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Review

Water–Energy–Food Nexus and Hydrosocial Conflicts in Peruvian Mining–Agriculture Basins: An Integrative Review with Water Footprint Evidence

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Abstract

Water scarcity in Peru is increasingly shaped by competing sectoral demands, particularly between large-scale mining and agriculture. Both sectors rely heavily on limited freshwater resources in arid coastal and Andean basins, generating complex trade-offs between economic productivity, environmental sustainability, and social equity. This review synthesizes and critically evaluates current knowledge on water footprint (WF) dynamics within mining–agriculture systems, integrating hydrosocial theory, water–energy–food nexus thinking, and sustainability transition frameworks. Mining activities in Peru are characterized by high blue and grey water footprints, associated with intensive extraction processes and contamination risks, while agriculture exhibits diverse water footprints depending on crop type, irrigation efficiency, and climatic conditions. The interaction of these sectors creates hydrosocial conflicts driven by unequal water allocation, environmental degradation, and institutional fragmentation. This paper identifies key drivers of conflict and evaluates emerging pathways for sustainability transitions, including technological innovation, nature-based solutions, and participatory governance mechanisms. An integrative conceptual framework derived from a thematic synthesis of the reviewed literature is proposed. The findings provide actionable insights for policymakers and researchers seeking to reconcile economic development with water sustainability in resource-constrained environments.

Keywords: water footprint; mining; agriculture; Peru; hydrosocial systems; sustainability transitions; water governance; nexus approach

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1. Introduction

Peru is characterized by a highly skewed spatial distribution of water resources, with 97% of freshwater resources found in the Amazon basin [1], while the bulk of the population, agricultural production and industry are found in the dry coastal and Andean regions [2]. This uneven distribution has been linked to constraining water availability in economically active regions.

Available evidence suggests that water scarcity is most acute between mining and agricultural uses in Andean basins, where water availability is scarce and water allocation is in dispute [3,4]. These relations are further aggravated by climate change, glacier melt, and a growing demand for water by the mining sector [5].

Mining is a central sector for the Peruvian economy, accounting for a substantial proportion of total exports and gross domestic product (GDP), mostly in copper, gold and silver [6,7]. Mining takes place in high-elevation Andean areas, where water is scarce and ecosystems are vulnerable [8]. At the same time, agriculture plays a vital role in food security and rural livelihoods, particularly for rural farmers in the Peruvian Andes, whose farming systems rely on access to water [9].

Mining–agricultural interactions have been linked to growing water quantity, quality and access issues, especially in shared water basins [10]. Such interactions often unfold as hydrosocial conflicts, in which water conflicts are closely tied with governance, equity and environmental justice concerns [11]. These considerations call for a better understanding of water use through frameworks that consider both quantitative and socio-institutional water use dimensions. Such interactions are especially apparent in mining-intensive basins like Cajamarca, Apurimac, Cusco, Moquegua and Arequipa of Peru where extractive activities intersect with irrigation-based agricultural systems and glacier-based hydrological regimes. The cases of conflicts related to projects like Conga, Tia Maria, Las Bambas, Espinar, and Quellaveco show that the issues of water allocation are not just hypothetical, but directly intertwined with the problem of territorial governance, seasonal water shortage, groundwater degradation, the risk of contamination, and vulnerability of downstream agriculture. Consequently, to comprehend competing water footprints in Peru, it is necessary to have an applied socio-hydrological approach that is able to bridge the gap between hydrological processes and governance structures, basin-scale allocation dynamics, and region-specific sustainability issues.

The water footprint (WF) concept developed by Hoekstra et al. [12] offers a holistic framework to quantify water consumption and pollution in terms of blue (surface and groundwater), green (rainwater), and grey (polluted water) water. Yet, while WF analyses in Peru have mostly focused on single sectors, little has been said about the interactions between mining and agriculture in shared water basins [13].

This review seeks to fill this gap by assessing the state of knowledge on competing water footprints in mining–agriculture systems in Peru. The goals are to (i) describe the water footprint of mining and agriculture; (ii) examine trade-offs and hydrosocial conflicts between water uses; (iii) assess governance and institutional frameworks; and (iv) explore opportunities for the transition toward sustainability.

This review integrates water footprint analysis with hydrosocial and nexus perspectives to evaluate mining–agriculture interactions in Peru. Particular attention is given to basin-scale water allocation, contamination pathways, governance arrangements, and sustainability responses documented in major mining regions.

2. Methodology

2.1. Review Design and Conceptual Approach

This study employed a directed integrative review process involving systematic literature screening, qualitative thematic synthesis and conceptual systems analysis. The objective of the review was to explore the relationship between conflicting water footprints in mining–agriculture systems, hydrologic processes, governance, hydrosocial conflicts and sustainability transition pathways in Peru.

To our knowledge, this is one of the first reviews that synthesizes water footprint, hydrosocial, nexus, asymmetry and sustainability transition theories into a conceptual framework for mining–agriculture systems in Peru. Despite the fact that the review considers qualitative interpretations regarding governance, conflict and institutional asymmetries, these factors were always examined in terms of water footprint processes, water abstraction, consumptive use, generation of pollution, pressure of allocation, and hydrological processes at basin scales. As a result, the analytical thrust of the research is still within the dynamics and sustainability implication of competing water footprints.

2.2. Literature Search Strategy

A comprehensive search of the literature was conducted in the databases Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. We searched for peer-reviewed journal articles, government reports, international assessments, and technical papers published from 2010 to 2025.

The search terms included combinations of terms related to water footprint, mining systems, agricultural water consumption, governance and approaches to the water–food–energy nexus. The primary search combinations included: "water footprint" AND "mining" AND "Peru" "water footprint" AND "agriculture" AND "Andes" "hydrosocial" AND "water governance" AND "Peru" "water–energy–food nexus" AND "mining agriculture" "grey water footprint" AND "mining contamination" "blue water footprint" AND "irrigation systems" and "hydrological conflicts" AND "Peru". Additional references were identified through backward citation tracking from highly cited review papers and institutional reports.

2.3. Inclusion and Exclusion Criteria

Inclusion criteria were that studies contained one of the following: quantification of blue, green or grey water footprints; hydrologic impacts of mining; analysis of irrigation schemes and water use efficiency; examination of hydrosocial conflicts or governance; use of the nexus or socio-hydrological approaches and emphasis on Peru or other Andean socio-hydrological systems. The review excluded: Studies not focused on interactions between water resources; studies with methods that are not clearly reported; only engineering technical studies with no hydrologic or governance interest; duplicate records and non-scientific opinion articles with no empirical or conceptual contribution.

2.4. Screening and Selection Procedure

The screening process was divided into three steps. First, after first-hand database searches, duplicate records were removed. Then, titles and abstracts were scanned to assess topical relevance. Third, full-text reviews examined methodological and conceptual fit to mining–agriculture water interactions. The screening, eligibility assessment and final selection of the literature follow a PRISMA-inspired flow chart. The screening procedure involved de-duplication, title/abstract screening, full-text assessment and a thematic relevance check based on water footprint, hydrosocial, nexus and mining/agriculture interaction criteria. The database finally comprised research on mining water use, irrigation systems, hydrological impacts, governance fragmentation, water conflicts and adaptive transition mechanisms in Peruvian or other Andean basins. The search returned 427 records. Following de-duplication, 356 articles were screened for title and abstract. After the relevance check, 124 full-text papers were assessed for eligibility and 78 studies were finally selected for thematic synthesis and conceptual integration. We used a PRISMA-based flow diagram for screening studies in integrative re-views (Figure S1).

2.5. Data Extraction and Analytical Variables

The selected studies provided data on: water footprint (blue, green and grey); groundwater abstraction patterns; irrigation efficiency estimates; sources of contamination and hydrochemical effects; water allocation mechanisms; governance structures; conflict typologies; sustainability interventions; technological adaptation strategies; and ecosystem restoration mechanisms. For better analytical coherence, information was structured into four analytical categories: Hydrologic water footprint processes; hydrosocial governance and institutions; nexus and sectoral interdependencies; and sustainability transition mechanisms. To enhance applicability at the contextual level, the review focused on empirical evidence on the Peruvian mining–agriculture basins where hydrological stress, institutional fragmentation, and socio-environmental conflicts have been widely reported. Special focus was given to the literature on Cajamarca, Arequipa, Apurimac, Cusco, Ancash and Moquegua, since these areas are severe hotspots of mining–water–agriculture interactions with a background of climatic variability as well as rising resource competition.

