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Leveraging Artificial Intelligence for Comprehensive Analysis of Community and Rural Aqueduct Systems

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Abstract

This interdisciplinary study presents a comprehensive evaluation of fourteen community-managed rural aqueduct systems in Pasto, Colombia, integrating technical, environmental, administrative-financial, and psychosocial dimensions. The research employs a mixed-methods approach, incorporating both structured and unstructured data. These data are analyzed through Exploratory Data Analysis, dimensionality reduction techniques, and generative artificial intelligence (AI) tools. The methodology employed is anchored in the framework of Integrated Water Resources Management (IWRM), a multifaceted approach to managing water resources. This framework facilitates a nuanced understanding of the sustainability challenges and management practices that characterize decentralized rural water supply systems. The findings of the study indicate that while technical variables are predominantly structured and quantifiable, psychosocial dimensions rely heavily on unstructured, qualitative data. Preliminary technical analysis indicated that while water sources generally exceed current demand, treatment coverage is limited, and none of the systems meet potable water standards. A thorough review of the environmental assessments yielded several key findings. First, there were notable deficiencies in source protection, planning, and regulatory compliance. Second, while there was some progress in administrative components, digital and labor formalization remained critical gaps. The psychosocial results indicated a high level of community commitment; however, they also revealed limited participation, weak leadership legitimacy, and persistent institutional distrust. AI-enhanced text mining and sentiment analysis facilitated the clustering of aqueducts into distinct management profiles, revealing divergent emphases between technical operations and administrative-social performance. Overall, the study demonstrates the value of AI-supported diagnostics for community water systems and recommends integrating participatory methodologies and adaptive public policies to foster equitable, resilient, and sustainable rural water governance.

Keywords: Rural Water Supply; Community Water Management; IWRM; Artificial Intelligence; Environmental Sustainability; Water Quality; PUEAA; IRCA; PSMV.

1. Introduction

Safe access to drinking water in rural areas remains one of the most significant challenges to sustainable development and social equity worldwide. According to UNESCO (2020) and the FAO (2023), over 40% of the global population

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lives in regions affected by water stress. Rural communities are particularly vulnerable due to climate change, environmental degradation, and limited infrastructure investment [1, 2]. In this context, Andersen (2020) emphasizes that addressing water and climate challenges requires integrated approaches that incorporate environmental, social, and economic dimensions into water management [3]. This principle, which is central to the United Nations' Integrated Water Resources Management (IWRM) framework, offers a robust foundation for enhancing the sustainability and resilience of water systems.

In Latin America, and particularly in Colombia, community water supply systems have emerged as essential local solutions for securing this fundamental human right, serving millions of people who depend on self-managed systems for their water supply [4, 5]. However, numerous studies indicate that the sustainability of these systems is threatened by weaknesses in the protection of water sources, administrative informality, limited community participation, and inadequate water quality [6, 7]. Consequently, the development of robust rural water systems involves not only financial capital and infrastructure but also elements related to human and social development and their connection to natural resources. This perspective is supported by Colmenares et al. [8], who identified administrative inconsistencies that hamper sustainable water management, thereby negatively impacting social, human, environmental, and financial development and affecting the livelihoods of rural families.

The literature on Integrated Water Resources Management (IWRM) highlights that effective responses to these issues require a holistic approach capable of simultaneously addressing technical, environmental, administrative-financial, and socio-cultural dimensions [9, 10]. Experiences in Colombia and other rural regions have shown that a narrow focus on infrastructure or operational aspects does not guarantee the long-term resilience of water supply systems [4, 11]. Factors such as watershed conservation, transparency in financial management, equitable user participation, and social cohesion are equally critical to ensuring service continuity and quality [12, 13].

This study, which was conducted under the "Water, Source of Life" project, focused on the management of rural community water systems in San Juan de Pasto, Colombia. An interdisciplinary approach was adopted to holistically assess the sustainability and efficiency of fourteen rural systems by integrating technical, environmental, administrative-financial, and psychosocial variables. The primary objectives were to identify critical gaps and to develop evidence-based recommendations for enhancing the sustainability and resilience of water supply in rural settings [10]. By combining quantitative and qualitative approaches, this research aligns with international recommendations to strengthen rural water governance through participatory assessments and contextualized empirical evidence [14, 15]. The integrated methodology employed in this work was designed to overcome the limitations of traditional diagnostics by providing a more nuanced and granular understanding of the factors affecting the sustainability and efficiency of these vital systems.

Following this introduction, Section 2 describes the study area and methodology, detailing the application of exploratory data analysis and artificial intelligence techniques for processing structured and unstructured data. Section 3 presents the results for each of the four components, highlighting key performance patterns and identified issues. Section 4 discusses the findings in light of previous studies and the IWRM framework, proposing guidelines for public policies and community strategies. Finally, Section 5 offers the conclusions and specific recommendations formulated to enhance water resource management in these rural water systems.

2. Material and Methods

2.1. Study Area

This study evaluated fourteen community water supply systems located in the rural area of the municipality of Pasto, in Colombia, South America. The systems were selected as part of the "Alianza Agua Fuente de Vida" project, an inter institutional initiative aimed at enhancing their operational efficiency. Figure 1 shows the location of the study area and the distribution of the assessed systems [16].

Pasto, located in the department of Nariño, Colombia, is situated at an elevation of approximately 2,596 meters (8,520 feet) above sea level. The area experiences a temperate climate with significant rainfall throughout the year, even during the driest months. The average annual temperature is around 11.2° C. The climate is characteristic of the Andean region in South America [16]. The fourteen water supply systems draw their water from small sources with flow rate ranging from 4.5 to 95 L/s and population of users ranging from 70 to 3,260. All the systems employ different technologies, from the most sophisticated, such as compact plants, to the simplest, which consist of storage tanks with chlorination systems. Most of the water is used for domestic and agricultural purposes.

Leveraging data from the project '*Impact Evaluation of the Water Source of Life Project in the Rural and Community Water Supply Systems of the Eastern Corridor of Pasto during the 2016-2020 Observation Window*", an analysis of variables by component was conducted. This project established that a comprehensive diagnosis of rural and community water supply systems requires their division into four key components: Technical, Environmental, Administrative-Accounting, and Psychosocial.

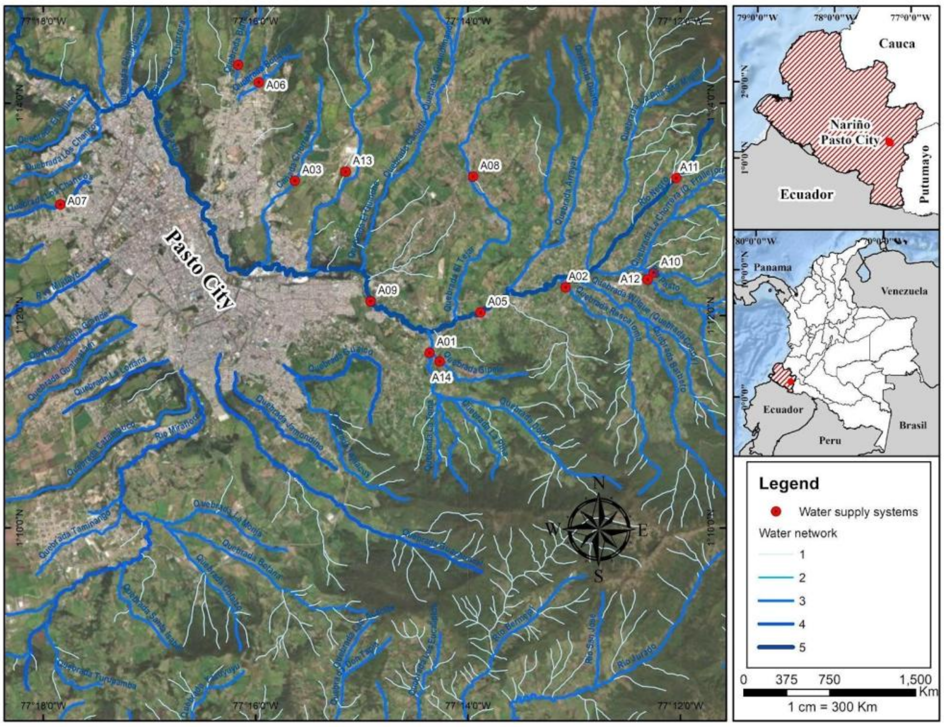

Figure 1. Geographic Distribution of rural and community water supply systems in Pasto Municipality

This research employs a comprehensive multicriteria approach to evaluate the status of the water supply systems, as detailed in the provided flowchart (Figure 2). The methodology is structured around four essential dimensions: Technical, Environmental, Administrative-Accounting, and Psychosocial. The process begins with the selection of an initial set of variables for each dimension using secondary information. For instance, 31 variables were initially identified for the technical component and 41 for the administrative-accounting component. These variables underwent a rigorous refinement process, including expert validation and a pilot test. This step enabled a significant reduction to a final, definitive set; for example, 7 variables for the technical dimension and 18 for the administrative-accounting dimension. This streamlined variable set was then applied to all fourteen water supply systems to provide a holistic diagnosis of their status.

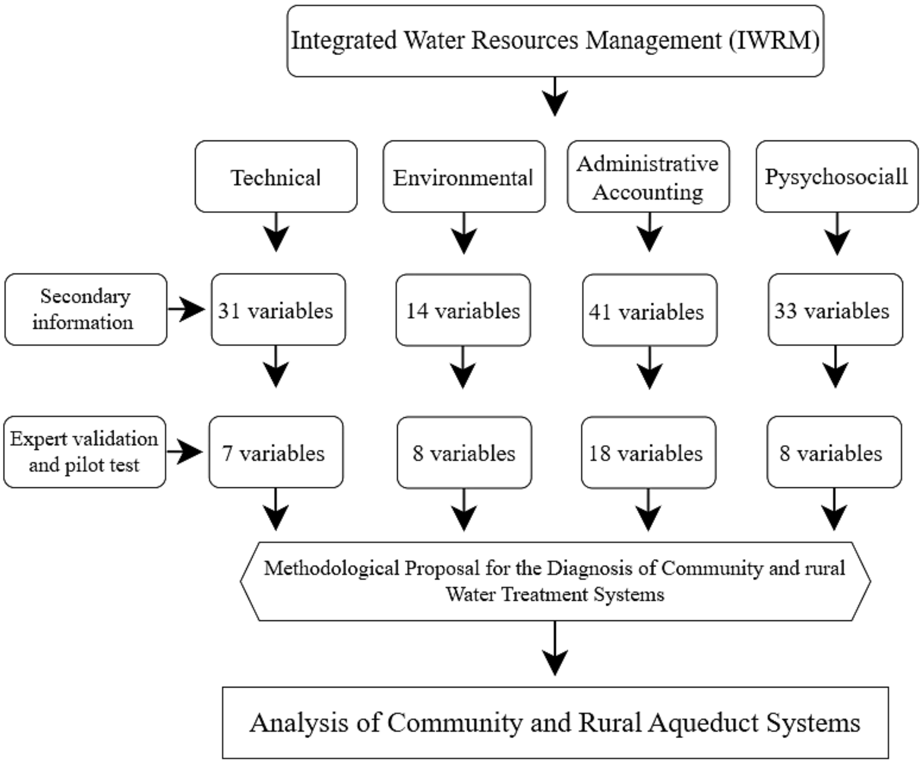

Figure 2. Multicriteria approach: Variable Analysis

2.2. Methodological Approach

Exploratory Data Analysis and Relationship Assessment across Multiple Components. This study employs a methodology that focuses on data exploration (including Exploratory Data Analysis and text mining), dimensionality reduction (such as PCA and Factor Analysis), and the analysis of relationships (e.g., correlation). A combined approach was used to analyze the data, integrating qualitative and quantitative analysis with Generative Artificial Intelligence (GAI) tools. This approach is based on a systematic review and analysis of structured and unstructured data, as illustrated in Figure 3.

