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Dynamics of Water and the Páramos

Understanding sustainability issues in Andean irrigation systems

análisis de los desafíos de sostenibilidad en sistemas de riego de los Andes

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Abstract

Irrigated agriculture consumes approximately 70 % of the world's freshwater, making sustainable water delivery imperative. Strategies for sustainable water use, incorporating technical, agronomic, managerial, and institutional advancements are urgently needed, especially in developing countries such as those in the Andes, where agriculture is crucial for socioeconomic growth. Identifying the main issues related to sustainability of irrigation systems are essential, but limited information exists, as most studies focus on small groups of systems rather than a diverse range. To address this, we analyzed data from surveys conducted in 2022 by the Regional Government of Azuay, Ecuador, with representatives of water user associations. We adapted the methodology outlined in the United Nations World Water Development Report 2023 to evaluate these mountain irrigation systems, considering socioeconomic, water resources, users and governance factors. Our study included 235 irrigation systems with irrigated areas ranging from 0.5 to 2400 hectares, classified into four groups: (a) micro (<10 ha), (b) Small (10-100 ha), (c) Medium (100-500 ha), and (d) large (>500 ha). The most urgent issues identified include water allocation not proportional to the irrigated area, agricultural production no longer being the primary source of income, and non-compliance with management rules and fee payments. Most of the issues are due to weak governance. Our findings highlight the complexity of irrigation systems and the barriers to their development. This comprehensive analysis provides insights for building effective policies and emphasizes the importance of regular assessments, which should include systematic monitoring, data collection, and the development of performance indicators.

Keywords: Water allocation, Governance, Decision-makers, Water User Associations, Irrigated agriculture.

Resumen

La agricultura de regadío consume aproximadamente 70 % del agua dulce mundial, por lo que resulta necesario asegurar un suministro sostenible. Se requieren estrategias para el uso sostenible del agua, que incorporen avances técnicos, agronómicos e institucionales, especialmente en países en desarrollo en los Andes, donde la agricultura es crucial para el crecimiento socioeconómico. La identificación de temas relacionados con la sostenibilidad en sistemas de riego es esencial, pero la información existente es limitada, ya que la mayoría de los estudios se centran en pocos sistemas. Se analizaron los datos de encuestas realizadas en el 2022 por el Gobierno Provincial del Azuay, Ecuador, con representantes de juntas de riego. También, se adaptó la metodología del Informe Mundial sobre el Desarrollo del Agua 2023 para evaluar estos sistemas, considerando los factores socioeconómicos, recursos hídricos, usuarios y gobernanza. Nuestro estudio incluyó 235 sistemas de riego con áreas irrigadas que varían de 0,5 a 2400 hectáreas, clasificados en cuatro grupos: (a) micro (<10 ha), (b) pequeño (10-100 ha), (c) mediano (100-500 ha) y (d) grande (>500 ha). Los problemas más urgentes identificados incluyen la asignación de agua no proporcional al área irrigada, la producción agrícola que ya no es la principal fuente de ingresos, el incumplimiento de reglamentos y el pago de tarifas. La mayoría de estos problemas se deben a una gobernanza débil. Nuestros hallazgos destacan la complejidad de los sistemas de riego y las barreras para su desarrollo. Este análisis integral proporciona ideas para políticas efectivas y enfatiza la importancia de evaluaciones regulares, que deben incluir monitoreo sistemático, recolección de datos y desarrollo de indicadores.

Palabras clave: Asignación de agua, Gobernanza, Tomadores de decisiones, Juntas de riego, Agricultura de regadío.

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1 Introduction

Water resources are not only essential for sustaining various sectors of society, including food production, energy generation, and the provision of goods and services, but they also serve as crucial economic drivers in many regions (Sauer et al., 2010; United Nations, 2021). Beyond its essential necessity, the significance of water has become a fundamental factor that influences economic activities and overall societal development. In particular, the way in which agriculture uses freshwater resources is important to ensure availability across diverse sectors and to safeguard ecosystems (FAO, 2020). Agriculture is the largest consumer of water globally and uses approximately 70 % of the total water withdrawn for irrigation purposes (United Nations, 2021; Wada et al., 2016; Wisser et al., 2008), highlighting the urgent need for effective management strategies, especially in developing countries where agriculture is pivotal for socio-economic growth (Li et al., 2020), such as in the Andes.

Moreover, agriculture is considered to have the lowest value-added on a global scale, particularly in low- and middle-income countries (United Nations, 2021), which underscores the challenges faced in optimizing its economic contributions. Concerns arise regarding the enhancement of agricultural water productivity while ensuring food security (Bjornlund et al., 2023), particularly in supporting farmers who rely heavily on irrigated agriculture for their livelihoods (United Nations, 2023). Irrigation has emerged as an important driver of yield growth and has played an essential role in facilitating substantial increases in production (Alexandratos and Bruinsma, 2012), thereby underlining its significance in agricultural development.

To achieve sustainable irrigation management, comprehensive strategies encompassing technical, agronomic, managerial, and institutional dimensions are imperative (Gutierrez et al., 2014; Sirimewan et al., 2021a). Irrigation systems involve multiple actors that require interactions between stakeholders to achieve full functionality (van Rooyen et al., 2017). Moreover, irrigation demands extensive infrastructure and expertise to facilitate water access, storage, and conveyance to the schemes, while ensuring equitable distribution to farmers' fields, and environmental needs (Parry et al., 2020). Effective management of water resources, distribution, rights, and maintenance operations involves both local communities and institutional frameworks (van Rooyen et al., 2017).

Social cooperation within communities plays a key role in sustainable irrigation management. Historically, community-managed irrigation systems in the Andes have demonstrated the effectiveness of collective action and collaboration (Hoogesteger, 2015). This is the case of Water User Associations (WUAs), which manage irrigation resources through participatory approaches and have emerged as significant facilitators of collective action, mobilizing communities towards common goals (Hoogesteger, 2013, 2015). Therefore, establishing participatory cooperation among stakeholders is strategic for facilitating water governance and decision-making processes (FAO, 2016; United Nations, 2023).

