

Article

Participatory Management of Rainwater in Informal Urban Contexts: Case Study of San Isidro Patios, Bogotá, Colombia

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Abstract

This paper describes the implementation of a rainwater harvesting and treatment system in an informal urban community in Bogotá, using a participatory methodology based on Service Learning (SL). The project began with a territorial diagnosis and community prioritization of needs, identifying access to water and its quality as the main issue. Together with the community, a system for rainwater capture, pretreatment, storage, and filtration was designed and built, adapted to local conditions. Monitoring of physicochemical and microbiological parameters across different climatic periods showed significant improvements in the quality of treated water, meeting national standards for most indicators. Simultaneously, an educational process was carried out through workshops and hands-on activities, strengthening local capacities and promoting hygiene and water management practices. The analysis highlights the system's adaptability to climate variability, community ownership, and the replicability of the model. It concludes that the integration of appropriate technology, community participation, and education can effectively improve access to and quality of water in vulnerable urban contexts, contributing to quality of life and sustainable development.

Keywords: rainwater; treatment; consumption; service learning



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1. Introduction

Environmental health is essential for the well-being of people, animals, and plants, as ecosystem balance protects biodiversity and prevents disease. Issues such as contaminated water and lack of sanitation and hygiene particularly affect vulnerable populations, making it crucial to understand the relationship between health and the environment in order to achieve Sustainable Development Goals (SDGs), including access to clean water and sanitation [1]. Historically, human settlements were located near freshwater sources, but population growth led to the development of techniques such as well drilling and aqueduct systems to ensure water access, which is vital for agriculture, hygiene, and health, thus establishing water as a fundamental right [2,3].

According to the Food and Agriculture Organization of the United Nations (FAO), rainwater harvesting has been practiced for over five thousand years to meet human needs. Due to population growth, the collection of rainwater has been promoted, especially in arid and semi-arid regions, as an alternative for irrigation and domestic use. This approach is

technically viable and cost-efficient, as it only requires a collection and distribution system, saves energy, and is cost-effective. However, its availability depends on the season, and its microbiological quality requires treatment before human consumption [4–7]. A systematic review of epidemiological studies found that consuming rainwater reduces the risk of gastrointestinal diseases compared to unimproved sources, although it shows no significant differences compared to improved sources, and in some cases, outbreaks associated with its consumption have been reported. These findings highlight the importance of promoting rainwater harvesting, as it not only helps ensure supply during periods of scarcity, but also can improve quality of life, reduce costs, and encourage environmental health. Environmental health is the rational and sustainable use of water resources, provided that proper treatment and management measures are implemented to minimize health risks [8].

Traditionally, two main approaches have been followed to ensure access to water: seeking new sources or efficiently managing existing ones. However, the first option has often been prioritized, to the detriment of public health. The World Health Organization (WHO) defines health as a state of complete well-being, making access to water essential for ensuring health [7,9,10]. In developing countries, deficiencies in water management have been identified, often related to administrative problems, lack of resources, and insufficient political commitment. These factors prevent water from meeting the quality standards necessary to prevent disease [11–13].

The relationship between microorganisms in water and public health highlights the importance of treating drinking water to avoid disease outbreaks that can affect large populations. A study conducted in Latin America and the Caribbean showed that improving access to safe drinking water reduces child mortality, especially among children under five years of age. This demonstrates a direct relationship between sanitary conditions and the incidence of diarrheal diseases, emphasizing that guaranteeing access to potable water is essential for public health [3,14–16].

Therefore, various treatment methods have been proposed to improve the quality of water intended for human consumption, as proper water treatment is one of the key determinants for enhancing public health. It helps prevent infectious diseases, particularly gastrointestinal and respiratory illnesses caused by microorganisms present in water [17–19]. Moreover, water contamination due to the presence of certain chemical components and industrial or domestic waste affects ecosystems and, consequently, the health of communities living near discharge sites with such characteristics [20,21].

At the household level, various treatment methods have been documented to eliminate turbidity, color, and pathogenic microorganisms responsible for disease. These methods can be classified into: (I) systems that use heat or ultraviolet light (such as boiling, solar radiation, solar disinfection, or UV lamps); (II) chemical treatments (coagulation, flocculation and precipitation, adsorption, ion exchange, or chemical disinfection); and (III) physical removal procedures (sedimentation or clarification, filtration through membranes, ceramic filters, filters with granular media or sand, or aeration) [22,23]. Regarding the use of filtration systems at the household level, international research has examined the feasibility of various technologies for rural communities. These technologies include slow sand filters [24,25], ceramic candle filters [26,27], membrane filters [28] and ceramic pot filters [29,30]. In Colombia, some studies related to ceramic candle and pot filters have been documented, although these have been implemented only for short periods of time [30,31].

Thus, treatments based on slow sand filtration remove between 93% and 100% of *Giardia*; in the case of *Cryptosporidium*, removal rates have reached between 99.99% and 99.997% [32]. Based on epidemiological evidence, it is argued that the levels of *Giardia* cysts remaining in drinking water (0.11 cysts/L) after slow sand filtration processes are not sufficient to cause infections [33,34].

Household rainwater harvesting with storage and point-of-use treatment can significantly reduce the burden of diarrheal diseases and improve water access in impoverished communities with limited infrastructure. A domestic system with a 400 L capacity can reduce the total burden of diarrheal disease by 9%, and when combined with point-of-use treatment, the reduction can reach up to 16%, although effectiveness varies depending on seasonality and the volume used [35]. Moreover, these systems help reduce energy consumption and greenhouse gas emissions compared to centralized systems, manage runoff, and prevent flooding. However, their adoption faces barriers such as lack of incentives, limited technical knowledge, and public perceptions regarding the sufficiency of municipal water [36].

The main objective of this work is to implement a rainwater harvesting and treatment system at the Altos del Cabo Foundation by Fondacio, located in the San Isidro Patios area of Bogotá, Colombia, to improve access to water resources and optimize health conditions in a community without access to potable water. To achieve this, Service Learning (SL) is used as a socio-technical methodology that promotes community participation in socially oriented initiatives and avoids assistentialism, while strengthening students' empathy and social commitment. Projects framed within SL are curricular proposals that seek the active involvement of students and teachers in pedagogical processes guided by hands-on experience in communities with unmet needs. This approach enables students to acquire both disciplinary and community-based competencies, fostering dialogue, empathy, and a comprehensive understanding of the territory from both the physical and social perspective [37–39].

The experiential approach of Service Learning (SL) connects the academic environment with local communities, promoting collaboration between students and faculty to address local needs through open dialogue, network building, and knowledge transfer, thereby fostering social transformation. This pedagogical approach enables students to strengthen their competencies through practice and the application of knowledge, supported by well-structured community projects with a clear educational focus. It emphasizes key characteristics such as inclusion, replicability, collaboration, and the creation of partnerships [38–41]. Additionally, SL encourages the development of both human and disciplinary skills through education and community engagement, enhancing participants' self-esteem and confidence. It is grounded in social interaction and constructivist learning, where real-life problems guide the learning process. For this to be effective, proper teacher guidance and the design of relevant strategies and educational materials are essential, regardless of the learning modality employed [42–47].

Service Learning (SL) is grounded in experiential pedagogy and constructivism, promoting active learning through the integration of theory and practice in real-world contexts, along with critical reflection and social engagement [43,48–50]. Rooted in Dewey's ideas, SL supports academic education as well as personal and social development by involving students in authentic experiences that foster critical thinking and community commitment [43,51–53]. Constructivism emphasizes the importance of engaging with real-life problems and collaborating to develop key competencies such as life skills and citizenship, integrating the curriculum with social action [54,55]. Thus, SL offers a transformative methodology that merges community action, knowledge acquisition, and the development of values [43,51,54].

1.1. Background

The implementation of rainwater harvesting systems in communities with limited access to conventional infrastructure, such as in Guachtuq, Guatemala, has proven to be an effective strategy for improving water security in terms of quantity, quality, and access. The

project, which benefited 12 households, increased water availability but faces challenges for scalability due to the high costs associated with system oversizing, potential quality issues from lack of treatment, and the transfer of water security responsibility from the public sector to individual households. Regarding water quality, the article highlights that although rainwater is naturally low in salts and contaminants, it can be affected by the collection of dust, organic matter, and microorganisms from catchment surfaces. Microbiological contamination (particularly fecal coliforms) is the main concern. To ensure potability, the implementation of first-flush systems, filtration, disinfection, and regular maintenance of roofs and tanks is recommended, along with community training in good water management practices. Periodic monitoring of quality parameters is essential to identify risks and adjust treatment strategies, and the need for low-cost, easy-to-maintain technologies adapted to the local context is emphasized. In summary, the project's scope demonstrates that rainwater harvesting can be a viable and sustainable alternative to improve water quality and availability, provided that appropriate control and treatment measures are implemented to meet consumption standards [56].

The construction of an integrated rainwater harvesting system, including chlorination treatment, safe storage, and basic sanitation in rural communities in Kenya, demonstrated a significant impact in reducing the risk of diarrhea in children under five years of age. The project, implemented in 12 intervention villages and 6 comparison villages, showed that the combination of point-of-use disinfection (chlorination with sodium hypochlorite), the use of safe storage containers, access to rainwater sources, and the presence of household latrines independently and jointly decreased the incidence of childhood diarrheal diseases. Weekly monitoring over eight weeks revealed that water quality improved primarily due to the reduction in microbiological contamination, measured through the presence of fecal coliforms and the control of residual chlorine in stored water. Additionally, the study highlighted that point-of-use disinfection is more effective at preventing recontamination than using improved containers alone, and that the integration of interventions in water, sanitation, and community education is essential to maximize public health impact and ensure the sustainability of water quality in vulnerable rural settings [57].