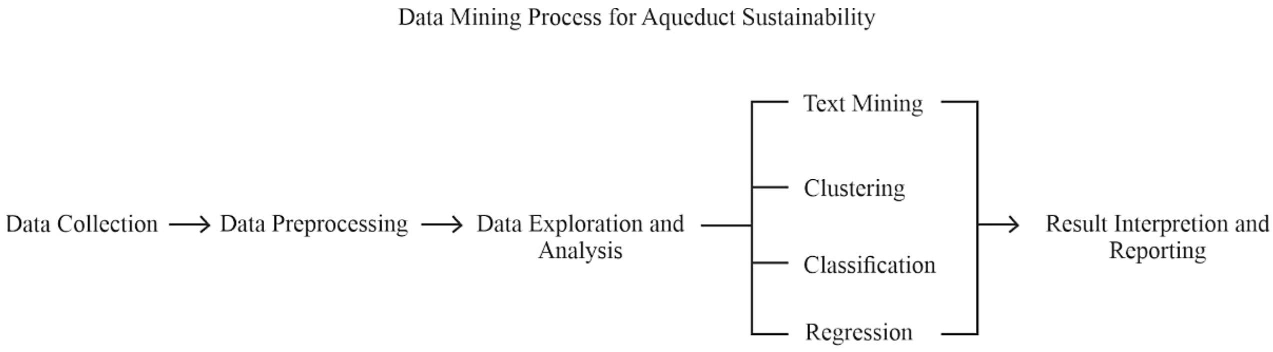

Figure 3. Analysis of structured and unstructured data

The analytical methodology was divided into three parts:

(a) Systematic Review:

A systematic search approach was conducted to identify relevant studies, following the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes), to determine the appropriate analytical techniques [17]. The search included databases such as Scopus, ScienceDirect, Elicit, and SciSpace, focusing on open access English-language articles and reviews published between 2019 and 2024. These sources were selected for their coverage of key disciplines relevant to the study, including Business, Management and Accounting, Environmental Science, Engineering, and Social Sciences. A prompt pattern was employed using to guide the search process and ensure comprehensive and relevant results [18]. This approach was designed to gain a comprehensive understanding of the complex factors influencing the sustainability and efficiency of rural and community water systems (see Figure 4).

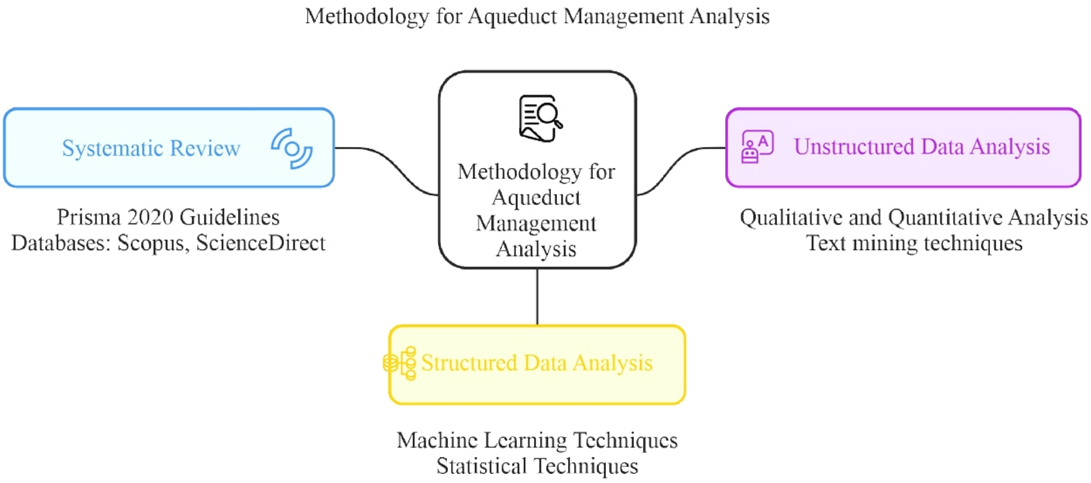

Figure 4. Data Mining for Aqueduct Sustainability

(b) Analysis of Unstructured Data:

A combined qualitative and quantitative approach was employed for analysis of unstructured data, such as technical reports, utilizing text mining techniques and Generative Artificial Intelligence (GAI) tools (Figure 5). Text was extracted from the technical, environmental, administrative-accounting, and psychosocial components, organizing them into separate .txt files [19]. The text was then pre-processed through a series of steps, including transformation, tokenization, normalization, and filtering. Text mining techniques such as hierarchical clustering, topic modelling, sentiment analysis, and hashing similarity were utilized in this analysis [20]. This process allowed for the evaluation of data from technical reports, facilitating an understanding of the operational and management dynamics of these systems, identifying how their characteristics influence performance and sustainability, and generating information to improve water management strategies in rural contexts.

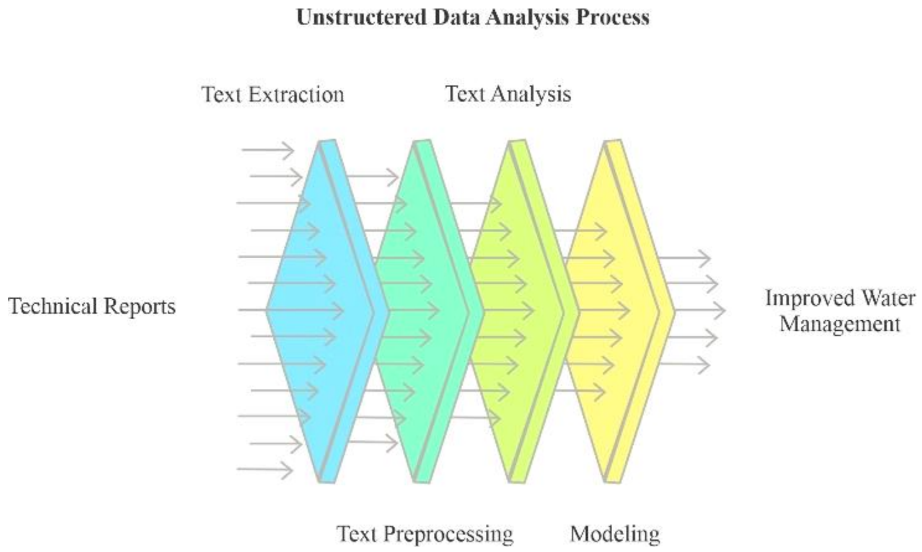

Figure 5. Unstructured Data Analysis Process

For the hierarchical analysis, a dendrogram was employed. This type of diagram visually represents how different elements (text or data) are progressively grouped together based on their calculated similarities, revealing the hierarchical structure of their relationships. Separately, for the sentiment analysis, bar charts were utilized. These graphs illustrate the polarity (e.g., positive, negative, neutral) of sentiments expressed in relation to each of the distinct components of the community water system (such as technical performance, water quality, management, or social impact).

(c) Analysis of Structured Data:

Structured data, such as data from technical reports, was pre-processed to prepare it for analysis and the implementation of statistical and machine learning techniques. The hybrid methodological framework was inspired by the KDD [21], CRISP-DM, and SEMMA [22] methodologies. Furthermore, GAI tools were employed to facilitate data interpretation, which included the generation of Matlab, R, and Python scripts (Figure 6).

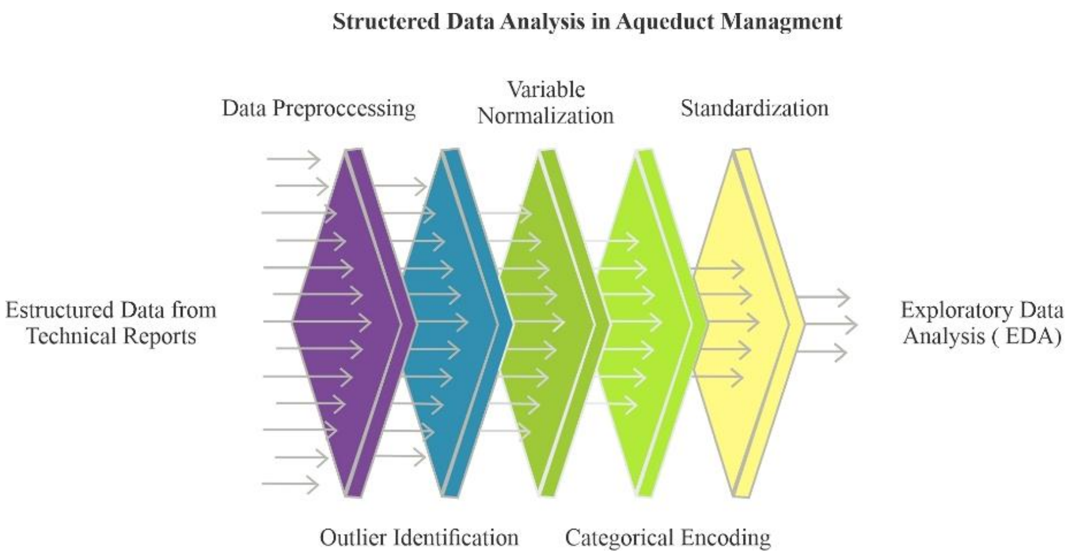

Figure 6. Structured Data Analysis in aqueduct Management

Overall, the study highlighted the importance of the integrated management of rural and community aqueducts, which requires the consideration of technical, environmental, administrative, financial, and psychosocial variables. The research employed a multidisciplinary approach and Generative Artificial Intelligence (GAI) tools to analyze data and draw conclusions about aqueduct management practices.