WUAs often face issues such as inadequate implementation strategies and unclear delineation of roles and responsibilities, among others (United Nations, 2023). These obstacles can significantly impede the effective functioning of WUAs and undermine their ability to achieve sustainable irrigation management goals. One of the most pressing problems is the lack of data and information of all aspects concerning the operation, management and impact of irrigation systems, including the farmers' well-being. There are only a few studies about irrigation management and socioeconomic development in the Andes. Communal et al. (2016) and Hoogesteger (2013) examined changes in water distribution management among small-scale farmers and analyzed community cooperation in managing irrigation systems in the northern Ecuadorian Andes, emphasizing the significance of local initiatives and community engagement in sustainable water resource management practices. Meanwhile, Gutierrez et al. (2014) and Leroy et al. (2022) provided broader perspectives on irrigated agricultural development and institutional changes within WUAs in the Andean region. Leroy (2019) focused on the perception of socioeconomic causes of water scarcity within WUAs in Colombia and Venezuelan páramos. Together, these studies highlight the need for integrated approaches that consider both the local contexts and broader institutional frameworks.

Most existing studies in the Andes have focused on a single or on small groups of irrigation systems, making it challenging to understand the organization, functionality and sustainability of irrigation in the region, especially given the large variations in irrigated area and number of users in those systems. There is limited information on the current physical conditions of irrigation schemes, coordination between users and management, operation and maintenance of the systems, the impact of droughts, and the effect of irrigation on users' livelihoods. Addressing these knowledge gaps is essential for developing comprehensive strategies for sustainable irrigation management in the region.

To our knowledge, no study has focused on a wide range of irrigation systems and how WUAs manage them. To address this gap, this study analyzes and identifies the main sustainability problems faced by users within a large sample of mountain irrigation systems, aiming to provide relevant information to decision-makers for informed interventions.

We adapted the methodology outlined in the United Nations World Water Development Report 2023 (United Nations, 2023), which provides a comprehensive categorization of factors influencing the performance of WUAs and the level of cooperation among stakeholders involved in irrigation systems. While the scope of this study is not to assess the performance of WUAs per se, we used this categorization framework to critically examine the management and sustainability of irrigation systems. We considered the following factors: socioeconomic conditions, water resources, governance, and user dynamics. Our analysis is based on a dataset obtained by the Azuay Regional Government through surveys conducted in 2022 with representatives of 235 WUAs across the province in the southern Ecuadorian Andes.

2 Materials and Methods

2.1 Study Region: Mountain irrigation systems of Azuay

The Azuay Province, located in southern Ecuador, encompasses two zones: the Inter-Andean region, limited by the western and eastern Andean cordilleras, and the western coastal region (Tenesaca et al., 2017). Covering an area of 8,309.6 km^2, Azuay exhibits significant bioclimatic diversity, resulting in seven distinct bioclimatic zones. These include ecosystems, such as páramo grasslands, evergreen montane forests, and areas influenced by human activities (Tenesaca et al., 2017). The regional climate is marked by considerable variability. Research in the Paute Basin demonstrates significant spatiotemporal differences, particularly in precipitation, where mean annual totals range from approximately 660 mm in inter-Andean valleys to over 3400 mm on eastern cordillera slopes receiving substantial Amazonian moisture (Celleri et al., 2007). Temperature also shows significant variation with altitude and exposure, creating diverse thermal conditions from cold, humid páramos to milder lower valleys (Campozano et al., 2016; Celleri et al., 2007).

The provincial territory is predominantly characterized by steep slopes, which limit agricultural mechanization, particularly owing to irrigation challenges. There are risks of water and wind erosion, as well as soil mass movement. Less than 15% of the provincial territory consists of plains and rolling hills, which are generally stone-free and suitable for various types of agricultural mechanization, with some restrictions (GPA, 2018).

The rural areas of Azuay are known for their agricultural and livestock economies (GPA, 2018). In Azuay, agricultural practices are mainly focused on self-consumption and are frequently combined with other non-agricultural activities (GPA, 2019). The III National Agricultural Census highlights the cultivation of various crops in Azuay, including intercropping of maize and bean, potatoes, broad beans, peas, carrots, and diverse fruit trees. These agricultural practices largely use traditional methods with minimal technological implementation (GPA, 2019). In terms of cultivated area, Azuay covers approximately 205,281 hectares dedicated to agriculture and livestock (ESPAC, 2023). The irrigation systems in the province are public, communal and private, which are often managed by WUAs.

2.2 Data sources

The data used in this study were obtained from the inventory of irrigation systems conducted by the provincial government of Azuay in 2022. Prior to this inventory, the available information pertaining to irrigation systems within the province was scattered across various sources and governmental institutions, thus lacking a consolidated, complete and coherent dataset. In line with the strategic objectives of the provincial irrigation plan, the task of data collection was undertaken to formulate policies to ensure effective water management specifically for irrigation purposes. In addition, the design of the survey involved collaboration among an interdisciplinary team from the local government, a non-governmental organization, consultants and the University of Cuenca.

While approximately 400 irrigation systems have been reported to be operational within the province, the information at hand pertains solely to 267 irrigation systems. Furthermore, of these 267 systems, 168 irrigation systems have been georeferenced, as depicted in Figure 1. Certain data gaps emerged across various questionnaire topics stemming from respondents' limited access to information and logistical challenges. Considering these factors, we specifically used a dataset of 235 irrigation systems, ensuring a reliable foundation for the analysis.