2.6. Methodological Limitations

This research is subject to the limitations of using secondary sources, and is a conceptual synthesis, rather than primary hydrological data or basin-scale numerical model. Water footprint values are sourced from secondary literature based on various approaches and scales. Also, the effectiveness of governance, intensity of conflict, and transitions towards sustainability involve socio-political processes that cannot be captured solely by quantitative indicators. As a result, the proposed framework should be viewed as an integrative conceptual framework to guide future empirical operationalization, rather than a predictive model.

2.7. Quantitative Contextual Evidence for Peru

Peru's water resource distribution is highly uneven: the Atlantic/Amazon basin contains approximately 97% of available freshwater, while much of the population, agro-export production, and industrial activity is concentrated in the Pacific coastal region [14]. Agriculture is the dominant water user, accounting for about 80–88% of national water withdrawals or consumptive surface water use. However, agricultural water use efficiency remains low, commonly estimated at 30–45%, and approximately 57% of existing irrigation and drainage infrastructure is reported to be in poor condition [14]. These figures indicate that competition between agriculture and mining is not only a question of total water availability, but also of spatial mismatch, irrigation inefficiency, and basin-level allocation pressure.

Figure 1 synthesizes key quantitative indicators reported in national and international assessments of Peruvian water resources. The figure highlights four structural characteristics relevant to mining–agriculture interactions: (i) the dominance of agriculture in national water withdrawals, (ii) the unequal distribution of freshwater resources among hydrographic regions, (iii) differences in irrigation efficiency between traditional and modern irrigation systems, and (iv) the strong mismatch between population concentration and freshwater availability. Together, these indicators demonstrate that water conflicts in Peru emerge not only from total water demand but also from geographic disparities in water availability, inefficient water use, and competing sectoral pressures.

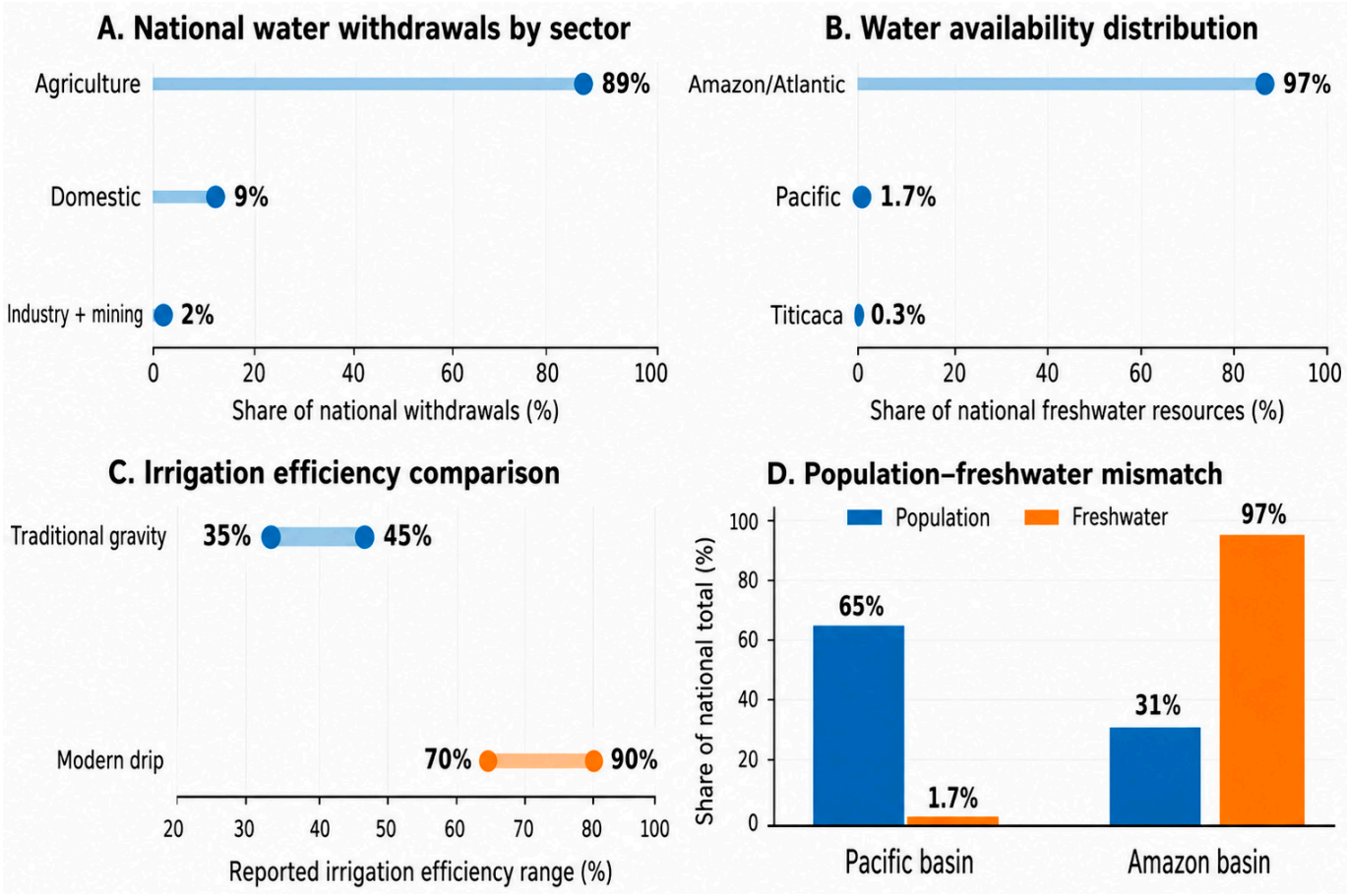

Figure 1. Quantitative indicators of water resource pressures relevant to mining–agriculture interactions in Peru. Data sources: World Bank [15], OECD [16], ANA [17].

3. Quantitative Synthesis of Water Footprint Evidence

Although this review primarily adopts a qualitative and integrative perspective, the literature provides several quantitative indicators that help contextualize competing water demands in Peruvian mining–agriculture systems. Reported evidence indicates substantial differences between the intensity, spatial concentration, and environmental implications of water use in the two sectors [15]. Mining activities are characterized by concentrated blue water withdrawals and elevated grey water footprints associated with contamination risks, whereas agriculture exhibits greater variability depending on crop type, irrigation technology, climatic conditions, and geographic location [16]. Table 1 summarizes the representative quantitative indicators reported in the reviewed literature. Quantitative indicators were extracted from 28 studies reporting water use, irrigation, contamination, or governance metrics relevant to mining–agriculture interactions.

Table 1. Comparative synthesis of water footprint indicators reported for mining and agriculture in Peru.

Indicator	Mining Systems	Agricultural Systems	Main Implications
BWF	0.5–2.5 m^3\ton water at processed ore	900–3000+ L kg^{-1}	Competition for freshwater resources in water-scarce basins
BWF	Limited contribution	Quinoa, potatoes	Dependence on precipitation and soil moisture

Table 1. *Cont.*

Indicator	Mining Systems	Agricultural Systems	Main Implications
GWF	Heavy metals, acid mine drainage, and industrial effluents	Nutrient leaching and agrochemical runoff	Water quality degradation
Groundwater dependence	High in several mining-intensive basins	Moderate to high in irrigated coastal agriculture	Increased pressure on aquifer systems
Irrigation efficiency	Not applicable	40–50% in traditional gravity; >80% in modern drip irrigation	Large potential for water savings
Water-quality risk	High due to metal contamination and acid drainage	Moderate due to diffuse nutrient and pesticide pollution	Increased environmental and regulatory pressures
Spatial concentration of impacts	Localized but intense	Broadly distributed across watersheds	Different governance and management requirements

Note: Sources: Synthesized from studies reviewed in this manuscript [10,14–17].