3. Results

The proposed method was applied to 14 community and rural water supply systems using structured and unstructured data analysis techniques. The data were categorized into technical, environmental, administrative-accounting, and psychosocial components using the Methodological Proposal for the Diagnosis of Community and Rural Water Supply Systems, adopting a multidisciplinary and transdisciplinary approach within the framework of Integrated Water Resources Management (IWRM). Table 1 presents the key components of this diagnostic methodology applied to community and rural water treatment systems. The framework is structured around four main dimensions: technical, environmental, psychosocial, and administrative-accounting. Each component addresses specific aspects that enable a comprehensive assessment of the systems' operation and sustainability, considering both physical infrastructure and community participation as well as financial management. The four components were established as the guiding dimensions for study.

Table 1. Components of the diagnostic methodology

Component	Description	Source
Technical	This component refers to the infrastructure and technology used for capturing, treating, and distributing water. It includes hydraulic system design and implementation of sustainable technologies.	[23]
Environmental	This component considers ecosystem conservation, watershed management, and environmental sustainability. It involves actions to protect water sources and promote efficient usage practices.	[24]
Psychosocial	This component analyzes community participation, empowerment, and social cohesion in water management. Includes forming community groups and strengthening local organization.	[25]
Administrative-Accounting	This component involves financial management and transparency in resource handling; it includes maintaining clear records and complying with relevant regulations. It is essential for ensuring economic sustainability of the aqueduct.	[26]

3.1. Structured and Unstructured Variables

Table 2 presents the classification of the variables considered in the diagnostic methodology, organized by component and data type. Each variable is associated with a specific dimension (environmental, psychosocial, technical, and administrative-accounting) and is identified as either structured or unstructured data. This organization guided the collection, analysis, and processing of information, enabling a more precise and comprehensive evaluation of community and rural water supply systems. In the applied diagnostic methodology, a total of 41 variables were initially analyzed across the environmental, psychosocial, technical, and administrative-accounting components. Of these, 22 variables corresponded to structured data and 19 to unstructured data. However, based on the analysis refined through artificial intelligence tools, the final number of relevant variables considered for the study was consolidated to 39.

Table 2. Classification of variables by component and data structure

Component	Variable	Variable IA	Data Type
Technical	1. Flow rate	1. Flow rate	Structured data
	2. Desander	2. Guaranteed flow	Structured data
	3. Disinfection	3. Maintenance time	Structured data
	4. Holding tank	4. Users	Structured data
	5. Maintenance time	5. Water treatment plant	Unstructured data
	6. Users		
	7. Water treatment plant		Unstructured data
Environmental	1. Water concession - Concessioned flow (L/s)	1. System Age (Years)	Structured data
	2. PUEAA	2. Plumber Experience (Years)	Structured data
	3. WQRI (IRCA annual average7)	3. Users per Service Connection	Structured data
	4. Permit for dumping / PSMV	4. Users per habitant (Population Served)	Structured data
	5. Solid waste collection system / PGIRS	5. Tariff regime	Unstructured data
	6. Tariff regime	6. Organization type	Unstructured data
	7. Value charged to user	7. WQRI (IRCA annual average7)	Unstructured data
	8. Age of the aqueduct	8. PUEAA	Unstructured data

Admin.- Accounting	1. Employment hiring	1. Employment hiring	Structured data
	2. Social security system contributions	2. Social security system contributions	Structured data
	3. Employee compensation with minimum social security income	3. Employee compensation with minimum social security income	Structured data
	4. Bank account	4. Bank account	Structured data
	5. IFRS financial statements	5. IFRS financial statements	Structured data
	6. Accounting support	6. Accounting support	Structured data
	7. Accounting software	7. Accounting software	Structured data
	8. Electronic invoicing	8. Electronic invoicing	Structured data
	9. Electronic payroll	9. Electronic payroll	Structured data
	10. Special tax regime	10. Special tax regime	Structured data
	11. Business registration renewal	11. Business registration renewal	Unstructured data
	12. Institutional philosophy	12. Institutional philosophy	Unstructured data
	13. Manuals of board position	13. Manuals of board position	Unstructured data
	14. Users up to date with payments	14. Users up to date with payments	Unstructured data
	15. Incentives or bonuses	15. Incentives or bonuses	Unstructured data
	16. Occupational health and safety elements	16. Occupational health and safety elements	Unstructured data
	17. Knowledge of accounting concepts	17. Knowledge of accounting concepts	Unstructured data
	18. IFRS policies	18. IFRS policies	Unstructured data
Psychosocial	1. Rate	1. Rate	Structured data
	2. Satisfaction with service	2. Satisfaction with service	Unstructured data
	3. Effectiveness	3. Effectiveness	Unstructured data
	4. Problematic	4. Problematic	Unstructured data
	5. Management	5. Management	Unstructured data
	6. Participation	6. Participation	Unstructured data
	7. Transparency	7. Transparency	Unstructured data
	8. Planning	8. Planning	Unstructured data

3.2. Structured Data Analysis Results

An Exploratory Data Analysis (EDA) was conducted on the structured variables of fourteen community and rural water systems, aiming to identify patterns, trends, and potential anomalies. The process involved data cleaning, imputation, normalization, and encoding, followed by descriptive statistics and graphical visualizations. This analysis enabled the characterization of technical, environmental, administrative-accounting, and psychosocial components, providing key inputs for a comprehensive evaluation under the Integrated Water Resources Management (IWRM) approach. Table 3 presents the variable reclassification process of the components and variables used under the IWRM framework, including their AI-driven reclassification and the analysis of their attributes as structured or unstructured data.

Table 3. Components, variables and reclassification

Component	Number of initial variables	Reclassified variables after pilot testing	Reclassification of variables for IA-based analysis	Number of variables for structured data	Number of variables for unstructured data
Technical	37	7	5	4	1
Environmental	14	8	8	4	4
Administrative-accounting	41	18	18	10	8
Psychosocial	33	8	8	1	7
TOTAL	**125**	**41**	**39**	**19**	**20**

Figure 7 presents a comparative analysis of component variables across four domains—Technical, Environmental, Admin-Accounting, and Psychosocial—highlighting both their evolution through different analytical stages and their classification by data structure. Figure 7(a) illustrates the progressive reduction of variables from the initial dataset, through pilot testing, to the final selection used for M-based analysis, revealing a significant refinement process. Figure 7(b) categorizes these final variables into structured and unstructured formats, showing that while Technical and Environmental components are predominantly structured, Admin-Accounting and Psychosocial domains contain a more balanced mix, with a notable presence of unstructured data. This dual perspective supports a deeper understanding of data complexity and informs the selection of appropriate analytical methods.

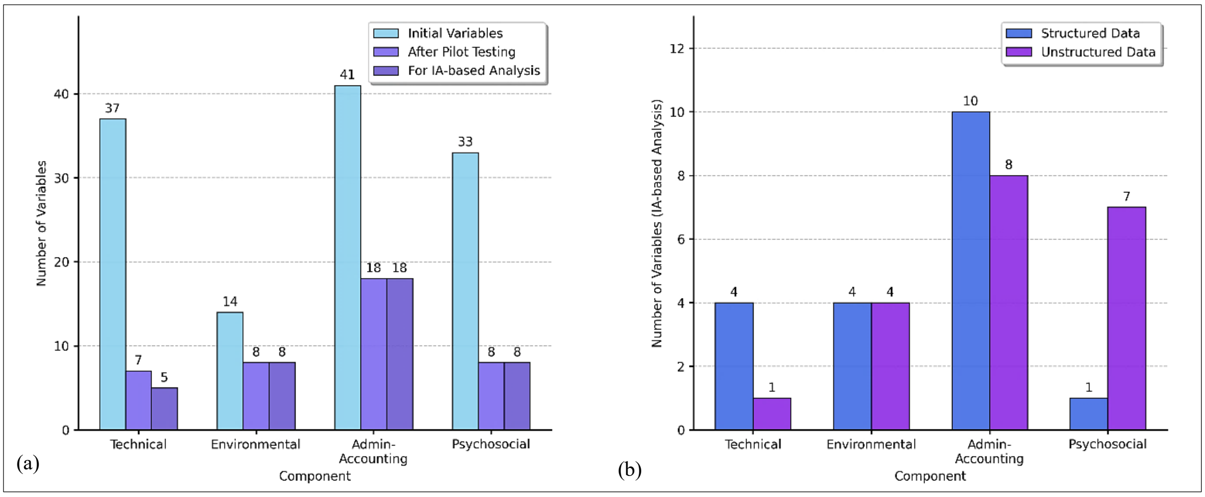

Figure 7. Presents the component variable data, divided into structured and unstructured data

Technical Component

Table 4 presents the descriptive statistics for the numerical variables from the technical component, focusing on data from fourteen community aqueducts. The analysis was conducted using Exploratory Data Analysis (EDA) to identify patterns, distributions, and correlations relevant to understanding the operational efficiency of these systems and to inform management practices.

Table 4. Descriptive metrics for numerical variables of the technical component

Variable	Mean	Standard deviation	Min	Max	Shapiro-Wilk (p-value)
Maintenance time (d)	50.54	49.24	0.50	180.00	< 0.05
Operating Flow (L/s)	4.09	2.7	0.8	12.00	< 0.05
Water concession flow (L/s)	6.02	3.28	0.80	12.00	< 0.05

Figure 8 illustrates the flow analysis and potential expansion capacity of the aqueducts, focusing on their ability to accommodate a larger user base relative to the water concession flow. This assessment is critical for understanding the operational limits and scalability of each system. The figure highlights how available water resources can support future demand by analyzing current flow rates against infrastructure capacity. The analysis also considers the expansion rate, offering insights into the feasibility of increasing coverage while maintaining operational efficiency and service quality. This contextual understanding is essential for informed decision-making regarding the long-term sustainability and growth of the aqueducts.

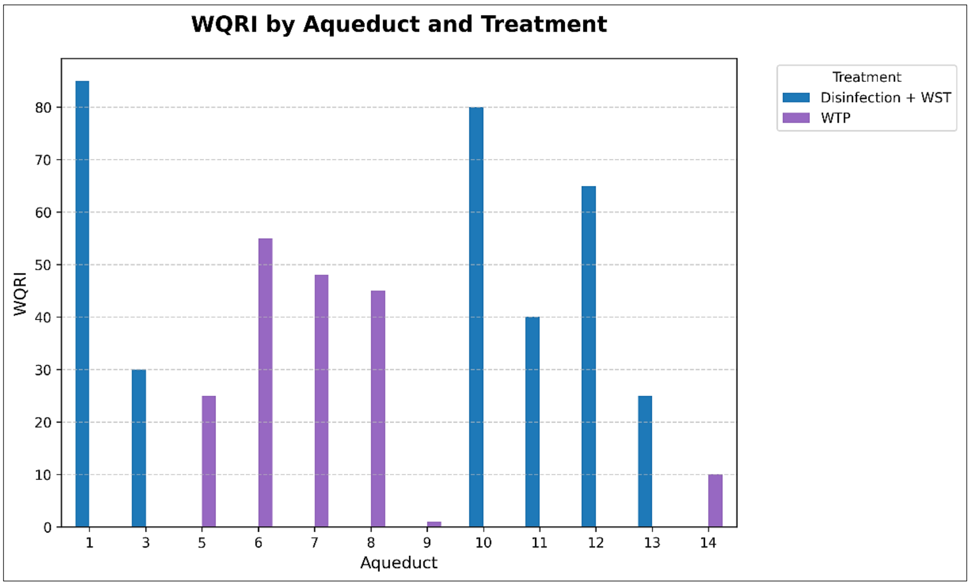

Figure 8. Flow Analysis and Expansion Potential of Community Aqueducts Based on Concessioned Flow

This component also examines the relationship between the type of water treatment process implemented and the Water Quality Risk Index (WQRI), as depicted in Figure 9. The X-axis identifies the individual aqueducts, and the series indicates the treatment type applied. Here, WTP (Water Treatment Plant) denotes a conventional treatment process, while WST (Water Storage Tank) indicates a system limited to disinfection and storage. The Y-axis shows the WQRI percentage, enabling an evaluation of how treatment methodologies influence water safety. It should be noted that the WTP systems typically employ a conventional process, including coagulation, flocculation, accelerated sedimentation, filtration, disinfection, and final storage in a WST.

