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ORIGINAL

Use of adaptive systems for the sustainable management of water and water resources

Uso de sistemas adaptativos para la gestión sostenible del agua y recursos hídricos

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ABSTRACT
Objective: To analyze the relationship between adaptive water resource management and water sustainability in recharge zones in the face of climate change. Methodology: A quantitative, non-experimental, cross-sectional and correlational-explanatory research was carried out, with a sample of 287 participants linked to the use, management, operation and planning of water. The information was collected through a Likert-type questionnaire validated by expert judgment, with adequate levels of reliability. Results: Adaptive management reached a medium-high level, with better ratings in participatory governance and community learning; however, the monitoring of the resource and the use of technologies showed opportunities for improvement. Water sustainability was also at a medium-high level, although it presented weaknesses in climate resilience and compliance with protection measures. The correlational analysis showed a positive, high and significant relationship between both variables, and the regression identified monitoring, participatory governance and decision-making as the main predictors. Conclusions: Strengthening adaptive management contributes to protecting recharge areas, improving water sustainability and increasing territorial resilience.

Keywords: adaptive management, water sustainability, water recharge, water governance, climate change.

RESUMEN
Objetivo: Analizar la relación entre la gestión adaptativa del recurso hídrico y la sostenibilidad hídrica en zonas de recarga frente al cambio climático. Metodología: Se desarrolló una investigación cuantitativa, no experimental, transversal y correlacional-explicativa, con una muestra de 287 participantes vinculados al uso, administración, operación y planificación del agua. La información se recolectó mediante un cuestionario tipo Likert validado por juicio de expertos, con adecuados niveles de confiabilidad. Resultados: La gestión adaptativa alcanzó un nivel medio-alto, con mejores valoraciones en gobernanza participativa y aprendizaje comunitario; sin embargo, el monitoreo del recurso y el uso de tecnologías evidenciaron oportunidades de mejora. La sostenibilidad hídrica también se ubicó en nivel medio-alto, aunque presentó debilidades en resiliencia climática y cumplimiento de medidas de protección. El análisis correlacional mostró una relación positiva, alta y significativa entre ambas variables, y la regresión identificó al monitoreo, la gobernanza participativa y la toma de decisiones como principales predictores. Conclusiones: Fortalecer la gestión adaptativa contribuye a proteger las zonas de recarga, mejorar la sostenibilidad hídrica y aumentar la resiliencia territorial.

Palabras clave: gestión adaptativa, sostenibilidad hídrica, recarga hídrica, gobernanza del agua, cambio climático.

INTRODUCTION

Water resource management presents significant challenges for territorial sustainability, particularly in recharge areas that are subject to climate variability, pressure from agricultural systems, rapid population growth, or environmental degradation. These areas are strategic for water infiltration, storage, and regulation; therefore, their protection depends on management models capable of responding to dynamic scenarios and increasingly complex social demands. In this context, adaptive management has emerged as an alternative to traditional approaches, as it emphasizes flexibility, social learning, stakeholder participation, and the capacity to adjust to climate uncertainty (Pahl-Wostl, 2007; Pahl-Wostl, 2009).

Desde la gobernanza del agua, la sostenibilidad no depende solamente de la disponibilidad física del recurso gestionado, sino de la forma en que instituciones, comunidades y usuarios coordinan decisiones, responsabilidades y mecanismos de protección. Huitema et al. (2009) indican que la gobernanza adaptativa permite el análisis de los arreglos institucionales y de la participación social como elementos esenciales para el tratamiento de problemas hídricos complejos. Complementariamente, Akamani (2023) también menciona que la gobernanza adaptativa favorece la transición hacia estrategias de adaptación basadas en ecosistemas.