Results of Quantitative Synthesis

The reviewed evidence indicates that mining and agriculture exert fundamentally different pressures on water resources. Mining operations generally require between 0.5 and 2.5 m^3 of water per ton of processed ore and generate disproportionately large grey water footprints because of heavy metal contamination, acid mine drainage, and industrial effluents [18]. These impacts tend to be spatially concentrated within high-altitude headwater catchments where hydrological sensitivity is greatest.

In contrast, agricultural water footprints are more heterogeneous and strongly dependent on crop type, irrigation method, and geographic location. Traditional Andean crops such as quinoa and potatoes primarily rely on green water resources, whereas export-oriented crops grown in coastal irrigation systems frequently exceed 3000 L kg^{-1} and depend heavily on blue water withdrawals [16]. Reported irrigation efficiencies below 50% in many traditional irrigation systems further increase water demand and intensify competition with other sectors [15,17]. Collectively, these findings suggest that water conflicts in Peru emerge not only from absolute water use but also from differences in water use intensity, spatial concentration, contamination risks, and institutional allocation mechanisms.

4. Hydrosocial Nexus Reframing of Water Footprints in Mining Agriculture Systems

The most common signs that are still utilized to understand the pressure of hydrology, ecological dependence, the level of pollution, and the dynamics of inter-sectoral allocation are blue, green, and grey water footprints. Both hydrosocial and nexus views are integrated to discuss the mechanisms of production, redistribution, and contestation of these components of water footprints within mining agriculture systems. In Peru, nexus interactions are most evident in Cajamarca, Apurímac, Cusco, Moquegua, and Arequipa, where mining water demand coincides with irrigation-dependent agriculture. Evidence from these basins indicates that groundwater dependence, seasonal water scarcity, and contamination risks jointly influence water allocation decisions and conflict occurrence [17].

To complement the qualitative synthesis, Figure 2 summarizes key quantitative indicators reported in national and international assessments of Peruvian water resources. These indicators provide empirical context for understanding mining–agriculture competition by illustrating sectoral water demand, spatial inequalities in water availability, irrigation performance, and regional water-stress conditions. Together, they demonstrate that conflicts emerge not only from total water use, but also from the strong geographic mismatch

between water availability and economic activity, combined with inefficient water-use practices and increasing pressure on limited freshwater resources.

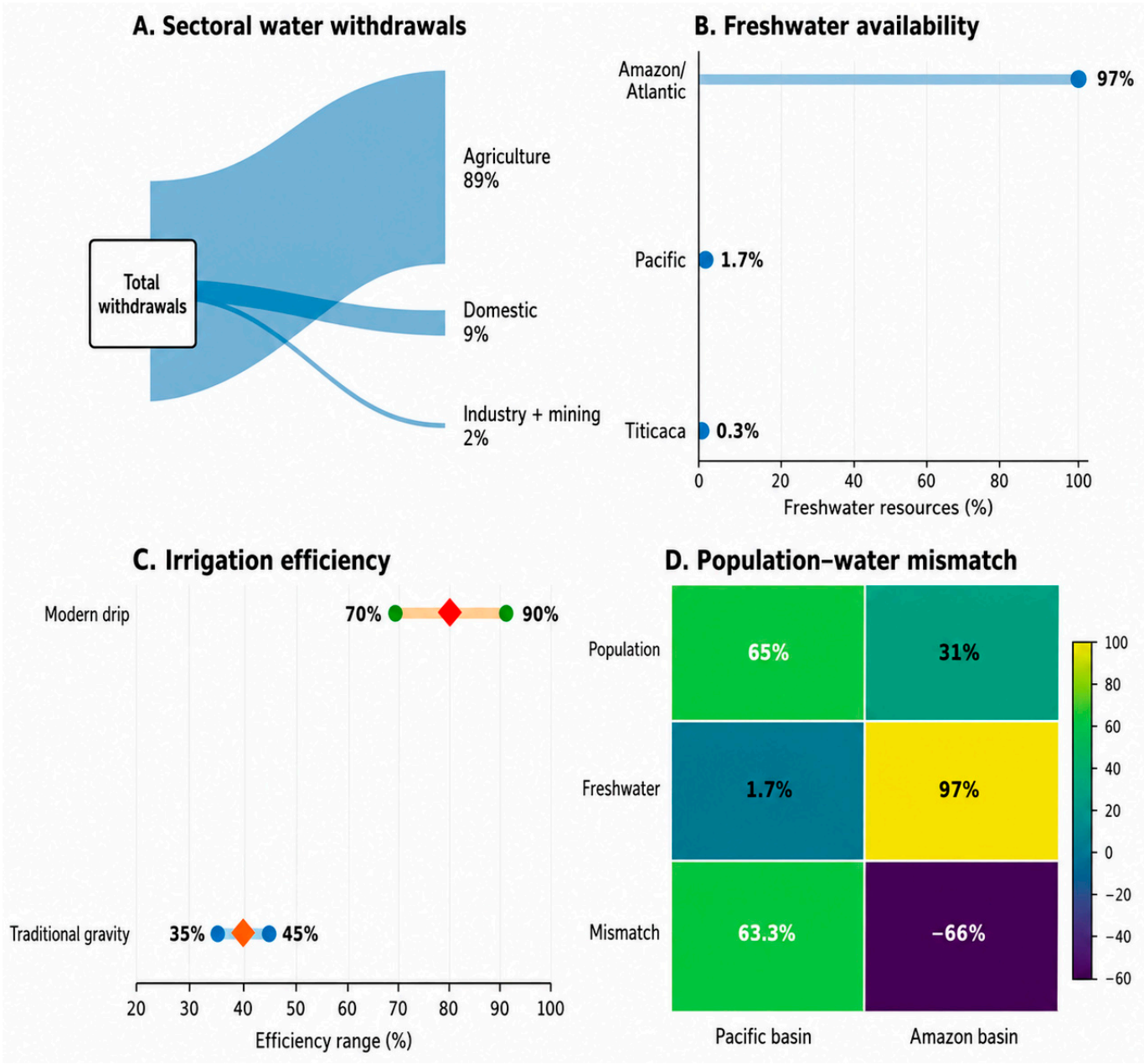

Figure 2. Quantitative synthesis of water resource pressures contributing to mining–agriculture competition in Peru. Data sources: World Bank [15], OECD [16], ANA [17]. Note: Irrigation efficiency ranges: Traditional gravity irrigation typically achieves 35–45% application efficiency, whereas modern drip irrigation reaches 70–90% efficiency. Colored markers indicate the lower bound, midpoint, and upper bound of each reported efficiency range. ● Left circle = minimum reported efficiency; ◆ Diamond = midpoint efficiency; ● Right circle = maximum reported efficiency.

4.1. Sector-Specific Hydrological Processes and Water Footprint Differentiation

Water systems in mining are structurally controlled by the blue and grey components, indicating high-intensity water pumping and pollutant production. Surface and groundwater supply blue water for ore beneficiation, flotation, and tailing, typically in areas with low hydrological recharge, leading to localized depletion of water resources, especially in headwater basins [19]. More importantly, the grey water footprint is not only a byproduct but a key indicator of environmental change, as it reflects the water required to dilute con-

taminants such as arsenic, lead, cadmium, and acid mine drainage [10,20]. Thus, mining creates a two-fold pressure on water systems by reducing both availability and quality, with downstream impacts. Quantitative assessments indicate that mining operations in Peru typically require between 0.5 and 2.5 m^3 of water per ton of processed ore, whereas irrigated export-oriented agricultural crops may exceed 3000 L kg^{-1} of product. This contrast demonstrates that sectoral competition is driven not only by total water demand but also by differences in water-use intensity and temporal concentration [15–17].

