosystems sustained by glacial and wetland water flows. These examples emphasize the interconnectedness of water management, biodiversity protection, and community livelihoods. Table 1 summarizes 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	Muñoz-Saravia 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 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 salinization 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 salinization of coastal aquifers at rates of 0.3–1.2 g L^{-1} per decade in Brazile 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 modernization of water governance. Furthermore, it explores how WFM supports the realization 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 presented a narrative review research approach, which is suitable in integrating interdisciplinary evidence in the fields of 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 such methods 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 of Scopus, Web of Science, and Google Scholar were searched to find a structured literature search. To complement peer-reviewed literature, grey literature was also included from international and regional institutions such as FAO, UNESCO, UNEP, IPCC, IUCN, and the Peruvian National Water Authority (ANA). A combination of policy-relevant material on water governance and climate adaptation in Andes, as well as empirical studies on the same, were chosen through these sources. The presented search included year of 2000-2025 because this is the timeframe during which water footprint evaluation, Indigenous water management, and climate-change effects in the Andes have been the most active. In the English and Spanish searches were carried out to make it regional.

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 followed 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 synthesized 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 standardized effect-size comparisons. Nonetheless, the methodology allows integrative analysis of disciplines and scales of governance and provides an in-depth perception of the issue 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 the joint force responsible for water shortage and hydrological instability in the Andes, which have severe downstream impacts on the water security of the coast. Findings are likewise consistent in indicating that the traditional Andean water systems that include 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 the Indigenous governance and rights-based approaches 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 of community-led management with remote sensing, hydrological modelling, and water footprint indicators have the best potential to increase resilience throughout the Andean-coastal continuum with increasing climate change.

WATER FOOTPRINT MANAGEMENT AND its SIGNIFICANCE for ANDEAN SOCIO ECOLOGICAL SYSTEMS

This study adopts a narrative review approach, which is particularly suitable for synthesizing knowledge across diverse and interdisciplinary domains such as water footprint management, biodiversity conservation, and human rights. Because more than 70% of 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 organizations 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 gaps in knowledge was based on areas where the literature revealed inconsistent findings, under-researched issues, or missing connections [30] between 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 as low as 50-60% [32]. These inefficiencies impose significant pressure on water resources, especially during dry seasons, particularly during dry seasons when demand peaks. The challenge is further compounded by crop choices: 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, WFA, which disaggregates green, blue, and grey components, becomes essential to identify and prioritize interventions that balance agricultural productivity with water conservation. Comparative studies outside the Andes have demonstrated that lining canals and adopting pressurized 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 litters of water per kilogram of production, while maize demands nearly 1,222 litters per kilogram [33]. By comparison, quinoa averages between 1,200-1,500 litters per kilogram, 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 demand significant irrigation, while quinoa and other native crops exhibit higher resilience to water scarcity through their reliance on green water. Applying water footprint accounting (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 with variability and uncertainty on water footprint estimates of crops. The values of water footprint are highly dependent on the local climatic conditions (temperature, precipitation and evapotranspiration), soil properties (texture, depth and water holding capacity), irrigation technology (surface, sprinkler or drip) and the management practices (planting density and fertilization). In the Andes, the sharp altitudinal gradients and strong seasonal differences further increase the spatial heterogeneity of the green, blue and grey components of water . Also, the differences in methods of the various studies, including the selection of evapotranspiration models, spatial resolution of remote sensing data, and assumptions of effective precipitation cause uncertainty in the estimates of the footprint [35]. The values of water footprint must therefore be viewed as ranges to be expected and not as

exact values and as such site-specific measurements and sensitivity analyses are necessary when applying WFM to Andean agricultural systems.

Water footprint in 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, clarifying priorities for conservation and equitable distribution. 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 due to 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 indicatory as opposed to universal in nature with emphasis put on the fact that a site-specific evaluation should be conducted before replication.

In the Andes, indigenous management of water governance is very diverse and local instead of universal. As an example, Quechua communities of the Peruvian Andes central and southern region tend to coordinate irrigation by communal acequias organized by rotating assemblies (faenas) [39] whereas 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 which are legally established and represent various historical and institutional pathways. By being aware of this diversity, Indigenous water governance is not treated as one model and it points to the necessity of integrating WFM in the context.

Although most of the old Andean water systems are adaptive and resilient in nature, not all of them are sustainable in the current climate pressures. 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 to by introducing refined allocation regulations, hydrological monitoring, or additional measures of efficiency in order to survive in the face of mounting climate change. To implement WFM effectively and in a culturally-appropriate manner, it is vital that the certain practices that should be resilient and adaptation-dependent are identified.

Measuring and monitoring water footprints in the Andean context

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 GLDAS data. 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 Organization's WaPOR database has supported multiple case studies applying 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 depletion accounting for water managers. 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]. Standardized indicators to connect 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 fertilizers or pesticides, to meet water quality standards [41]. These indicators, expressed in cubic meters per tonne of product (m^3/ton) or litters per kilogram (L/kg), provide a standardized 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 fertilizers, mining, and wastewater. Integrating these metrics allows WFM to move beyond generalized 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 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.

