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DYNAMICS OF WATER AND THE PÁRAMOS

COMMUNITY MANAGEMENT AND SUSTAINABILITY IN ANDEAN IRRIGATION SYSTEMS THROUGH INDICATORS OF EFFICIENT WATER USE IN AGRICULTURE

GESTIÓN COMUNITARIA Y SOSTENIBILIDAD EN SISTEMAS DE RIEGO ANDINOS MEDIANTE INDICADORES DE USO EFICIENTE DEL AGUA EN LA AGRICULTURA

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Abstract

Globally, increasing competition for water and the effects of climate change have heightened the need to assess the sustainability of irrigation systems, particularly in strategic ecosystems such as the Andean páramos. However, there is a gap in methodological tools that integrate indicators adapted to community-based contexts and aligned with global frameworks such as the Sustainable Development Goals (SDGs) and the Principles for Responsible Investment in Agriculture and Food Systems (RAI Principles). This study aims to define indicators for evaluating the sustainability of community-managed irrigation systems in Ecuador. The MESMIS framework and the Delphi technique were applied using a participatory approach that involved community leaders, technicians, academics, and students. A total of 31 indicators were defined, organized into seven attributes and five dimensions (environmental, social, economic, political, and technological), and aligned with nine SDGs and seven RAI Principles. The results reveal critical issues related to water use efficiency, governance, equity, and system resilience. The proposed framework enables a comprehensive and context-specific evaluation of irrigation systems and provides a practical tool for public policy design. In conclusion, this research helps bridge the existing methodological gap and reinforces the role of community irrigation systems as key pillars for sustainable and resilient agriculture.

Keywords: MESMIS, páramos, sustainable irrigation, community water management, sustainability indicators.

Resumen

A nivel global, la creciente competencia por el agua y los efectos del cambio climático han acentuado la necesidad de evaluar la sostenibilidad de los sistemas de riego, especialmente en ecosistemas estratégicos como los páramos andinos. Sin embargo, existe un vacío en herramientas metodológicas que integren indicadores adaptados a contextos comunitarios y alineados con marcos globales como los Objetivos de Desarrollo Sostenible (ODS) y los Principios de Inversión Responsable en Agricultura (CSA-IRA). Esta investigación tiene como objetivo definir los indicadores para evaluar la sostenibilidad de sistemas de riego comunitarios en Ecuador. Se consideró la metodología MESMIS y la técnica Delphi mediante un enfoque participativo que incluyó líderes comunitarios, técnicos, académicos y estudiantes. Se definieron 31 indicadores, organizados en siete atributos y cinco dimensiones (ambiental, social, económica, política y tecnológica), articulados con nueve ODS y siete Principios CSA-IRA. Los resultados evidencian puntos críticos en la eficiencia hídrica, gobernanza, equidad y resiliencia de los sistemas. La propuesta permite una evaluación integral y contextualizada de los sistemas de riego, y ofrece una herramienta práctica para el diseño de políticas públicas. En conclusión, se contribuye a cerrar el vacío metodológico existente y se fortalece el rol de los sistemas de riego comunitarios como pilares para una agricultura sostenible y resiliente.

Palabras clave: MESMIS, páramos, riego sustentable, gestión comunitaria del agua, Indicadores de sostenibilidad.

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1 Introduction

The sustainability paradigm has broadened the analytical framework of natural systems by integrating economic, environmental, and social dimensions applicable to agricultural production (González et al., 2006; Guo and Yu, 2022). However, Talukder et al. (2020) question whether sustainable agricultural systems can truly ensure food security, particularly in low-income countries. These authors argue that achieving this goal requires a "sustainable intensification" of resource use, such as water, through advanced technologies that minimize or eliminate adverse environmental impacts, such as rainwater harvesting (Cachipuendo et al., 2024). In this context, irrigation, considered a key system in agriculture, must be evaluated from a sustainability perspective.

Irrigation plays a fundamental role in water and food security (Darzi-Naftchali et al., 2020), and its sustainability should be analyzed in the context of climate change, taking into account factors such as natural resource conservation, technological innovation, and water use efficiency in agriculture (Velasco-Muñoz et al., 2018; Darzi-Naftchali et al., 2020). Irrigation is commonly regarded as a means of production that enhances water management in agriculture (Wang and Wu, 2018), as well as a socio-ecological-technical system that integrates physical, organizational, social, and natural components (Newman et al., 2011). Nonetheless, its management faces technical and financial challenges, especially in contexts where irrigation governance has been transferred from government agencies to farmer associations or private entities (Nagrah et al., 2016; Shalsi et al., 2022). This shift has led to uneven performance and limited practical outcomes (Araral, 2005).

For rural communities, irrigation is not merely an agricultural production tool (Brugnach et al., 2017), but a complex system where nature, community, and infrastructure converge (Cachipuendo Ulcuango et al., 2021). Its operation generates social, environmental, and economic interrelations (Fernald et al., 2012), which are structured within organizations that manage and operate irrigation systems according to each country's legal framework (Herrán et al., 2017). Given the climate crisis and population growth, it is increasingly necessary to boost food production in alignment with the Sustainable Development Goals (SDGs) and the Principles for Responsible Investment in Agriculture (CSA-IRA) (Jägermeyr et al., 2017).

Considering the sociocultural, environmental, political, and technological dynamics of irrigation systems, it is essential to identify integrative mechanisms that enable the analysis of critical points across their components in order to establish sustainable and efficient water use strategies.