The documented experience in India demonstrates that rainwater harvesting can be an effective solution to improve water security in rural and peri-urban communities with limited infrastructure. The project evaluated the quality of collected rainwater and found that, without treatment, it met standards for non-potable uses such as bathing. However, only chlorination with sodium hypochlorite enabled the water to meet potable water standards by significantly reducing microbial load and biological oxygen demand. This disinfecting effect, however, was temporary (lasting 30 to 37 days), requiring periodic applications to maintain the safety of stored water, especially if intended for human consumption. The study calculated the potential volume of rainwater collection based on roof area and annual precipitation, applying disinfection to 33,000 L and monitoring residual chlorine to ensure treatment effectiveness. In addition, the importance of monitoring physicochemical and microbiological parameters (turbidity, pH, total dissolved solids, conductivity, and coliforms), controlling specific contaminants (heavy metals, nutrients, or organic compounds), and comparing results with international standards was emphasized. The article highlights that improving water quality depends on integrating appropriate treatment technologies (chlorination, filtration, or solar disinfection), implementing first-flush systems, maintaining the systems regularly, and providing community training, along with periodic quality monitoring. Together, these actions enable the achievement of potable water standards and support the replication of this strategy in vulnerable contexts, significantly contributing to public health and water security [58].

The Thai experience in rainwater harvesting and storage highlights the positive impact of functional design, multi-scale implementation, and community participation in achieving sustainable access to clean water in rural areas. The project, supported by initiatives such as TUNGNAM, integrates catchment areas, conveyance systems, and storage in domestic jars and community tanks, enabling year-round supply and promoting self-management through training, revolving funds, and education in health and construction. Regarding water quality, the article notes that although stored rainwater does not always meet international standards, it is often superior to other rural water sources and can be significantly improved with proper management practices. The evaluation includes total and fecal coliforms (frequently present without treatment) and heavy metals (zinc, lead, and copper from metal roofs). To ensure potability, the implementation of first-flush systems, filtration, disinfection (chlorination, boiling, SODIS), safe storage, and regular maintenance is recommended, along with periodic monitoring and community education. The Thai case demonstrates that the integration of appropriate technology, institutional support, and local participation can transform access to and quality of water in rural communities, provided that comprehensive, locally adapted control and treatment strategies are applied [59].

In the study conducted in the subarctic community of Black Tickle-Domino, Canada, a pilot project for domestic rainwater harvesting was implemented with the goal of improving access to and use of water resources in a highly vulnerable setting. It is important to highlight that although the project increased water availability for general use and reduced the effort and costs associated with water collection, no monitoring or quality analyses were performed on the harvested water. For this reason, the rainwater obtained through the installed systems was not used for direct human consumption, but solely for hygiene and cleaning activities. The absence of physicochemical or microbiological data limits the evaluation of the water's potability and underscores the need to incorporate quality monitoring in future interventions of this kind [60].

Community-based management of rainwater harvesting in rural areas, as described in the analyzed article, relies on local organization and the participation of residents to ensure access to and quality of water resources. Although the main focus is on social sustainability and self-management, the article emphasizes that community perceptions of water quality are crucial for the acceptance and use of these systems. The importance of regular maintenance of roofs, tanks, and catchment systems is stressed, along with proper cleaning and safe storage to prevent contamination. While no specific analytical data are reported regarding physicochemical or microbiological parameters, the article acknowledges that education, training, and community monitoring are essential to maintain trust in the collected water and to ensure its safe use. In summary, water quality in these systems depends on both technical practices and social engagement, with community management and knowledge ownership being key factors for sustainability and continuous improvement in water access in rural settings [61].

The study "Rainwater Harvesting as an Alternative Water Source in Semarang, Indonesia: The Problems and Benefits" analyzes the implementation of rainwater harvesting systems in two communities in Semarang, evaluating their impact on water access and use, as well as the problems and benefits associated with both individual and communal models. The study highlights that rainwater harvesting helps reduce water vulnerability, the use of groundwater, and costs related to water supply. However, its use remains mostly limited to non-potable purposes due to community perceptions regarding water quality. It is important to note that this study did not conduct any physicochemical or microbiological analyses of the collected water; the information presented is based solely on user perceptions and comparisons with other local sources, which limits the objective assessment of its suitability for human consumption [62].

On the other hand, the organization TECHO Colombia, which operates in 19 Latin American countries, aims to overcome the poverty experienced by millions of people living in informal settlements through the coordinated action of residents, young volunteers, and strategic partners. The organization develops rainwater treatment systems based on a process that captures and channels rainwater into a storage tank, from which it is pumped through a chlorination mechanism designed to eliminate pathogenic microorganisms present in the water. The system includes a flow equalization structure to clarify the water, as well as a contingency mechanism to manage excess flow caused by heavy rainfall. The organization does not report data on water quality parameters, as it directly recommends that the collected water be used only for non-potable purposes, avoiding direct human consumption [63].

Considering that the reviewed background emphasizes filtration processes as a viable treatment option for rainwater, the following section presents experiences in which filtration technologies have been implemented at the community level to improve water quality conditions for human consumption.

The use of slow sand filtration technology as a sustainable and effective system for decentralized water decontamination processes is demonstrated in the Guayabal de Siquima Project, led by Engineers Without Borders Colombia. This project focused on improving the water quality of a community in the department of Cundinamarca, Colombia, where workshops were conducted using participatory action methodologies for the implementation of slow sand filters. In addition, 14 filtration units were provided to the community, benefiting 16 families. According to the results obtained, the applied filtration system eliminated 90% of total and fecal coliforms during the maturation period of the filter bed. Moreover, the organoleptic properties of the water improved after treatment, confirming a reduction in suspended solids and facilitating access to safe water for the residents of the intervened community [64].

The purification of water through slow sand filters in the community of Kuychiro-Cusco, Peru, aimed to treat water from the Kuychiro River for human consumption through a slow filtration process. The study on the implementation of the filtration systems, as well as the water analysis, revealed that the samples met the technical specifications required for human consumption. Furthermore, it was demonstrated that this technology is easily accessible, manageable, and maintainable for people with limited resources, with an average flow rate of approximately 2 L per hour [65].

The Action Against Hunger Foundation (ACF) in Nariño, Córdoba, and Putumayo, Colombia, is an international non-governmental organization whose aim is to improve and ensure adequate nutrition in vulnerable communities, as well as to address issues related to sanitation, water quality, and infrastructure. The foundation's contribution in the field of water and sanitation is based on training, empowerment, and the application of tools for water resource management, implementing as a key strategy the mass distribution of candle-type water purification filters, storage tanks, and collaboration in research processes in partnership with the University of Boyacá [66].

Likewise, the study of technological alternatives for the basic treatment of rainwater for domestic use in the Los Lagos Community Council, located in Buenaventura, Colombia, highlights the importance of collecting rainwater in high-precipitation areas. In this context, channel systems and storage tanks were implemented to collect rainwater, which was then subjected to a filtration process using ceramic candle filters. This technology consists of two ceramic candles and two 20 L polyethylene containers stacked one above the other: the upper container holds the ceramic candles—the filtering medium—while the lower one stores the treated water, ready for direct human consumption. The community received training on the proper use and benefits of these systems [5].

Given the aforementioned context, the aim of this study was to contribute a solution to the lack of drinking water by implementing affordable and sustainable techniques focused on a rainwater harvesting and treatment system. This system was based on an initial pretreatment stage followed by a slow sand filtration process to ensure water decontamination.

1.2. Problem Statement

In Colombia, the water crisis is evident in the significant risks to both water quality and access faced by rural and urban areas. The 2022 National Water Study reports that 51% of rural municipalities and 40% of urban municipalities are at risk due to water quality issues. This means that over half of the rural population consumes water that fails to meet the recommended microbiological and physicochemical standards for human consumption. Of the 1103 municipalities analyzed, 818 are classified as risk-free, 154 present low risk, 85 medium risk, and 18 high risk, while 19 municipalities did not report any data on water quality. Departments such as Bolívar, Córdoba, La Guajira, and Sucre are affected in more than 50% of their municipalities, including six departmental capitals. In addition, there are recurring water shortages reported in Bolívar, Cesar, Córdoba, and Santander, where some communities have endured interruptions in drinking water service for more than two years. This situation highlights the urgent need to strengthen aqueduct infrastructure, improve urban and rural planning, and ensure safe access to water, as the water crisis directly impacts public health and the quality of life of millions of Colombians [67,68].

Bogotá, the capital of Colombia, is divided into 20 localities, with Chapinero being the second and located in the central-eastern part of the city. Zonal Planning Unit 89 (UPZ 89) is situated in the rural area of Chapinero and includes neighborhoods such as San Luis and San Isidro Patios (Figure 1), the latter located in the Eastern Hills and accessible only via the road to La Calera. San Isidro consists of five unregulated sectors within an environmental reserve adjacent to the Páramo de las Moyas. Its development is linked to former stone quarries that attracted a population engaged in material extraction for construction during Bogotá's urban expansion between 1940 and 1970 [69].



Figure 1. San Isidro Patios location. Source: the authors (geospatial location).