Integration of water footprint into local water management systems

The process of incorporating water footprint management in local water governance systems in the Andes has several major research gaps that must be fulfilled to attain sustainable use of water in the region. Among the key gaps is the poor knowledge of the implications of using management of water footprints on the local communities, especially the marginalized populations such as the indigenous people and the smallholder farmers. Although the latter is gradually being applied, the water footprint management practices are 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 which deal with the effect of such measures on the livelihoods of the locals and the convergence of such conservation measures with the traditional water rights. A study by Hailegnaw et al. [48] sheds light on the necessity to explore the domains of socio-economic influences more thoroughly, particularly, on the interests of the marginalized population, and the mutually-communal relations between the latter and contemporary forms of governance. Also, Leroy et al. [49]emphasize taking into account the local socio-political processes in the implementation of the strategy of management of the water footprint. Community engagement in WFM can be operationalized 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 been, however, minimal research done on the issues and the successes of the combination of these practices with modern methods such as drip irrigation and micro-sprinklers. The study should be conducted to examine the compatibility between such systems in existence, problems that were encountered in the integration, and what brought about more sustainable consumption of water. 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] posits that the decentralized methodology of interaction between these systems should be comprehended to realize effective conservation of water 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.

Table 2: Traditional and indigenous water management infrastructures in the Andes

Practice	Hydrological function	Ecological benefits	Documented effect	References
Amunas (pre-Incan infiltration canals)	Divert and infiltrate rainfall and runoff into subsurface aquifers for delayed downstream release	Restores dry season flows; recharges groundwater; reduces erosion	↑Dry-season flow by ~7.5%; 30-45-day delay	Sonkar et al. [48]
Waru-waru (raised fields)	Enhance soil moisture retention and reduce frost risk through microclimate buffering	Increased soil moisture and yield resilience	↑25-50% yield; ↓ET 15–30%	Nina et al. [16]
Terracing (andenes)	Reduce runoff and soil erosion on steep slopes	Stabilizes slopes; increases infiltration	↑Water-use efficiency 40%; ↓erosion 50%	Boelens et al. [2]
Atajados (earthen micro-dams)	Capture and store rainfall and small runoff flows	Supports dry-season irrigation; recharges aquifers	↑Crop water availability 10–20%	Sittig, [52]
Acequias (community canals)	Distribute water equitably via communal rules	Strengthens social capital; equitable access	↓Water conflicts; ↑efficiency	Lynch [53]
Bofedales (high-Andean wetlands)	Store and slowly release water throughout the year	Maintain baseflow; support biodiversity	baseflow sustained	Ross et al. [54]
Qochas (artificial ponds)	Collect rainwater and runoff for multi-purpose use	Boost livestock water supply; improve microclimate	↑Soil humidity by 20%; ↓runoff	BAHAL'OKWIBALE et al. [55]
Pukios (underground infiltration galleries)	Channel subsurface flow to surface outlets	Provide perennial water sources; prevent evaporation	Stable year-round flow in arid valleys	Esenarro et al. [56]
Waru ponds (wet-field reservoirs)	Retain excess rainwater and recycle it	Balances soil water and groundwater	↑Groundwater table stability	Nina, [57]
Camellones (mounded rows)	Improve drainage and moisture regulation	Enhance soil aeration and productivity	↑Crop yield 15–35%	Howeler, [58]

Pallares (natural grass buffers)	Filter sediments and nutrients near streams	Improves water quality; stabilizes banks	↓Sediment load 20–35%	Ross et al. [54]
Fog catchers (atrapanieblas)	Condense fog moisture in coastal highlands	Supplement freshwater for irrigation	4-7 L m^{-2} day^{-1} yield	Scharnke [59]
Ayllu governance systems	Collective decision-making for irrigation	Ensures rotational water equity and cooperation	↓Conflict incidence by 60%	Meléndez, [60]
Pasture rotation in wetlands	Manage livestock intensity for hydrological balance	Prevents overgrazing; enhances wetland recovery	↑Vegetation covers 30%; ↑water retention 18%	Ross et al. [54]

The other gaps that have not been exploited fully are equity in water footprint management, especially in the big agribusiness versus small farms. Increasing water consumption of industrial-scale agriculture may intensify the preexisting shortages in water access, which will particularly impact the local population disproportionately. Socio-economic differences in water access should be researched and ways by which vulnerable groups would not be disproportionately affected by the water footprint management need to be found. Uhlenbrook et al. [61] consider fair distribution of water a critical form of sustainability and warn that massive farming activities should not distract the interests of the local population. The authors note that participatory water management plays a significant role in holding marginalized groups by including them in the decision-making process, which is crucial towards attaining equality in water distributions [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. The efficiency of water governance models that are community-based, more research needs to be conducted as well in this aspect. Although the community-based governance system is introduced in some parts of the Andes, there is inadequate study of its contribution to the effectiveness of water footprint management. Evaluation of how participatory decision-making, water-sharing agreements, and community-led initiatives can be merged with modern-day water management activities is important. Bos and Brown [63] explain the possibilities of the local governance to promote conservation of water, yet more studies are required to elucidate which processes guarantee its effectiveness. The decentralized management may foster conservation levels of water, but it needs investigation to find out its capability circulating around water footprint management.