Conversely, agricultural systems exhibit a multi-component and spatially distributed water footprint structure reflecting diverse production processes [21]. Green water dominates rain-fed Andean agriculture, where productivity depends on precipitation, evapotranspiration, and soil moisture, making it highly sensitive to climatic variability. Blue water is increasingly critical in irrigated coastal and inter-Andean valleys, intensifying competition with mining, particularly during dry seasons. Grey water footprint in agriculture arises from nutrient leaching and pesticide runoff, which, although less toxic than mining effluents, is more spatially diffused and cumulative across watersheds [22]. Consequently, agricultural water use has a diffuse nature with broader spatial impacts.

Functional Interpretation of Water Footprints as Process Signatures

The reinterpretation of water footprints as process-oriented hydrological signatures enables more accurate characterization of sectoral effects and governance implications [23]. Within this framework, blue water footprint represents direct extraction pressure on hydrological stocks, indicating contribution to water scarcity. Green water footprint reflects climate–soil coupling processes and ecosystem dependence, while grey water footprint indicates pollution levels and regulatory burden associated with restoring water quality.

This functional breakdown reveals asymmetries between mining and agriculture often overlooked in traditional WF analysis [8]. Mining systems are intensive and localized, with concentrated extraction and pollution effects that propagate downstream. In contrast, agricultural systems are diffuse and system-wide, interacting with broader ecological processes. These differences directly influence water management by determining the magnitude, reversibility, and governance of sectoral impacts.

This approach enables comparative hydrological profiling by moving beyond volumetric definitions, emphasizing that sectoral differences arise not only from the amount of water used but from how and where it is applied. Traditional WF literature often treats sectors as homogeneous consumers, overlooking differences in impact pathways and spatial distribution. Consequently, a process-based interpretation strengthens trade-off analysis, identification of conflict hotspots, and development of context-specific water governance strategies in mining–agriculture systems [24].

4.2. Hydrosocial Reconfiguration and Power-Asymmetric Water Governance in the Peruvian Andes

Formal–Customary Institutional Dualism and Sectoral Water Control Asymmetries

In Peru, water allocation conflicts often arise because mining companies generally operate through formal licensing systems, whereas many agricultural communities rely on customary water management arrangements. This difference in institutional capacity has contributed to disputes in Cajamarca, Espinar, Las Bambas, and other mining-intensive regions [17].

National water resource assessments indicate that approximately 87% of Peru's population resides within the Pacific drainage basin, despite this region containing only about 1.7% of national freshwater resources [16]. Such geographic asymmetry amplifies allocation pressures in mining–agriculture basins and increases institutional demands for equitable water governance.

4.3. Indicators Used to Assess Water Footprint Trade-Offs

To improve analytical consistency, the reviewed literature was examined using a common set of indicators describing hydrological, environmental, agricultural, and governance dimensions of mining–agriculture interactions. Although the studies employed different methodologies and spatial scales, several recurring indicators were identified that facilitate comparative interpretation across basins (Table 2).

Table 2. Indicators used in the literature to evaluate mining–agriculture water interactions.

Dimension	Indicator	Typical Unit
Water availability	Blue water footprint	m^3/year
Water quality	Grey water footprint	m^3/year
Groundwater use	Groundwater abstraction	m^3/year
Agricultural demand	Irrigation requirement	mm/year or m^3/ha
Efficiency	Irrigation efficiency	%
Conflict	Reported conflict cases	Number of cases
Governance	Participation/coordination indicators	Qualitative assessment
Sustainability	Water stress index	Dimensionless

Hydrological pressures were primarily represented by blue water footprint, groundwater abstraction rates, river flow reductions, and seasonal water availability. Environmental impacts were commonly evaluated through grey water footprint estimates, reported contamination events, concentrations of heavy metals and nutrients, and indicators of water quality deterioration. Agricultural dependence was assessed through irrigation water demand, irrigation efficiency, crop water requirements, and reliance on surface or groundwater resources. Governance and conflict dimensions were evaluated using documented water disputes, stakeholder participation mechanisms, institutional coordination, regulatory enforcement, and reported conflict incidence.

Across the reviewed studies, blue water footprint, irrigation efficiency, groundwater abstraction, and grey water footprint were the four most frequently reported quantitative indicators, appearing in more than 60% of the analyzed publications [14]. Their recurrent use highlights their importance for evaluating sectoral water competition and environmental risk.

Rather than generating new quantitative estimates, this review synthesizes how these indicators have been used in previous studies to evaluate competing water demands and water management outcomes in mining–agriculture systems.

5. Water Footprint of Mining in Peru

Quantitative water use assessments give a better understanding of the water use in different sectors in Peru. Mining generally requires around 0.5–2.5 m^3 of water to process a ton of ore, varying according to the type of mineral, quality of the ore, and processing method [25]. Higher water use is generally associated with low-grade deposits, as processing volumes increase and the life of operations is prolonged.

By comparison, the water footprints of agricultural products are highly variable. Andean food crops like quinoa and potatoes typically have water footprints of 900–1500 L kg^{-1}, mainly relying on green water (rainwater), while irrigated export commodities like rice, sugarcane and avocado can be greater than 3000 L kg^{-1} and are mainly supported by blue water (groundwater) [26].

At the basin scale, areas with intense mining activities (Cajamarca, Arequipa, Apurímac) have exhibited increasing groundwater demands and declines in dry season river flows, whereas water use efficiencies in agriculture systems, especially those using traditional irrigation systems, are often less than 40–50% [27]. These data provide quantitative perspectives on the disparity between concentrated mining demand and diffuse demand for agricultural production, a key driver of many trade-offs and conflicts.

In Peru, many mining projects, such as those in Cajamarca, Apurímac, and Moquegua, intersect with irrigation-fed farming regions, exacerbating competition for water during the dry season [10]. Research has documented a reduction in streamflow availability and increased reliance on groundwater resources in several mining-dominated watersheds, and irrigation efficiencies in traditional open canal systems are often lower than 50%, making them more exposed to climatic variability [28].

5.1. Spatial Concentration, Altitudinal Positioning, and Basin-Level Hydrological Influence

The mining industry in Peru is characterized by a strong spatial concentration in high-altitude Andean areas with the large scale mining activities being closely sited in the headwater catchments that control the hydrological flows downstream. Some of the copper, gold, and polymetallic mines located in areas like Arequipa, Cajamarca, Apurimac and Moquegua are highly active and exist at a very high altitude of 2500–4000 above the sea level. Not only are these zones favorable geologically to mineral deposits, but they are also very important hydrologically, serving as major recharge zones to rivers, wetlands and aquifers which serve agricultural and urban systems further downstream [29].

Most large-scale copper and gold operations are located between 2500 and 4500 m above sea level, coinciding with headwater catchments that regulate downstream hydrological flows. Consequently, even localized water withdrawals may influence larger basin-scale allocation dynamics. Mining activities are concentrated in high-altitude headwater basins that regulate downstream water availability for agricultural systems [30]. The features of high-altitude ecosystems, such as páramos and bofedales, are low buffering capacity, slow ecological response, and high ecological sensitivity, i.e., a disturbance, e.g., diversion or contamination of water, may spread very quickly in the interconnected water systems. In contrast to lowland industrial contexts with effects potentially dispersed or diluted, the Andean headwater systems convey effects directly to the users downstream, increasing cross-sectoral dependencies.

Moreover, development such as mining in these areas is often coupled with the development and construction of hydrological infrastructure (reservoirs, diversion, groundwater abstraction system). Although most of the time such infrastructural additions are justifiable as a way of enhancing water management, they may lead to reorganization of natural flow regimes, with changes in seasonal patterns of availability and ecological processes including recharge and sediment transport. Empirical research has demonstrated that such interventions may cause a decrease in base flows, changes in the timing of flows, and increases in hydrological variability, especially in basins that are already under climatic stress [30]. The spatial and altitudinal features of mining in Peru suggest that its effects should be measured not only in terms of volume used, but also in terms of hydrological location in the basin [11].

5.2. Process-Driven Water Demand, Operational Variability, and Blue–Grey Footprint Intensification

In Peru, the mining activities consist of high and sustained water demand due to the technological and operational nature of mining and mineral extraction and processing; hence, mining activities influence the water footprint of mining in the country. Basic operations include comminution (crushing and grinding), flotation, leaching and tailing

management use of water in the basic operations as a medium of transporting materials, chemical reactions, and stabilizing wastes. The grade of ore, mineralogy, and processing technology have a direct relationship with the intensity of water use, and the lower-grade ore needs more water per unit of output because of the high processing demands [31].