In the Andes, agricultural water comes mainly from surface and groundwater sources fed by glaciers-which have decreased by 25% over the past 30 years due to climate change (Gallegos et al., 2018)-as well as from wetlands formed in the paramo ecosystem, which capture rain and fog that subsequently infiltrate the soil. However, paramo and high Andean forest ecosystems are losing their water retention capacity due to anthropogenic and climatic causes (Llambí et al., 2012). In response, irrigation organizations have implemented strategies such as pressurized irrigation, which have improved the resilience of farmers and communities (Cachipuendo, 2022). Therefore, the sustainability of these systems requires a comprehensive evaluation that considers social, environmental, economic, political, and technological dimensions (Chile and Ortiz, 2021).

Traditionally, the study of irrigation systems has followed a disciplinary approach, focusing on specific indicators such as physical water use efficiency at the plot level, economic performance, and environmental impacts (Cachipuendo Ulcuango, 2021). This fragmented approach does not comprehensively address system sustainability nor the interrelationship among its dimensions. Methodologies such as MESMIS (Framework for the Evaluation of Natural Resource Management Systems Incorporating Sustainability Indicators) offer tools based on systems thinking to assess sustainability dynamically, flexibly, and in ways adapted to local realities (Masera et al., 2000).

Evaluating the sustainability of a natural system entails identifying its physical, social, environmental, political, and economic components and analyzing their interactions through systemic models (Samian et al., 2015; Carmona et al., 2013). In the Andes, irrigation system evaluation is structured into three subsystems: nature, community, and land use (Cachipuendo Ulcuango, 2021). Each subsystem requires specific indicators, such as water availability and quality (Costa et al., 2022), the organizational capacity of communities (Turner et al., 2016), water use economic efficiency (Meng et al., 2022), and irrigation technology adoption (Laali et al., 2022). The use of frameworks like MESMIS allows for the integration of indicators and the simultaneous assessment of sustainability dimensions, including stakeholder participation (Sarandón, 2010; Franco et al., 2012). This approach has proven effective in Andean contexts for evaluating agroecosystems and livestock or agricultural production systems (Vallejo et al., 2020; Tongo and Soplín, 2022).

Globally, sustainability must align with the SDGs, which provide a framework for addressing common global challenges and developing policies tailored to local contexts (United Nations, 2015; Persson et al., 2016). Additionally, the CSA-IRA Principles aim to ensure responsible investment in agriculture and irrigation systems, although their non-binding nature poses challenges for producers when disputes arise with investors (Stephens, 2013).

In Ecuador, given the community-based organization managing irrigation systems, there is a need for tools to evaluate their sustainability while accounting for local realities without losing sight of global objectives. Therefore, the objective of this study is to define indicators for evaluating the sustainability of irrigation systems in Ecuador within the MESMIS methodological framework, taking into account their relationship with the SDGs and the CSA-IRA Principles.

2 Materials y Methods

2.1 Study Area

This research was conducted in Ecuador, located on the northwestern coast of South America. The country is crossed by the equatorial line and has altitudes ranging from 0 to 6.263 meters above sea level. The largest irrigated areas are primarily found in the provinces of Guayas (260 000 ha), Chimborazo (124000 ha), and Pichincha (107000 ha). Of the total irrigated land, 22% corresponds to public irrigation systems, 40% to community-managed systems, and 38% to private systems (Gaybor, 2019). There are 3.425 community-managed irrigation systems distributed mostly across the Ecuadorian Andes. These systems have been constructed by users through communal labor (in spanish "mingas") in steep mountainous regions. They serve plots averaging less than one hectare and are operated by smallholder farmers engaged in subsistence agriculture, often under precarious conditions that compel them to seek additional employment outside their agricultural production units (UPAs) (Gaybor, 2019).

Considering the types of inter-community, community, collective, and public irrigation systems (Cachipuendo Ulcuango et al., 2021), the study identified three inter-community irrigation systems in the provinces of Tungurahua, Pichincha, and Cotopaxi; twelve community-managed systems—one in Carchi, two in Imbabura, three in Pichincha, two in Cotopaxi, two in Tungurahua, and two in Chimborazo; four collective or associated irrigation systems in Pichincha; and one public irrigation system in Carchi.

2.2 Scope of the Research and Indicator Definition

The research used a descriptive and correlational scope and was developed using the MESMIS methodology, complemented by the Delphi Panel technique (expert consultation). This methodological combination enabled the identification and definition of a set of 31 indicators aimed at evaluating the sustainability of irrigation systems. The process was structured in four stages (Figure 1).

(1) Definition of the irrigation system functioning model. This stage was carried out through six focus groups involving 36 community leaders. A structured guide with ten questions on the management and operation of the irrigation system was used as the data collection instrument.

(2) Identification of diagnostic criteria and critical points of the irrigation system, following the guidelines of the MESMIS methodology (Masera et al., 2000; Astier et al., 2008). Semi-structured interviews and surveys were conducted with a group of 18 key informants: 6

technicians, 4 academics, and 8 graduate students. This process allowed for the delimitation of the main criteria for assessing the sustainability of irrigation systems.

(3) Definition of indicators. In this stage, a Delphi Panel was formed with 12 experts in irrigation system management and governance, representing government institutions, universities, and the private sector. The process included two rounds of consultation: the first focused on the conceptual validity and relevance of the proposed indicators, and the second aimed at determining the degree of influence of each indicator on system sustainability.