Implications of gaps

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 favoring 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 the ability of governments 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 rigor 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 toward 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 sustains 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 stabilizes 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.

Ecological significance of the Andes: unique species and habitats

Andes is considered among the most biodiverse regions in the world, and its abundance is unmatched, and many species and ecosystems are drastically different depending on altitude and geography. The area has a variety of ecosystems, such as cloud forests, high-altitude wetlands, temperate, classical rainforests and parched piosferas. The ecosystems do not just harbor unique plant and animal species, but they are also ecologically critical for regulating hydrology and biodiversity across the South American continent [69]. Biodiversity is especially high in cloud forests located in lower and mid-altitude Andes. The forests are also marked by abundance of mist and moisture which establishes a distinct microclimate to host numerous plant species, moss and epiphytes. These ecosystems support rare and emblematic species, including the Andean (spectacled) bear (*Tremarctos ornatus*) and the endangered mountain tapir, along with a rich diversity of birds, amphibians, and reptiles [70]. For example, Sangay National Park in Ecuador one of the most ecologically intact Andean reserves harbors 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 to the endemic species like the Andean flamingo, the vicuna and various species of high-altitude plants which grow in not nutrient-rich soils. The ecosystems also help in the regulation of water quality thus they are crucial to biodiversity as well as human consumption of water. These ecosystems are strongly related to the water availability, and disturbance in water resources implies a direct danger to the existence of these species and the ecosystems [72] (Figure 2).

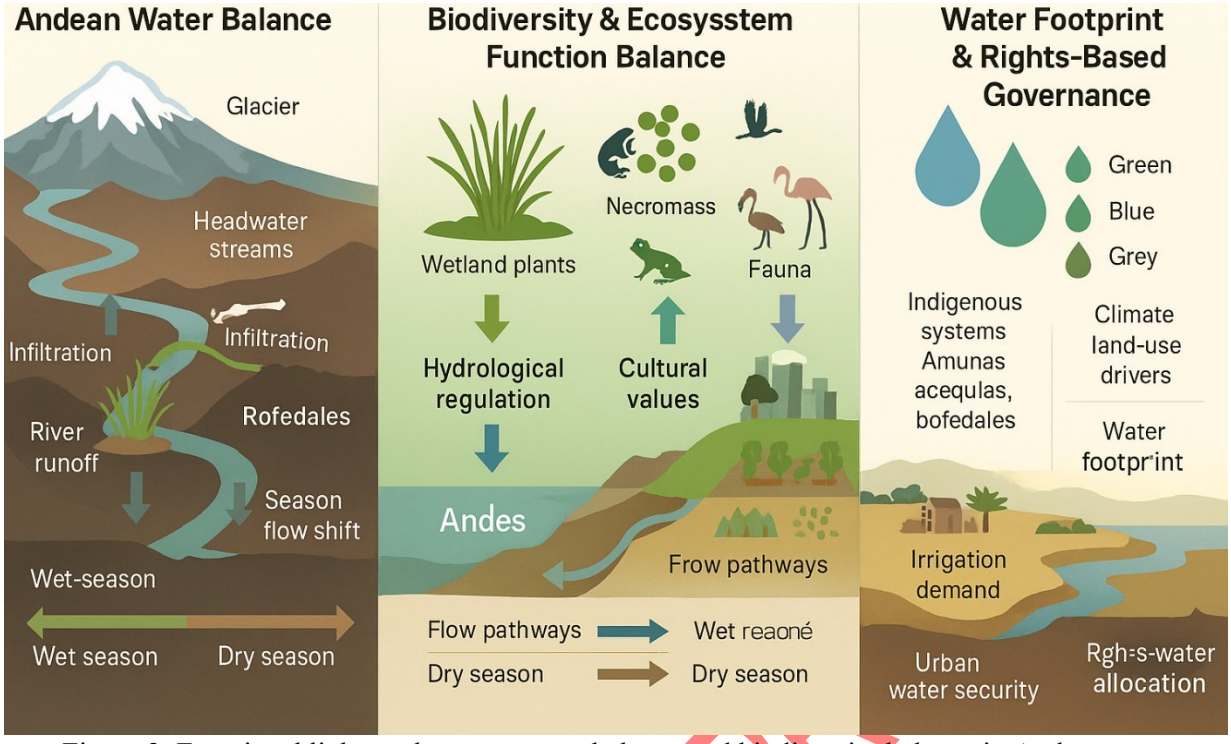

Figure 2: Functional linkages between water balance and biodiversity balance in Andean ecosystems

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, but 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 stabilize 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 fibers 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. This 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 fertilizer 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 emphasize 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 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 destabilizes 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 prioritize 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 standardized 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 resulted in the disappearance of fish populations and the displacement of migratory bird species such as the Andean flamingo (*Phoenicoparrus andinus*) and 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 consumptive and grey-water footprint controls 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 the resilience of wetlands 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 arsenic and mercury levels have been recorded in rivers adjacent to mining zones, impacting aquatic macroinvertebrates and fish communities that form the base of the food web. The standardized 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 summarized in Table 3.