This sector, of informal and unplanned origin, is home to approximately 22,000 inhabitants and is not officially recognized as part of the city's urban area. It presents significant urban, environmental, and socioeconomic deficiencies. The degradation and loss of the

soil's water absorption capacity, attributable to the implementation of urban infrastructure within an environmental reserve area, along with the contamination and drying up of existing water sources due to direct consumption and inadequate management by residents, severely affect biodiversity [69–71]. Additionally, residents suffer from socio-spatial segregation due to the lack of basic service infrastructure, poor public transportation and road and utility networks, and the absence of employment opportunities, vocational training, and the development of sustainable productive processes [72]. Despite these challenges, this territory holds valuable potential due to its location and proximity to Bogotá's financial center, as well as the environmental richness provided by the reserve in which it is located.

In the territory, approximately 2500 families face various limitations regarding access to and the quality of public services, such as illegal connections or the complete absence of electricity, sewage, and water supply systems. According to community leaders, around 200 households lack access to a piped water system and must rely on rainwater harvesting (often untreated), wells, or alternatively, purchase bottled water to meet their basic consumption needs. The area also contains several surface water sources, including the Teusacá River and the La Amarilla and Morací streams. Although the community has access to water sources for consumption, inadequate management of household solid waste, construction debris, and untreated wastewater discharge has led to a high level of microbiological and physicochemical pollution, making these sources unsuitable for direct use. Additionally, isolated wells are observed in the area, supplying some households, although they are not common in the region.

Due to technical issues related to the water supply service provided by the company Acualcos, a community-managed aqueduct, families that are not formally connected to the service often resort to making irregular connections to the main pipeline. This situation affects homes located in the lower areas of the territory, as the water supply fails to reach them with adequate pressure, further exacerbating the shortage problem in the sector. It can be concluded that the rural aqueduct network is insufficient to supply all households, which have increased in number exponentially due to unsustainable and unplanned land occupation.

Therefore, due to the existing water supply problem, families choose to store as much water as possible in large containers. However, this storage, whether from the aqueduct or from rainwater, is inadequate. The containers lack lids, are in poor condition, and are dirty, which turns them into breeding grounds for mosquito and fly larvae. These vectors negatively affect the local population, causing skin conditions, cross-contamination of food, gastrointestinal diseases, and general discomfort related to habitability in both housing and public spaces.

2. Materials and Methods

The objective of the methodology is to promote the participation of both the interdisciplinary student group and the involved communities, enabling students, professors, and community stakeholders to address water scarcity challenges in Altos del Cabo and the Fundación in San Isidro Patios. This methodology, based on the Service-Learning (SL) approach, fosters ethics, social and environmental responsibility, and an integrative work perspective through the formulation and implementation of a participatory project focused on rainwater harvesting and treatment [73].

Phase 1. Participatory identification of the territory

Territorial planning and diagnosis were based on tools to collect primary information, using Quality of Life indicators to reflect the real needs of the inhabitants. An action–research approach with a qualitative focus was designed, aimed at generating information that facilitates decision making within communities, promotes social

change, and contributes to transforming reality. This process also sought to encourage individuals to recognize their role in the appropriation of their territory, starting with an observation phase [74].

- Contextualization involved understanding the environment in which the problem developed. This included analyzing, in collaboration with teachers and students, the social, economic, environmental, and cultural factors that shape the territory.
- Observation focused on collecting data about the environment. This observation was conducted directly through three visits to the territory and indirectly through the review of bibliographic sources.
- Document analysis included the review of relevant documents, reports, statistics, and other records that provided information about the water access issues faced by a portion of the community.
- The identification of the target group was carried out with the support of the staff from Altos del Cabo by Fondacio. The participants were selected among those involved in community processes promoted by this organization in the territory. The study engaged 50 people from the San Luis Altos del Cabo community in San Isidro Patios, located in the Chapinero district of Bogotá, Colombia. It included six civil engineering students and three professors; three architecture students and one professor from the Universidad Católica de Colombia; two civil engineering students and two bioengineering students from the Catholic University of Leuven, Belgium; and one professor from the Film and Television program at Universidad Jorge Tadeo Lozano. This sample was defined based on a methodological perspective using non-probability sampling.

Non-probability sampling involved students, faculty members, and community participants. It was chosen due to limited access to the territory and the prevailing security and resource conditions in San Isidro Patios. This sampling method is based on the intentional selection of key participants. First, students and professors affiliated with university programs related to basic sanitation, housing infrastructure, public health, bioengineering, and architecture were selected for their relevant training and experience. Second, community leaders and residents affected by water-related issues were chosen, prioritizing those facing greater difficulties and health problems associated with water access. This strategy enabled the organization of participatory and educational actions led by the Altos del Cabo Foundation, facilitating project implementation in technical, participatory, and educational aspects. Although it does not ensure statistical representativeness of the entire population, it provides validity and reliability within the subset of participants involved [74].

- Approval and permit acquisition in the territory: A written informed consent form was obtained from all participants, following approval by the Ethics Committee of the Universidad Católica de Colombia and the directives and responsible parties at Altos del Cabo by Fondacio. Regarding ethical considerations, it was ensured that individuals involved in the project faced issues related to the supply of water for human consumption. They were informed through written consent that the information collected during the project would be handled confidentially and anonymously, as the data would be used exclusively for academic purposes. Participants were also informed of their right to withdraw from the process at any time without penalty or the need to explain their reasons. Furthermore, in collaboration with the staff of the Altos del Cabo by Fondacio Foundation, the project promoted the participation of vulnerable groups such as women, children, and the elderly.
- Territory analysis: the group of students and professors conducted an analysis of the territory, considering sociocultural, socioeconomic, regulatory, environmental, and

physical–spatial variables, in order to gain a comprehensive understanding of the context in which the project was developed.

- Use of tools for the collection of primary information: These field activities were supported by the methodology proposed by [75], whose main objective is to collect data in the field, taking into account a series of variables organized to characterize territories at the urban level. This method guided the field observations carried out jointly with the community.
- Identification of territorial problems: the characterization of the territory and interaction with local leaders, networks, and organizations made it possible to identify a context related to the quality of life in the area.
- Comprehensive definition of the problem: the neighborhood informality of the territory was linked to its direct impact on problems associated with urban habitability and the quality of life of its inhabitants.

Phase 2. Recognition and analysis of the problem scenario

The objective of identifying and understanding the context of problematic situations, as well as prioritizing them within the environment, was achieved through participatory techniques such as direct work with focus groups. This approach also enables all participants to recognize themselves as cultural and social beings in relation to others. Consequently, and in accordance with the action-research methodology [74], the second phase was implemented, which consists of designing a solution to mitigate the issue of access to water for human consumption, based on the characterization of the territory. The activities carried out are detailed below:

- Interpretation of results: a situational framework of the territory was established based on urban habitability indicators that characterize informal settlements.
- Identification of patterns or themes: This identification was carried out through the prioritization of indicators and their relationship with the territory's informality, according to the residents' perceptions. To this end, the indicators were submitted to a vote to determine whether they should receive high, medium, or low priority in order to improve habitability conditions and, consequently, quality of life under the "One Health" approach. This prioritization was synthesized into several key themes requiring attention in the territory.
- Clear communication of field data results: an analysis report of the indicators was prepared and delivered to Altos del Cabo by Fondacio, presenting the causes, consequences, effects, and conclusions of the findings in the territory, thereby justifying the project's focus on the quality of water for human consumption.

Phase 3. Characterization and strengthening of skills and resources

Students, professors, and community members perceive an atmosphere that encourages the communication of ideas, which are translated into adapted designs and actions that provide creative solutions to the problems addressed. Consequently, following the three phases of action research, the CDIO methodology—Conceive, Design, Implement, and Operate—was applied, in accordance with the proposal by [76]. Based on the issues prioritized by the community, the one that received the most votes was selected: the supply and quality of water for human consumption, specifically concerning the use of rainwater in the territory. To address this, a rainwater harvesting and treatment system was conceived, given the scarcity of this resource in parts of the community, which leads to habitability problems related to the use of the environment, the provision of basic services, hygiene in the home, and the minimum vital consumption, which can result in illnesses among the inhabitants. The activities carried out were as follows:

- Definition of the technical requirements for the rainwater harvesting and treatment system, in accordance with the situational framework of the community. To achieve this, treatment system proposals consulted in the background research and by [77] were reviewed.
- Identification of the raw materials and supplies needed for technology transfer to the community. Based on the technologies reviewed for rainwater harvesting and filtration, a list of materials was prepared in collaboration with the participating students and faculty.
- Modeling of a design for a rainwater harvesting and treatment system, based on the information consulted.
- Presentation of the proposed design to the community at Altos del Cabo by Fondacio, concluding that a pilot system would be built in that physical space, allowing the community to monitor, adjust, and later replicate it in their homes.

Phase 4. Project design

This stage refers to the planning of the project proposal, which must ensure the execution of a community service initiative linked to activities that contribute to the joint learning of both students and the community simultaneously. In this context, it was necessary to align with the Conceive, Design, Implement, Operate (CDIO) methodology proposed by [76] during the design phase. To this end, the team of professors and students carried out the following activities:

- Modeling of the habitability characteristics of Altos del Cabo by Fondacio, analyzing the distribution of spaces, the condition of the roof, gutters, and rainwater storage tanks.
- Drafting of the plans for the rainwater harvesting and treatment system for its proper placement at the foundation's headquarters.
- Development of the budget for the rainwater harvesting and treatment system to be built at the foundation's headquarters.
- Planning of the construction of the rainwater harvesting and treatment system in collaboration with the community.