(4) Analysis of the indicators in relation to the SDGs and CSA-IRA Principles. A semantic analysis was conducted to establish the correspondence and alignment of the indicators with these international reference frameworks. This analysis revealed that the defined indicators for evaluating community-managed irrigation systems align with 10 Sustainable Development Goals and 7 CSA-IRA Principles (Table 1), underscoring the potential of functioning irrigation systems to contribute to the achievement of global sustainable development objectives.

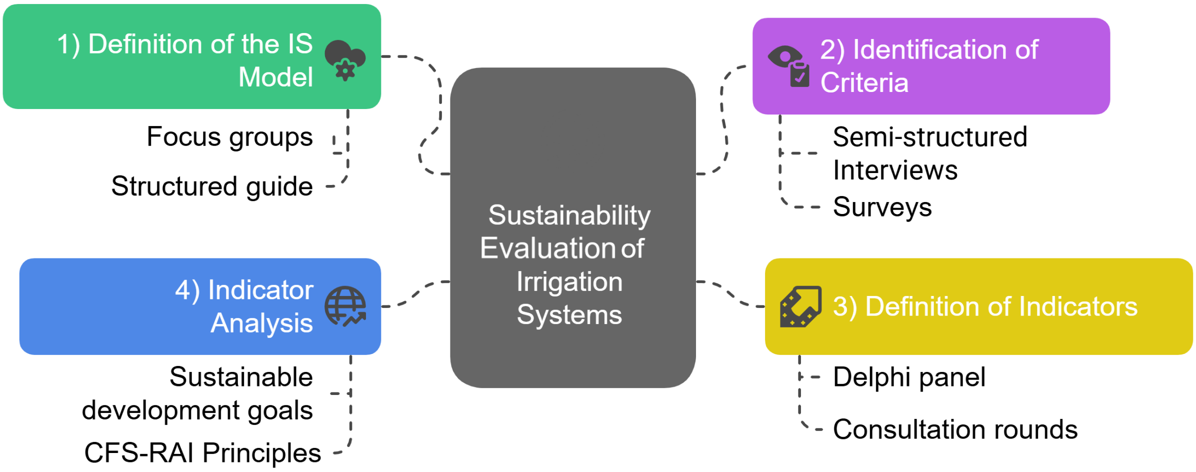

Figure 1. Stages and Methods for the Construction of Indicators for the Evaluation of Irrigation.

3 Results

The results of this research reflect a comprehensive methodological approach for evaluating the sustainability of community-managed irrigation systems in the Ecuadorian Andean context. Through the application of the MESMIS framework and the Delphi technique, a diagnostic model was developed to identify the key components of the irrigation system-nature, community, and infrastructure-as well as the main critical points affecting its performance. A total of 31 indicators were defined, aligned with seven sustainability attributes and five dimensions (environmental, social, economic, technological, and political), and articulated with nine Sustainable Development Goals (SDGs) and seven CSA-IRA Principles. The findings reveal structural, organizational, and technical limitations that influence water efficiency, equity in distribution, governance, and the resilience of these systems, providing a solid foundation for the design of public policies and community strengthening strategies.

3.1 Functioning Model of the Irrigation System

The functioning model of a community-managed irrigation system is based on three fundamental elements: nature, community, and infrastructure (Figure 2). The nature subsystem includes the water inputs into the system, which depend on exogenous factors such as temperature, precipitation, wind, and solar radiation. In the case of the Ecuadorian highlands (Sierra), the main water sources are the permanent Andean snowcaps and the paramos, whose high Andean forest ecosystems capture water and release it to lower elevations through springs or runoff (Llambí et al., 2012). However, anthropogenic activities such as the expansion of the agricultural frontier, burning of paramo vegetation, and grazing reduce the aquifer recharge capacity, constituting significant internal factors that affect the system.

The community subsystem encompasses human actions at the individual, communal, or collective levels that impact the physical, economic, social, and environmental efficiency of agricultural water use. Water management in irrigation systems involves specific procedures for the access, conveyance, storage, distribution, and efficient application of water, aimed at minimizing waste. Four key factors were identified within this subsystem: i) Knowledge- Refers to the users' understanding, individually or collectively, of the optimal irrigation timing based on crop type; ii) Social Participation– Includes user involvement in community activities, decision-making processes, and training or capacity-building programs; iii) Institutional- Pertains to the organization's ability to operate, maintain, and manage the system, including aspects such as water scheduling, leadership rotation, and the type of organization; iv) Economic- Refers to the financial capacity of users and organizations to access funding, maintain and upgrade the system, as well as the existence of policies that support these activities.

The infrastructure subsystem comprises the physical components that enable the capture, conveyance, storage, distribution, and efficient application of water to crops. Technological innovation is a key aspect, as technology levels vary depending on the type and size of the irrigation system. In the studied cases, sprinkler and drip irrigation systems predominate, characterized by their degree of pressurization, automation, and water-saving methods. Efficient infrastructure not only reduces water waste but also optimizes its application, thereby ensuring the sustainability of the system.

Table 1. SDGs and CSA-IRA Principles Related to the Sustainability Indicators of Irrigation Systems in Ecuador. Source from (Garcés and Padilla, 2020).