La incertidumbre asociada al cambio climático ha impulsado nuevas formas de planificación hídrica orientadas a decisiones flexibles y sostenibles. Haasnoot et al. (2012) plantean que los sistemas hídricos sometidos a cambios ambientales requieren trayectorias de gestión capaces de ajustarse en el tiempo. Posteriormente, Haasnoot et al. (2013) desarrollaron el enfoque de rutas dinámicas de política adaptativa, útil para tomar decisiones robustas en contextos de alta incertidumbre. En esta misma línea, Kwakkel et al. (2015) señalan que las estrategias adaptativas pueden fortalecerse mediante herramientas de apoyo a la decisión, mientras que Haasnoot et al. (2024) resaltan que la adaptación efectiva exige monitoreo, aprendizaje continuo y capacidad institucional para modificar las acciones cuando las condiciones cambian.

El cambio climático ha incrementado la presión sobre los sistemas hídricos al modificar patrones de precipitación, disponibilidad de agua, eventos extremos y condiciones de uso en territorios agrícolas y comunitarios. Loucks (2022) advierte que estos desafíos requieren decisiones más innovadoras y adaptativas. Asif et al. (2023) también señalan que los impactos climáticos sobre los recursos hídricos demandan estrategias sostenibles de manejo, orientadas a la eficiencia, protección y resiliencia. Por su parte, Tsakiris (2023) sostiene que la gestión adaptativa del agua debe integrar la incertidumbre hidrológica y promover respuestas preventivas, flexibles e integradas.

Se coinciden estudios recientes en la necesidad de que la gestión sostenible del agua asuma las dimensiones ambiental, social, tecnológica e institucional. Lyra y Loukas (2022) afirman que la evaluación de escenarios de gestión sería una herramienta para orientar decisiones adaptativas en cuencas agrícolas. En el campo de la gestión del agua en contextos de cambio climático, Ciampittiello y cols. (2024) afirman que es fundamental partir de marcos de gestión de carácter global que consideren la variabilidad climática y la presión de las actividades humanas. En esta línea, Dai y cols. (2025) sostienen que la gestión inteligente del agua es la intersección entre la innovación tecnológica y la gobernanza para el desarrollo de políticas orientadas a la sostenibilidad ecológica y económica.

Asimismo, la gestión del agua en los países en desarrollo está condicionada, en parte, por la escasa disponibilidad de información, las dificultades de control sobre los sistemas de gestión del recurso hídrico, la escasa monitorización y articulación institucional. Desde este punto de vista, Makanda y otros (2025) proponen fortalecer los sistemas de apoyo a la toma de decisiones para evaluar el cumplimiento de las medidas de protección del agua. En la misma línea García-Ávila y cols. (2026), para los acuíferos, afirman que las estrategias de la gestión adaptativa pueden ayudar a mejorar la calidad del agua y la sostenibilidad.

A pesar de estos avances, todavía existe la necesidad de generar evidencia empírica sobre la relación entre la gestión adaptativa y la sostenibilidad hídrica en territorios donde interactúan usuarios comunitarios, actores institucionales y sistemas productivos. Gran parte de la literatura se ha concentrado en enfoques conceptuales, modelos de planificación o análisis de política, pero son menos frecuentes los estudios que examinan esta relación desde contextos locales de recarga hídrica. Por ello, la presente investigación tiene como objetivo analizar la relación entre la gestión adaptativa del recurso hídrico y la sostenibilidad en zonas de recarga hídrica frente al cambio climático. El estudio busca aportar evidencia útil para fortalecer la planificación territorial, la gobernanza del agua y las estrategias de protección de fuentes en escenarios de creciente vulnerabilidad ambiental.

METHODS

Research Approach and Design

This study employed a quantitative approach with a non-experimental, cross-sectional design and a correlational-explanatory scope. The design was non-experimental because the variables were not manipulated but analyzed as they naturally occurred in the study context. It was cross-sectional, as data collection was conducted during a single period, and correlational-explanatory, as the aim was to determine the relationship between adaptive water resource management and water sustainability, as well as the predictive value of their main dimensions. The research focused on analyzing water recharge areas associated with community, agricultural, and institutional water management systems. This design enabled the analysis of perceptions from various stakeholders involved in the use, administration, operation, and planning of water resources, reaffirming that water sustainability depends on environmental factors as well as social, technical, and institutional decisions.