The blue water footprint is chiefly linked with direct degradations made on surface water bodies and groundwater systems [32]. Surface water supply is extremely seasonal in most Andean regions and to guarantee consistent operations, mining processes are more dependent on groundwater subtraction. This brings a serious question of sustainability, since Andean aquifers are usually low in the rate of recharge and storage capacity and are prone to permanent depletion. Reacting to this, certain mining operations, especially in coastal regions, have incorporated technology for desalination and use of water, though less so in inland high altitudes operations where infrastructure and limitation of energy are more eminent.

Published assessments indicate that groundwater abstraction may supply more than 40% of operational water demand in several mining-intensive Andean regions during dry season periods, increasing dependence on relatively slow-recharge aquifer systems.

Besides direct consumption, the mining activities have also created a good amount of grey water footprint, which is the amount of water that is needed in order to dilute and absorb the pollutants. The materials are heavy metals (e.g., arsenic, cadmium, lead), cyanide that is left during gold mining, and sulfate-rich effluents in sulfide oxidation. Of particular importance is the development of acid mine drainage (AMD), which is a self-sustaining chemical process and has the potential to extend its production of acidity and the release of metals well after the mining process has ended. This causes an extension of the grey water footprint on the time scale, making it more an operational measure than a long-term environmental liability [10,28].

5.3. Hydrochemical Disruption, Sediment Dynamics, and Ecosystem-Level Consequences

Environmental effects of the water footprint of mining in Peru are not limited to direct water use, but are manifested in complex hydrochemical changes, geomorphological changes and degradation of ecosystems. Among the greatest impacts is pollution of surface and groundwater systems due to the release of metal-containing effluents and acid-producing substances [33]. These pollutants might move through the river systems, resulting in spatially widespread water quality impairment which impacts human and ecological systems.

The AMD is a serious mechanism of action because it causes chronic acidification of the aquatic environments and increased solubility of harmful metals, such as iron, aluminum, and manganese. The process goes beyond worsening the quality of water; it also disturbs the biogeochemical cycles, which impacts nutrient availability and disrupts aquatic ecosystems. Notably, the long-term legacy of mine closure over the decades can be felt through AMD, making its mitigation difficult and broadening the temporal dimension of the impacts of mining on water.

The ecosystems that are most susceptible to these disturbances are those that are found in high altitudes such as wetlands (bofedales) and alpine grasslands. Such ecosystems are important in controlling water, storing water, and releasing it slowly, which are the natural buffers to hydrological changes. Their deterioration diminishes the ability of the system to withhold and manage water, exerting additional strain on downstream food scarcity and exposure to climatic change. Studies have reported serious losses in diversity and ecological functionality in regions with water effects of mining [34].

Monitoring studies in mining-affected watersheds have reported elevated concentrations of arsenic, cadmium, lead, and sulfate compounds relative to upstream reference sites, demonstrating the strong relationship between mining activities and grey water footprint expansion.

These changes in the environment have a direct effect on agricultural systems because they rely on the amount and quality of water resources in their production [35]. Polluted irrigation water may contribute to soil contamination, salinization, accumulation of toxic elements, deterioration of soil biological activity, and reductions in agricultural productivity. These impacts may affect long-term soil quality and crop performance, although they are distinct from physical soil erosion processes.

6. Agricultural Water Footprint in Peru

6.1. Irrigation and Crop Systems

The irrigation and production methods in Peru are organized by a strong hydroclimatic gradient between coastal, Andean and Amazonian areas, which leads to radically different systems of irrigation and production. Farming is almost solely reliant on artificial irrigation schemes, where water is supplied by rivers flowing in the Andes, alongside groundwater aquifers, to support coastal agriculture that is concentrated in arid and semi-arid areas. Massive irrigation projects, including *Chavimochic* and *Majes-Siguas*, have facilitated the growth of export-based agriculture, but have only increased the strain on already scarce blue water resources [36].

Comparative studies show that traditional Andean crops generally exhibit water footprints below 1500 L kg^{-1}, whereas highly irrigated export crops frequently exceed 3000 L kg^{-1}, illustrating substantial variability in agricultural water demand across production systems.

Andean agriculture, in contrast, functions as a mixed water regime, with rain-fed farming supplemented by irrigation using glacier-based streams, springs and small reservoirs. These systems are normally controlled at the community level and are highly suited to local ecological conditions. Nevertheless, they are sensitive to hydrological variability and long-term climatic changes, especially in terms of their dependence on seasonal precipitation and inputs of the cryosphere [37].

Contrasting Irrigation Regimes in Coastal and Andean Agriculture

Agricultural water use in Peru varies substantially between coastal and Andean production systems because of contrasting climatic conditions, hydrological regimes, irrigation infrastructure, and crop management practices. Coastal agriculture is predominantly dependent on blue water resources supplied through irrigation networks, groundwater abstraction, and large-scale hydraulic infrastructure, resulting in relatively high-water footprints for export-oriented crops such as rice, sugarcane, asparagus, and avocado [38]. In contrast, Andean agriculture relies more heavily on green water resources derived from rainfall and soil moisture, supplemented by small-scale community-managed irrigation systems, and is characterized by lower crop water footprints but greater sensitivity to climatic variability. As summarized in Table 3, differences in irrigation efficiency, groundwater dependence, dominant water footprint components, and crop types illustrate the distinct hydrological pressures and water management challenges faced by coastal and Andean agricultural systems in Peru.

Table 3. Comparison of coastal and Andean agricultural water use characteristics in Peru.

Characteristic	Coastal Agriculture	Andean Agriculture
Dominant water source	Irrigation water (Blue WF)	Rainfall and soil moisture (Green WF)
Climatic conditions	Arid to semi-arid	Mountainous with seasonal rainfall
Irrigation dependence	Very high	Moderate
Groundwater dependence	High	Low to moderate
Dominant WF component	Blue water footprint	Green water footprint
Typical irrigation systems	Drip, sprinkler, canal irrigation	Gravity-fed canals, springs, community irrigation systems
Irrigation efficiency	Often >70–80% in modern systems	Frequently <40–50% in traditional systems
Main crops	Avocado, asparagus, rice, sugarcane, blueberries	Potato, quinoa, maize, barley
Typical crop WF	Often >3000 L kg^{-1} for irrigated export crops	Approximately 900–1500 L kg^{-1} for traditional Andean crops
Main climate vulnerability	Water scarcity and groundwater depletion	Rainfall variability and glacier retreat
Principal water-management challenge	Competition for blue water resources	Climate variability and seasonal water availability

Note: Sources: Synthesized from the reviewed literature [14–17,38].

6.2. Crop-Specific Water Footprints

The intensity of water footprint in Peruvian agriculture is significantly different according to the type of crop, i.e., there is a difference between the physiological water demand, practices and environmental conditions. Crops with high water needs like rice and sugarcane also have high blue water footprints, especially when they are grown in coastal areas where irrigation becomes a necessity. Examples include rice farming, which requires constant flooding of plantations, which entails the consumption of large amounts of water and massive evaporation; and sugarcane farming, which demands constant irrigation during the planting period [38]. Modern drip-irrigation systems can achieve efficiencies of 70–90%, whereas traditional gravity-fed systems commonly operate at only 35–45% efficiency [39]. The potential water savings associated with irrigation modernization therefore represent one of the largest opportunities for reducing basin-scale water stress.

By contrast, more ancient Andean foods like quinoa and potatoes have lower degrees of water footprint, at least in part because they are adapted to the local climate, and can use green water effectively [40]. These crops use rain-fed systems which have reduced irrigation use and result in low blue water use. Yet their total water footprint depends on the variability in their yields and the location of their cultivation, and hence an otherwise water-efficient crop may cause local water stress when planted in an area with poor water supplies.