Phase 5. Implementation of the model

The purpose of this phase is to transform ideas into tangible realities. This stage is crucial in the development of the AS methodology, where support and supervision during implementation are essential. Therefore, based on the third phase of the action–research process and the CDIO methodology, the rainwater harvesting and treatment system was implemented and operated at the facilities of Altos del Cabo by Fondacio. The objective was to ensure that its physical infrastructure and social logistics could enable the replication of the process by the participating community to benefit other families in the territory.

- Work teams composed of faculty members, students, and community members were formed for the construction of the system on the foundation's premises.
- Based on the teams formed, the physical space of the foundation was adapted, the necessary materials for the construction of the system were acquired, and these materials were prepared and stored with the collaboration of the community.
- Functions were assigned for the construction of the system, following the previously defined models.
- The construction of the system was carried out in a participatory manner together with the community.
- Adjustments were made to the system in relation to the accessories.

- The system was officially presented in the territory, led by the Altos del Cabo by the Fondacio Foundation, in an event attended by community organizations, volunteers, and the students and faculty involved.
- Water quality sampling was conducted during both rainy and dry periods to evaluate the system's efficiency at removing contaminants.

Phase 6. Closure and replication

In this final phase, the aim is to assess whether the scope of the project, as agreed upon by students and the community with the support of professors, has been fulfilled, and to ensure that this knowledge is effectively transferred to the community for replication. Therefore, considering the need to create participatory educational spaces aligned with a constructivist approach, an educational model was proposed to work collaboratively with the community. This methodological proposal positions education as a fundamental element for the transfer of the rainwater harvesting and treatment system in a territory that faces constant shortages of potable water, based on the design of an instructional model according to [45]. The following steps outline this model:

Step 1: Analysis. This initial phase focused on identifying and understanding a specific problem, as well as exploring potential solutions. To carry out this process, the needs analysis developed during the participatory territorial identification in Phase 1 was used. The result was a list of instructional goals that guided the design and implementation of the knowledge transfer proposal.

Step 2: Design. In this stage, a detailed framework was developed to achieve the instructional goals, considering key elements such as a description of the target audience and the context. The final outcome included clear objectives, instructional strategies, and a sequence of activities.

Step 3: Development. This phase involved creating the transfer plans and producing the necessary educational materials. Instructional resources were designed and materials were prepared for use in the teaching–learning process.

Step 4: Implementation. The instructional design was implemented in the community, aiming to ensure understanding of the content, mastery of skills, and transfer of knowledge.

Step 5: Evaluation. The process concluded with an evaluation to determine the effectiveness of the instruction. In this case, formative evaluation was carried out during the development of the educational model to improve knowledge transfer to the community. Finally, each didactic strategy used was evaluated to ensure coherence with the constructivist approach, which emphasizes learning based on the student's lived experience.

3. Results

In this research, a participatory territorial assessment was conducted. This process involved the analysis of 20 indicators related to land tenure, location, and the surrounding environment of the settlements (Figure 2). The evaluation aimed to assess the settlements' capacity to meet basic habitability requirements while minimizing adverse impacts on the well-being of residents in an urban context. In addition, the way land is occupied and distributed was examined, taking into account the housing dynamics inherent to the informality of the area.

Among the validated indicators of tenure, location, and environment in the territory, it was observed that the area consists of six neighborhoods, none of which are legalized. Seven fixed noise sources were identified, including six bars and one school. Additionally, three polluted surface water bodies were identified, including one river and two streams, which receive domestic wastewater discharges. The territory hosts over 80 tree species, predominantly non-native pines, exceeding 2 m in height. This area is located within one environmental reserve, the Páramo de las Moyas. Furthermore, one commercial

zone was detected, consisting of ten establishments, including two hardware stores, two bakeries, one auto repair shop, and five stores selling food and cleaning products. An institutional use zone was also delineated, comprising thirteen properties, including one school, four daycare centers, four community halls, one health center, and three churches. Five vacant lots were identified as construction sites, along with one park, one soccer field, and four green areas considered unsafe by the community. Additionally, three landslide points were recorded due to mass soil movements, as well as two settlements experiencing flooding due to high precipitation in the region. Regarding non-existent indicators, no sources of air pollution or electromagnetic waves were observed. Similarly, there are no areas of prostitution, industrial zones, or sites selling psychoactive substances. There are no narrow alleys, and no plots or buildings have legal recognition.

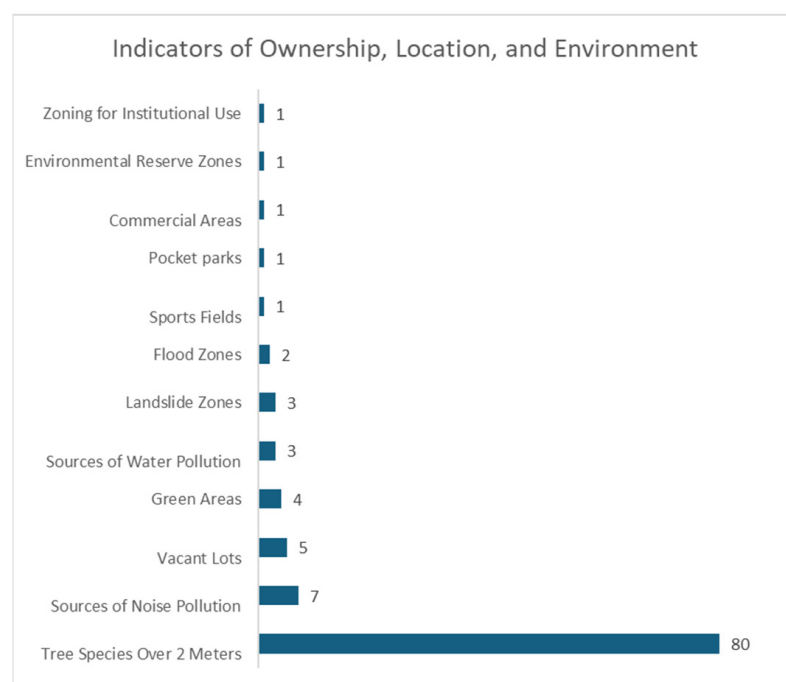


Figure 2. Indicators of ownership, location, and environment. Source: the authors.

Secondly, 15 indicators related to access and coverage of basic services and infrastructure were identified (Figure 3). These indicators are essential to ensure infrastructure that meets the hygiene, comfort, and urban public service needs required by city residents, with the goal of improving their quality of life and health conditions.

Regarding these indicators, it was found that, out of approximately 2500 homes, around 1100 are illegally connected to the water supply network, of which 224 do not have access to potable water. The water service provided by the company Aqualcos frequently experiences discoloration issues, especially during the rainy season. Additionally, approximately 883 homes lack connection to the public sewer system and instead use septic tanks. Four open dumping sites for solid waste and debris were recorded, three of which are located in surface water bodies and one in a green area. Furthermore, 800 homes do not have natural gas service and consequently purchase bottled gas for cooking, while 200 homes are illegally connected to the electricity service. The territory has five access roads, three of which are primary and two secondary, all in poor condition. There is only one basic medical center for community care and a space dedicated to music and art promotion, located at Altos del Cabo by Fondacio. Regarding absent indicators, the territory lacks basic infrastructure such as bike lanes, sports centers, police stations, emergency and disaster response systems, libraries, and local government service centers.

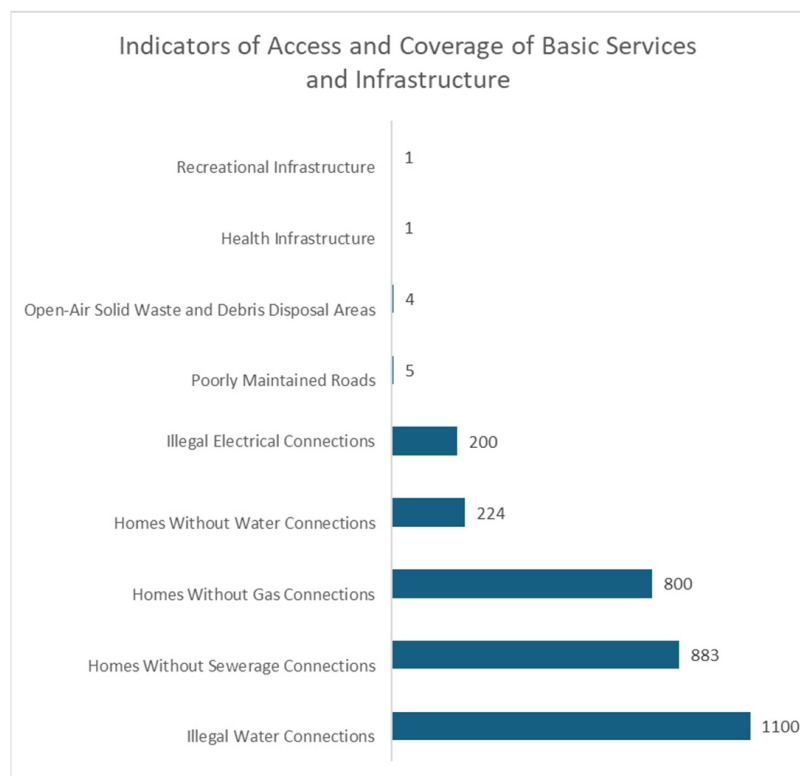


Figure 3. Indicators of access and coverage of basic services and infrastructure. Source: the authors.