Population and Sample

The study population comprised users, community representatives, technicians, operators, and institutional actors involved in water resource management in recharge areas. Stratified sampling by actor type was used to select participants, aiming to incorporate diverse perspectives within the water management system.

The sample included 287 participants, distributed among users of community water and irrigation systems, representatives of water boards or committees, technicians or operators, and local institutional actors. This composition enabled the collection of information from both direct users of the resource and those involved in its administration, control, or planning.

Table 1. Distribution of the sample by type of actor

Participant type	Frequency	Percentage
Users of community water and irrigation systems	214	74.6%
Representatives of water boards, committees, or associations	42	14.6%
Technicians or operators involved in water management	18	6.3%
Local institutional actors	13	4.5%
Total	287	100%

Note. Percentages calculated based on 287 participants involved in water use, management, operation, or planning.

Inclusion criteria were: being over 18 years of age, residing or working in an area associated with water recharge, having a direct relationship with the use, administration, operation, or planning of water, and voluntarily agreeing to participate in the study. Incomplete surveys, duplicate responses, and participants without direct involvement in the analyzed water system were excluded.

Study Variables

The independent variable was adaptive water resource management, defined as the set of practices, decisions, and capacities aimed at responding flexibly to environmental, climatic, and institutional changes that affect water availability and use. This variable was organized into six dimensions: participatory governance, resource monitoring, institutional flexibility, community learning, use of technologies, and decision-making.

The dependent variable was water sustainability, defined as the system's capacity to maintain the availability, quality, efficiency, equity, and resilience of the resource over time. This variable was structured into six dimensions: water availability, resource quality, efficiency of use, equity in distribution, climate resilience, and compliance with protection measures.

Table 2. Operationalization of the variables

Variable	Dimensions	Measurement scale
Adaptive water resource management	Participatory governance, monitoring, institutional flexibility, community learning, use of technologies, and decision-making	5-point Likert
Water sustainability	Availability, quality, efficiency, equity, climate resilience, and compliance with protection measures	5-point Likert

Note. Variables measured using a 5-point Likert scale, according to the dimensions of adaptive management and water sustainability.

Data Collection Technique and Instrument

Data were collected using a survey, with a structured questionnaire consisting of 32 items rated on a five-point Likert scale: 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree.

The instrument was organized into two sections. The first section collected general information about the participants, such as actor type, connection to water management, and length of involvement with the water system. The second section assessed the dimensions of adaptive management and water sustainability. The distribution of items allowed for a balanced measurement of both variables, avoiding an overemphasis on a single dimension of the issue.

Instrument Validity and Reliability

Content validity was assessed by a panel of seven experts with experience in water management, environmental sustainability, research methodology, and territorial planning. The criteria considered were clarity, relevance, coherence, and appropriateness of the items. As a result of the validation process, minor adjustments were made to the wording of five items to improve participant comprehension.

The internal consistency of the instrument was evaluated using Cronbach's alpha coefficient and McDonald's omega. In the pilot test, administered to 31 participants with characteristics similar to those of the final sample, the instrument achieved an overall Cronbach's alpha of 0.91 and a McDonald's omega of 0.92, values considered adequate for quantitative studies. In the final application, reliability by dimension remained above 0.80, demonstrating internal stability of the measurement.

Data Collection Procedure

Data collection was conducted through both in-person and digital administration of the questionnaire, depending on participant availability and access conditions in the communities or institutions. Prior to participation, the study objectives, the voluntary nature of participation, and the confidentiality of the information were explained.

The application process was carried out in three phases. In the first phase, stakeholders associated with water systems and recharge zones were identified. In the second phase, the questionnaire was administered to participants selected according to the defined strata. In the third phase, responses were reviewed, incomplete records were excluded, and the database was consolidated for statistical analysis.

Data Analysis

The data were processed using descriptive and inferential statistics. First, frequencies, percentages, means, and standard deviations were calculated to describe the behavior of the variables and their dimensions. Subsequently, the distribution of the data was assessed using normality tests to select the appropriate statistical procedures.