	SDG		**CSA - IRA Principles**
2	Zero Hunger	1	Contribute to food security and nutrition
5 6	Gender Equality Clean Water and Sanitation	2	Contribute to sustainable and inclusive economic development and poverty eradication
8	Decent Work and Economic Growth	3	Promote gender equality and women's empowerment
9 10	Industry, Innovation and Infrastructure Reduced Inequalities	6	Preserve and sustainably manage natural resources, enhance resilience, and reduce disaster risk
11	Sustainable Cities and Communities	7	Respect cultural heritage, traditional knowledge, and support diversity and innovation
12	Responsible Consumption and Production	8	Promote safe and healthy agricultural and food systems
15 16	Life on Land Peace, Justice and Strong Institutions	9	Incorporate inclusive and transparent governance structures, processes, and grievance mechanisms

3.2 Diagnostic Criteria and Critical Points of the Irrigation System

A total of 13 diagnostic criteria were identified, covering the seven sustainability attributes. Subsequently, 21 critical points were linked to the sustainability dimensions and system components (Table 2).

The critical points identified were organized according to the key sustainability attributes defined in the methodology. This classification enables a systematic analysis of the main weaknesses and opportunities for improvement in community-managed irrigation systems. The following section presents the findings corresponding to each sustainability attribute.

Table 2. Critical Points Identified for the Sustainability of Community Irrigation Systems in the Ecuadorian Andes.

Attributes	Diagnostic Criteria	Critical Points	Sustainability Dimensions	System Elements
1. Productivity	System efficiency	Water loss across infrastructure components and at plot-level application	Environmental	Nature
			Technological	Infrastructure
	Water use performance	Use of irrigation in low-profit crops, generating limited employment opportunities	Economic	Community
			Social	
		Lack of understanding of the relationship between investment benefits and economic return from production	Economic	Community
		High investment cost per irrigation project	Economic	Community
2. Stability	Conservation, quality, and protection of resources	Reduced water availability due to degradation of water sources from anthropogenic activities	Environmental	Nature
			Technological	Infrastructure
		Water body pollution due to agricultural activity	Environmental	Nature
		Predominance of monoculture systems	Environmental	Nature
3. Reliability	Relationship between system revenues and costs	Insufficient self-managed resources for maintenance, repair, or replacement activities	Economic	Infrastructure
			Social	Community
4. Resilience	Risk prevention mechanisms	Lack of practices to prevent evapotranspiration	Environmental	Nature
		No measures implemented to promote soil water retention	Environmental	Nature

	Irrigation technification	40% of systems do not pressurize water for irrigation	Technological	Infrastructure
5. Adaptability	Learning and training processes	Irrigation users lack knowledge of efficient water use alternatives	Technological	Community
	Capacity for change and innovation	Users reject technical and social changes	Technological	Community
6. Equity	Equitable distribution of water and gender	Water distribution does not consider crop type or surface area	Political	Community
		Youth and women are not involved in organizational leadership	Political	Community
	Cost and benefit distribution	Tariffs are set per user without considering profitability or water consumption	Economic	Community
7. Self-reliance (Self-management)	Organizational capacity for system management and operation	Conflicts exist between irrigation systems and users over access and water use	Social	Community
		Weak water governance between user organizations and the State generates conflicts	Political	Community
		Leadership is often held by individuals unfamiliar with the dynamics of irrigation systems	Social	Community
	Participation in system management and operation	User participation exists, but contributions are considered per individual, not by surface area	Social	Community
	Dependency on inputs and external factors	Inefficient management of financial resources; lack of reinvestment in the system	Economic	Community

3.3 Productivity

Irrigation systems ensure the timely and high-quality provision of water to increase productivity in irrigated areas Morris (2019); Contero and Cachipuendo (2021). Their evaluation requires consideration of technical, economic, and social efficiency, identifying critical points such as water waste due to infrastructure deterioration or poor management-issues that can be addressed through improvement actions and farmer training. Another key diagnostic criterion is water use performance, which includes critical aspects such as low crop profitability, cost–benefit ratios, and employment generation.

3.4 Stability

This attribute assesses the conservation, quality, and protection of resources. From an environmental perspective, critical points include water pollution, scarcity, and the predominance of monocultures. A sustainable community irrigation system requires sufficient availability of water in both quantity and quality, ensured by the protection of water sources and the promotion of biodiverse production systems. Soil sustainability is also a relevant factor within this attribute.

3.5 Reliability

Reliability is examined through a single diagnostic criterion: system income and opportunity costs. Critical points include operation and maintenance costs, and system-generated revenues (economic dimension). In the social dimension, insufficient or ineffective regulations for irrigation system management were identified.

3.6 Resilience

This attribute evaluates the system's ability to implement measures that reduce risks and strengthen resilience to climate change in agricultural contexts (Ward, 2022). In the environmental dimension, two critical points were identified: the lack of practices to reduce evapotranspiration and the absence of actions that enhance soil water retention. In the technological dimension, a critical point was the low level of irrigation technification.

3.7 Adaptability

The agricultural sector faces increasing competition for water due to being the largest consumer and the effects of climate change. This attribute assesses adaptive capacity through two criteria: strengthening learning and training processes for efficient water use, and the ability to innovate and adopt new irrigation technologies (van Opstal et al., 2022).