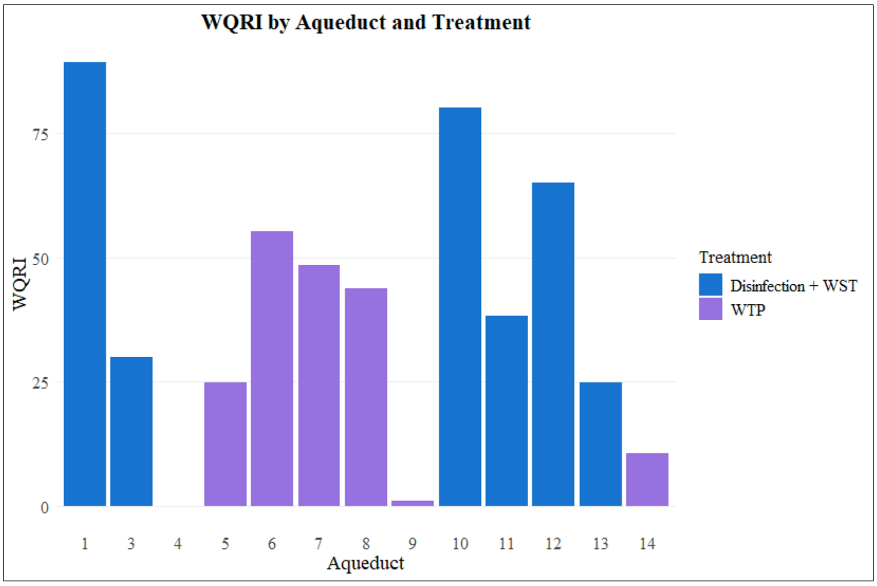

Figure 9. Relationship Water Quality Risk Index (WQRI) and water treatment process.

Environmental Component

The specific metrics calculated for the numerical variables of the environmental component are presented in Table 5. The evaluation reveals the distribution type and allows for the determination of the most appropriate measure of central tendency for data analysis.

Table 5. Descriptive metrics for numerical variables of the environmental component

Variable	Mean	Median	Standard deviation	Minimum	Maximum	Shapiro-Wilk (p-value)
a) System Age (Years)	34.57	37.00	9.78	17.00	48.00	> 0.05
b) Plumber Experience (Years)	12.62	10.81	9.08	1.00	30.00	> 0.05
c) Users per Service Connection	297.91	97.91	268.74	30.00	1115.00	< 0.05
d) Users per habitant (Population Served)	1340.50	1294.25	983.51	150.00	3075.00	> 0.05

Regarding the numerical variables, these findings underscore the necessity of utilizing the median, as opposed to the mean, for analyzing variables prone to skewed distributions, such as 'Users per Connection' and 'Total Users' observed in this context. The median provides a more accurate and robust representation of typical operational conditions and capacities, guarding against planning misinterpretations driven by outlier values and providing a sounder basis for assessment and intervention strategies. Visual summaries of the key numerical variables discussed are presented in Figure 10.

The numerical variables summarized in Figure 10 provide critical insights for strategic planning. System age informs the assessment of infrastructure condition, guiding maintenance and rehabilitation planning to ensure service reliability. Similarly, operator experience data underscores the need for succession planning to preserve institutional memory. Finally, an analysis of service connection density clarifies the typical operational model, which is a prerequisite for designing effective tariff structures and maintenance strategies.

The analysis of categorical variables within the environmental component, detailed in Figure 11, also yields significant insights into key operational and management characteristics of the surveyed rural and community water systems.

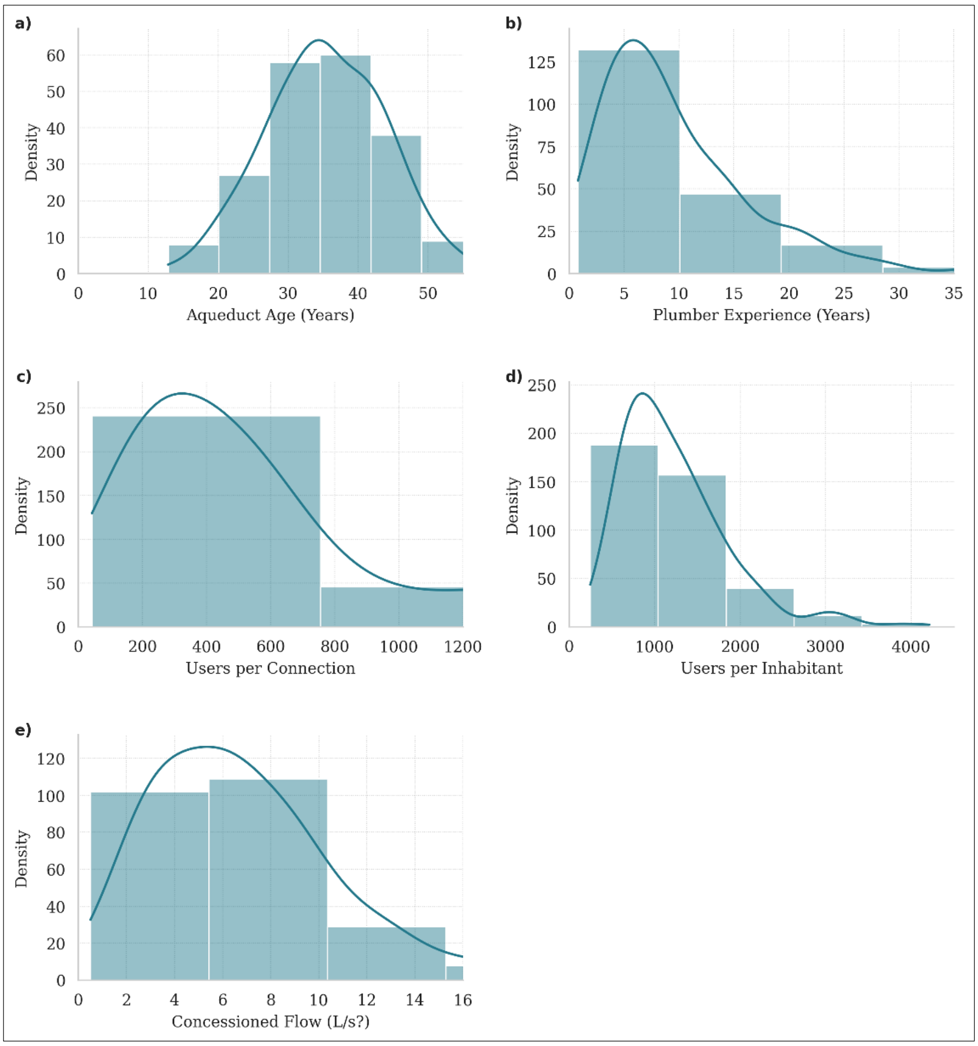

Figure 10. Key Numerical Variables Relevant to the Environmental Component

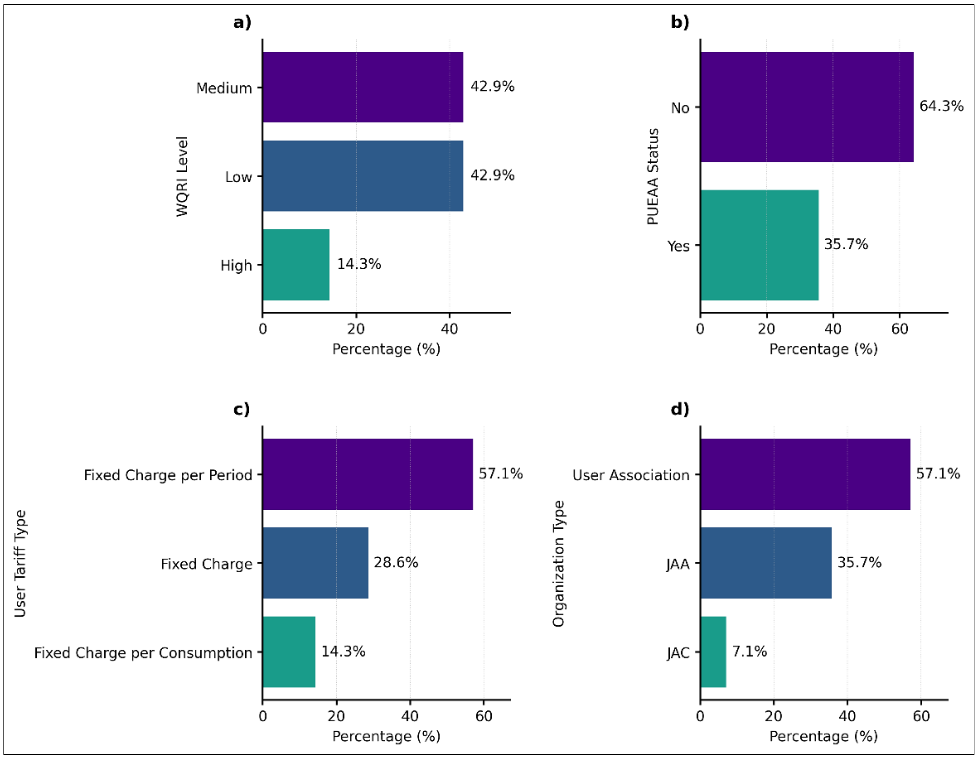

Figure 11. Key categorical Variables Relevant to the Environmental Component

The categorical variables presented in Figure 11 offer insights into the structural challenges confronting the community-based organizations responsible for managing these systems. The data highlights critical areas for improvement, including the need to ensure consistent water quality, advance long-term environmental sustainability planning, and implement tariff structures that secure financial viability while promoting water conservation.