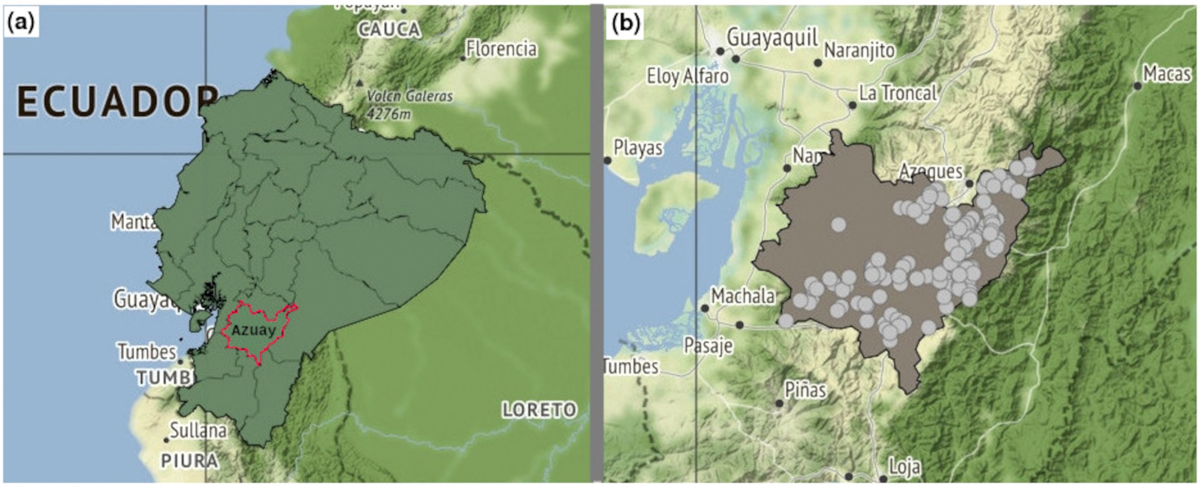

Figure 1. (a) Location of Azuay Province in Ecuador. (b) Irrigation systems in Azuay Province. The colored dots on the map indicate the position of 168 georeferenced irrigation systems.

The survey targeted representatives from each WUA. Data gathering was conducted *on-site* using the open-source data collection and survey tool Kobo Toolbox (*www.kobotoolbox.org*). Kobo Toolbox is a globally used platform for data collection, management, and visualization, facilitating offline data collection even in remote locations with limited connectivity. The surveys included an extensive questionnaire of 400 questions covering 11 topics, including general information about location, water use, infrastructure, operational aspects, socio-administrative management, and prevailing irrigation practices.

2.3 Classification of irrigation systems

To understand the main issues encountered by users of irrigation systems, we classified these systems into four groups according to the size of the irrigated area. Since the irrigated areas can vary between 0.5 ha and 2400 ha, this classification allowed the analysis of comparable systems, to assess their primary challenges and strengths. The irrigation systems were categorized as follows: a) Micro Systems, with an irrigated area of less than 10 hectares; b) Small Systems, with an area from 10 to 100 hectares; c) Medium Systems, with 100 to 500 hectares; and d) Large Systems, with an irrigated area exceeding 500 hectares.

We analyzed various aspects related to irrigation and examined the role of WUAs to provide a comprehensive overview of the sustainability of irrigation systems. This analysis included assessing water quality perception, water allocation, water distribution, water sources for intake, infrastructural issues within the irrigation systems, role of the operator, water fees, water rights, and the establishment of boards, among others. By comparing these aspects, we identified key areas that require attention.

Based on the survey responses, we discussed the main challenges faced by these systems. This study represents a first attempt to understand the current state of irrigation systems, and assess their sustainability.

2.4 Water allocation and dependence on agricultural activities

Some of the most pressing questions are related to the differences in water distribution, basically the number of users/farmers that have water rights and the overall water allocated to the systems. These issues arise from the fact that farm sizes can vary widely from very small plots to big farms; thus, it is unknown the real number of water rights holders in each irrigation system and whether there is a relationship between them and total water allocation. We used scatter plots to examine the relationship between the number of users and the water allocated based on their irrigated area.

To evaluate potential differences in irrigated area per user and allocated discharge per user across irrigation system size categories, we employed the non-parametric Kruskal-Wallis test. This approach was chosen because the data violated assumptions of normality (Shapiro-Wilk test, $p < 0{,}001$) and homogeneity of variances (Levene's test, $p < 0{,}001$). Post-hoc pairwise comparisons using Dunn's test with Bonferroni correction were performed to identify specific group differences, with statistical significance set at $\alpha = 0{,}05$. Additionally, we explored potential associations among key variables (irrigated area, number of users, water rights cost, water fees) using Spearman's rank correlation.

Another frequent question is how agricultural and livestock production in these systems contribute to the farmers' subsistence. To investigate the reliance of farmers on these productive activities for their livelihoods, we employed boxplots. This approach enabled us to visually depict the variability and extent of dependence on agriculture and livestock across different irrigation systems.

2.5 Comparison of socioeconomic, water resources, governance and users' factors among irrigation systems

We extracted the data from the surveys to study the characteristics and factors that influence the functionality of WUAs and the sustainability of irrigation systems, as outlined in the United Nations World Water Development Report 2023. Table 1 provides an overview and summary of the information extracted from the surveys, which were analyzed and compared for each category of irrigation system (i.e., micro, small, medium, and large). This analysis allows to identify the most urgent priorities for addressing issues surrounding the sustainability of irrigation systems, with in turn affects food and water security.

3 Results and Discussion

3.1 Water allocation and dependence on agricultural activities

Discharge from streams and rivers is the main source of water for irrigation (71 % of systems), followed by water springs (26 %), lakes (2 %) and ground water (1 %). The most common systems are communal (90 %), followed by private systems (7 %) and public (3 %). Most irrigation systems are operated by WUAs (78 %) locally called "Juntas de riego", which are non-profit community organizations tasked with providing irrigation and drainage services according to Article 48 of the Regulation of the Water Resources and Water Use Law, 2015 (Correa, 2015). WUAs coordinate the administration, operation, and maintenance of the irrigation systems. According to the classification of irrigation systems, 62 medium systems have the highest total number of users (8433). Small systems also have an important number of users (121 systems with 6781 users). On the other hand, only 11 large irrigation systems serve a substantial number of users (5348). Conversely, there are 41 micro systems which 1,468 users, indicating the prevalence of smallholdings.