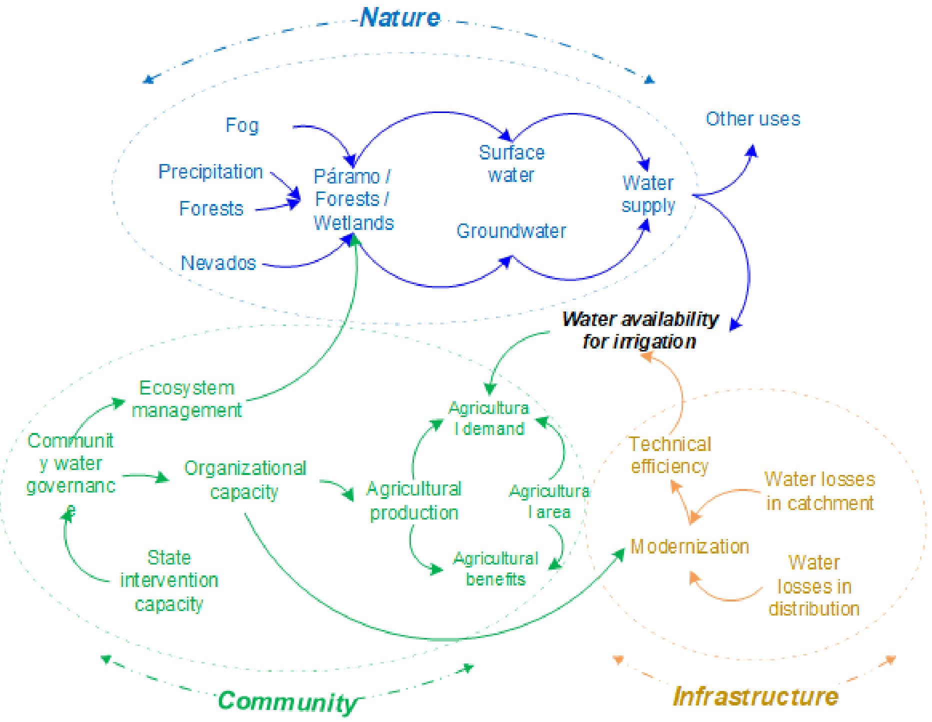

Figure 2. Model of operation of the community irrigation system.

3.8 Equity

Equity in water resource distribution is crucial to prevent conflicts and may be approached through the principle of "equitable distribution" (Elmusa, 1994). This attribute considers water allocation according to crop water requirements, irrigated area, and the participation of women and youth (social dimension). It also assesses tariff structures based on budget, irrigated surface, and crop profitability (economic dimension).

3.9 Self-sufficiency and Self-management

Community-managed irrigation systems face significant limitations regarding self-sufficiency and self-governance (Cortez, 2000). This attribute is analyzed through criteria such as the empowerment of irrigators to organize and manage financial resources (social–governance dimension), the level of user participation in system management (social dimension), and dependence on external inputs and factors (economic dimension).

3.10 Relationship Between Irrigation System Evaluation Indicators and the SDGs and CSA-IRA Principles

In addition to the internal analysis of irrigation systems, it is essential to link the defined indicators with global reference frameworks that guide sustainability. This integration allows for the evaluation of not only local performance but also the contribution of these systems to the fulfillment of international commitments (Table 3).

The following outlines the indicators corresponding to each MESMIS attribute:

Productivity: Seven indicators related to efficient water use and economic productivity were identified, covering social, environmental, economic, and technological dimensions. These indicators are linked to SDGs 8, 9, and 12, and CSA-IRA Principles 1, 2, and 6.

Stability: Four indicators reflect the importance of water availability and quality, associated with SDGs 2, 6, 11, and 15, and CSA-IRA Principles 1, 6, and 7.

Reliability: Two indicators cover aspects of the economic and social dimensions, related to SDGs 8, 10, and 16, and CSA-IRA Principles 2 and 9.

Resilience: Three indicators measure the system's capacity to withstand climate-related changes, linked to SDGs 3 and 5, and CSA-IRA Principles 1, 6, and 8.

Adaptability: Two indicators assess technological innovation and the adaptive capacity of irrigators, associated with SDGs 12 and 11, and CSA-IRA Principles 3 and 7.

Equity: Five indicators address the participation of women and youth, generational transition, and equitable water access, related to SDGs 2, 5, 9, 10, and 16, and CSA-IRA Principles 1, 3, and 7.

Self-sufficiency and Self-management: This attribute includes nine indicators related to governance and economic sustainability, aligned with SDGs 10 and 16, and CSA-IRA Principles 2, 7, and 9.

These indicators provide a comprehensive foundation for evaluating the sustainability of irrigation systems based on their contributions to the SDGs and CSA-IRA Principles, enabling the design of strategies aimed at continuous improvement.

A detailed description of the 31 defined indicators is presented below. This section includes the conceptual framework, calculation methods, and units of measurement, enabling their practical application in the sustainability assessment of community-managed irrigation systems.

System efficiency from water intake to plot

Calculated as the sum of the flows reaching irrigated plots divided by the intake flow at the water catchment point, expressed as a percentage of equation 1.

$$E(\%) = \frac{\sum Q_{\text{plots}}}{Q_{\text{intake}}} \times 100\% \qquad (1)$$

On-plot water application efficiency

The ratio between crop water requirements and the amount of water applied through sprinklers or drip irrigation within the agricultural production unit (UPA), expressed as a percentage in equation 2. Where: EA = application efficiency; CWR = crop water requirement; W_{applied} = water applied by the emitter (Playan, 1994).

$$EA(\%) = \frac{CWR}{W_{\text{applied}}} \qquad (2)$$

Economic return per volume of water used

The monetary benefit generated per volume of irrigation water used (USD/m^{-3}) according with Ríos et al. (2016).

$$Y_1 = \frac{\text{Profit}(USD)}{V(m^3)} \tag{3}$$

Water volume per employment generated

Measures the number of agricultural jobs created per cubic hectometer (1 million m^3) of water used according to Hussain et al. (2007).

$$Y_2 = \frac{\text{Jobs}(units)}{V(m^3)} \tag{4}$$

Benefit-cost ratio

Calculated by dividing the total income from irrigated agricultural production over 10 years by the total costs of irrigation infrastructure and crop establishment according with equation 5.

$$\frac{B}{C}(USD) = \frac{\text{Total income}}{\text{Total cost}} \tag{5}$$

Investment per hectare

Expressed in USD/ha, this indicator enables standardized comparison of investment levels across irrigated areas.