Finally, four indicators related to the physical and functional conditions of housing were analyzed (Figure 4). These indicators facilitate interactions among residents, both with their families and neighbors, promote privacy, and contribute to preventing or exacerbating physical and mental health problems among the inhabitants.

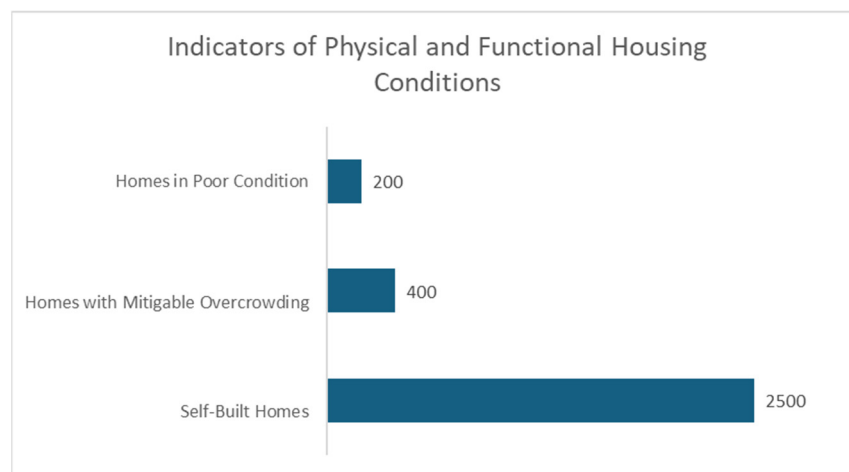


Figure 4. Indicators of the physical and functional conditions of the dwelling. Source: the authors.

Regarding the indicators of physical and functional housing conditions, it was observed that the houses feature a block and reinforced concrete portico system, with self-construction being the norm in the 2500 housing units. Approximately 400 of these homes experience overcrowding, housing more than seven people in spaces without adequate separation. Additionally, 200 houses show deterioration in walls, roofs, and facades, and the structures do not exceed two stories in height.

Considering this situational framework, a participatory process was conducted to prioritize the areas in which the community requires support to improve their habitability and quality of life conditions. This prioritization is detailed below:

High Priority:

1. Water supply and quality for human consumption, focusing on the collection of rainwater in the territory.
2. Improve the color characteristics of potable water.
3. Control contamination in surface water sources.
4. Legalize neighborhoods, plots, and houses in the area.
5. Expand the sewer network to homes lacking this service.
6. Address localized landslides and flooding processes in collaboration with district authorities.
7. Regulate the open dumping of solid waste and debris.
8. Attend to homes in poor condition, addressing problems related to construction materials and overcrowding.
9. Improve access to preventive health programs in the community.
10. Legalize informal connections to the water supply and electricity networks in homes.

Medium Priority:

1. Improve the infrastructure of secondary roads and sidewalks in the area.
2. Establish cleaning brigades in protected areas and surface water sources.
3. Include commercial zones in environmental education processes related to waste and noise.
4. Promote the recovery of public spaces in vacant lots.
5. Create partnerships for the construction of parks and multi-sport courts.

Low Priority:

1. Review the use of propane gas in homes and its possible impacts.
2. Classify tree species over two meters in height and assess their risk levels.

Based on the prioritization of the themes, it was determined that the main focus of the project to be developed jointly with the community would be the utilization and treatment of rainwater. This need was identified as urgent by the residents, who emphasized the importance of having academic support to propose a solution adapted to the habitability context of the territory.

Consequently, a rainwater harvesting and treatment system was designed, conceived in four phases. The first phase, called the initial rain collection and purification phase, focuses on removing large organic materials such as leaves, branches, and other particles that accumulate on roofs and must be eliminated due to their high organic content. This is achieved through a gutter and piping system that purifies the first rainwater in a tank. The second phase, called pre-filtration, removes smaller suspended solids carried by runoff and regulates flow; if precipitation is high, a drainage system acts as a contingency in case of overflow in the storage tanks of both the first rainwater and the pre-filtered water. The third phase, called pre-filtered water storage, involves storing the water in a flow-equalization tank where, by gravity, the remaining suspended solids in the rainwater settle. Subsequently, in the fourth filtration phase, the water is filtered using a system proposed by [77], which removes approximately 99% of the dissolved solids that affect the organoleptic and microbiological characteristics of the water. With a clear understanding of the four treatment phases, a list of raw materials and inputs was prepared, enabling the modeling of the system design (Figure 5).

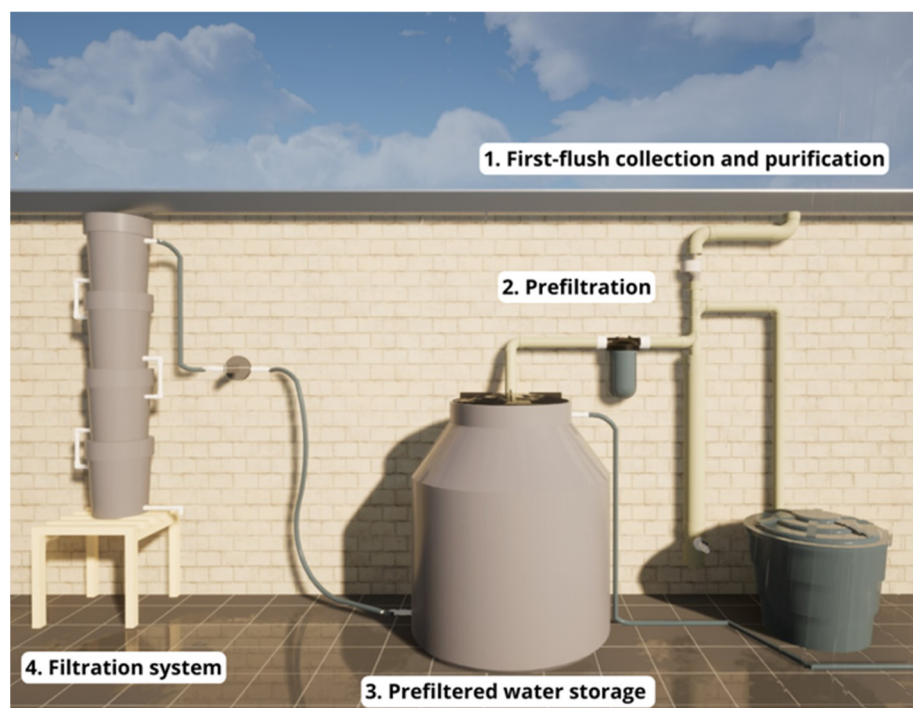


Figure 5. Modeling of the rainwater collection and treatment system. Source: Lina Marcela Ramirez Leon, Melissa Maria Rubiano Cortes, and Leidy Daniela Tacuma, architecture students from the Universidad Católica de Colombia.

With the proposed system model in hand, it was presented to the community to address questions, gather feedback, and determine its construction site within the physical facilities of Altos del Cabo by Fondacio, which is responsible for replicating the pilot plan throughout the territory (Figure 6).

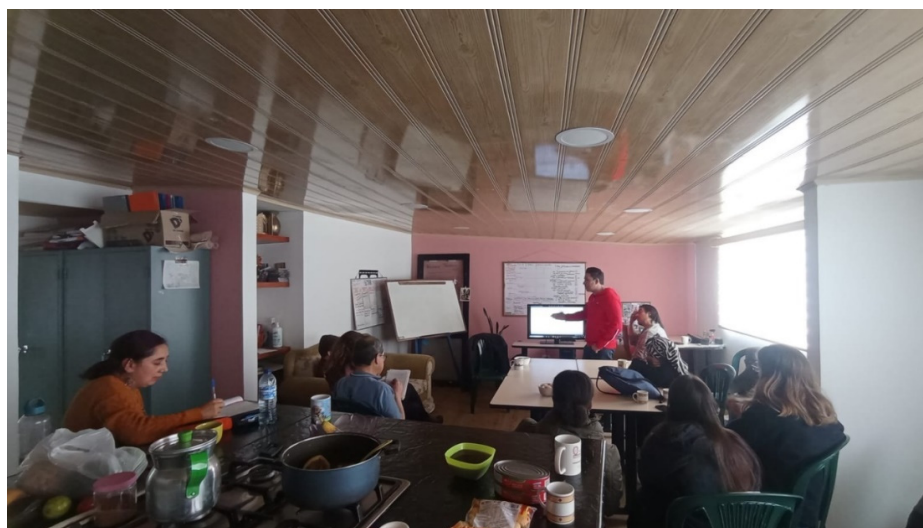


Figure 6. Meeting with leaders of Altos del Cabo by Fondacio and the community. Source: the Authors.

After co-designing the system model with team members and the community, the system design was developed and implemented at the foundation's physical facilities. To this end, habitability conditions were modeled in relation to the spatial distribution of the infrastructure, establishing various system locations with the aim of capturing the maximum amount of precipitation per roof area, while considering factors related to habitability and safety within the housing (Figure 7).