Table 1. Factors affecting the sustainability of irrigation systems. Modified from United Nations World Water Development Report 2023.

Factor	Information
Socioeconomic	Main crops, Production for self-consumption, Primary productive activity, Target markets for sale, Added-value in products, Marketing challenges, Production losses associated with irrigation practices, Affiliation to rural producers' organizations, Harvest and transportation losses.
Water resources	Irrigation systems located above 3000 m a.s.l, Flow rates, Irrigation method, Reservoir systems, Irrigation infrastructure status, Water conveyance, Maintenance frequency, Water quality, Reduction in water flows, Increased frequency of droughts/floods, Water shifts in dry seasons.
Governance	Water usage fees, Water distribution rules, funding for restoration projects, Type of organization, Legal status, Water rights, Support and cooperation, Regulations.
Users	Problems in the irrigation system, Operation and maintenance of the system, Training of operators, Training of other users, Social capital, administrative, managerial and accounting skills.

We found an unequal water distribution among users, regardless of their irrigated area. Indeed, the large scatter in Figure 2 illustrates a lack of relationship between the irrigated area per user and the allocated water discharge (l/s) per user. This disparity is evident across all system categories, where the number of users varies disproportionately for the same water flow and the allocated flow varies significantly for the same number of users. Some systems exhibit a very low water allocation per hectare, rendering them unsustainable. This situation may have arisen due to various factors, such as an increase in the number of users after the system's construction, or inaccurate measurements during the water allocation study. Conversely, some systems have a higher than necessary allocated discharge. It is imperative for local authorities to oversee these systems to address the unequal water distribution among users. Continuous monitoring is essential to ensure the sustainability of the systems.

The Kruskal-Wallis test revealed significant differences in allocated discharge per user across irrigation system size categories ($\chi^2 = 40{,}43$, $df = 3$, $p < 0{,}001$). Post-hoc Dunn's tests (Bonferroni corrected) indicated that small and micro systems differed significantly from large and medium systems ($p < 0{,}05$), while no significant difference was found between large and medium systems ($p = 0{,}489$). Similarly, irrigated area per user varied significantly across system categories ($\chi^2 = 112{,}97$, $df = 3$, $p < 0{,}001$). Post-hoc comparisons showed that users in small and micro systems had significantly different irrigated areas compared to those in large and medium systems ($p < 0{,}001$), again with no significant difference between large and medium systems ($p = 0{,}9425$). These results indicate that irrigation system size is significantly associated with the per-user distribution of both irrigated area and allocated water, suggesting greater disparities in smaller systems.

Spearman correlation analyses among irrigated area, number of users, water rights cost, and water fees yielded only weak associations, indicating no strong linear relationships between these variables in this dataset.

The livelihood of farmers depends on agricultural and livestock activities to varying extents (Figure 3). Medium and large systems demonstrate a more direct reliance on productive activities, whereas small and micro systems exhibit wider variation. From the 235 irrigation systems analyzed, 151 (64 %) relied on agricultural activities for more than 70 % of their livelihoods. Specifically, this includes 43 medium systems with 5,167 users, 77 small systems with 3,785 users, 7 large systems encompassing 2,593 users, and 24 micro systems covering 952 users. This analysis underscores the significance of irrigated agriculture in the rural economies of mountainous regions. However, while these numerous small and micro systems are evidently crucial for local livelihoods, their overall productivity and long-term economic sustainability may be constrained by common challenges. Research by Berhe et al. (2022) on small-scale irrigation in Ethiopia, for instance, reveals that many such schemes operate below their design potential due to persistent issues in operation, maintenance, and the capacity of local managing institutions, often exacerbated by limited financial resources.

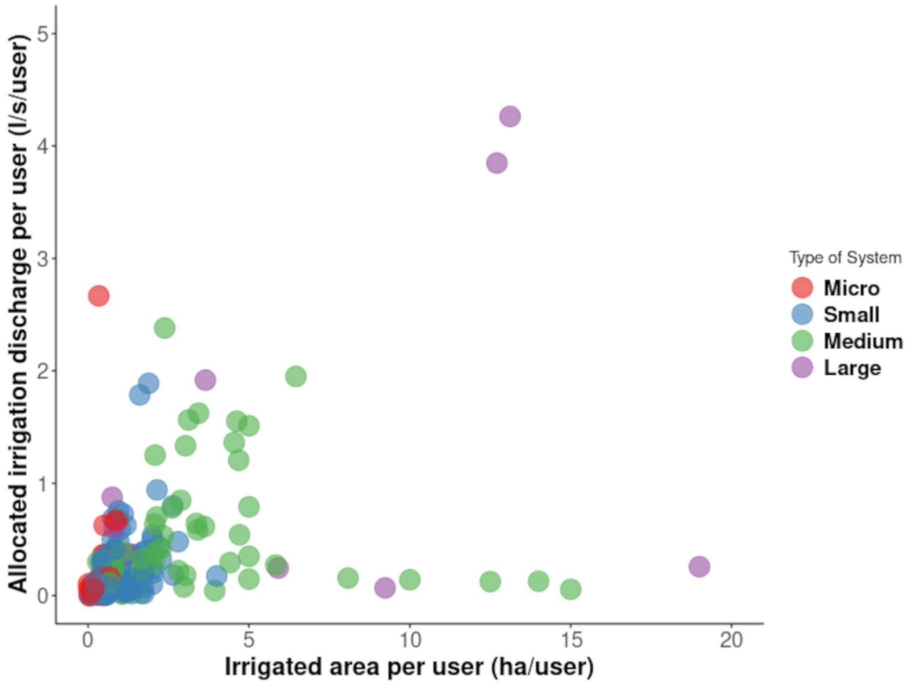

Figure 2. Relationship between irrigated area (ha/user) and allocated water discharge (l/s/user) for each category of irrigation system.