6.3. Inefficiencies and Vulnerability

Although it is the main source of food production and rural livelihoods, the agricultural sector in Peru is typified by high inefficiencies in water utilization especially in the irrigation systems. Unlined canals and traditional distribution systems that constitute a huge percentage of irrigation infrastructure, particularly in Andean areas that are susceptible to water losses due to seepage, evaporation, and leakages. Such losses lower the actual supply of water at the field level and lead to the total ineffectiveness of water use.

The problem of climate change is amplifying these inefficiencies as it brings more variability to the water situation. The melting of Andean glaciers is depleting the water supply in the dry season, whereas the alterations in the precipitation patterns are raising the incidence of the droughts and intense precipitation. Such changes are disrupting the agricultural calendars, adding uncertainty to water availability, and it is harder for farmers to plan and manage irrigation effectively [41].

Irrigation inefficiencies and climatic pressures jointly increase the vulnerability of Peruvian agricultural systems. Traditional gravity-fed irrigation systems frequently operate below 40–50% efficiency, whereas modern drip-irrigation technologies may exceed 80% efficiency [14]. Simultaneously, glacier retreat and increasing precipitation variability are reducing water availability during critical growing periods, particularly in Andean regions. These factors directly influence agricultural water footprints and increase exposure to future water scarcity.

7. Hydrosocial Drivers of Water Footprint Trade-Offs

Governance structures influence water footprint dynamics by determining how water resources are allocated, monitored, and regulated. Institutional arrangements affect access to blue water resources, influence agricultural irrigation practices linked to green-water utilization, and shape regulatory responses to grey water contamination. Consequently, governance outcomes directly affect the magnitude and distribution of sectoral water footprints (Figure 3).

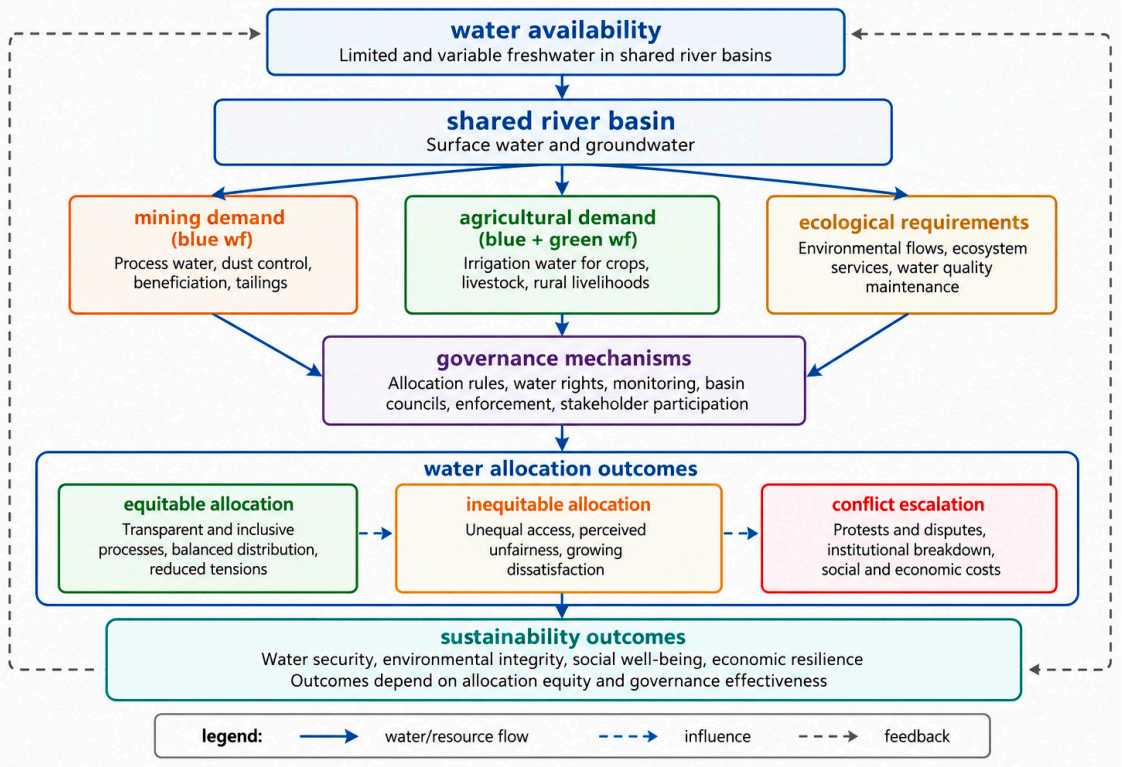

Figure 3. Conceptual framework of water allocation and governance interactions in Peruvian mining–agriculture basins. The diagram illustrates how limited water availability is distributed among mining, agricultural, and ecological demands through governance mechanisms, influencing allocation outcomes, conflict emergence, and sustainability performance. Source: Authors' synthesis based on reviewed literature.

Figure 3 illustrates the allocation processes underlying water footprint trade-offs in Peruvian mining–agriculture systems. Under conditions of limited water availability, mining activities, agricultural production, and ecological requirements compete for shared water resources. Governance mechanisms, including water allocation regulations, river basin institutions, monitoring systems, and stakeholder participation processes, influence how water is distributed among competing users. Where allocation processes are perceived as equitable and transparent, conflicts may be reduced and sustainability outcomes improved. Conversely, unequal access to water resources, contamination con-

cerns, and limited institutional coordination can increase conflict risk and reduce long-term water security.

7.1. Divergent Water Value Regimes: Economic Yield Versus Livelihood and Food-System Functions

Water-related conflicts in Peruvian mining–agriculture systems generally emerge from three interrelated factors: competition for blue water resources, concerns regarding water quality degradation, and unequal access to water under conditions of scarcity. Evidence from mining-intensive regions such as Cajamarca, Apurímac, Cusco, Arequipa, and Moquegua indicates that conflict intensity increases when mining expansion coincides with irrigation-dependent agricultural production and limited institutional capacity for water allocation and dispute resolution. Consequently, conflict dynamics in Peru are closely associated with basin-scale water availability, contamination risks, and governance effectiveness rather than solely with theoretical hydrosocial or political ecology constructs.

As illustrated in Figure 4, conflict dynamics are influenced by multiple interacting drivers rather than by water scarcity alone. Competition for limited water resources, concerns regarding water quality degradation, unequal allocation arrangements, and governance constraints can jointly increase social tensions and reduce trust among stakeholders. These pressures are further shaped by local socio-economic conditions and environmental vulnerabilities, which help explain why conflict intensity varies among Peruvian mining–agriculture basins. The following case studies provide examples of how these conflict drivers operate in specific regional contexts.