Investment per irrigation user

Determined by dividing the total system investment by the number of irrigation users in equation 6. Being: MIUR = amount in dollars of investment per irrigation user; NUSR= number of users of the irrigation system.

$$MIUR = \frac{\text{Total Investment}}{NUSR} \tag{6}$$

Water scarcity index

Ratio between agricultural water demand and available supply at the catchment point, expressed as a percentage in equation 7. Where: D = demand (m^3), Ws = water supply (m^3). Ic = Scarcity index expressed in % (Ríos et al., 2016).

$$Ic = \frac{D}{Ws} \times 100 \tag{7}$$

Water source conservation practices

Quantified by practices such as reforestation, fencing, controlled grazing, and preservation of source areas, evaluated on a scale based on the number of practices implemented.

Water Quality Index (WQI)

Based on the Canadian Council of Ministers of the Environment WQI (CCMEWQI); its calculation was get by applying equation 8. F1 = scope (non-compliant variables), F2 = frequency (non-compliant tests), F3 = amplitude (degree of deviation).

$$CCMEWQI = 100 - \frac{\sqrt{F1^1 + F2^2 + F3^2}}{1{,}732} \tag{8}$$

Crop diversity in UPAs

The Shannon-Wiener Index was adapted for this calculation, as detailed below the excesses of each data out of range when compared to its threshold (Chidiac et al., 2023). Where P_i is the proportion of individuals of the i-th crop and is calculated as follows $P_i = n_i/N$, N is the total number of individuals; n_i is the number of plants per crop, N the number of all plants of all crops and S is the number of species (Valdez et al., 2018).

$$DC = -\sum_{i=1}^{S} P_i ln P_i \tag{9}$$

O & M cost-income ratio

To calculate this ratio, first add up the total annual operating, maintenance, and administrative costs and divide them by the net income from annual production, as detailed in equation 10.

$$\frac{C}{I} = \frac{\text{Operating,maintenance and administration costs}}{\text{Annual production}} \tag{10}$$

Existence of regulations for the management and administration of the system

This indicator evaluates the presence and application of internal regulations governing the operation, maintenance and administration of the irrigation system. These regulations are essential for effective governance, as they establish clear rules that guide decision making, promote participation and prevent conflicts (Perugachi and Cachipuendo, 2000). The absence or weakness of these rules indicates a low level of governance and may compromise the institutional sustainability of the system. It is expressed on a scale of 1 to 5 where: 1 = nonexistent, 2 = very weak, 3 = partially implemented, 4 = implemented with limitations, 5 = fully implemented and functional.

Windbreak-based microclimate generation

Ratio of farms implementing windbreaks to the total number of farms, expressed as a percentage.

Organic matter incorporation

Percentage of UPAs that incorporate organic matter into soils; may include complementary measures such as organic matter content and moisture level (Tácuna et al., 2015).

Irrigation system technification level

Based on infrastructure type, condition, and irrigation method, rated on a scale from 1 (low) to 5 (high).

Knowledge of irrigation water needs

Assessed through a qualitative scale: very good, good, fair, poor (Hussain et al., 2007).

Acceptance of technological and social change

Based on adoption of innovative practices in the past five years; desirable threshold is 7 or more (Fonseca-Carreño et al., 2016).

Water distribution according to crop water requirements and area

For this distribution (flow), the water requirements according to the type of crop (q) multiplied by the production area (A) are considered according to equation 11.

$$Q = q(L/s/ha) \times A(ha) \tag{11}$$

Women and men participating in the organization's board of directors

The participation of stakeholders in community systems is an essential condition, especially of women, as it ensures a more equitable management while guaranteeing their right to water. It is estimated as the percentage of women on the organization's board in relation to the total number of members of the organization (Chidiac et al., 2023).

Young people participating in the organization's board of directors

Similarly, the participation of young people in the leadership of the organization reflects social sustainability in terms of transition among the actors to assume water management. It is estimated as the percentage of young people on the organization's board with respect to the total number of members of the organization (Chidiac et al., 2023).

Tariff regime based on the annual budget

This indicator shows the economic sustainability and, depending on the components considered in the budget, the irrigation system can be efficiently managed and operated; it is expressed in terms of existence and degree of compliance on a scale of 1 to 5.

Tariffs based on surface area and crop profitability

This indicator evaluates whether the irrigation system applies differentiated tariffs according to the area cultivated and the profitability of the irrigated crops. A tariff structure based on these criteria promotes equity and economic efficiency in the management of water resources by considering the productive capacity of each agricultural unit. Unit of measurement qualitative scale from 1 to 5.

Project management

The organization's capacity to generate and finance projects is an indicator of the level of strategic and operational planning to improve the system. It is estimated as high: 5-4 projects; medium 3-1 projects and low 0 (Arnés et al., 2013).

Coordination of actions with public institutions

This indicator has to do with the governance of the systems and evidences in level of coordination of the organization with public institutions in order to achieve funding for projects, technical assistance, credit, training and other actions as part of the implementation of national or local policies and legal frameworks (Cobo et al., 2018). High level is estimated as: 5-4 actions; medium 3-1 actions and low 0 or none.