Administrative-accounting Component

Figure 12 illustrates the results of the Exploratory Data Analysis (EDA) applied to the administrative-accounting variables of the evaluated rural and community water supply systems. The results, presented as percentages, are divided into two categories: "Complies" and "Does Not Comply." High compliance is observed in areas such as accounting support, occupational health and safety protocols, and commercial registry renewal. However, significant gaps are noted in aspects like electronic payroll, IFRS policies, and the use of accounting software, highlighting critical areas that need institutional strengthening.

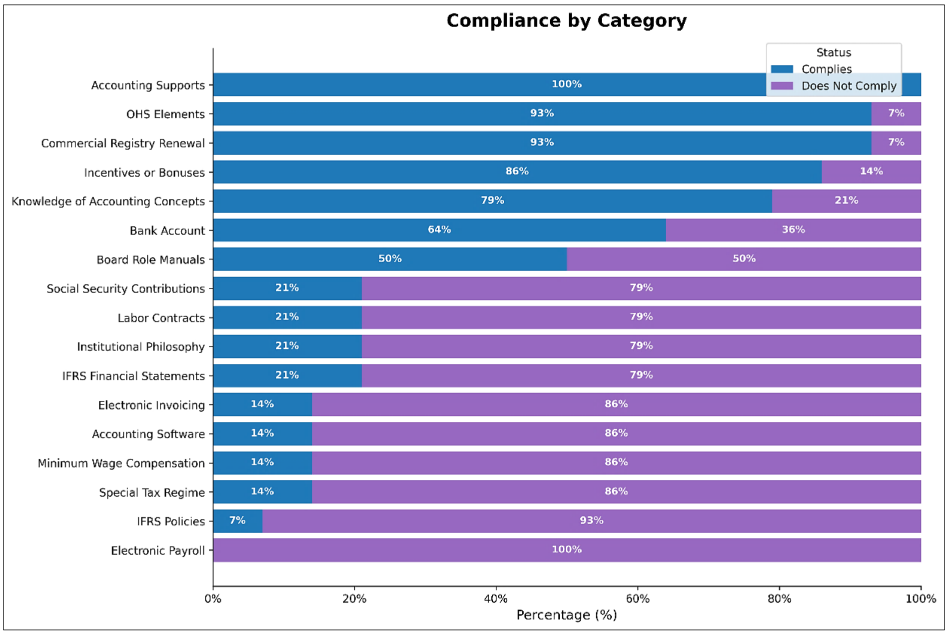

Figure 12. Analysis of compliance with the variables of the administrative-accounting component

Figure 13 shows the percentage of users who are up-to-date with their payments across various aqueducts. Each bar represents the compliance level per aqueduct, highlighting those that achieve 100% on-time payments as well as those with lower compliance. The chart also includes mean (76%) and median (78%) reference lines to assess overall performance. This information helps identify aqueducts with effective payment management practices, as well as those that need strategies to improve user payment behavior.

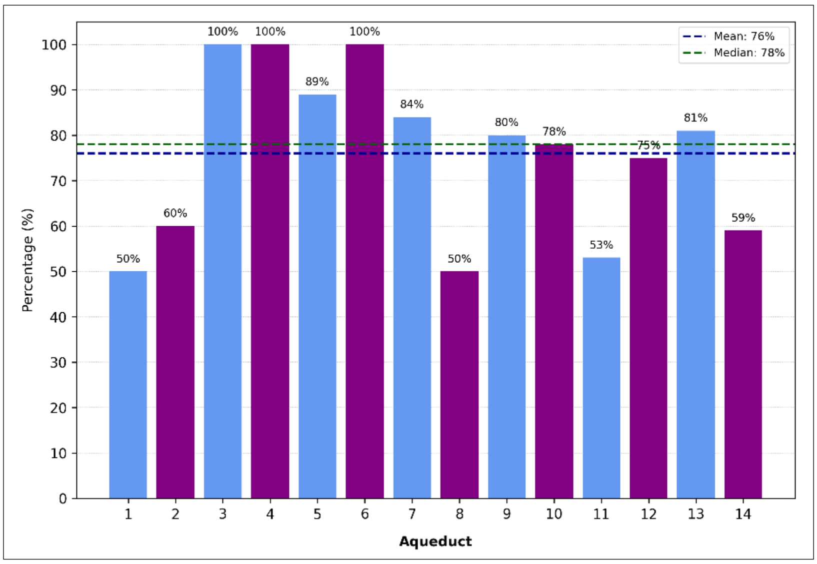

Figure 13. Users up to date with payment by aqueduct

Psychosocial Component

The psychosocial dimension plays a key role in understanding the sustainability and governance of community-managed water systems. It examines how perceptions, participation, social organization, equity, and ethical practices shape the relationship between communities and their water services. By analyzing both structured and unstructured variables, this component helps identify strengths, weaknesses, and opportunities that directly impact community ownership, operational efficiency, and long-term resilience of water systems. Figure 14 summarizes the results of the psychosocial assessment, which was based on 13 core variables related to perception, participation, governance, and sustainability. The responses are categorized as Yes, Partially, and No, enabling a clear visualization of performance and perception levels across dimensions. These findings reveal patterns, highlight critical gaps, and point to priority areas for strengthening community and institutional frameworks.

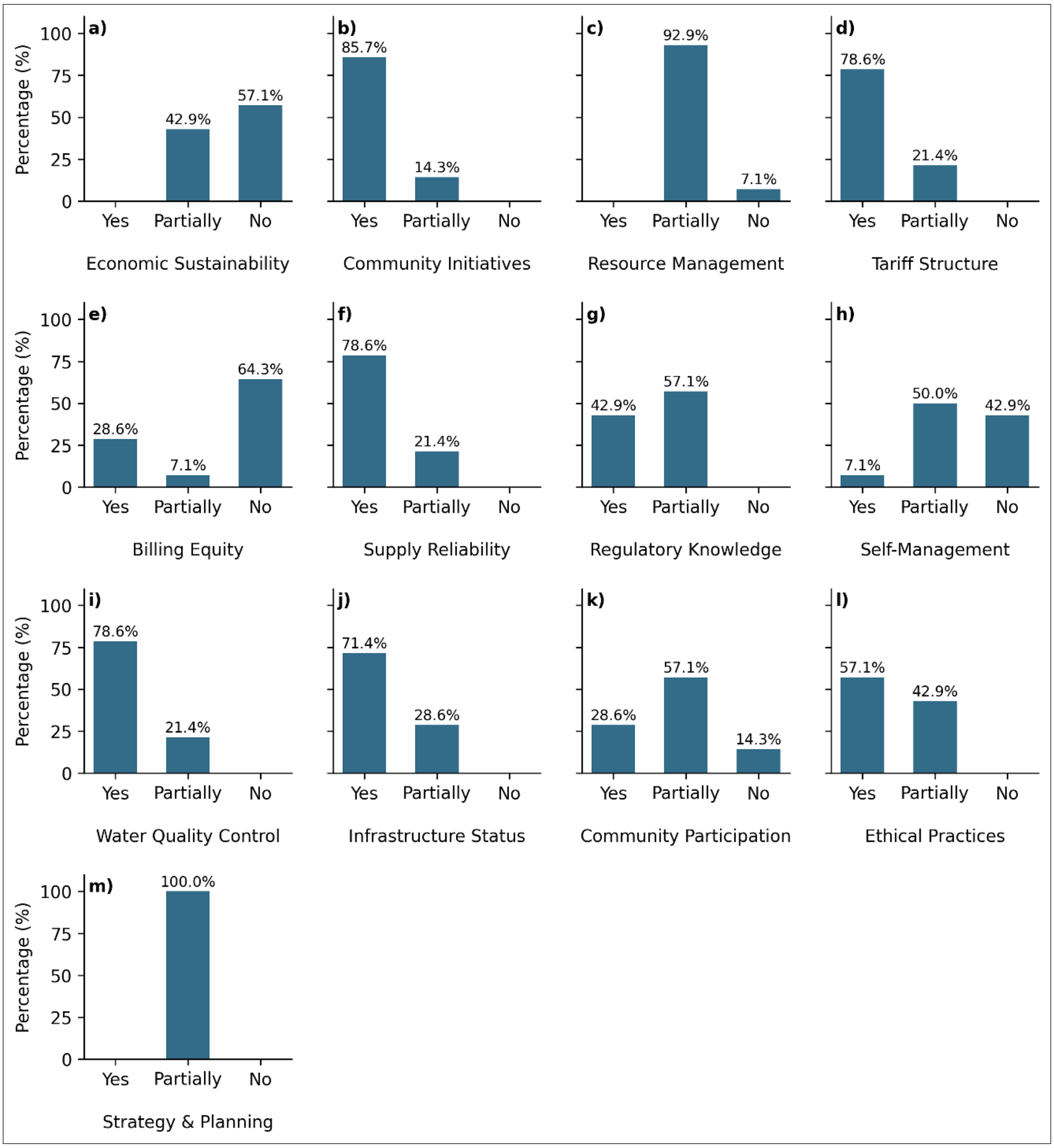

Figure 14. Graphical Analysis of the Psychosocial Component

The contrast with previous studies reveals that the symbolic appropriation of infrastructure requires sustainable deliberative spaces and consolidated organizational capacities to be transformed into effective collective action [27]. In the absence of such conditions, what Chambers [28] defines as nominal participation predominates, where attendance at collective arenas does not necessarily ensure real agency or the transformation of power relations. In this regard, ethnographic research in the Colombian Pacific demonstrates that, despite high levels of social cohesion, dynamics of exclusion affecting women and youth persist, thereby undermining the legitimacy of leadership structures [29].

Furthermore, multiple studies converge in showing that both technical and psychosocial training act as decisive moderating factors. Participatory educational interventions and sustained institutional accompaniment not only enhance co-responsibility but also strengthen the legitimacy of local leadership [30, 31]. These findings are consistent with international scholarship: Bakker [32] and Lemos & Agrawal [33] argue that the sustainability of community water systems relies less on physical infrastructure and more on the organizational, technical, and financial capacities of communities, while Freire [34] stresses that critical education is indispensable to prevent social cohesion from becoming a mechanism of control exercised by local elites.

In summary, the results indicate that the psychosocial dimension of community aqueducts in Colombia is shaped by three interdependent factors:

- Symbolic appropriation as a cultural and emotional foundation.
- Technical and psychosocial training as a prerequisite for agency and innovation.
- Differentiated institutional accompaniment as a guarantee of inclusion and leadership legitimacy.

Therefore, the sustainability of community aqueducts cannot be conceived as an exclusively technical outcome; it requires the recognition of internal social dynamics, the promotion of legitimate leadership, and the design of differentiated public policies that respond to the territorial and cultural diversity of rural communities.

3.3. Unstructured Data Analysis Results

Unstructured data analysis is based on qualitative variables, which were initially categorized as unstructured. Subsequently, sentiment analysis techniques were applied to discern the underlying attitudes and emotions within the data, transforming qualitative information into quantifiable insights and facilitating a deeper understanding of the studied context.