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	Upstream irrigation diversion and mining effluents	Ecosystem collapse; bird/fish loss	Regional mobilization; basin forum	Urgent need for basin governance & rights enforcement	Zhu et al. [80]
Cajamarca, Peru	Gold mining (As, Hg contamination)	Decline in macroinvertebrates, fish	Community protest; weak enforcement	Governance–mining conflict persists	Meléndez on et al. [60]

Páramos, Ecuador	Agricultural expansion, drainage	↓Baseflow, pollinator decline	Rewetting and community restoration	Biodiversity recovery post-restoration	Potts et al. [82]
Mendoza Basin, Argentina	Groundwater overuse for viticulture	Wetland desertification	Allocation reform; aquifer monitoring	Improved recharge stability	Straffelini et al. [83]
Southern Peru Bofedales	Overgrazing and drainage	↓Wetland capacity, amphibian loss	Wetland restoration and grazing control	↑Hydrological resilience	Ross et al. [54]
Cotopaxi, Ecuador	Upstream diversion	Irrigation shortages	Constitutional right to water case	Legal success for indigenous irrigation rights	Ariyanti, [51]
Santa River, Peru	Glacier retreat and hydro demand	↓Dry-season flow, habitat loss	Adaptive reservoir management	Water energy biodiversity trade-offs exposed	ANA, [12]
Vilcanota Basin, Peru	Climate change and tourism	↑Water pollution, wetland loss	Ecotourism co-management	Improved awareness and policy inclusion	Davies et al. [84]
Altiplano Lakes, Bolivia–Peru	Mining and evapotranspiration	↓Waterbird habitat	Cross-border monitoring network	Highlighted transboundary water governance needs	Torres-Batlló et al. [85]
Cordillera Blanca, Peru	Glacier retreat altering runoff	Species shifts; wetland shrinkage	Glacier-lake adaptation plans	Strengthened resilience metrics	Mark and Seltzer, [86]
Huancavelica, Peru	Deforestation and mining	↓Water quality and baseflow	Community-led reforestation	Ecosystem service restoration	Daneshvar et al.[87]
Cochabamba Valley, Bolivia	Urban sprawl and irrigation demand	Aquifer depletion	Decentralized water-user committees	Improved allocation efficiency	Omann et al. [76]
Santa Elena, Ecuador	Droughts and poor irrigation infrastructure	Crop loss, salinization	Public–community irrigation projects	Increased efficiency by 25%	Hoogesteger et al. [88]
Tarija Basin, Bolivia	Water privatization and inequality	Reduced access for smallholders	Social movements; policy reversal	Established legal limits on privatization	Boelens et al. [2]
Arequipa Valley, Peru	Industrial agriculture and energy expansion	River depletion; fish decline	Basin dialogue platform	Integrated planning between sectors	Daneshvar et al. [87]

Strategies for using water footprint management to enhance biodiversity conservation

The WFM provides a structured way to link 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, such as adopting drip irrigation 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 [89]. These methods strengthen ecological resilience but often face scaling limitations due to labor 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, making it necessary to complement 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 [90]. 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 [91]. International law has now accepted the right of water as a human right. In 2010, a resolution of the United Nations Human Rights Council recognized an explicit 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, but this right 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 mountain–coast rights-based governance. Enforcement of the human right to water in Andean states faces persistent implementation constraints. Common challenges include fragmented mandates between national water authorities, environmental regulators, and subnational governments; limited budget and technical capacity for monitoring and compliance; and weak sanctioning power when influential actors (e.g., mining, hydropower, agro export) violate allocation rules or