Coordination of actions with civil society institutions

Like articulation with public institutions, this indicator accounts for governance between civil society actors that may be neighboring irrigation organizations and from the same basin or sub-basin (Cobo et al., 2018). It is estimated as high level: 5-4 actions; medium 3-1 actions and low 0 or none.

Level of democratic alternation of leadership

This indicator will be estimated to the extent that it has been identified in the critical points of the organization. It is qualitative in nature. It is estimated by means of a categorical scale: high when what is established in the regulations regarding the election and renewal of leadership and decision-making is met; medium if it is partially met; and low, when it is not met (González et al., 2006).

Leaders' level of knowledge of system management and administration

This indicator measures the degree of knowledge that irrigation system leaders have about technical, social, environmental and governance aspects related to water use and management. An adequate level of knowledge is essential to ensure effective management, strengthen social sustainability and facilitate the implementation of regulations that prevent conflicts within and outside the organization (González et al., 2006). Unit of measurement: qualitative scale from 1 to 5, where: 1 = no knowledge, 2 = basic knowledge, 3 = medium knowledge, 4 = high knowledge, 5 = comprehensive and effectively applied knowledge.

Level of equity in maintenance work contributions according to surface area

The management and administration of the system requires the participation of all users; however, a critical point is the inequity in maintenance work. Participation in the work according to the surface area of each user is an indicator of equity. It is a qualitative indicator: high=yes, low=no.

Irrigation system management

This indicator reflects the practices that are necessary for efficient economic management of the system. Sustainability will be reflected by the existence of three basic instruments: planning, budget and accounting. Thus, it will be considered high when there are 3 instruments, medium when there are 2 and low when there is 1 or none.

Reinvestment in the irrigation system

For this indicator, the Reinvestment Return (RR) will be considered according to equation 12.

$$RR = \frac{\text{Total cash flows generated}}{\text{Total cash flows reinvested}} - 1 \qquad (12)$$

4 Discussion

This study successfully defined 31 indicators to assess the sustainability of community-managed irrigation systems in Ecuador, aligned with the Sustainable Development Goals (SDGs) and the CSA-IRA Principles. The definition of these indicators was achieved through a participatory methodology based on the MESMIS framework and the Delphi Panel technique, allowing the inclusion of the characteristics of irrigation systems within the Ecuadorian Andean context. In accordance with the proposed model, three essential components were identified: nature, community, and infrastructure. These closely interrelated elements reflect the ecological, social, and technical dynamics that shape irrigation management in Andean territories (Cachipuendo Ulcuango, 2021; Mazabel and Caldera, 2018). The model's characterization helped to understand how endogenous factors (organizational capacity, internal management, level of technification) and exogenous factors (climate variability, pressure on water sources) influence the sustainability of these systems.

The analysis of 13 diagnostic criteria and 21 critical points were distributed across seven sustainability attributes—productivity, stability, reliability, resilience, adaptability, equity, and self-management—revealed common structural weaknesses. For instance, under the productivity attribute, deficiencies were observed in system efficiency and the low profitability of irrigated crops (Morris, 2019; Contero and Cachipuendo, 2021), which affects both economic viability and the rational use of water resources.

System stability was found to be at risk due to the degradation of water sources and biodiversity loss, consistent with previous studies warning of the deterioration of paramo ecosystems (Llambí et al., 2012). Likewise, the limited implementation of conservation practices highlights the need for approaches that integrate environmental management with productive planning (Chile and Ortiz, 2021).

Regarding reliability, limited financial capacity for operation and maintenance, along with weak implementation of internal regulations, undermines the systems' economic and institutional sustainability (Perugachi and Cachipuendo, 2000). This finding aligns with research that links water governance to the existence of clear rules and effective participation mechanisms (Cobo et al., 2018).

Table 3. Sustainability Indicators in Relation to the SDGs and CSA-IRA Principles.

Attributes	**N°**	**Sustainability Indicators**				**SDG - CSA-IRA Relationship**		
		Description	**Unit of Measurement**	**Minimum Value**	**Maximum Value**	**SDG**	**Goals**	**CSA-IRA Principles**
A1	1	Efficiency of the system from the catchment to the field	%	50	90	9	9.5 Increase scientific research and technological capacity.	6
	2	Efficiency of water application in the field	%	50	96	9	9.5 Increase scientific research and technological capacity	1
						12	12.2 Achieve efficient use of natural resources	6
	3	Ratio of economic return to volume of water used	m3/$	0.1	10	8	8.4 Improve efficient and respectful consumption and production	2
	4	Ratio of volume of water used to the number of jobs generated	m3/day	0.1	10	8	8.5 Achieve full employment and decent work.	2
	5	Benefit-cost ratio	unit	0.1	1	8	8.2 Raise productivity through diversification, technology and innovation.	1
	6	Amount of investment per hectare	$/ha	500	4000			2
	7	Amount of investment per irrigation user	$/user	100	4000			
A2	8	Scarcity index	%	40	90	9	9.5 Increase scientific research and technological capacity.	6
						11	11.1 Support for urban, peri-urban and rural linkages.	
	9	Source water conservation practices	unit	1	5	11	11.4 Protect cultural and natural heritage.	6
						15	15.1 Ensure the conservation and sustainable use of ecosystems.	