This suggests that the potential of the micro and small systems in our study area to substantially enhance agricultural output and secure lasting economic benefits for users could be undermined if these prevalent operational and financial difficulties, also highlighted by Berhe et al. (2022), are not effectively addressed. Conversely, only 10% of irrigation systems depend on agricultural and livestock activities for 25% or less of their livelihoods. This low dependence may be attributed to the presence of peri-urban systems and migration of people to bigger cities, potentially leading to land abandonment and jeopardizing food security. Additional factors, such as the younger population's preference for non-agricultural employment, may also contribute to this trend. Many users or farmers may seek alternative means of subsistence by working in nearby urban areas. In order to understand these issues and the actual conditions of irrigation systems, it is crucial to continue data collection, emphasizing additional relevant, complementary, and critical information to support informed decision-making.

3.2 Comparison of socioeconomic, water resources, governance and users' factors among irrigation systems

Socioeconomic factors influencing irrigation systems are described in Table 2. The primary crops across all systems include pastures, intercropped maize beans, and vegetables. Except for medium systems, the percentage of land used for pastures surpasses that for crops. This could be explained by the fact that most of the production area in Azuay is intended for natural and cultivated pastures (GPA, 2018). Livestock activities, particularly dairy production, hold significant economic importance in Azuay, accounting for 8 % of the national milk production (GPA, 2018). However, dairy production yields are low, indicating the need to strengthen management practices to make it more competitive and equitable for producers.

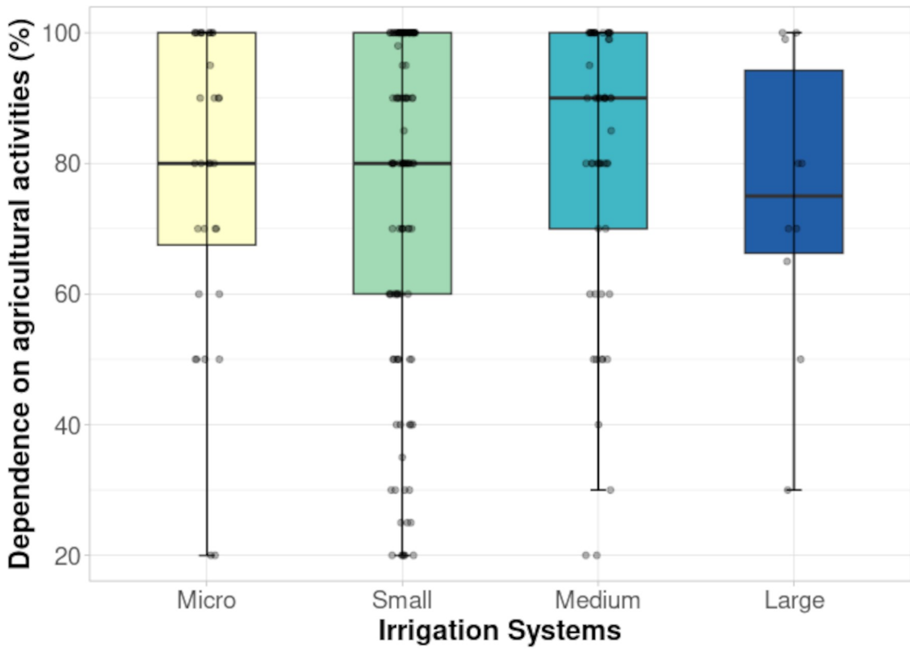

Figure 3. Livelihood dependence on agricultural and livestock activities for each category of irrigation systems.

Farmers stated that the main factor contributing to production losses is the lack of irrigation water. In small systems, there is a concern about the misuse of water, which worsens the situation. People from medium systems perceive that droughts further affect production. Effective water management practices can mitigate the risks associated with water scarcity and distribution inequalities, which are critical for sustaining agricultural livelihoods and rural economies. Decision-makers need to prioritize interventions that enhance irrigation infrastructure, promote sustainable water use, and support the overall resilience of the agricultural sector.

Productive activities are primarily subsistence-level, even among irrigation systems with larger irrigated areas (i.e., small, medium, and large), with most production intended for self-consumption. This situation contributes to increased rural migration and challenges to local food security. On the other hand, the prima-ry challenge faced by all irrigation systems is securing a fair price for their products to ensure profitability. A key issue is the absence of clear policies and incentives for supporting small-scale farmers in obtaining fair prices for their products. Middlemen frequently purchase produce at significantly low prices, capturing a disproportionate share of the profits. The lack of fair trade exacerbates the situation, compelling producers to accept reduced prices to avoid product loss, thus perpetuating the advantageous position of middlemen in the market chain. This finding strongly aligns with research by Rebaï (2017), who identifies the economic vulnerability of family farmers in Azuay as stemming principally from their lack of market access and subordination to intermediary actors, severely limiting their commercial integration. Indeed, the persistence of such market-related challenges for small agricultural associations, despite policies aiming to support them, is also highlighted by Gómez-Ceballos et al. (2021) in Ecuador, where significant difficulties in how markets operate for these associations were found to hinder their economic progress.

Table 2. Socioeconomic factors influencing sustainability for each category of Irrigation Systems. Multiple responses allowed; totals may exceed 100 %.

Socioeconomic factors	**Micro systems (<10 ha)**	**Small systems (10-100 ha)**	**Medium systems (100-500 ha)**	**Large systems (>500 ha)**
Main Crop %	Pasture (83 %)	Pasture (97 %)	Pasture (84 %)	Pasture (100 %)
Second Crop %	Vegetables (81 %)	Intercrop maize/ beans (83 %)	Intercrop maize/ beans (84 %)	Intercrop maize/ beans (73 %)
Production for self-consumption	Yes (73 %)	Yes (65 %)	Yes (60 %)	Yes (55 %)
Main Target market[mo]	Cantonal (76 %)	Cantonal (69 %)	Cantonal (84 %)	Cantonal (82 %)
Added value in products	No (76 %)	No (74 %)	No (81 %)	No (64 %)
Marketing challenges[mo]	Low prices (73 %)	Low prices (82 %)	Middlemen (81 %)	Low Prices / Middlemen (64 % each)
Primary production loss factor[mo]	Lack of water (71 %)	Lack of water (58 %)	Lack of water (57 %)	Lack of water (73 %)
Affiliated to Producer Organizations	7 %	13 %	13 %	18 %
Harvesting and transportation losses	Yes (10 %)	Yes (16 %)	Yes (21 %)	Yes (9 %)

[mo] = Respondents could select multiple options for factors marked (mo) in the original survey; percentages reflect selection frequency for each option. "Main" indicates the most frequent response.