discharge limits. Policy contradictions also emerge when constitutional or statutory recognition of water rights and environmental protections coexists with development policies that prioritize extractive concessions, large-scale irrigation expansion, or inter-basin transfers, creating gaps between rights "on paper" and realized 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 [92]. 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 determine equity outcomes in the process of 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 negotiating arenas; gender inclusive governance thus has influence on both procedural equity (voice) and distributional equity (allocation). It may be weakened by migration, which is often caused by climatic stress, changes in the economy where labor to perform maintenance as a community (faenas) is eroded besides disrupted local knowledge of water. Simultaneously, the outmigration of youth might speed up intergenerational loss of knowledge in activities like the amunas maintenance, bofedales management and rotational allocation thereby lowering the adaptive capacity in the long run [93]. Rights-based frameworks are thus reinforced by the action that enhances the level of 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 [91]. However, these worldviews are diverse and evolving. For example, Quechua groups in Cusco maintain ritual ties with springs (*puquios*) [94] and wetlands, while Aymara communities in Bolivia emphasize collective irrigation governance through ayllu-based systems [95]. Recognizing this plurality avoids essentializing 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 considerations as indigenous have been a controversial issue 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 has been made under which the rights of nature and indigenous people concerning their territories will be stated, the execution of these rights is still tenuous. In Peru, indigenous water rights have received partial legal recognition; however, these rights are frequently undermined by national water policies that prioritize 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 the indigenous peoples that have been developed after several centuries also form part of ethical considerations of 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 realization and appreciability of the native rights to water can diminish the unsustainability in fair treatment of water in the Andes as the people can govern as per their water resource and safeguard their cultural universes. Distributing water fairly is a major issue in the Andes especially to the remote and rural settlements. Such societies are sometimes prone to inaccessible clean water because of geographical inaccessibility, no infrastructure and inability to fortify monimately.

Although urban populations can usually access water piping systems, the rural and indigenous populations in Andean highlands usually have limited to poor resources of water supply 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 organizations to cooperate where it is necessary to not only provide but also make accessible, affordable and safe the access to water. The Andean region faces persistent challenges such as 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 organizations 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, resource mobilization and collaborate with local community to develop and prescribe sustainable water solutions.

WATER FOOTPRINT MANAGEMENT as a TOOL for SUSTAINABLE AGRICULTURE and ECOSYSTEM PROTECTION

Water footprint management refers to the systematic assessment and regulation of water consumption across agricultural production systems to ensure efficient use of freshwater resources. By quantifying the volumes of blue, green, and grey water used during crop cultivation and food production, this approach enables the identification of inefficiencies and areas where water use can be optimized. 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.

Efficient water uses in agriculture: role of irrigation technologies

In this study, eco-efficient practices' are defined as water-saving measures such as drip irrigation or pre-Incan *amunas* that maximize productivity per unit of water [96] [97]. Sustainable methods include practices like rotational grazing in high-altitude *bofedales*, which maintain forage production while preserving hydrological functions [98]. Better management practices' refer to strategies such as lining canals to reduce seepage losses or crop rotations that minimize evapotranspiration [97]. These distinctions help clarify how WFM translates into concrete interventions in the Andean region. The new irrigation methods like the drip irrigation and spray irrigation are becoming instrumental in water saving and enhancing water efficiency utilization [99]. Drip irrigation in which the water is delivered to the plant roots reduces the actual water loss since there is low evaporation of water and runoffs. In this system, crops receive precisely the amount of water required, thereby minimizing wastage and improving productivity. Another important water-saving technology is the sprinkler irrigation system, 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 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 arrangements have a potential in their power to alter the current way of farming in the Andes not only in sustaining the farmers in their way of living but also in ensuring that the ecosystem within which these water bodies are located remains healthy [100].

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 incentivize 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 heterogeneity of habitats and expand the use of agrochemicals enhancing grey water footprints and ecological pressures [101]. It is because of these reasons that, modernization of irrigation should be incorporated into basin-level allocation regulations and environmental water protection, so that the efficiency gains are converted to actual water savings and biodiversity gains.

Crop selection and water footprint reduction in Andean farming

The other important method of lowering water footprint of agriculture in the Andes is a selection of water efficient crops. Less water is used to grow such crops as quinoa that grow well in high-altitude areas compared to the conventional crops like maize and potatoes. The farmers can also minimize their water usage by adopting varieties that are resistant to drought thus ensuring food security. In the Cordillera Blanca of Peru, restoration of ancient *amunas* has increased groundwater recharge and sustained dry season flows, supporting both agriculture and aquatic ecosystems [96]. 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 is beneficial not only for lowering irrigation costs but also for supporting local biodiversity, as the cultivation of native and climate-resilient crops is typically better suited to Andean environments. 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 help maintain soil fertility, reduce reliance on artificial irrigation, and improve long-term soil water retention Figure 3. The heatmap-style visualization reflects relative differences in total water demand, integrating green and blue water components reported in the literature, with higher color intensity indicating greater water consumption per unit of yield. Quinoa exhibits the lowest footprint (≈1500 L kg^{-1}), largely due to its reliance on green water and physiological tolerance to water stress, whereas 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 the application of organic manure further contribute to water conservation by reducing evaporation losses, enhancing soil moisture content, and improving soil structure. The combination of all these practices makes it possible to streamline the consumption of water, save the quality of soil, and minimize the overall water footprint of agriculture in the area [102].