	10	Water quality index	%	50	100	6	6.3 Improve water quality. Reduce pollution and wastewater.	6
	11	Crop diversity in the UPAs	%	50	100	2	2.5 Preserve the genetic diversity of seeds.	17
						15	15.4 Ensure the conservation of mountain ecosystems.	
A3	12	Ratio of operating, maintenance and administrative costs to revenues	unit	1	5	8	8.2 Raise productivity through diversification, technology and innovation.	2
						10	10.1 Income growth of 40% of the poor population.	
	13	Existence of regulations for the management and handling of the system	unit	1	5	16	16.b Strengthen the participation of developing countries in OOII.	9
A4	14	Generation of microclimates through windbreaks	%	50	100	2	2.4 Promote sustainable and resilient agricultural practices.	6
	15	Incorporation of organic matter in the soil	%	50	100			1 8
	16	Technification level of irrigation systems	unit	1	5	9	9.5 Increase in scientific research, technological capacity.	1 8
A5	17	Level of knowledge of the amount of water to be applied on the plot	unit	1	5	12	12.2 Achieve efficient use of natural resources.	3
	18	Level of acceptance of technological and social changes	unit	1	5	11	11.a Support linkage of urban and rural areas.	7
A6	19	Water distribution according to crop water requirements and surface area	unit	1	5	2	2.4 Sustainable and resilient agricultural practices.	1
	20	Women and men involved in the organization's board of directors	unit	1	5	5	5.5 Ensure access to sexual and reproductive health and rights.	3
	21	Young people who participate in the organization's board of directors	unit	1	5	10	10.3 Ensure equality of opportunity	3
						16	16.b Promote and enforce laws and policies (human rights).	
	22	Tariff regime based on the annual budget	unit	1	5	9	9.5 Increase scientific research and technological capacity.	7
	23	Pricing based on area and profitability of the crop	unit	1	5			
A7	24	Organizational capacity in project management	unit	1	5	10	10.3 Ensure equality of opportunity	7

					16	16.b Promote and enforce laws and policies (human rights).	
25	Articulation of actions with public institutions	unit	1	5	16	16.6 Create effective and transparent institutions.	9
26	Articulation of actions with civil society institutions	unit	1	5		16.7 Encourage citizen participation.	
27	Level of leadership alternation	unit	1	5			
28	Level of knowledge of management and handling of the system by leaders	unit	1	5			
29	Level of equity in labor input for maintenance based on surface area	unit	1	5			
30	Financial management of the irrigation system	unit	1	5	16	16.5 Reduce corruption and bribery.	2
31	Reinvestment in the irrigation system	unit	1	5		16.6 Create effective and transparent institutions.	

The resilience attribute revealed the absence of adequate mechanisms to cope with climate stress, such as irrigation technification and soil moisture conservation practices (Ward, 2022), which compromises the adaptive capacity of these systems in the face of extreme events. In this regard, technological innovation emerges as an urgent necessity.

In terms of adaptability, limited appropriation of knowledge and technologies by irrigators was evident, restricting their ability to respond to socio-environmental changes (van Opstal et al., 2022). This limitation also affects the equity attribute, particularly due to the low participation of youth and women in decision-making spaces, which hampers generational renewal and social inclusion (Elmusa, 1994; Chidiac et al., 2023).

Finally, in the dimension of self-management, the analysis revealed weak institutional articulation and deficiencies in leadership and financial management, reflecting low organizational self-sufficiency. This situation compromises community governance and threatens long-term sustainability (Cortez, 2000; González et al., 2006).

The alignment of the indicators with 10 SDGs and 7 CSA-IRA Principles (Garcés and Padilla, 2020; FAO, 2014) reinforces the strategic contribution of these irrigation systems to sustainable development. Thus, the methodological proposal offers an operational tool for evaluating and intervening in community-managed irrigation systems from a holistic, dynamic, and context-sensitive perspective (Pérez-Serrano et al., 2021).

Nevertheless, certain limitations must be acknowledged: the validation of the indicators was restricted to the Ecuadorian Andean context; the application of the Delphi Panel technique entails subjective biases; and the linkage to the SDGs and CSA-IRA is conceptual in nature. These limitations highlight the need for future research to further the empirical validation and adapt the model to other geographical contexts.

5 Conclusions

This research developed a comprehensive methodological framework for assessing the sustainability of community-managed irrigation systems in the Ecuadorian Andes by defining 31 indicators organized into seven key attributes: productivity, stability, reliability, resilience, adaptability, equity, and self-management. These indicators were grouped into five analytical dimensions-environmental, social, economic, technological, and political-and structured around three core components of the system: nature, community, and infrastructure.

The findings reveal multiple critical issues affecting the sustainability of these systems, such as water use inefficiency, weak governance, low participation of key groups, and limited adaptive capacity to climate change. Through the participatory MESMIS approach and the Delphi Panel technique, the study achieved a contextualized characterization of the systems, enabling their alignment with ten SDGs and seven CSA-IRA Principles.

At the regional level, the results offer a practical tool for community stakeholders, public institutions, and policymakers to design, monitor, and evaluate water management strategies in irrigated territories. At the global level, this proposal contributes to international sustainability reporting, positioning community-managed irrigation systems as key actors in resilient and inclusive agriculture.

However, it is recommended that the indicators be empirically validated in other contexts and that broader stakeholder engagement be promoted during their implementation to strengthen applicability and impact. This study thus represents an important step forward in constructing integrative methodological frameworks for sustainable water management in agriculture and in reducing pressure on strategic ecosystems such as the paramo.

Authors' contributions

C.C.: Conceptualization, data processing, discussion. M.I.: Conceptualization, data processing, discussion. N.R.: Conceptualization, data processing, in relation to the indicators with the SDGs and IRA principles.

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