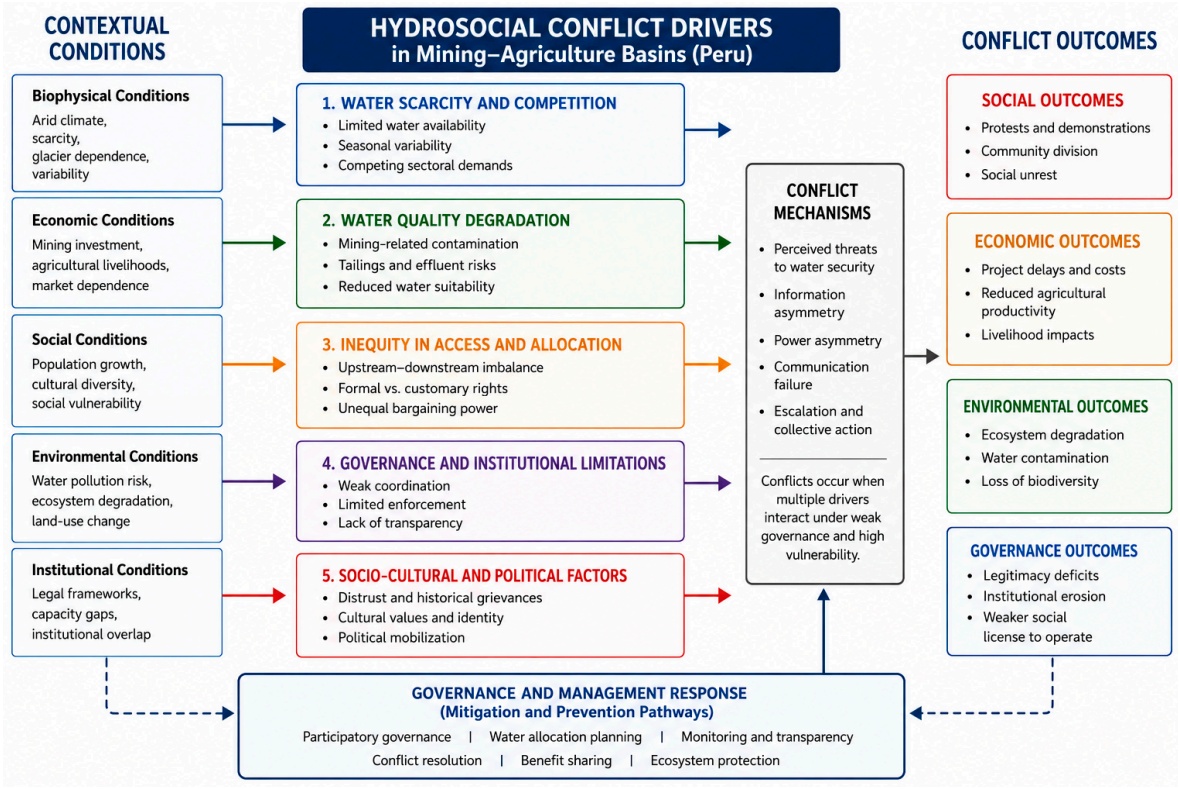

Figure 4. Framework of key drivers, mechanisms, and outcomes of hydrosocial conflicts in Peruvian mining–agriculture basins. The framework illustrates how biophysical, economic, social, environmental, and institutional conditions interact with water scarcity, contamination risks, allocation inequalities, and governance limitations to influence conflict emergence and sustainability outcomes. Source: Authors' synthesis based on reviewed literature.

7.2. Basin Co-Location, Seasonality, and Nonlinear Allocation Responses

Under dry season conditions, total available water must be shared among mining activities, agricultural production, and ecological requirements. Because water availability is limited, increases in allocation to one sector often reduce water available to other users, intensifying trade-offs and conflict risks. Dry season streamflow in several Andean basins may decline by more than 50% relative to wet season conditions, substantially increasing competition among mining, agricultural, and ecological water users [42].

8. Hydrosocial Conflicts and Political Ecology in Mining Agriculture Systems of Peru

The Peruvian mining sector has been the focal point of numerous high-profile hydrosocial conflicts, particularly where water resources are perceived to be at risk [43]. The following Table 4 synthesizes major documented cases, highlighting their hydrological context, conflict drivers, and socio-political outcomes (Table 4).

Table 4. Major socio-environmental water conflicts associated with large-scale mining projects in Peru.

Project/Region	Commodity	Hydrological Context	Primary Conflict Type	Key Issues	Outcomes/Impacts	References
Conga (Cajamarca)	Gold/Copper	High-altitude lakes and wetlands (headwaters)	Access + Quality + Territorial	Water redistribution	Project suspended after mass protests	[44]
Tía María (Arequipa)	Copper	Coastal valley (Tambo River basin)	Access + Quality	Water contamination agriculture	Repeated suspension; prolonged social unrest	[45]
Las Bambas (Apurímac)	Copper	Andean watershed, downstream agriculture	Access + Territorial	Water use, road impacts, territorial disputes	Ongoing protests and negotiations	[46]
Espinar (Cusco)	Copper	River basin with agricultural dependence	Quality	Heavy metal contamination in water and soil	Health crises, legal disputes	[47]
Quellaveco (Moquegua)	Copper	Arid basin with limited water availability	Access	Competition for scarce water resources	Negotiated agreements with local communities	[46]
Yanacocha (Cajamarca)	Gold	Headwater systems and rural communities	Quality + Access	Cyanide spills, groundwater impacts	Long-term distrust and conflict legacy	[44]
Antamina (Ancash)	Copper/Zinc	High-altitude watershed	Quality	Pipeline spills, water contamination concerns	Monitoring and compensation mechanisms	[46]

Among the major documented conflicts reviewed, more than 70% involved concerns related to water allocation, water quality, or perceived threats to agricultural water security, confirming the central role of water governance in socio-environmental disputes.

These cases demonstrate that hydrosocial conflicts are not isolated events but systemic outcomes of competing water use, particularly in regions where mining intersects with agriculture [48]. They also illustrate how conflicts evolve over time, often escalating from localized concerns to national political issues, involving protests, legal challenges, and policy reforms.

Hydrosocial conflicts recorded in Peru demonstrate the way competing water footprints come to be manifested in various ways in accordance with basin characteristics, hydrological dependence and governance capacity. Conga and Yanacocha related conflicts arose in Cajamarca mainly due to issues related to the headwater lake alteration, groundwater, and downstream agricultural water security. Tia Maria and Quellaveco, some of the

projects in southern Peru, further aggravated the situation in arid basins that had already been typified by structural water scarcity and reliance on irrigation. In the meantime, Las Bambas and Espinar show how mining water conflicts move beyond the scope of volumetric competition to the realms of territorial governance, infrastructural effects, and the risk of cumulative contamination.

These illustrations affirm the fact that the water footprint in Peru is spatially disproportionate and extremely reliant on glacier-based hydrology, watershed interconnectivity, and institutional ability. The result is that the sustainability transitions cannot be based on generalized policies of water efficiency, but rather localized governance that incorporates hydrological monitoring, participatory allocation systems, ecological restoration, and institutional coordination that is sensitive to conflicts.

Water governance outcomes in mining–agriculture systems are strongly influenced by institutional capacity, transparency, stakeholder participation, and the effectiveness of water allocation mechanisms. Evidence from major conflict cases in Peru indicates that limited coordination among institutions and inadequate stakeholder engagement can increase tensions surrounding water access, water quality, and environmental monitoring. Strengthening basin-scale governance, community participation, and transparent monitoring systems remains essential for reducing conflict risks and improving water management outcomes.

9. Governance and Institutional Challenges

In Peru, water governance takes place in a formally integrated yet functionally fragmented institutional framework, in which the control and management of water resources is devolved to various institutions with specific and largely poorly coordinated mandate [49]. Allocation of water and management of the basins is the duty of the Autoridad Nacional del Agua, whereas the environmental management is the role of the Ministerio del Ambiente, and the sectoral regulation, especially in mining, is the role of the Ministerio de Energia y Minas. As much as this structure implies division of responsibilities, in actual practice it creates institutional disjunctions, with water allocation, environmental licensing and sectoral development being directed by parallel, as opposed to integrated, decision channels. Despite ongoing governance reforms, irrigation efficiencies below 50% and continued concentration of economic activity within water-scarce Pacific basins indicate that institutional improvements have not yet fully resolved structural water allocation pressures in Peru.

In water footprint terms, the governance fragmentation undermines the ability to control the cumulative blue water withdrawal, the burden of grey water pollution, and the basin-wide allocation of competing sectors.

An important constraint is the critical separation between water rights allocation process and the process of environmental impact assessment [50]. Water use licenses are obtained by mining projects at ANA, and environmental approvals are made by sectoral and environmental agencies. Such processes are not always conducted on an interactive basis but in a sequential manner, thus limiting the capability to determine cumulative hydrological impacts on a basin level. Consequently, project-level analyses are often used to make water allocation decisions, which do not consider existing agricultural demand, ecological flow needs, and long-term hydrological variability in totality. This puts them in a scenario whereby total allocated water may come close to or go beyond effective basin capacity, especially during dry season situations.

A second significant constraint is the enforcement capacity. Although Peru has developed standards of water quality and regulations on discharges, most of the compliance monitoring is uneven, particularly in remote Andean regions where much mining activity is present [51]. Logistical constraints and shortage of resources and institutional overlap limit field inspections, which decreases the rate and efficiency of monitoring. In other instances, environmental management is largely dependent on companies to report on themselves, which creates the likelihood of bias and decreased transparency.