To examine the relationship between adaptive water resource management and water sustainability, Spearman's correlation was applied, considering the ordinal nature of the Likert scale and the data distribution. In addition, multiple linear regression was used to identify which dimensions of adaptive management best explained water sustainability. The adopted level of statistical significance was $p < 0.05$.

Finally, an internal consistency analysis by dimension and a review of collinearity among predictors using the variance inflation factor were conducted. This allowed verification of the model's stability and reduced the risk of biased interpretations in the results.

Ethical Considerations

The research adhered to the principles of voluntariness, confidentiality, and academic use of information. Participants were informed about the purpose of the study and could withdraw at any time without consequence. No sensitive data that could individually identify respondents were collected, and the information obtained was used exclusively for research purposes.

RESULTS

The results indicated that adaptive water resource management received a medium-high overall rating among participants, with a global mean of 3.71. The highest-rated dimensions were participatory governance and community learning, while the use of technologies and resource monitoring received lower scores, suggesting limitations in technical monitoring and the incorporation of digital tools for water management.

Table 3. Descriptive statistics of adaptive water resource management

Dimension	Mean	Standard deviation	Level
Participatory governance	3.89	0.74	High
Water resource monitoring	3.52	0.81	Medium
Institutional flexibility	3.67	0.78	Medium-high
Community learning	3.82	0.72	High
Use of technologies	3.41	0.86	Medium
Decision-making	3.76	0.75	Medium-high
Overall adaptive management	3.71	0.77	Medium-high

Note. Likert scale from 1 to 5, where higher values indicate a more favorable perception of adaptive management.

Regarding water sustainability, the global mean was 3.64, reflecting a favorable, though not fully consolidated, perception. The highest-scoring dimensions were water availability and equity in distribution. In contrast, climate resilience and compliance with protection measures showed lower means, indicating persistent weaknesses in the system's capacity to respond to droughts, climate variability, and environmental pressures.

The reliability of the instrument was adequate in all evaluated dimensions. The overall Cronbach's alpha was 0.91 and McDonald's omega was 0.92, demonstrating high internal consistency. At the dimension level, values ranged from 0.81 to 0.89, exceeding the minimum acceptable criterion of 0.70 for quantitative studies.

Table 4. Descriptive statistics of water sustainability

Dimension	Mean	Standard deviation	Level
Water availability	3.78	0.79	Medium-high
Resource quality	3.61	0.82	Medium-high
Efficiency in use	3.58	0.80	Medium
Equity in distribution	3.74	0.76	Medium-high
Climate resilience	3.46	0.87	Medium
Compliance with protection measures	3.39	0.89	Medium
Overall water sustainability	3.64	0.82	Medium-high

Note. Likert scale from 1 to 5. The classification of levels was based on the low, medium, and high ranges defined for the study.

The correlational analysis showed a positive, strong, and statistically significant relationship between adaptive water resource management and water sustainability. The Spearman coefficient was 0.684, with a significance level less than 0.001. This result indicates that greater development of adaptive management practices is associated with a higher perception of water sustainability in the analyzed recharge zones.

Table 5. Instrument reliability by dimensions

Variable / Dimension	Cronbach's alpha	McDonald's omega
Participatory governance	0.86	0.87
Water resource monitoring	0.84	0.85
Institutional flexibility	0.82	0.83
Community learning	0.88	0.89
Use of technologies	0.81	0.82
Decision-making	0.85	0.86
Water sustainability	0.89	0.90
Global instrument	0.91	0.92

Note. The values obtained indicate adequate internal consistency in all dimensions of the instrument.

Analysis of the dimensions of adaptive management revealed that water resource monitoring exhibited the highest correlation with water sustainability, followed by participatory governance, decision-making, and the use of technologies. This indicates that water sustainability depends not only on community participation, but also on the capacity to generate information, monitor the status of the resource, and make timely decisions.

Table 6. Correlation between adaptive management and water sustainability

Related variables	Spearman's rho	Two-tailed significance	Interpretation
Adaptive water resource management – Water sustainability	0.684	0.000	Strong positive relationship

Note. The correlation is significant at the $p < 0.001$ level.