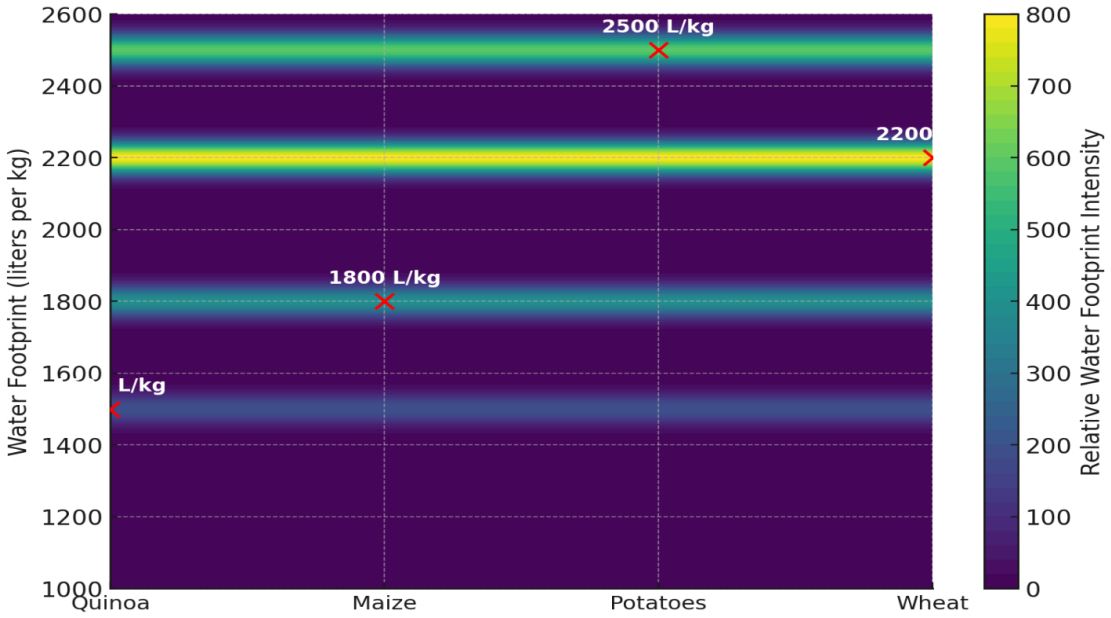

Figure 3: Comparative water footprint intensity of major crops cultivated in Andean and Andean-fed agricultural systems.

Note: This figure has been produced from the current manuscript by the authors and data were copied from the source: Arjen et al. [41]. Values represent approximate total water footprints (L kg^{-1}), synthesizing green and blue water components from published assessments. Color intensity indicates relative water demand, highlighting crop-dependent differences relevant for water footprint management and irrigation planning.

Community-led water conservation practices: integrating traditional knowledge

The practice of water conservation among the Andean communities is one that has existed through several decades. Techniques like terracing, canal irrigation, and aqueducts have enabled these peoples to handle their water resources efficiently thus resulting to constant availability of water to be used both as domestic tools as well as water resources used in agricultural activities. These practices are fundamental strategies for sustaining livelihoods under conditions of scarcity. A closer examination reveals that indigenous practices and technical conservation approach often share common objectives, even if expressed through different methods. For example, Andean terracing reduces runoff and soil erosion, which mirrors modern soil and water conservation engineering that promotes slope stabilization and moisture retention [103]. Similarly, communal irrigation canals (acequias) function not only as cultural institutions but also as decentralized systems of equitable water allocation and demand management, aligning with contemporary goals of participatory governance and environmental flow protection [91]. Ritualized water-sharing assemblies echo principles of adaptive co-management, ensuring seasonal adjustment of water allocations much like scientific recommendations for dynamic allocation under climate variability [91] [95]. By explicitly recognizing 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 [97] [75]. Bridging these two knowledge domains highlights that conservation goals such as soil fertility, biodiversity protection, and equitable access are already embedded within indigenous systems and can be reinforced, rather than replaced, by modern science [2]. An illustrative example is terracing, widely practiced 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 [104]. 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 [105].

Water recycling and wastewater treatment systems for sustainable water use

Reuse of treated wastewater is a new phenomenon happening in sustainable water usage; especially in areas where there is scarcity of water like in 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 concerns about contamination. 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 optimize 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 where treated wastewater may be utilized in non-edible production such as crops or landscaping whereby the quality of water is not too 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 [106]. This practice also reduces pressure on freshwater resources, providing farmers with a more reliable water supply during dry seasons. Nonetheless, it is essential that wastewater treatment systems meet strict health and environmental standards to prevent soil and water pollution and ensure long-term sustainability. Khan et al. [107] 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 [108] can inform allocation decisions by identifying periods and locations of excessive blue-water use or elevated grey-water loads [109]. When embedded within basin-scale planning tools and water accounting frameworks (e.g., WFA and WA+), these technologies support scenario analysis, prioritization of interventions, and transparent negotiation among stakeholders, 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 analyzing large datasets, AI models can optimize irrigation schedules to minimize water wastage while maximizing 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 [110]. Such systems can determine when to irrigate, how much water to apply, and at what intervals, thereby reducing inefficiencies in irrigation. In addition, the incorporation of deep learning and predictive analytics has made it possible to tailor irrigation strategies to specific crops and regions, further enhancing water efficiency and sustainability. Another significant innovation for water resource governance is the adoption of