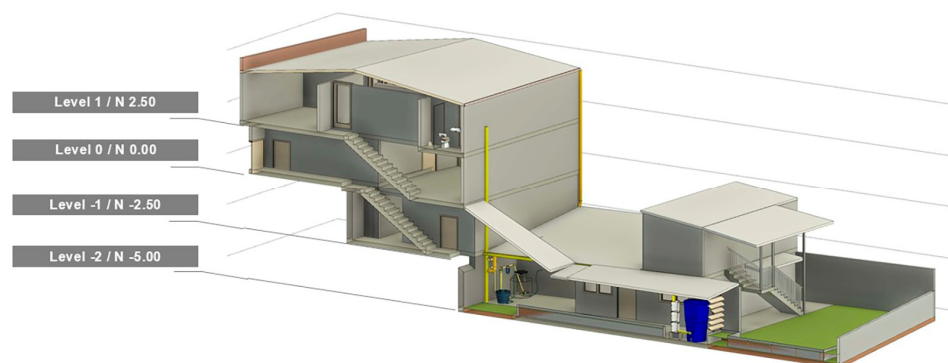


Figure 7. Modeling habitability in relation to the spatial distribution of Altos del Cabo by Foundation. Source: Lina Marcela Ramirez Leon, Melissa Maria Rubiano Cortes, and Leidy Daniela Tacuma, architecture students from the Universidad Católica de Colombia.

After presenting the modeled design to the foundation's facilities, the best location for installing the system was participatively determined, taking into account parameters such as the live load capacity of the structure, roof area, ease of collection and transport of treated water, available space for construction, and proximity of the system's overflow contingency mechanism to a drainage point due to heavy precipitation. Based on these considerations, it was concluded that the system should be located on the first floor at the rear, near the nursery (Figure 8). This allowed for measurements to be taken on-site at the foundation to define the schematic plans for the system to be built (Figure 9).

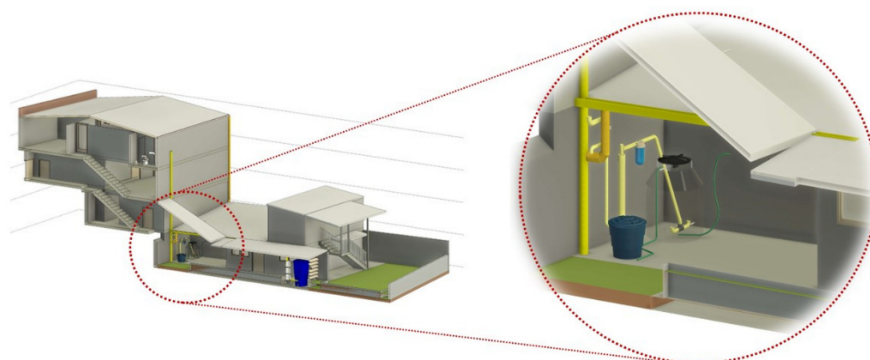


Figure 8. Location of the system. Source: Lina Marcela Ramirez Leon, Melissa Maria Rubiano Cortes, and Leidy Daniela Tacuma, architecture students from the Universidad Católica de Colombia.

Based on the development of the technical drawings, the required quantities of inputs, resources, and raw materials were calculated. This process enabled the performance of unit price analyses and the definition of the overall system budget, estimated at approximately 1,400,000 Colombian pesos, equivalent to 350 US dollars. According to reviewed technical documents and precedents, the annual maintenance cost of the rainwater harvesting and treatment system is estimated at 5% of the initial investment cost, amounting to 70,000 Colombian pesos, or approximately 17 US dollars. This maintenance cost depends on the system's complexity in relation to water conveyance lines, cleaning frequency, replacement of consumables (granular materials and polyvinyl chloride—PVC—accessories), and the community's ongoing training in system operation. Additionally, the life cycle of the system's structural components (tanks, gutters, and PVC pipes) typically ranges from 15 to 20 years, provided that annual maintenance is conducted and no major structural damage occurs. In the case of slow sand filters, the filtering materials require replacement every five years, although the filter structure itself may last between 10 and 15 years.

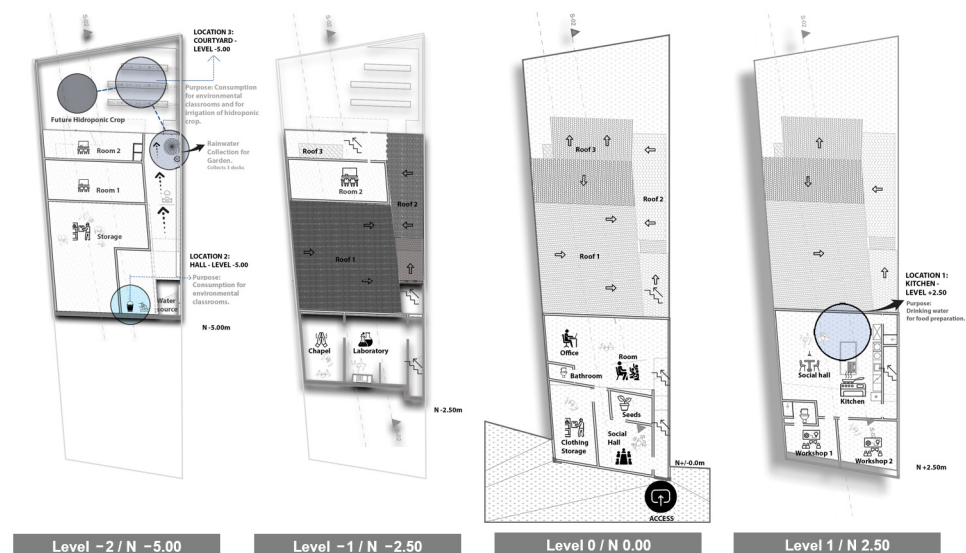


Figure 9. Schematic plans of the system and its location in the foundation's physical plant. Source: Lina Marcela Ramirez Leon, Melissa Maria Rubiano Cortes, and Leidy Daniela Tacuma, architecture students from the Universidad Católica de Colombia.

Subsequently, the necessary materials were procured from the local commercial area, thereby supporting local businesses and reducing transportation costs. The construction of the system was planned collaboratively with the community, dividing participants into three teams. The first group was responsible for preparing the materials and supplies, the second group undertook the construction of the rainwater harvesting and pretreatment system, and the third group was tasked with building the filter for the final treatment of rainwater, in accordance with the proposed system design.

During the implementation phase, the site was prepared based on prior modeling, and construction was carried out in collaboration with the community, adhering to the proposed design and following the participatory planning process (Figure 10). Adjustments were made to the PVC components of the prototype based on real-time performance monitoring, effectively enabling the collection and treatment of rainwater.



Figure 10. The constructed system. Source: the authors.

With regard to the system's location, its construction took into account key factors such as the available space, accessibility for collecting the treated water, a roof surface area of 108.21 m², and the structural integrity of the walls for anchoring the system. The accessibility of the site for community members to receive training on the construction, use, and maintenance of the prototype was also considered. The results demonstrated that the system is functional in terms of both location and operation, effectively treating rainwater for daily hygiene and consumption, while minimizing exposure to waterborne pathogens. The community was advised that the treated water is safe for use, provided that additional household disinfection methods such as boiling or the addition of chlorine are applied. The results are detailed in Table 1.

Table 1. Analysis of average drinking water quality parameters.

Parameter	Rainwater (Average)	Treated Water (Average)	Standard 2115 of 2007 on Drinking Water Quality in Colombia	Observations
Color	25	3	15	The color decreases significantly after treatment, meeting the standard. The initial high value may be due to the carryover of organic matter and dust, especially after dry periods.
Turbidity (NTU)	25	2	2	The initial turbidity is high, typical of rain that carries accumulated particles. Treatment reduces it to the regulatory limit.
Conductivity (μS/cm)	81.02	81	1000	Low values, characteristic of rainwater. No significant increases were observed after treatment.
pH	6	7.2	6.5–9	The pH of rainwater is slightly acidic, but treatment adjusts it to neutral values, within the regulatory range.
Acidity (mg/L CaCO ₃)	15	5	50	Acidity decreases after treatment, which reduces the potential corrosiveness of the water.
Total Alkalinity (mg/L CaCO ₃)	9	12	200	Low values, typical of rainwater. Treatment slightly increases alkalinity, promoting chemical stability.
Total Coliforms (CFU/100 mL)	Countless	5	0	High microbiological contamination in rainwater, especially after heavy rainfall. Treatment drastically reduces the presence of coliforms, although it does not always eliminate them completely.
Coliformes Fecales (UFC/100 mL)	Countless	2	0	Similar to total coliforms, disinfection is effective but not absolute.
Total Hardness (mg/L CaCO ₃)	20	30	300	Soft water, no significant changes after treatment.
Dissolved Oxygen (mg/L)	1.1	6	≥4	Dissolved oxygen is low in rainwater, probably due to organic matter and bacterial activity. Treatment and aeration increase its concentration.

The values reported in the table correspond to averages of measurements taken during three distinct climatic periods: fluctuating rainfall (August 2024), high precipitation (November 2024), and drought (January 2025). This approach enables the identification of trends and variations in the quality of collected and treated rainwater under different hydrometeorological conditions. Additionally, water sample collection and preservation were conducted in accordance with the guidelines established in [78], and laboratory tests

followed the standard methods proposed in [79]. The samples were analyzed at the Water Quality Laboratory of the Universidad Católica de Colombia, using various water quality testing methods, including membrane filtration for the determination of total and fecal coliforms, an Orbeco turbidimeter, a Hanna digital pH meter, a Hach multiparameter analyzer, a Mettler Toledo benchtop conductivity meter, and laboratory glassware and specific reagents for titration in those physicochemical tests that required it.

Context of the sampling periods:

August (fluctuating rainfall): a period characterized by variability in the frequency and intensity of rainfall, leading to intermittent contaminant runoff from the atmosphere and the roof surface.