Table 7. Correlations between dimensions of adaptive management and water sustainability.

Adaptive management dimension	Spearman's rho with water sustainability	Two-tailed significance
Participatory governance	0.612	0.000
Water resource monitoring	0.641	0.000
Institutional flexibility	0.537	0.000
Community learning	0.584	0.000
Use of technologies	0.596	0.000
Decision-making	0.603	0.000

Note. All correlations were positive and significant at the $p < 0.001$ level.

The multiple linear regression model identified the explanatory contribution of the dimensions of adaptive management to water sustainability. The model was statistically significant, with an adjusted R^2 of 0.53, indicating that 53% of the variability in water sustainability can be explained by the adaptive management dimensions included in the analysis.

The results support the existence of a significant relationship between adaptive management of water resources and water sustainability. Furthermore, they show that monitoring, participatory governance, and decision-making are the factors with the greatest explanatory power within the model. Collectively, these findings indicate that water recharge zones require not only community participation, but also technical information, continuous monitoring, and flexible institutional mechanisms to respond to the effects of climate change and pressures on the resource.

Table 8. Multiple linear regression model for water sustainability.

Predictor	Standardized beta	t	Significance
Water resource monitoring	0.291	5.84	0.000
Participatory governance	0.224	4.67	0.000
Decision-making	0.183	3.92	0.000
Use of technologies	0.169	3.51	0.001
Community learning	0.142	2.98	0.003
Institutional flexibility	0.108	2.31	0.021

Note. Dependent variable: water sustainability. $R^2 = 0.54$; adjusted $R^2 = 0.53$; $F = 55.82$; $p < 0.001$.

DISCUSSION

The study results demonstrated a positive, strong, and statistically significant relationship between adaptive management of water resources and water sustainability in recharge zones. This finding confirms that water sustainability depends not only on the physical presence of the resource, but also on the capacity of local and institutional actors to organize, monitor, adjust, and sustain decisions in response to environmental pressures and climate change scenarios. In this context, adaptive management is positioned as a key component for strengthening source protection, improving water distribution, and increasing the resilience of water systems.

The dimension with the greatest explanatory power was water resource monitoring, demonstrating that the availability of technical information and regular monitoring of water status are fundamental conditions for making timely decisions. This result is consistent with Kelly et al. (2023), who argue that adapting irrigation strategies within the season improves responses to changes in water availability. Similarly, Giupponi and Sgobbi (2013) highlight that decision support systems are relevant for improving water management in developing countries, especially when there are institutional and technical limitations.

Participatory governance also showed a significant relationship with water sustainability. This indicates that the involvement of users, water boards, technicians, and institutional actors promotes shared responsibility in resource protection. This finding aligns with Pollard et al. (2023), who emphasize that adaptive governance requires systemic feedback processes that enable learning, adjustment, and improvement of collective decisions. Likewise, Ribeiro and Johnsson (2018) point out that water governance is strengthened when there are patterns of coordination among actors, shared rules, and management mechanisms that extend beyond the isolated actions of institutions.

The use of technologies received a moderate rating and showed a significant correlation with water sustainability. Although it was not the highest-rated dimension, its influence confirms that technological tools can contribute to monitoring, efficiency, and resource planning. This result is consistent with Lakhiar et al. (2024), who indicate that precision irrigation technologies can improve water use efficiency, productive yield, and reduce environmental impacts. It is also related to Oğuztürk (2025), who highlights that artificial intelligence-driven irrigation systems can support more sustainable management through automation, data analysis, and optimization of water consumption.

Institutional flexibility had the lowest predictive weight in the model, although it maintained a significant relationship with sustainability. This result suggests that institutions and local organizations may be willing to adapt, but still face limitations in modifying rules, procedures, or responses to changing scenarios. This situation is consistent with Dias et al. (2022), who note that adaptive governance and water security in the context of climate change require institutional structures capable of responding with greater coordination and learning. Consequently, water sustainability requires not only community participation, but also institutions with genuine adaptive capacity.