Sensitivity Analysis

The cluster analysis, represented by the dendrogram, reveals the hierarchical clustering of terms and themes based on their similarity and frequency of occurrence (Figure 15). A dendrogram is a hierarchical diagram that visualizes the degree of association among variables, enabling the identification of structural patterns and distinctive approaches in aqueduct management. In this context, the term "sensitivity analysis" refers to a methodological process that evaluates the robustness of the findings by examining how variations in data or criteria influence the grouping and interpretation of results. The analysis identifies two principal clusters: one oriented toward technical dimensions, characterized by keywords such as "analyze," "variable," and "hydric"; and another encompassing administrative, environmental, and social dimensions, with terms such as "compliance," "management," and "service."

This division demonstrates divergent perspectives and underscores the necessity of integrating technical components with administrative, environmental, and social considerations. Furthermore, the cluster and sentiment analysis enhances the interpretation by highlighting how emphasis and meaning are distributed across clusters, thereby elucidating both contrasts and complementarities. To support this process, a systematic search approach was applied to identify relevant studies, following the PRISMA 2020 guidelines, to determine the most appropriate analytical techniques for data interpretation.

The search included databases such as Scopus, ScienceDirect, Elicit, and SciSpace, focusing on open-access, English-language articles and reviews published between 2019 and 2024. These sources were chosen for their coverage of key disciplines, including Business, Management and Accounting, Environmental Science, Engineering, and Social Sciences. A prompt pattern was employed to guide the search and ensure comprehensive and relevant results, providing a broad understanding of the complex factors influencing the sustainability and efficiency of rural and community water systems. Additionally, specific AI platforms for text mining and sentiment analysis were used to classify and cluster the terms, applying tools integrated with Scopus, ScienceDirect, and open-source algorithms to extract, categorize, and group terms according to frequency and semantic proximity. The outcomes were validated through triangulation, which combined the systematic review protocols (PRISMA), the robustness of AI-driven text mining, and expert qualitative judgment. For example, sentiment classifications were verified by comparing automated categorizations with manual qualitative assessments, ensuring both accuracy and contextual consistency in the interpretation of results.

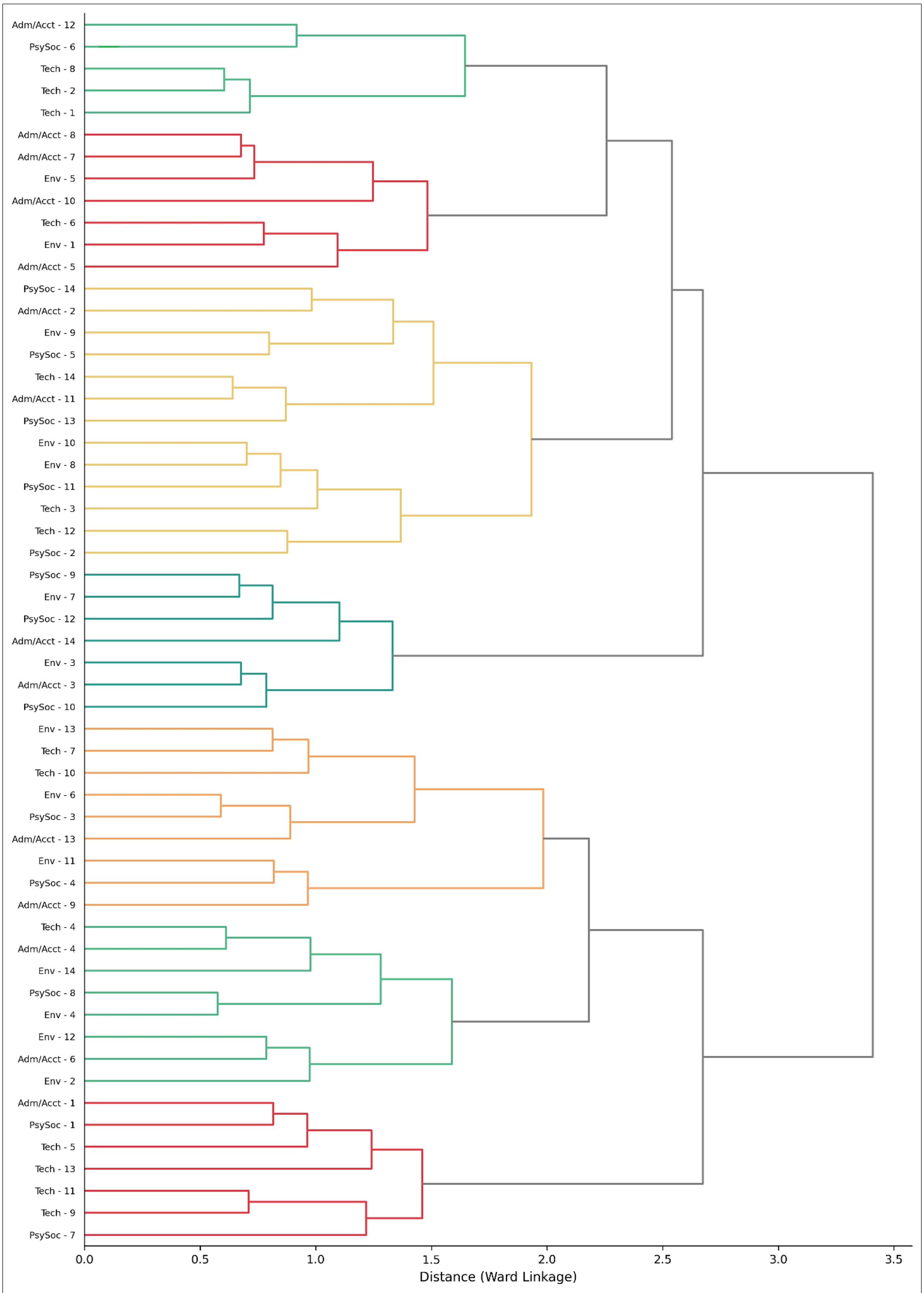

Figure 15. Dendrogram

Hierarchical Clustering Analysis

The clustering analysis identified two primary groups:

Table 6 presents the results of a lexical cluster analysis applied to the diagnostic methodology, revealing two distinct thematic groupings. Cluster 1 reflects a technical orientation, characterized by terminology such as *analyze*, *variable*, and *hydric*, indicating a focus on data-driven and system-based aspects. In contrast, Cluster 2 encompasses an administrative, environmental, and social perspective, with key terms like *compliance*, *management*, and *service*, suggesting an emphasis on regulatory frameworks, operational oversight, and stakeholder engagement. This classification supports a multidimensional understanding of the diagnostic approach and its underlying priorities (see Figure 16).

Table 6. Analysis identified of the diagnostic methodology

Cluster 1 (Technical Focus): Associated with terms like "analyze," "variable," and "hydric."
Cluster 2 (Administrative, Environmental, and Social Focus): Highlighting terms such as "compliance," "management," and "service."

This segmentation suggests a need for better integration between technical operations and management practices.

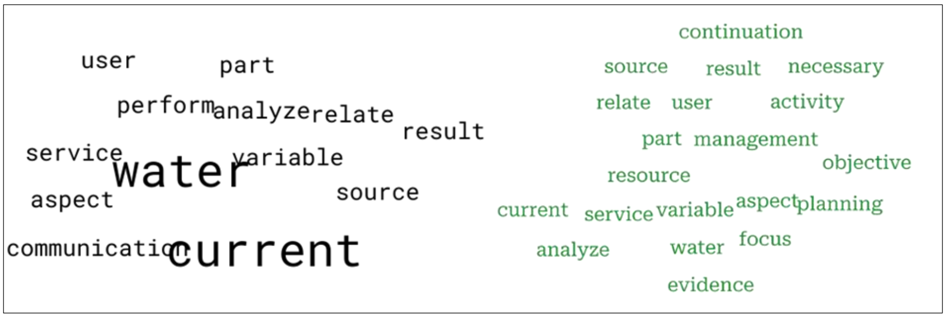

Figure 16. Word Clouds by Cluster in Hierarchical Clustering Dendrogram

Sentiment Analysis

The sentiment analysis revealed the following trends (see Table 7):

Table 7. Trend analysis

• The technical component displayed more negative sentiment, with key themes related to system deficiencies, water supply challenges, and maintenance issues.	• The environmental, administrative-accounting, and psychosocial components exhibited predominantly positive sentiment, emphasizing effective resource management and community participation.

4. Discussion

The predominance of structured data (80%) indicates that technical information can be effectively organized into tabular or categorical formats, enhancing its accessibility and processability by AI systems. However, certain fields require a balance between structured and unstructured formats to capture nuanced insights beyond numerical representations.

In the environmental domain, the 50/50 distribution of structured and unstructured data highlights the need for both quantitative metrics and qualitative descriptions. Structured data, such as numerical measurements, ensure standardized assessments, while unstructured sources, including reports and observations, provide contextual depth. Similarly, the administrative-accounting sector leans slightly towards structured data (56%), given its reliance on financial records and formal processes. Conversely, the psychosocial domain exhibits a strong predominance of unstructured data (87.5%), reflecting its qualitative nature. Interviews, narratives, and observations play a crucial role in capturing human experiences, emotions, and social interactions, where rigid categorizations may fall short. This reliance on unstructured formats suggests an emphasis on interpretative methodologies, prioritizing contextual understanding over strictly quantitative classifications.

4.1. Technical Component

The exploratory data analysis (EDA) of the technical component highlights critical aspects of infrastructure and operational performance essential for efficient system management. The findings in Table 4 show that the operating flow is significantly lower than the concession flow, indicating that the evaluated water sources have the capacity to supply the current population. Furthermore, Figure 8 illustrates that the calculated flow, which corresponds to the water required based on the number of users, is considerably lower than the granted flow. This suggests that the expansion rate is approximately 50%, indicating the potential to extend service to additional users without overloading the system.

However, technical field visits revealed that some systems require more flow than initially estimated, pointing to inefficient water use practices. The visits identified a near-total lack of precise flow control, with no mechanisms to regulate the inflow and outflow of water. These systems are essentially operating at the granted flow rate, which has led to water being used for activities beyond its intended scope, such as irrigation and industrial or commercial uses. This emphasizes the need to complement technical calculations with field evaluations to diagnose actual water demand more accurately. A study by Torres Serrano & Sánchez Talero [35] examined water supply systems in rural and peri-urban communities in Colombia, highlighting the issue of aqueducts supplying more water than needed. The research found prevalent discrepancies between perceived household water use and actual supply. This over-supply was often attributed to system losses, non-domestic water use, and inefficient management practices. The study emphasized the need for improved flow control mechanisms to align water supply more closely with actual demand, avoiding inefficiencies in both resource use and system performance.