Another prevalent issue is the lack of organization and opportunities to participate in productive associations, which have the potential to facilitate direct market access. This observed weakness resonates with Rebaï (2017) central argument that strengthening farmer organizations is fundamental for overcoming market access barriers and improving rural-urban linkages. According to Rebaï (2017), reinforcing these organizations is crucial not only for improving economic integration and negotiation power with public authorities but also for potentially fostering collaboration among farmers to enhance productive systems and natural resource management (Ostrom, 1990). Notably, the Provincial Government of Azuay has made efforts to establish direct markets, aiming to benefit producers and ensure equitable remuneration for their endeavors. This approach not only enhances long-term profitability for farmers but also ensures a consistent supply of high-quality products for consumers.

Table 3 presents factors related to water resources. Users of irrigation systems state that the status of irrigation infrastructure ranges from good to regular. However, in larger systems, infrastructure is often rated as bad to regular, indicating a need for increased maintenance expenses. Larger systems report the need of more frequent maintenance, approximately every month, in contrast to smaller systems, where maintenance is more sporadic (6 to 12 months). The frequent need for maintenance (mainly for sediment cleaning and repairing leaks) underscores the problems of large systems. These insights have important management implications, suggesting that large systems face additional costs and that targeted actions should be taken to understand and address specific issues in these systems.

While over 55 % of farmers perceive the water quality from their irrigation systems as good, cases of medium quality are often associated with organic residues from agriculture and livestock near water sources. Regarding farmers' perception of water flow variations, a significant decrease in flows is reported, particularly in larger irrigation systems. This reduction in flows is linked to the expansion of the agricultural frontier and, in some cases, the clearing of native vegetation and primary forests to grow pasture for livestock breeding. These impacts mainly affect the lower part of the catchment area, with users in this zone experiencing greater impacts compared to those in the headwaters. In any case, a degrading water quality and a reduction in discharge could negatively impact food security and have to be taken in consideration by policy makers and water managers.

Indeed, the degradation of resources like water and soil can ultimately undermine the viability of agricultural systems and livelihoods. This aligns with findings by López-Carr et al. (2017), who identified soil degradation as a key driver of out-migration from rural communities in Guatemala, suggesting a critical link between resource health and the potential for population displacement or system abandonment if such degradation is not addressed. Despite the high altitude (over 3000 m.a.s.l), few irrigation systems still function, particularly for micro and small-scale farming, where irrigation is inappropriate due to the conservation status of these zones.

Table 3. Assessment of Water Resources factors influencing sustainability in four types of Irrigation Systems. Multiple responses allowed; totals may exceed 100 %.

Water Resources factors	Micro systems (<10 ha)	Small systems (10-100 ha)	Medium systems (100-500 ha)	Large systems (>500 ha)
Irrigation systems >3000 m a.s.l.	29 %	26 %	16 %	9 %
Main irrigation method[mo]	Sprinkler (68 %)	Sprinkler (74 %)	Gravity-fed irrigation (69 %)	Sprinkler /gravity-fed irrigation (64 % each)
Systems with reservoirs	54 %	46 %	37 %	27 %
Infrastructure status	Good (34 %)	Good (31 %)	Good (24 %)	Regular (27 %)
Main Maintenance frequency	6 months (27 %)	6 months (30 %)	6 months (36 %)	6 months / 1 month (36 % each)
Water quality perception	Good (66 %)	Good (60 %)	Good (68 %)	Good (55 %)
Sediments in irrigation water	Yes (56 %)	Yes (60 %)	Yes (52 %)	Yes (82 %)
Perception of declining water flows	Yes (51 %)	Yes (65 %)	Yes (74 %)	Yes (82 %)
Perceived Main Cause Flow Reduction	Native forest clearing (71 %)	Native forest clearing (79 %)	Native forest clearing (82 %)	Native forest clearing (46 %)
Change of water shifts during dry seasons	No (61 %)	No (82 %)	No (76 %)	No (82 %)
Increased droughts in the past decade	51 %	63 %	76 %	82 %

[mo] = Respondents could select multiple options for factors marked (mo) in the original survey; percentages reflect selection frequency for each option. "Main" indicates the most frequent response.

Another critical concern is the continued reliance on traditional irrigation methods (i.e., not pressurized) that contribute to significant water losses. Moreover, most irrigation systems do not have dams or reservoirs to mitigate the impact of drought, rendering them vulnerable. This susceptibility is corroborated by users' perceptions of increased droughts lately. Despite their awareness of drier seasons, no policies or adaptation strategies have been implemented. This situation highlights a broader challenge in water governance. Research in Central Asia by Abdullaev et al. (2025), for example, underscores that addressing water scarcity effectively requires more than pursuing efficiency alone; it demands a shift in governance. They argue that true adaptation necessitates dismantling significant existing barriers and fundamentally reorienting water governance approaches to build robust, long-term preparedness for an uncertain future. Complementing this view, Sirimewan et al. (2021b) emphasize, from a socio-technical perspective, that while adopting improved technologies like sprinkler or drip irrigation is vital for sustainable water use, these technical solutions cannot succeed in isolation. Their research in Sri Lanka highlights that the successful uptake of such efficient practices also depends critically on supportive social, management, and regulatory environments.

Governance issues in the irrigation systems are examined in Table 4. The absence of clear regulations is evident within irrigation systems, particularly concerning water-use fees, water distribution and water-rights acquisition. It was surprising to find that a significant number of WUAs lack legal recognition (29 – 44 %). This lack of formal status presents several drawbacks. Without legal recognition, WUAs face challenges in managing their systems effectively, securing funds for system improvements, and engaging with NGOs and other external organizations. Legal recognition is crucial for WUAs to operate with full authority, access financial resources, and collaborate with stakeholders to enhance the sustainability and efficiency of their irrigation systems.