blockchain technology. Blockchain can enhance 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 decentralized 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 is also connected to the deployment of digital technologies as such. Issues with the privacy of data are observed when the hydrological, agricultural, or household water-use data is gathered with no distinct approval or protection, especially in Indigenous lands. Digital divides that are associated with the connection, literacy and availability of hardware can leave marginalized communities out of enjoying the equal benefits of AI-enabled systems of decisions [49]. Additionally, the visualization of value judgments in model design by algorithmic decision-making may support status quo power inequity when outputs are perceived as objective or fair. To prevent these threats, transparency, free prior informed consent, domestic data possession, and participatory model interpretation should be the rules in the realm of digital WFM, which means that technology, not community-led governance, should be supported.

Remote sensing and drones for water footprint monitoring

The application of remote sensing technologies and drones is transforming the monitoring of water use and agricultural productivity in real time. Multispectral and thermal imaging sensors mounted on drones provide detailed information on crop health, soil moisture levels, and overall water consumption. These tools give farmers unprecedented accuracy in assessing crop requirements, thereby enabling precision farming practices. At a broader scale, satellite-based remote sensing is increasingly employed to detect critical water footprints at regional levels. Satellites are particularly effective for monitoring vegetation health, water availability, and environmental conditions, generating large datasets that support optimized water use across entire farming systems. Together, these technologies simplify the process of water resource monitoring and management, thereby enhancing agricultural sustainability [111].

Vertical farming in high-altitude or urban environments shows strong potential for reducing the agricultural water footprint. Vertical farming and GM drought-tolerant crops have the potential to save water but are yet to be tested in remote Andean highland locations [112]. Vertical farming also needs a stable electricity supply, climate-managed infrastructure, technical skills, capital access, which is not usually the case with rural Andean populations. Likewise, GM crops have also been introduced with regulatory challenges, cost of seed 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 prioritized.

In this 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 optimize reuse. Importantly, vertical farming offers a promising solution for 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 optimize 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 visualization 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.

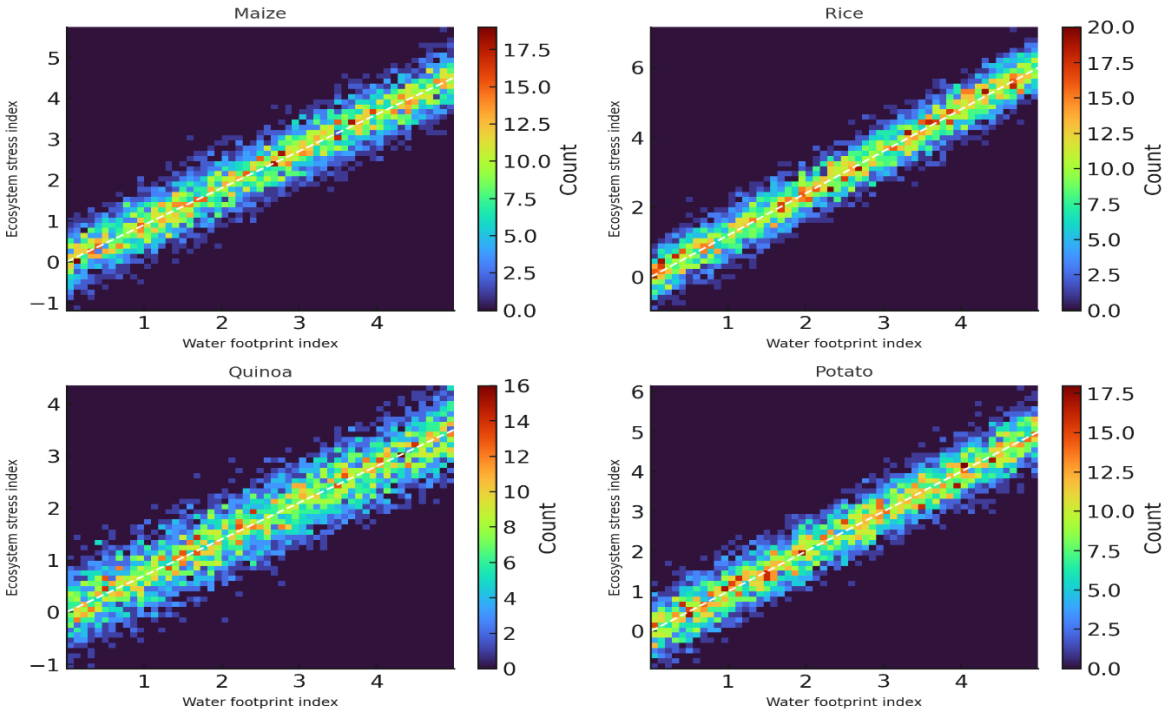

Figure 4: Density-based correlation plots illustrating key water ecosystem relationships between Andean socio-hydrological systems