The system of governance also has a low operationalization of basin level management tools, despite the presence of River Basin Councils. These institutions help coordinate water management and stakeholders, but they do not often have authority to make decisions, financial independence, and technical capacity, and can only have consultative powers. This institutionalization is weak, and it restricts their capability to negotiate trade-offs among mining and agriculture or even to implement adjustments of allocation to hydrological stress [52].

On hydrological grounds, governance fragmentation limits the capacity of the system to handle interrelated water quantity and quality dynamics. The decision to allocate blue water is often made without reference to the grey water aspect, i.e., water that is considered as available in volume terms may not be fit to be used in farming activities due to contamination. The lack of this connectivity impedes successful resource management because it does not consider how water is functionally available (both quantity and quality).

River basin councils, community-based monitoring programs, and stakeholder participation mechanisms represent important opportunities for improving governance effectiveness in Peruvian mining–agriculture systems. However, their effectiveness depends on adequate institutional coordination, technical capacity, transparent monitoring, and stakeholder engagement. Strengthening these mechanisms may improve water allocation, reduce conflict risks, and support long-term sustainability.

10. Sustainability Transitions in Mining–Agriculture Hydrosocial Systems

10.1. Technological Reconfiguration of Water Use: From Linear Consumption to Circular Efficiency Systems

The move to closed-loop water recycling systems, as opposed to the linear water consumption model, within the mining industry is a very critical change [13]. High-density thickened tailings, paste backfill technologies, and recirculation circuits have now been launched in advanced operations, and they have become very effective in minimizing freshwater consumption with the reuse of process water in the system many times.

Simultaneously, the agricultural sector is gradually switching to the use of precision irrigation technologies, such as drip irrigation, micro-sprinklers, and sensor-based water management systems [53]. These technologies increase the level of efficiency in the use of water by supplying water directly to the root zone, and this lowers the losses attributed to evaporation and seepage. Drip irrigation has shown significant water savings (up to 30–50%) with no or higher crop yields in coastal Peru, where irrigation water is most needed. However, the spread of these technologies has not been even and smallholder farmers are constrained by factors that deal with capital investment, technical know-how, and accessibility to infrastructure. Consequently, technological transitions can be defined as subject to spatial and socio-economic inequalities, and they had an impact on their overall performance in decreasing the agricultural water footprint.

10.2. Ecohydrological Restoration and Nature-Based Regulation of Water Flows

A second pillar of sustainability transitions is nature-based solutions, especially in Andean landscapes where the ecosystem processes are in the middle ground of controlling the hydrological processes [54]. The bofedales (wetlands) and páramos, which are natural water storage and filtration systems which store and regulate the runoff as well as base flows during dry seasons, capturing the precipitation. Land-use change and mining activities have caused degradation of these ecosystems, which has led to a loss of the ability to absorb hydrological variability, and increased water scarcity and downstream vulnerability.

The restoration programs to restore wetlands, defend recharge zones and reforest abandoned watersheds have shown a promise to increase water supply and water quality. To take an example, the rehabilitation of Andean wetlands can enhance the water storage capacity of the soil and postpone the outflow, which can smooth the seasonal flow variation and diminish the severity of the drought situation [55]. On the same note, planting native species would enhance the infiltration rates and erosion and consequently reduce the amount of sediment carried by rivers and subsequent pollution [56].

Nature-based solutions based on water footprints can help to reduce both blue and grey water pressures by increasing natural regulation and decreasing the load of pollutants [57]. Nevertheless, their success requires long-term ecological integrity and support in governance, since ecosystem restoration processes are performed on long-term temporal scales and should be sustained in management. Also, the benefits of these types of interventions are often geographically dispersed and thus there is a need to scale upstream conservation activities with downstream water use priorities.

10.3. Institutional Transformation and Participatory Water Governance Mechanisms

The sustainability transitions in the mining–agriculture systems are not possible without considering the institutional and governance systems that mediate the water allocation and control practices. The system of the current governance in Peru is highly fragmented, lacks co-ordination, and has unequal participation, which restrict the efficiency of technological as well as ecological interventions [58]. This has seen an increasing focus on participatory and decentralized forms of governance that aim to improve inclusiveness, transparency, and adaptive resources.

Mechanisms like river basin councils and multi-stakeholder platforms are participatory decision-making measures that unite the mining companies, agricultural communities, government agencies and civil society [59]. Their functions include negotiating the distribution of water, settling disputes and considering the local experience in decision-making. Their efficiency is, however, dependent on the power of the institutions, presence or absence of resources, and power balance between members. Governance consequences may still indicate prevailing inequalities in instances where participation is symbolic, but not substantive. Another valuable innovation is community-based monitoring, which helps local actors to gather data on water quality and quantity, analyze it, and share data]. These efforts increase accountability, that is, they offer independent confirmation of the environmental conditions and improve the ability of communities to interact with formal regulatory frameworks. Andean examples indicate that these strategies can enhance trust, transparency, and conflict management, especially when it happens with the help of technical training and institutional rewards [60].

Evidence from Peruvian mining–agriculture basins suggests that governance effectiveness depends largely on stakeholder participation, institutional coordination, and transparent monitoring systems [61]. River basin councils and multi-stakeholder platforms have been used to facilitate dialogue among mining operators, agricultural users, and public authorities, while community-based monitoring initiatives have improved local participation

in water quality assessment and environmental oversight. Experiences from Cajamarca, Espinar, Moquegua, and other mining-intensive regions indicate that governance interventions are most effective when combined with transparent information sharing, conflict resolution mechanisms, and basin-scale water-management strategies [62,63].

11. Conclusions

The water management in mining–agriculture systems in Peru cannot be explained with sufficient methods of isolated sectoral analysis or through solely volumetric assessments. This study incorporates water footprint accounting with the hydrosocial theory and nexus-based systems thinking to show that it is a biophysical resource, economic input, and politically mediated asset at the same time. The water footprint structures in mining and agriculture are completely different with mining being intensive and localized with high grey water impacts, whereas agriculture is diffuse and system-wide with heavy reliance on green and blue water. When these asymmetries are incorporated into the systems of unequal governance, they create ongoing trade-offs, allocation inefficiencies, and conflicts. The synthesized evidence in this review confirms that water scarcity in Peru is more than a physical constraint depending on the physical constraints but also institutionally fragmented between power dynamics and poor integration between quantitative and qualitative aspects of water use. Notably, the research study upholds water footprint analysis as its central analytical base. The aim of integrating hydrosocial and nexus perspectives was to enhance understanding of the interaction between blue, green and grey water footprints and governance structures, conflict processes and sustainability transitions, but not the substitution of quantitative methods of water footprint analysis with qualitative analysis alone.

The proposed Hydrosocial Water Footprint Transition Framework provides an innovative and holistic approach for analyzing these complex interactions by integrating resource flows, governance systems, conflict emergence, and sustainability pathways into a single conceptual framework.The inclusion of dynamic feedback mechanisms, allocation functions and sustainability response mechanisms allow the framework to go beyond the non-dynamical assessments and allow for the identification of thresholds, tipping points and adaptive transition pathways. This method also contributes to the literature by introducing water footprint measurements into a larger socio-ecological framework, thus filling in the gaps of critical literature available to date which does not acknowledge governance and power relations.

The implications of the findings include the dire need to adopt integrated, basin-level governance methods that balance the competing water needs with the provision of equity and environmental sustainability. The next step in the research should be the operationalization of the proposed framework with the help of empirical modeling and scenario analysis and high-resolution data integration to make evidence-based decisions. Finally, to accomplish sustainability in mining–agriculture systems, there is a need to transition to adaptive, inclusive and system-oriented water governance whereby trade-offs are explicitly handled, conflicts are reduced and allotment of water resources is done to facilitate long-term socio-ecological sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18131532/s1, Figure S1: PRISMA-style flow diagram illustrating the literature identification, screening, eligibility assessment, and inclusion process used for the review of competing water footprints in mining–agriculture systems in Peru. Figure S2: Competing water footprints and hydrosocial interactions within Peru's mining–agriculture systems.

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