Another unexpected finding is that in a large number of irrigation systems, farmers do not pay water fees. According to Ecuadorian law specified in Article 116 of Regulation of the Water Resources and Water Use Law (Correa, 2015), all water users are mandated to pay fees for water usage. This finding highlights the weak enforcement of the regulations. While over 40 % of systems do not impose fees at all, it is remarkable that large systems comply with this regulation. The implementation of these fees aims to promote the independence of WUAs in managing irrigation systems and reducing their dependency on external institutions for infrastructure investment and maintenance. This independence ultimately aims to enhance the efficiency of water distribution.

A shift towards participatory governance is vital, incorporating principles of fair pricing designed to cover comprehensive costs like planning, climate adaptation, and maintenance (WWAP, 2019). Integral to the success of such governance, however, is the active prevention of management inefficiencies, which are identified as key factors that can increase system vulnerability and hinder proper water management (Pacheco-Peña et al., 2023).

Moreover, more than 70 % of irrigation systems operate independently, without collaborative arrangements with external institutions. This independence, combined with non-compliance with water use fees, often hinders effective irrigation management. While a significant majority of WUAs express a willingness to engage with external institutions, there are noticeable instances where WUAs are hesitant to participate in collaborative efforts. The reluctance observed in some WUAs is a critical factor for consideration by decision-makers. To navigate this, decision-makers should focus on two key actions: 1) actively and promptly supporting WUAs that are willing to collaborate, including fostering opportunities for NGOs, and 2) initiating a dialogue process designed to understand and address the reservations of those WUAs that are hesitant. Academia plays a pivotal role in addressing these issues. When tackling these governance challenges, decision-makers essentially choose from a spectrum of action, as FAO (2024) suggests. Options range from working within existing power structures to implementing more transformative changes that alter the influence of different actors (e.g., strengthening WUAs). This choice between incremental adjustment and structural reform is critical, affecting the feasibility and ultimate impact of governance improvements.

We found that farmers can acquire water use rights through various means. In addition to payments, water rights can be obtained by contributing labor to construct irrigation systems or through inheritance. In larger systems, participation in the legalization of irrigation systems serves as an alternative route for obtaining water rights. Additionally, the tying of water rights to either land or individuals leads to inequitable payments, as individuals' rights can be utilized across multiple plots. Moreover, the water allocated to users' plots does not consider the plot area, potentially resulting in either insufficient or excessive water for agricultural and livestock activities. Addressing these complexities effectively likely requires a multi-criteria analysis within a co-management framework, involving all actors to develop allocation and rights systems that promote both sustainability and efficiency (Rivera, 2016), acknowledging water's role in food sovereignty and local economies (Pacheco-Peña et al., 2023).

Table 4. Assessment of Governance factors influencing sustainability in four types of Irrigation Systems. Multiple responses allowed; totals may exceed 100 %.

Governance factors	Micro systems (<10 ha)	Small systems (10-100 ha)	Medium systems (100-500 ha)	Large systems (>500 ha)
WUAs paying water usage fees	59 %	65 %	58 %	73 %
Main Water distribution rule	Surface-independent water distribution (49 %)	Surface-independent water distribution (46 %)	Proportional to the surface area (42 %)	Proportional to the surface area (46 %)
WUAs received external catchment funding	No (61 %)	No (74 %)	No (82 %)	No (64 %)
WUAs have legal recognition	56 %	60 %	71 %	64 %
Main Organization Assisting Construction	Regional government (49 %)	Regional government (63 %)	Regional government (63 %)	Regional government (64 %)
Main Definition of water rights	Earned (participation in the construction) (54 %)	Purchased (59 %)	Purchased (60 %)	Purchased (55 %)
Main Type of water rights	Tied to land parcel (49 %)	Tied to land parcel (55 %)	Tied to land parcel (73 %)	Tied to land parcel (73 %)
WUA Willingness to Engage Externally	High (66 %)	High (69 %)	High (69 %)	High (82 %)
Internal Operation Guidelines Exist	Yes (61 %)	Yes (72 %)	Yes (68 %)	Yes (82 %)
Compliance with internal rules	Partially (37 %)	Yes (38 %)	Yes (47 %)	Yes (73 %)
Main Prohibited Social Practice[mo]	Water sharing (88 %)	Exchange shifts (98 %)	Exchange shifts (82 %)	Exchange shifts (100 %)

[mo] = Respondents could select multiple options for factors marked (mo) in the original survey; percentages reflect selection frequency for each option. "Main" indicates the most frequent response.

Despite the presence of internal regulations and internal operation guidelines for the irrigation system, especially in micro and small systems, compliance is often lacking, indicating a deficiency in governance necessary for effective and sustainable management. This lack of proper operation leads to disorganization, particularly in water distribution during water shifts.

Although users within irrigation systems do not exchange water shifts for products, work, or loans, the lack of clear regulations allows a significant percentage of users to access water from others. Water division is often decided by users, particularly in larger systems. This is an important aspect of governance and technical management. Further studies are needed to analyze how these practices can be improved to enhance irrigation management.

Table 5 lists the various user-related parameters. Users in all irrigation systems acknowledge that the main issue is infrastructural problems, which become more pronounced as the irrigation system grows larger owing to sediment accumulation and the high need for constant maintenance. A significant concern is the general absence of trained operators for irrigation systems. When someone is designated for this role, they often lack proper training and rely instead on limited experience. While some users have received training in areas such as technical management; socio-organizational aspects; and administration, operation, and maintenance, very few users in micro, small, and medium systems have accessed this training. In contrast, larger systems seem to have better organizational structures; however, nearly half of them do not have an irrigation operator, and of those that do, more than half are not well trained to perform the task.