November (high precipitation): a period with greater runoff volume, which may dilute some contaminants but also increase the transport of particles and microorganisms.

January (drought): a period with low rainfall frequency, which promotes the accumulation of dust and pollutants on the roof, which are then washed off during the initial rains following the dry period.

Following the implementation and monitoring of the pilot system at the Foundation, a knowledge transfer strategy was developed for the community through a course titled Healthy Housing and Safe Water. By applying the closure and multiplication method of the AS approach, the following results were obtained:

The main identified issues were presented, along with the proposed educational objectives. The challenges observed by the team members regarding the scope of the project included the following:

- The dwellings face issues related to the supply of potable water and lack adequate systems for rainwater harvesting. This is due to the absence of technical assistance in the design and construction of the houses, the overloading of the local aqueduct as a result of a high number of users, and limited community knowledge regarding proper hygiene practices, all of which contribute to unsanitary living conditions.
- Disorder and lack of cleanliness were observed in the wet areas of the homes (kitchens and bathrooms), primarily due to limited interest among residents in adopting hygiene and food handling practices.
- Some households use rudimentary systems for rainwater collection, which are in a deteriorated state and lack any form of water treatment.
- Water intended for human consumption is stored in poorly maintained containers, without proper protection against external contaminants.

These issues are likely to lead to illnesses among residents, such as gastroenteric infections, respiratory diseases, skin infections, and vector- and pest-borne diseases [80]. Therefore, the learning objectives established to address these challenges were as follows:

- Integrate the risk factors present in the dwellings into an educational program, implemented through a participatory course. This course aimed to identify the elements that directly affect residents' health and contribute to unsanitary conditions resulting from the lack of potable water.
- Raise community awareness about the risks present in their homes, helping them to understand and assess the negative impacts these factors have on individual and family health.
- Construct a rainwater harvesting and treatment system to ensure a safe water supply for communities facing water scarcity.

Additionally, the characteristics of the participants were described. Sixty percent of them were women between the ages of 20 and 40. Given the group's overall youth, it was considered essential to implement pedagogical strategies that would maintain their interest

and motivation, along with flexible schedules to facilitate attendance. The remaining 40 percent were adults between the ages of 41 and 75, of whom 10 percent had not completed basic education and 12 percent had no formal education at all. Furthermore, 57 percent of the participants were unemployed, while 43 percent were engaged in informal economic activities.

Based on the above, Table 2 presents the learning units, their objectives, duration, and the topics covered to facilitate the transfer of knowledge related to the system.

Table 2. Learning units for the Healthy Housing and Safe Water Course.

Learning Unit	General Objective	Duration	Topic
Healthy Housing	Develop skills to identify, control, and mitigate risk factors present in housing that can lead to water-related diseases.	4 h/week	Technical–Environmental
Good Practices in Healthy Housing	Apply good practices in healthy housing to control and mitigate risk factors related to water management and hygiene.	4 h/week	
Rainwater Harvesting and Treatment System	Transfer the construction process of an efficient system to harness rainwater in housing and promote the health of its inhabitants.	8 h/week	

Based on the established learning units, the following instructional objectives were defined to be communicated to the participants:

- Identify the risks associated with household water supply that may lead to illnesses among residents.
- Promote collaborative work in applying acquired knowledge, encouraging best practices in the context of healthy housing.
- Understand the extent of water-related problems by linking the home and its surroundings to factors that directly impact health and negatively affect quality of life.
- Strengthen networks of cooperation and trust within the community.
- Promote alternative water supply systems that contribute to improved health, particularly among the most vulnerable groups.
- Support processes that foster autonomy, empowerment, and community organization.
- Encourage the development of easily constructed and replicable technological solutions for rainwater harvesting in the area.
- Improve unhealthy household and personal habits through the implementation of good practices at home.
- Emphasize the importance of avoiding dependency, valuing the efforts and resources contributed by community members.

Subsequently, a logical structuring of the content was carried out for each didactic unit. Table 3 outlines the topics developed during the fieldwork.

Finally, the didactic strategies used to implement the system transfer course within the community were defined. Table 4 provides a breakdown of the didactic strategies employed.

In this way, Table 5 details the evaluation criteria used for each didactic unit of the course, with the aim of implementing a formative assessment approach.

Table 3. Didactic units.

Didactic Units	
Topic	Content
Healthy Housing Workshop 1	Definition of a healthy home Public services and health in housing Importance of water as a resource and responsibility Diseases related to hygiene in housing and water
Healthy Housing Workshop 2	Importance of handwashing Personal hygiene Hygiene in the home: cleaning in bedrooms, kitchens, and bathrooms Food handling in the home Healthy housing and surroundings
Good Practices in Healthy Housing Workshop 1	Maintenance and cleaning of wet areas in home (bathrooms and kitchen) Review, cleaning, and maintenance of water storage tanks Water-saving methods
Good Practices in Healthy Housing Workshop 2	How to make ecological cleaners Homemade water disinfection methods How to create homemade pH indicators
Rainwater Harvesting Technology Workshop 1	Raw materials, resources, and supplies Pre-treatment of rainwater Process of purifying the first rain Construction of the technology
Rainwater Filtration Technology Workshop 2	Raw materials, resources, and supplies Adsorption processes in filtering materials Physicochemical and microbiological parameters of quality and health Construction of the technology

Table 4. Didactic strategies by unit.

Didactic Units	Defined Didactic Strategies
Healthy Housing Workshop 1	Communicating the community's real situation regarding identified risk factors related to water and its impact on housing hygiene Facilitator's narration Group work Presentations Photographs and videos
Healthy Housing Workshop 2	Group work based on discussing the specific case of water scarcity for human consumption in the San Isidro Patios community Group presentations Identification of minimum conditions for a healthy home, with participants creating a model based on their discussions Explanation of handwashing
Good Practices in Healthy Housing Workshop 1	Participatory evaluation of technical concepts related to good practices in healthy housing to present results Practical workshop focused on good practices, reviewing exercises focused on practical applications (ecological cleaners and homemade filters)

Table 4. *Cont.*

Didactic Units	Defined Didactic Strategies
Good Practices in Healthy Housing Workshop 2	Workshop focused on executing good practice exercises considering specific responsibilities in group work and delivering a final product, which includes creating an ecological cleaner and justifying its role in enhancing public health quality of life Presentation of the ecological product Water disinfection methods (heat, chlorine, and ozonation)
Rainwater Harvesting and Conveyance Technology Workshop 1	Conducting a workshop based on similar cases to establish a comparison between technologies, evaluating before and after installation at the household level Participant evaluation of the proposed technology, assessed based on the identification of materials, supplies, and the construction process
Rainwater Filtration Technology Workshop 2	Analyzing the operation of the rainwater harvesting and treatment prototype built at the Foundation, reviewing the decontamination processes of the system, and comparing collected water versus treated water Participant reporting on diseases to be prevented in homes regarding the handling of water resources (hygiene and consumption), in a workshop format

Table 5. Evaluation criteria.

Criterion	Description
Viable	Optimizes resources; justifies the deliverable based on economic, social, and ecological aspects, and the materials used meet the workshop objectives. Presents a basic budget to demonstrate this viability.
Environmentally Responsible	Takes into account the impacts on the environment and health related to the deliverable.
Socially Inclusive	Justifies the benefit to society in terms of structural vulnerability and habitability in housing.
Innovative	Demonstrates the group's creativity in their presentation and justification.
Technically Feasible	Demonstrates compliance with the instructional objectives communicated to the students.

4. Discussion

The average results for collected and treated rainwater quality demonstrate the influence of seasonal variability on physicochemical and microbiological parameters, with distinct climatic patterns. During high precipitation months (November), we observed increased turbidity and microbial load due to greater surface runoff carrying particles, organic matter, and microorganisms. In contrast, dry seasons (January) led to temporary increases in color, turbidity, and microbial presence after initial rains as accumulated roof pollutants washed off—a well-documented phenomenon in rainwater harvesting research. Fluctuating rainfall periods (August) showed intermittent contaminant transport and variable water quality. These results demonstrate significant seasonal variations, highlighting the need for adaptive treatment processes and continuous monitoring to ensure water safety amid changing environmental conditions.

Regarding the impact of climate change on the system implemented in San Isidro Paltos, it is primarily associated with variability in precipitation patterns, rising temperatures, and changes in ambient humidity. These conditions pose challenges for both the availability and quality of the collected water. Intense rainfall can increase contaminant loads and turbidity, while prolonged droughts and high temperatures promote pathogen concentra-

tion and evaporation, reducing stored water volumes. Consequently, an efficient system design—including conveyance, storage, and treatment—is essential, along with continuous monitoring of water quality parameters and ongoing community training to enable timely responses to climate fluctuations affecting water availability. This adaptive approach not only ensures the safety of the resource but also enhances the system's resilience to climate uncertainty, positioning rainwater harvesting as a strategic and sustainable alternative amid the growing scarcity and degradation of conventional water sources.

Treatment efficiency analysis revealed the significant reduction of parameters such as color, turbidity, acidity, and microorganisms, allowing the treated water to meet regulatory limits for most of the indicators evaluated. However, some cases revealed incomplete removal of coliforms, highlighting the need to optimize household disinfection processes, particularly under conditions of high microbiological load associated with intense rainfall or the wash-off of accumulated contaminants following dry periods.