The assessment of key numerical variables, such as operating and granted flows, provides valuable insights into the operational capacity of the aqueducts. Although the mean and median values appear relatively consistent, the data reveal significant variability, indicating differences in scale and functionality across communities. This variability is further highlighted by extreme values in systems serving larger populations; for instance, the number of users per aqueduct ranges from 34 to 815. The results of the Shapiro-Wilk test, with p-values below 0.05, confirm that all numerical variables exhibit non-normal distributions. This statistical evidence indicates the presence of outliers—systems with unique characteristics, such as unusually high user numbers or specific maintenance needs. These findings highlight the inadequacy of standard water treatment strategies for the diverse operational conditions of rural and community aqueducts and underscore the need for tailored management approaches and infrastructure investment strategies.

This variability necessitates context-specific solutions. For example, in Ghana, community-managed water systems have significantly increased access to potable water in small towns and rural areas, although challenges related to sustainability and technical capacity persist [36]. Similarly, a case study in Sri Lanka demonstrates that a community organization successfully manages a water supply system serving a small town with approximately 1,000 service connections [37]. These examples highlight the importance of community management in addressing water access across different contexts, while also emphasizing the universal need to overcome challenges related to sustainability and capacity.

The analysis of water treatment processes and their relationship to the Water Quality Risk Index (WQRI) [38], as shown in Figure 2, reveals that only 50% of the aqueducts apply any type of treatment. Although treated systems show higher water quality levels within the sample, none meet the potable water standards for human consumption under Resolution 2115 of 2007 issued by the Ministry of Health and Social Protection of Colombia [39]. This situation reflects a combination of technical, operational, and administrative deficiencies and underscores the urgent need for targeted interventions to ensure water safety and regulatory compliance. Research by Ramos-Parra & Pinilla-Roncancio [40] on water quality in rural supply systems in Boyacá, Colombia, found that the absence of a treatment system was associated with lower odds of failing to meet the WQRI (OR 0.2, 95% CI 0.05–0.72) compared to systems with treatment. Their study concluded that the supply of unsafe water in rural Boyacá was associated with a lack of treatment infrastructure and insufficient operational control of treatment units. These factors are directly related to the presence of Escherichia coli and coliforms in the drinking water, a finding that is consistent with the results of the present study.

4.2. Environmental Component

The results of this study reveal a central paradox in the management of the analyzed community water systems: while they exhibit a solid operational foundation and experienced human capital, they face profound strategic weaknesses that threaten their long-term sustainability. The following discussion is organized around the primary strengths, vulnerabilities, and critical implications for planning and public policy.

A fundamental strength of these systems is their human and social capital, rooted in a community-based management model (JAAs or user associations) and the deep expertise of their technical personnel. The median operator experience of nearly 11 years constitutes a valuable asset of institutional knowledge that positively impacts service quality and continuity [41]. However, this very stability introduces a critical vulnerability. As highlighted by Feliciano et al. [42], while the long tenure of operators fosters trust and operational reliability, the absence of formal succession mechanisms renders this human capital a fragile resource that is susceptible to loss, thereby compromising the system's long-term sustainability.

This human capital operates within the context of an aging infrastructure. With a median system age of 37 years, a significant portion of the infrastructure is approaching or has surpassed its design life. This situation implies an inevitable increase in maintenance costs and failure frequency, signaling an urgent need for asset rehabilitation and replacement planning. These findings are consistent with a broader regional pattern. Torres Serrano & Sánchez Talero [35] documents how system age leads to recurrent failures and limits investment capacity for network expansion. In this context, the recommendation by Rivera-López & Suárez [43] for periodic renewals and asset management models becomes particularly relevant, not only to ensure service continuity but also to mitigate the environmental impact of inefficiency and resource overexploitation.

This fragility of institutional knowledge has been noted in similar contexts. Melo & Salazar [44] identifies the high dependency on veteran operators and the lack of training for new leaders as a systemic risk. Likewise, studies of rural water systems, such as those in Mocoa, confirm that resource limitations hinder generational turnover, compromising both efficient management and environmental stewardship.

Perhaps the most alarming finding is the systemic deficiency in proactive environmental management. Despite regulatory requirements [45, 46], environmental studies and watershed protection plans are virtually nonexistent. This deficiency is compounded by low adoption rates of mandatory Water Use Efficiency and Savings Programs (PUEAA) and a widespread lack of formal documentation for discharge permits [47]. Collectively, these results indicate a structural deficit in long-term planning rather than isolated failures, leaving the systems highly vulnerable to climate change, source contamination, and hydrologic variability. Although most systems currently present a moderate water quality risk (WQRI), this stability is fragile and could rapidly deteriorate without robust environmental management.

The sustainability of the studied systems is further compromised by financial models that fail to incentivize efficiency. The predominance of fixed tariff schemes—a finding consistent with recent studies—hinders both cost recovery and water conservation. This weakness is magnified by the scale of the analyzed systems; with a median of approximately 1,300 users, the lack of conservation incentives exerts considerable pressure on water sources. This risk is exacerbated when demand approaches available supply, a condition highlighted by Ruiz [48] and studies on the Water Use Index. In this context, a transition toward equitable, consumption-based tariff models, as recommended by Montoya [49], would not only improve financial viability but also serve as a key tool for demand management and resource conservation.

Finally, this study underscores the importance of selecting appropriate statistical metrics. For highly skewed variables, such as "users per connection," using the mean (297.91) instead of the median (97.91) would lead to an erroneous interpretation of the operational reality, suggesting a high-density model where a network of individual connections actually prevails. The use of the median [6, 50] is therefore crucial for accurate hydraulic modeling, equitable tariff design, and effective maintenance planning, preventing decisions based on outlier values.

To ensure sustainable and efficient management, support policies for community water systems must transcend the strengthening of operational capacities and focus on closing the identified strategic gaps. This requires actively promoting environmental impact assessments, formulating Water Use Efficiency and Savings Programs, modernizing tariff systems, and implementing long-term asset management planning [51, 52].

4.3. Administrative-Accounting Component

The analysis of the administrative-accounting component reveals significant heterogeneity in compliance across community aqueducts. While some systems report basic achievements such as occupational safety protocols and commercial registry renewal, others show marked gaps in adopting International Financial Reporting Standards (IFRS), electronic payroll, and accounting software. These findings highlight persistent informality and limited use of digital tools, which weaken financial transparency and institutional strengthening.

Similar results have been documented in the Colombian context. Villota Castillo [53], in a case study of three rural community aqueducts in Cali, identified weaknesses in organizational structure, administrative coordination, and monitoring processes that directly undermined efficiency and sustainability. Likewise, an assessment of water service providers in the municipalities of Ciénaga and Fundación (Magdalena) reported deficiencies in administrative and financial management, as well as difficulties in complying with the regulatory framework established by Law 142 of 1994 [54]. At the national level, the Superintendence of Public Services [55] has repeatedly highlighted shortcomings in financial and administrative reporting among community providers, a situation consistent with the patterns observed in this study.

Comparable evidence has been reported in other Latin American countries. In Ecuador, community water boards frequently face a lack of standardized accounting systems and weak regulatory enforcement, indicating a need for unified accounting manuals and procedures tailored to rural providers [56, 57]. These findings suggest that challenges in formalization and accounting practices extend beyond Colombia and reflect a broader regional pattern in community water governance.

In contrast, studies from countries with more consolidated regulatory frameworks illustrate notable differences. In Spain, administrative and accounting practices—particularly cost recovery mechanisms and financial auditing—have proven decisive for both financial sustainability and service quality [58, 59]. Similarly, evidence from Kenya shows that the systematic implementation of financial audits significantly improves transparency and strengthens the financial performance of water companies [60].

This comparative perspective leads to the conclusion that although deficiencies in administrative-accounting management are recurrent across rural water systems in Latin America, they are particularly acute in Colombia due to persistent informality and limited institutional capacity. The divergence from experiences in Spain and Kenya underscores the urgency of strengthening regulatory oversight, promoting digitalization, and professionalizing accounting practices. Such measures are essential to close existing gaps, align local systems with international standards, and enhance financial sustainability, transparency, and user trust in community-managed water services.

The administrative-accounting component of this research reveals marked heterogeneity in compliance with the evaluated requirements. The corresponding graph shows that only two variables reached 100% compliance: the provision of accounting support services and, to a slightly lesser extent, compliance with occupational health and safety protocols (93%), along with the renewal of the commercial registry (93%). These results reflect strengths in basic aspects of business formalization and the presence of technical or professional support, consistent with the provisions of Law 142 of 1994 [54] and current commercial regulations [61].

However, significant gaps were identified in critical elements for the sustainability and modernization of accounting systems. Variables such as implementing electronic payroll systems, adopting International Financial Reporting Standards (IFRS)-based accounting policies, and participating in special tax regimes exhibit the lowest compliance levels (7% and 14%, respectively), indicating a considerable lag in adapting to current regulatory standards [62].

The limited use of technological tools, such as electronic invoicing (14%) and accounting software (14%), reveals a digital gap that may hinder financial transparency and efficiency. This situation is inconsistent with the requirements set by DIAN and the guidelines established in Decree 1625 of 2016 [63]. Furthermore, low levels of compliance with labor contract formalization (21%) and contributions to the social security system (21%) reflect persistent informality in hiring practices. This is also evidenced by low compliance rates with the legal minimum wage and social security coverage (14%), as required by Colombian labor legislation [64].

Regarding organizational structure, variables such as the availability of procedure manuals (50%), the definition of an institutional philosophy (21%), and the understanding of basic accounting concepts (79%) show partial progress in *internal capacity-building*. Nonetheless, substantial opportunities for improvement remain [2].

Overall, the average compliance rate of 76%, with a median of 78%, suggests that while most systems maintain a reasonably efficient billing and collection process, there is still significant room for improvement. This pattern challenges common assumptions that rural communities inherently lack the capacity or willingness to pay, as recent studies on the financial sustainability of rural water systems have shown [65].

4.4. Psychosocial Component

The psychosocial dimension, which is key to understanding the community dynamics involved in water management, reveals mixed conditions in terms of perception, cohesion, and participation among stakeholders in the rural and community aqueducts of Pasto's Eastern Corridor. The results show that while there is a generalized sense of ownership toward the aqueduct, this does not always translate into active participation in decision-making or co-responsibility. This aligns with Freire's [34] proposition that critical awareness does not arise spontaneously but must be fostered through participatory educational processes that strengthen agency and transformative capacity.

Social cohesion, defined as the degree of solidarity, trust, and cooperation among community members [12], is a key factor in the success of community water management models. However, its presence alone does not guarantee inclusive governance. Studies have shown that in the absence of democratic and inclusive structures, cohesion can produce social control dynamics that perpetuate internal inequalities [13]. The analysis also shows that although leadership is often committed, it lacks full legitimacy and the necessary skills to facilitate broad participatory processes. This situation exemplifies what Chambers [28] termed "nominal participation," referring to engagement that is largely formal or symbolic, without real influence in decision-making.