Irrigation schedules often occur during both the day and night. This can lead to significant issues in terms of correct water use, particularly when irrigation occurs at night. Water losses are higher in systems where irrigation is not pressurized and lacks automatic control technology. Moreover, they can trigger mass movements and landslides. It is crucial to address these issues by implementing advanced irrigation technologies that allow for precise water control. In addition, establishing clear guidelines and providing training on optimal irrigation practices can help mitigate water waste and prevent landslides. Decision-makers should prioritize the adoption of automated irrigation systems and support initiatives that enhance the technical knowledge of farmers and irrigation system operators.

However, a key strength across all irrigation systems is the social capital that facilitates collective work through mingas for the common good. Indeed, mingas are the primary method for system maintenance and other activities. This reliance on collective action, rooted in local norms of reciprocity and trust, is crucial for the management and adaptation of Andean irrigation systems, a finding supported by research in both the Venezuelan Andes (Leroy et al., 2022) and the Ecuadorian Highlands (Hoogesteger, 2015).

Table 5. Assessment of "Users" factors influencing sustainability in four types of Irrigation Systems. Multiple responses allowed; totals may exceed 100 %.

"Users" factors	Micro systems (<10 ha)	Small systems (10-100 ha)	Medium systems (100-500 ha)	Large systems (>500 ha)
Primary system concern	Infrastructure (42 %)	Infrastructure (63 %)	Infrastructure (58 %)	Infrastructure (91 %)
Primary solution considered	Infrastructure improvement (59 %)	Infrastructure improvement (68 %)	Infrastructure improvement (66 %)	Infrastructure improvement (82 %)
Main Current operation and maintenance issue (mo)	Damage main irrigation canal (59 %)	Damage main irrigation canal (80 %)	Damage main irrigation channel (84 %)	Damage main irrigation canal (91 %)
Irrigation Schedule (Variable Day/Night)	-63 %	-72 %	-87 %	-100 %
System has an operator	No (78 %)	No (82 %)	No (65 %)	No (55 %)
Operator considered qualified	Yes (50 %)	Yes (73 %)	Yes (80 %)	Yes (60 %)
Operator received training	No (100 %)	No (64 %)	No (65 %)	No (40 %)
Other users trained to operate	No (68 %)	No (80 %)	No (71 %)	No (64 %)
Main user training topic received	Administration, operation, and maintenance (17 %)	Administration, operation, and maintenance (15 %)	Administration, operation, and maintenance (8 %)	Technical management of the system (36 %)
Main maintenance method	Collective efforts by users ("minga") (90 %)	Collective efforts by users ("minga") (94 %)	Collective efforts by users ("minga") (89 %)	Collective efforts by users ("minga") (100 %)

mo = Respondents could select multiple options for factors marked (mo) in the original survey; percentages reflect selection frequency for each option. "Main" indicates the most frequent response.
Minga: Word of Quechua origin that refers to a collective effort for the common good.

3.3 Limitations of the study

This study draws upon data from a 2022 survey administered by the Provincial Government of Azuay. While offering valuable regional insights into irrigation systems, this data source carries inherent limitations that should be indicated.

The primary limitation stems from the data collection method. Information was gathered from representatives of WUAs. Although these individuals are generally knowledgeable about their respective systems, their perspectives may not fully encompass the diverse experiences and views of all individual water users. Furthermore, responses could be influenced by their leadership roles, potentially introducing a degree of subjectivity. Consequently, data regarding specific quantitative or potentially sensitive topics, such as individual plot productivity or earnings, might reflect estimates rather than precise figures, as representatives may not possess or share complete information for all members.

Furthermore, the selection of WUA representatives as respondents might introduce a significant gender bias. If these representatives were predominantly male –a common scenario in such organizations– the survey would inherently fail to capture women's perspectives on crucial aspects like participation in decision-making roles or their views on the effectiveness and equity of irrigation system management. Consequently, the results may not fully represent the experiences and viewpoints of the entire user community, particularly concerning gender-specific challenges or priorities.

Despite these constraints, the survey data provides a valuable assessment of the status of irrigation governance and infrastructure in Azuay. The findings successfully identify key challenges and priority areas, offering essential guidance for targeted future research and policy development. This study also highlights the need for subsequent, more systematic data collection, potentially incorporating stratified sampling at the individual user level and methods designed to capture diverse perspectives, to support robust and equitable long-term water resource management.

4 Conclusions

After a comprehensive analysis of the comparative factors among irrigation systems, several critical issues regarding their management and sustainability were identified, requiring continued monitoring and further investigation. Effective governance has emerged as the main concern, as it influences system administration, funding acquisition, fee collection, and long-term stability. Without robust governance structures, these systems are struggling to function efficiently. Equitable water distribution is another significant issue; authorities must update and regulate water delivery to ensure that systems receive the technically required amount from available sources, adopting a technical-environmental approach to water allocation.

Lack of governance further hinders the sustainability of the system. Systems without governance cannot raise the necessary funds for operation and maintenance, establish a technical team for the day-to-day management and advisory roles, create operating rules, or achieve a legal status. The role of the regional government and the Ministry of Agriculture is crucial in supporting these systems by providing ongoing training for operators, legal constitutional support, and access to markets.

Moreover, in a significant number of systems, agricultural production is no longer the primary source of income, thereby putting food security at risk. Addressing this issue requires targeted intervention by public institutions. The system's vulnerability is also evident: if fee collection fails, the system stops operating; if the operator is unavailable, there is no replacement; without operating rules, the procedures are unclear; and in droughts, water scarcity becomes critical.

Systematic monitoring is necessary as the conditions may change. Annual monitoring will help track system evolution, analyze the impact of policies and interventions, and assess the effects of climate and socioeconomic conditions such as migration. Developing performance indicators suited to local realities is essential. By addressing these key areas, decision-makers can take targeted actions to improve the management and sustainability of irrigation systems, ultimately supporting resilience and productivity in the agricultural sector.

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Authors' contributions

G.B.: Conceptualization, methodology, formal analysis, data curation, writing-original draft preparation. R.C.: Conceptualization, methodology, funding acquisition, writing-review and editing.

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