In terms of chemical stability, the adjustment of pH and the slight increase in alkalinity after treatment contributed to improved water quality, reducing the risk of corrosion in distribution networks. Conductivity and hardness values remained low and stable—characteristic of rainwater—with no significant variation after treatment, indicating a low presence of dissolved salts and minerals. Dissolved oxygen, initially low in rainwater due to the presence of organic matter and bacterial activity, increased following aeration and treatment, thereby improving conditions for the storage, distribution, and use of the resource.

The rainwater harvesting and treatment system implemented shares notable similarities with successful international experiences in countries such as Guatemala, Kenya, India, and Thailand, as it adopts an approach that integrates collection, prefiltration, storage, and slow sand filtration, a technology widely validated for its efficiency in rural and periurban contexts. As in the cases of Thailand and Guatemala, the project was characterized by a participatory design process in which the community played a central role in defining, constructing, and implementing the system, thereby promoting local ownership and the long-term sustainability of the solution.

Furthermore, the structured educational component, implemented through the Healthy Housing and Safe Water course, replicated pedagogical approaches from related projects referenced in the literature and by TECHO Colombia. This allowed for the transfer of technical and public health knowledge to residents and encouraged the adoption of good hygiene and water management practices.

This combination of technical phases and participatory educational strategies not only facilitated the adaptation of the system to the specific conditions of the territory, characterized by informality, lack of infrastructure, and social vulnerability, but also contributed to improvements in water quality and community health, as evidenced by the water quality results and the users' appropriation of the system.

Table 6 presents a country-level comparison between the system developed in San Isidro Patios (Bogotá, Colombia) and projects of similar scope in Guatemala, Kenya, India, Thailand, and a subarctic region, based on three key criteria: the measurement of water quality parameters, participatory work with the community, and educational processes for technology transfer.

Table 6. Comparative table of projects of similar scope between different countries.

Project/Country	Measurement of Water Quality Parameters	Participatory Work with the Community	Educational Processes and Technology Transfer
San Isidro Patios (Colombia)	Periodic measurements (during periods of precipitation and drought) of physicochemical (color, turbidity, pH, conductivity, hardness, and dissolved oxygen) and microbiological (total and fecal coliforms) parameters were performed. Results show significant improvements after treatment.	Active participation in planning, operation, and maintenance. Community ownership of the system.	Training in safe use, monitoring, and maintenance. Continuing education to ensure sustainability and community ownership.
Guatemala	Emphasis on microbiological contamination and control through initial washing, filtration and disinfection.	Community training in management and treatment. Participation in maintenance and operation.	Community education programs for best practices and sustainability. Transfer of low-cost, easy-to-maintain technologies.
Kenya	Measurement of fecal coliforms, residual chlorine, comparison between sources (rain, wells, and surface water), and storage conditions. Weekly monitoring.	Comprehensive intervention; community involvement in safe storage, sanitation, and latrine use. Participation in hygiene and sanitation practices.	Education on disinfection, safe storage, and sanitation. Promotion of comprehensive health practices and safe water.
India	Measurement of turbidity, pH, dissolved solids, conductivity, coliforms, heavy metals, and nutrients. Monitoring of residual chlorine after disinfection.	Community participation varies, with an emphasis on the adoption of accessible technologies. Local initiatives for operation and maintenance.	Education on point-of-use treatment (chlorination, filtration, SODIS). Training for regular monitoring and maintenance.
Thailand	Assessment of total and fecal coliforms and heavy metals. Periodic monitoring and adjustment according to local conditions.	Community-led management and maintenance. Participation in design, operation, and revolving funds.	Training in the construction and maintenance of water tanks and jugs. Education campaigns on hygiene and water management.
Subarctic region of Canada	No physicochemical or microbiological analyses were reported.	Selection of participating households by local authorities. Participation in basic operation and maintenance.	Training participants in the use and maintenance of the systems. Promoting collective learning about rainwater harvesting.
Indonesia	No physicochemical or microbiological analyses were reported.	Interviews, surveys, and workshops with users and key stakeholders for the design, implementation, and evaluation of individual and community systems.	Socialization, information, and technological adaptation processes, including training in the use and maintenance of data collection systems.

The rainwater harvesting system in San Isidro Patios distinguishes itself from its international counterparts through its integrated monitoring of physicochemical and microbiological parameters across seasonal variations, enabling comprehensive water quality assessment and treatment validation. Unlike systems in Guatemala and Kenya that focus primarily on microbiological indicators through household disinfection (filtration/boiling/chlorination), or projects in Canada and Indonesia lacking reported water quality analyses, this approach provides systematic data to optimize treatment processes and ensure safety under diverse climatic conditions.

In terms of community participation, the project developed in San Isidro Patios fosters active and sustained involvement in planning, operation, and maintenance, similar to the experiences in Thailand and Kenya. However, it offers the added strength of a constructivist educational approach, with the direct application of transferred knowledge to ensure sustainability and technological appropriation. A relative weakness, compared to the projects in India and Thailand, may lie in the more limited diversity of treatment technologies and variability in the adoption of accessible innovations, as well as the potential reliance on the community for technical management, including maintenance and monitoring. Overall, the main strength of the developed system lies in its decontamination processes and community ownership, while its primary challenge is to ensure proper use, maintenance, and monitoring by the community through educational processes. This contrasts with international contexts where multiple technologies and gradual, adaptive transfer approaches have been integrated.

The project also stands out for its cost-effectiveness, having implemented a rainwater harvesting and treatment system for 350 USD—30 to 56 percent less expensive than similar projects in Guatemala (ranging from 500 to 800 USD). This substantial cost reduction was primarily achieved through the strategic use of locally sourced materials and active community participation in construction. Furthermore, its adaptability to the local context is particularly notable, as the design explicitly considered the unique architectural and living conditions of the informal settlement—an aspect frequently overlooked in other initiatives.

The multidisciplinary integration of engineering, architecture, and public health enabled the development of holistic solutions, such as optimizing water storage in limited spaces and preventing water-related diseases, thus surpassing the one-dimensional approaches seen in previous initiatives. These strengths not only enhanced access to safe water but also produced a replicable model for informal urban settings facing spatial and economic constraints.

Moreover, the AS methodology applied in the project demonstrates clear coherence between theoretical foundations and practical implementation, in alignment with its core principles of promoting community participation, avoiding dependency, and strengthening social engagement, as outlined in the guiding framework. This was evidenced during the territorial diagnosis, where 39 indicators related to habitability, services, and infrastructure were participatively analyzed, enabling the community to identify and prioritize their actual needs, particularly those concerning access to and quality of water for human consumption.

The collaborative construction of the rainwater harvesting and treatment system was carried out through community work teams, which fostered local ownership and facilitated the transfer of technical knowledge. Additionally, the educational strategy was implemented through the Healthy Housing and Safe Water course, designed under a constructivist approach that, as supported by theory, promotes active learning through engagement with real-world problems, group work, hands-on workshops, and reflective practices.

The activities included communication of real-life scenarios, case analysis, technology building, and formative evaluation based on the criteria of feasibility, inclusion, and innovation. This ensured that learning was directly linked to addressing the community's concrete needs and to developing life and citizenship skills. In this way, the AS methodology successfully integrated theory and practice, generating both formative and transformative impacts on participants and on the broader social environment in which the intervention took place.

In summary, the results obtained indicate that the project responded appropriately and coherently to the identified problem, providing a technically, educationally, and socially adapted solution that improves access to safe water, reduces exposure to health risks, and contributes to the well-being of the residents of San Isidro Patios. The intervention aligns with the priorities and needs identified through the participatory diagnosis.

5. Conclusions

The successful implementation of a community-based rainwater harvesting and treatment system in San Isidro Patios represents a significant stride toward improving water access and quality. This achievement was largely facilitated by the community's active participation throughout all project stages, which fostered strong ownership and ensured the technology's adaptation to local conditions, thereby moving beyond traditional assistance models.

Crucially, local training and empowerment bolstered community resilience, fostering the adoption of best practices and the safe use of treated water. This was instrumental in ensuring the system's long-term sustainability and positive impact within the community.

The rainwater harvesting and treatment system in San Isidro Patios exhibited a robust capacity for adaptation amidst increasing climate variability. Integrating rigorous multitemporal monitoring with optimized treatment and storage processes enabled the maintenance of collected water quality and safety throughout the project, even under significant fluctuations in precipitation, temperature, and ambient humidity. This adaptability is critical in the context of climate change, where extreme conditions and uncertain water availability are increasingly prevalent.

The results demonstrated significant improvements in the water's physicochemical and microbiological parameters, consistently meeting national standards for human consumption after applying the system's integrated decontamination processes. The marked reduction in color, turbidity, and microbial load, coupled with pH adjustment and chemical stability, confirms the system's effectiveness and its potential to ensure safe water access in vulnerable urban communities.

Regular monitoring of water quality parameters and preventive infrastructure maintenance proved essential for anticipating risks, adjusting treatment strategies, and extending the system's lifespan. This experience underscores the critical importance of integrating monitoring and cleaning routines into water resource management, particularly in contexts of high climate variability.

The integrated methodological approach, which seamlessly blended educational, technical, and social processes, successfully promoted behavioral change and the adoption of best practices in water management, hygiene, and infrastructure maintenance. Thus, the project not only delivered a technical water supply solution but also strengthened local capacities and social cohesion, yielding positive impacts on the quality of life and sustainable development of the territory.

In summary, this project made a relevant, coherent, and effective contribution to addressing the identified water access challenges. It decisively validated the participatory

approach and the AS methodology as strategic tools for tackling complex issues in contexts marked by environmental and social vulnerability.

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