Additionally, the data suggests a persistent instrumental view of community work, where people expect others to solve collective problems. This mindset, shaped by historical patterns of institutional exclusion and state neglect in rural areas, has led to dependency and distrust of institutions, hindering community empowerment.

To strengthen this component, it is essential to adopt integrated community development approaches that foster psychosocial capacities, self-management practices, organizational resilience, and active citizenship. In this sense, the human development approach proposed by Sen [66] is especially relevant, as it emphasizes expanding people's freedoms and capabilities to live the life they value—an idea that itself entails collective agency.

Furthermore, one of the main obstacles to adopting AI-based diagnostic approaches in rural community aqueducts is the structural gap in digital infrastructure and connectivity. In territories such as southern Colombia, where internet coverage is limited, unstable, or even nonexistent, AI systems face serious restrictions for real-time data collection, transmission, and processing. This technical limitation underscores the need for hybrid models that combine the potential of automated analysis with participatory and offline methodologies, thereby avoiding exclusive reliance on full digitalization.

Moreover, social resistance is a critical factor. In communities that have historically managed their aqueducts through self-governance, interpersonal trust, and local knowledge, the introduction of external technologies can generate distrust, particularly if they are perceived as mechanisms of control or as tools that displace community-based knowledge. Therefore, implementing AI cannot be reduced to a technical process but must involve social and pedagogical mediation to ensure community ownership, transparency in data use, and the strengthening of local governance.

Consequently, the sustainability of this approach depends on two strategic conditions: 1) overcoming infrastructure limitations through adaptive solutions, such as decentralized systems, low-cost hardware, and local data storage; and 2) promoting technological co-construction, where AI complements rather than replaces territorial knowledge, integrating it into processes of collective participation and decision-making. Only under these conditions can AI become a legitimate and valuable resource for rural water management, adding value without undermining community autonomy or reproducing digital inequalities.

Taken together, these findings demonstrate the need for differentiated public policies aimed at strengthening the institutional capacity of community aqueducts. Such policies should include permanent technical assistance, training programs tailored to rural contexts, and accessible financing mechanisms. As Bakker [67] and Lemos & Agrawal [33] suggest, the sustainability of community-managed water systems depends not only on physical infrastructure but also on the organizational, technical, and financial capacity of the managing communities. Failure to address these gaps jeopardizes not only operational continuity but also the fundamental human right to safe and dignified access to water for rural populations.

The prevailing trend in water management, supported by research, is that implementing some form of water treatment generally reduces the risk of non-compliance with quality standards, such as the Water Quality Risk Index (WQRI). However, a notable and atypical finding is that a high percentage of treated systems still fail to meet potability standards. This suggests that the significant investment and operational effort dedicated to treatment are proving critically ineffective in achieving the necessary legal and public health objectives.

This striking ineffectiveness demands a deeper investigation beyond general technical deficiencies. Explanations must specifically address the nature and quality of the treatment process, including dosage and operational control, potential post-treatment contamination (like post-chlorination issues), and the specific causes of non-compliance (e.g., whether microbiological or physicochemical parameters are at fault). This underscores that the core issue is not merely the absence of treatment (as seen in some cases), but the failure of existing treatment systems, highlighting the urgency and complexity of the required interventions.

To bridge the findings with policy recommendations and practical application, the following actions are proposed: Focus immediate efforts on water loss control by implementing micro-metering and zonal control programs, which require regulatory support and subsidies from the relevant ministry and execution by water utility boards. For infrastructure, a risk matrix based on user count and water quality should be developed to prioritize rehabilitation, with funding secured from local government offices (governor's/mayor's) and oversight provided by the Superintendencia de Servicios Públicos. To ensure treatment quality, a dedicated optimization team must provide technical assistance and essential equipment (compact chlorination and residual chlorine meters), requiring a joint effort between Secretarías de Salud and water utility boards to guarantee compliance with standards.

Achieving long-term financial and environmental sustainability requires establishing asset management models and periodic renovation cycles financed by the Ministerio de Hacienda or development banks. This must be complemented by adopting tariff structures with cross-subsidies for essential consumption, as regulated by the Comisión de Regulación de Agua Potable y Saneamiento Básico, and mandating simplified water use and savings plans for subsidy access, alongside community watershed management initiatives. Finally, addressing administrative and human capital involves combating informality and securing qualified personnel through a formal training program for operators (focusing on succession and operational manuals) and an incentivized labor formalization program, coordinated by the Ministerio del Trabajo and executed by the water utility boards.

5. Conclusion

This interdisciplinary study conducted a comprehensive analysis of community aqueduct management, integrating technical, environmental, administrative, financial, and psychosocial factors while employing Generative Artificial Intelligence (GAI). The analysis revealed a nearly balanced distribution between structured (49%) and unstructured (51%) variables across all components. This indicates that any AI-based analytical framework must integrate both traditional machine learning approaches for structured data and natural language processing techniques to interpret unstructured inputs effectively. Component-specific variability was observed in data types: while the Technical and Administrative-Accounting domains predominantly relied on structured variables (80% and 56%, respectively), the Psychosocial component was heavily dependent on unstructured data (87.5%). These findings underscore the necessity of tailoring data processing strategies to the nature of each domain to ensure robust and domain-sensitive AI modeling.

This preliminary classification of structured and unstructured variables represents a foundational step toward developing a robust methodology for applying artificial intelligence to evaluate rural aqueduct systems. By identifying the nature and distribution of the data, this work sets the stage for designing context-aware AI models capable of integrating heterogeneous data sources relevant to rural water management.

Technical analysis revealed critical infrastructure and operational aspects impacting aqueduct efficiency. While water sources generally exceeded current demand (operating flow significantly lower than granted flow, with expansion rates over 50% in most systems), field observations highlighted inefficient water use, with some aqueducts serving purposes beyond their intended scope. This emphasizes the need to integrate field assessments with calculated data for precise water demand projections. Significant variability in flow rates, particularly among systems serving larger populations, presented challenges in ensuring equitable and efficient service delivery. The non-normal distribution of key technical variables (Shapiro-Wilk test, $p<0.05$) indicated outliers and the inadequacy of standardized water treatment approaches, highlighting the need for tailored management and infrastructure investments. Importantly, only half the systems employed any water treatment, and none met potable water standards, underlining the need for targeted improvements to ensure safe and reliable water service.

Environmental analysis revealed significant variability in the assessed parameters. While most aqueducts exhibited low to moderate risk according to the WQRI, a notable portion fell into the high-risk category, indicating vulnerabilities in providing safe drinking water. Limited adoption of PUEAAs and deficiencies in discharge permit documentation and source protection plans were also observed. Statistical analysis highlighted the median, rather than the mean, as a more accurate representation of operational reality, especially for skewed distributions (e.g., users per connection). The median of approximately 1,294 users per aqueduct suggests that half the systems serve populations at or below this level, potentially straining water resources and infrastructure. These findings stress the urgent need to strengthen environmental planning and management, promoting environmental impact assessments, source protection plans, regulatory compliance, and more sustainable management practices to ensure long-term sustainability.

The administrative-accounting component revealed significant heterogeneity in compliance with the evaluated requirements. While some areas (e.g., accounting support, occupational health and safety, commercial registry renewal) showed high compliance (Figure 9), substantial gaps existed in areas crucial for long-term sustainability and modernization. Low compliance with electronic payroll, IFRS standards, and special tax regimes (7–14%) indicated a considerable lag in adopting best practices. Limited technological adoption (electronic invoicing and accounting software) and persistent informality in labor practices (low compliance with formal contracts, social security contributions, and minimum wage requirements) further undermined system sustainability. Although progress was observed in organizational structure and accounting knowledge (21–79%), significant improvements are still needed. Overall compliance (mean 76%, median 78%) suggested reasonable collection efficiency but highlighted areas for substantial improvement, challenging assumptions about limited payment capacity in rural communities.

Psychosocial analysis highlighted the importance of social dimensions in the sustainability and governance of community-managed aqueducts. While community commitment was evident (especially in local initiatives and service reliability perceptions), significant gaps threatened long-term viability. Over half lacked sustainable economic models, indicating financial instability, inadequate tariffs, or strategic planning deficiencies. Although most reported community initiatives (85.7%), their long-term impact requires further investigation. Deficiencies were identified in tariff equity, administrative transparency, community participation, and ethical governance. While water quality control and infrastructure adequacy were generally well-regarded, limited participation and transparency remain critical issues. Despite these challenges, the presence of strategic plans in all systems (100%) suggests potential for future progress. This complex interplay necessitates interventions to improve financial management, transparency, inclusive participation, and institutional capacity building to ensure long-term sustainability.

Generative Artificial Intelligence (GAI) proved crucial for optimizing data analysis, enabling a more comprehensive and integrated assessment of the aqueducts. This enhanced methodology represents a significant advancement in understanding and managing these systems, facilitating informed decision-making to achieve a safe, sustainable water supply, improved operational efficiency, and enhanced community well-being. Further research is needed to validate the methodology's applicability across larger sample sizes and diverse contexts. Incorporating participatory methodologies into the diagnostic process would further refine the proposed approach and strengthen the study's conclusions.

It is essential to ensure the public availability of the diagnostic tools developed in this study so they can be used, validated, and adapted by researchers and practitioners working on rural and community water systems. Open access to these resources would enhance transparency and replicability and promote interdisciplinary collaboration and knowledge transfer.

Regarding follow-up studies, this research should be viewed as a first step toward a proposed methodological development. The next stage will involve consolidating a methodology applicable to different aqueducts, allowing its usefulness to be evaluated in diverse contexts. Likewise, continuity must be ensured by monitoring the measured variables to analyze their behavior over time and generate evidence on the sustainability and effectiveness of aqueduct management practices.

Finally, efforts should be directed toward integrating qualitative and quantitative data. This integration will enable a more comprehensive understanding of the social, organizational, and governance dynamics that influence water systems while strengthening community training, social empowerment, and the construction of a more inclusive, resilient, and sustainable water governance framework.

5. Declarations

5.1. Author Contributions

Conceptualization, M.A., A.E., and J.L.; methodology, L.S. and R.O.; software, R.O., S.Ch., J.C., and M.A.; validation, L.S., R.O., J.C., A.C., S.Ch., and P.R.; formal analysis, L.S., R.O., J.C., A.C., S.Ch., A.E., M.A., and S.H.; investigation, L.S., R.O., J.C., A.C., S.Ch., P.R., J.I., and T.G.; data curation, L.S., R.O., J.C., A.C., S.Ch., and P.R.; writing—original draft preparation, L.S., R.O., J.C., A.C., S.Ch., and P.R.; writing—review and editing, L.S., R.O., J.C., A.C., S.Ch., and P.R.; visualization, R.O. and S.Ch.; supervision, L.S. and R.O.; project administration, R.O.; funding acquisition, L.S., R.O., J.C., A.C., S.Ch., and P.R. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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