Community learning received a high rating, indicating that communities recognize the importance of local experience, knowledge transmission, and cooperation in water management. However, its predictive weight was lower than that of monitoring and governance, suggesting that community knowledge needs to be integrated with technical information and institutional decisions to have a greater impact on sustainability.

Marques et al. (2020) argue that water governance should be understood as a network of actors within socio-ecological systems, where relationships, knowledge, and local practices influence resource management.

The results also indicate that water sustainability was perceived at a medium-high level, but with weaknesses in climate resilience and compliance with protection measures. This suggests that, although favorable practices exist, risks associated with droughts, agricultural pressure, degradation of recharge areas, and limited control capacity persist. In the Latin American urban context, Pineda-Morales et al. (2025) note that domestic water management and adaptive governance face challenges related to inequality, fragmented institutions, and pressure on supply systems. These aspects underscore that water sustainability requires differentiated interventions tailored to territorial conditions.

Taken together, the findings support the conclusion that adaptive management is a determining factor for the sustainability of water resources in recharge areas. The statistical model explained 53% of the variability in water sustainability, demonstrating considerable explanatory power. However, this also indicates that other factors may influence the phenomenon, such as specific climatic conditions, vegetation cover, productive pressure, infrastructure quality, financing, regulatory compliance, and users' environmental awareness.

From an applied perspective, the results suggest that strategies for protecting water recharge areas should prioritize strengthening monitoring, participatory governance, and evidence-based decision-making. Additionally, it is necessary to incorporate accessible technologies, enhance institutional capacity, and promote community learning processes oriented toward action. Water sustainability should not be addressed solely as a technical or exclusively social issue; rather, it requires integration of information, participation, regulation, technology, and territorial co-responsibility.

Finally, the study provides empirical evidence to understand how adaptive management can improve water sustainability under climate change scenarios. The main contribution lies in demonstrating that the dimensions of monitoring, governance, technology, and decision-making play a significant role in resource protection. As a limitation, the study was based on cross-sectional data; therefore, future research could incorporate longitudinal designs, direct water quality measurements, or comparative models between different recharge areas. Nevertheless, the results offer a useful basis for guiding public policies, community plans, and institutional strategies for sustainable water management.

CONCLUSIONS

The study established a strong, positive, and significant relationship between adaptive water management and the water sustainability of recharge areas. This finding indicates that when communities, institutions, and technical actors implement practices of control, participation, decision-making, and collective learning, they strengthen the conditions for water conservation, improve its use, and thereby respond more effectively to climate change.

The water monitoring variable had the greatest weight in the model, indicating that the information generated, periodic monitoring and control of sources, and their status are key aspects for management from a sustainability perspective. Without reliable data and with only imposed control systems, decisions will be reactive and limited; in contrast, monitoring enables anticipation of risks and problems, and guides protection actions.

Participatory governance was also identified as a relevant factor for water sustainability. The involvement of users, water boards, technicians, and institutional actors fosters shared responsibility in resource management, reduces isolated decision-making, and enables the development of agreements better suited to territorial needs. This confirms that water sustainability cannot depend solely on technical actions, but rather on collective processes of organization and management.

The results showed that the use of technologies and information-based decision-making contribute significantly to improving the sustainability of water resources. However, these dimensions still present opportunities for strengthening, especially in territories with limitations in access to digital tools, measurement systems, technical training, or institutional resources. Therefore, the incorporation of technologies should be progressive, context-specific, and aligned with local capacities.

Water sustainability is rated as medium-high, but exhibits weaknesses in climate resilience and the implementation of protection measures.

This indicates that while appropriate practices exist in the analyzed recharge areas, risks remain due to droughts, environmental degradation, productive pressure, and limitations in resources and capacity to respond to climate change.

In general, the study corroborates that adaptive management is effective in increasing the water sustainability of recharge areas. The main contribution of the study is to highlight social participation, practice control, learning, technology, and institutional flexibility as important elements in the protection of water resources under conditions of climate uncertainty. This provides a basis for public policies, community programs, and institutional strategies for the conservation of water sources, improvements in water use efficiency, and territorial resilience.

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CONFLICT OF INTEREST

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