Note: Each subplot shows a two-dimensional kernel density distribution (heatmap) overlaid with scatter points (white dots) and a 1:1 reference line (black diagonal). Warmer colours indicate higher data density. This figure has been produced from the current manuscript by the authors and data were copied from the source: Hamidov et al. [113]

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 and continuous supply of water for farming activities. Recent advances in desalination techniques have made the process more energy-efficient and cost-effective, enabling its adoption in areas with abundant seawater access but limited freshwater availability Figure 5. By combining desalination technologies with

innovative water treatment systems, reliance on traditional freshwater sources in the Andean coastal areas could be significantly reduced, ensuring a more reliable water supply for agriculture even during drought periods. The concept of the water-energy nexus, an emerging field of research, emphasizes the interconnections between water and energy use in farming. Recent progress in solar-powered irrigation systems and high-efficiency water pumps has lowered the 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 depends on costly pumping, the use of renewable energy sources such as solar and wind offers a practical and economically viable alternative to fossil fuels, while also advancing long-term sustainability [114].

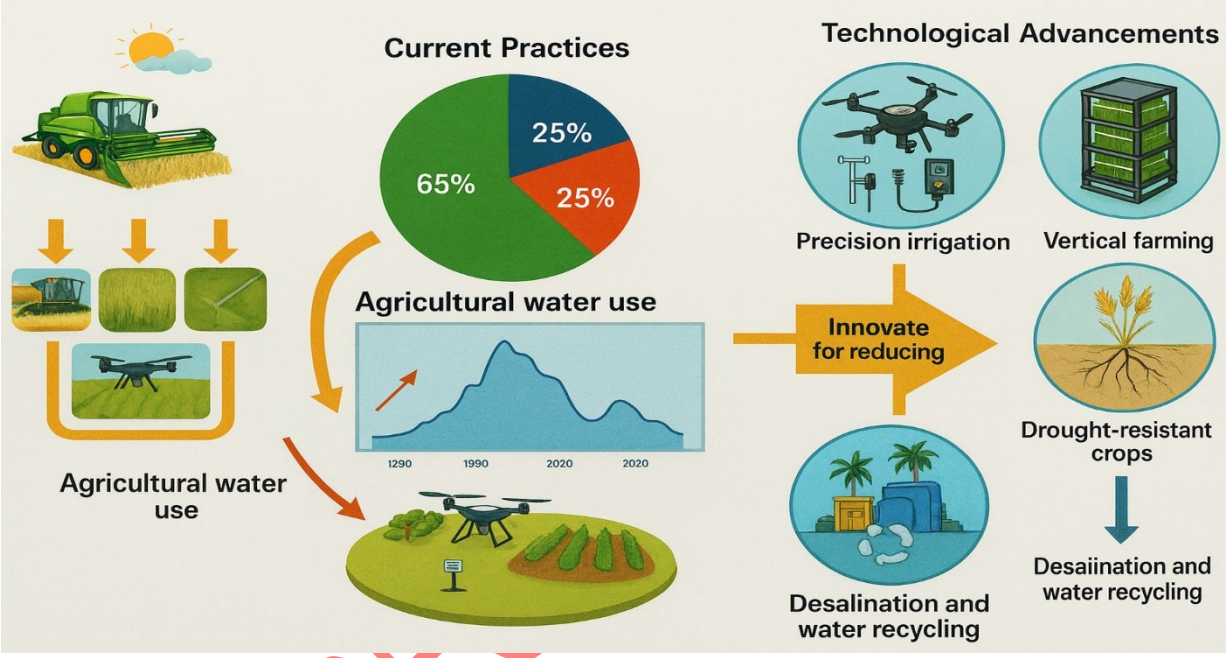

Figure 5: Conceptual framework of artificial intelligence and technological innovations for precision irrigation and water footprint optimization in Andean agriculture

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 over-extraction, land-use intensification, cryosphere loss, and pollution that exacerbate coastal salinization, 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 localized 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 the protection, restoration, and equitable management of water resources in the Andean headwaters.

CONFLICT OF INTEREST

Authors declared no conflict of interest to each other.

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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 conceptualization, methodology, data analysis, and writing of the manuscript. 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. project and quez-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.

ABBREVIATIONS

AI: Artificial Intelligence
ANA: Autoridad Nacional del Agua (Peruvian National Water Authority)
CESCR: Committee on Economic, Social and Cultural Rights
ET: Evapotranspiration
FAO: Food and Agriculture Organization of the United Nations
GM: Genetically Modified
IMRAD: Introduction, Methodology, Results and Discussion, Conclusion
IoT: Internet of Things
IPCC: Intergovernmental Panel on Climate Change
IUCN: International Union for Conservation of Nature
NbS: Nature-based Solutions
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 Organization
WaPOR: FAO Water Productivity through Open Access of Remotely Sensed Data
WA+: Water Accounting Plus
WFA: Water Footprint Assessment
WFM: Water Footprint Management

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