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Groundwater Resilience Assessment in a Communal Coastal Aquifer System. The Case of Manglaralto in Santa Elena, Ecuador

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Abstract: Resilience has several meanings, among them the ability to overcome difficulty and return to the state of providing service, even if the initial conditions change. Assessing resilience in an ecosystem, or any system, requires a concise methodology with standard variables and parameters. The current challenge presented by coastal areas is focused on overcoming problems related to the water supply through correct management. This paper aims to evaluate the communal coastal aquifer system with a matrix for assessing water resilience based on indicators in the Sustainable Development Goals (SDGs) in a socio-hydrological framework and the four axes of development (political, social, environmental, and cultural), to promote the development of new strategies for water sustainability. The method is based on (i) political, economic, social, environmental, and even cultural aspects involved in sustainable water management and (ii) the groundwater resilience assessment method (GRAM) design. The GRAM is used for a quasi-quantitative assessment of the resilience in a communal coastal aquifer system. This method was applied to the Manglaralto community; the results show a highly resilient groundwater system (62.33/100 points). Representatives of the community have achieved appropriate use, management, and conservation of the water resource by applying water harvesting and other technical criteria. Hence, they have avoided aquifer overexploitation and provided water to the community.

Keywords: resilience assessment; groundwater; coastal aquifer; rural community; Sustainable Development Goals and indicators

1. Introduction

Freshwater represents a small fraction of the available water on earth [1]. With water demand growing approximately 1% per year since the 1980s [2], global demand for the vital resource will continue to increase at a similar rate until 2050 and rise from 20% to 30% above the current use level [3]. Among the leading causes of increased water demand is the growth of the world population (urbanization), changes in consumption patterns (e.g., product preferences based on meat and sugar), improvement of living standards (economic growth, industrialization), and expansion of irrigated agriculture (increased production) [4,5].

Water resource exploitation, in combination with the intersecting effects of climate change [5,6] due to human activity, demarcates a new geological epoch (the Anthropocene) [7,8]. These factors have led to a shortage crisis scenario of unsustainable use of water, a global issue demonstrating that two-thirds of the world population experience severe water shortage conditions at least one month a year [9]. The alarming evidence has led to the creation of strategies to face water scarcity, focusing on its practical and sustainable management [10–12].

In general, resilience is defined by the Oxford English Dictionary as (i) the capacity to recover quickly from difficulties, and (ii) the ability of a substance or object to spring back into shape [13]. For Timmerman [14], in the domain of engineering and disasters, resilience is the ability of human communities to withstand external shocks or perturbations to their infrastructure and to recover from such perturbations. In the social and ecological domain, Holling [15] defined it as the amount of disturbance that can be sustained by a system before a change occurs in its mechanisms of control or its structure. Regarding groundwater systems, Sharma and Sharma [16] defined resilience as the ability of the system to maintain groundwater reserves despite significant disturbances.

Resilience is known as the adaptive capacity of a system to a change generated by external pressures while maintaining certain vital functions. This concept has gained a prominent place in water policies [17,18], ranging from water resource management at the hydrographic basin scale, to drought and flood management, to climate change adaptation in the water services sector (e.g., [18–25]). In the human–water interaction context, three types of systems and subsystems in the framework of resilience emerge: (i) the water subsystem, with hydrological resilience to anthropogenic risks; (ii) the human subsystem, with social resilience to hydrological risks; and (iii) the socio-hydrological subsystem, with socio-hydrological resilience [26].

Defining and understanding the system is key to any assessment of resilience [26–28]. Hence, knowing the system allows examination of its state, evolution, and variables. Thus, the evaluation leads to the proposal of strategies/measures for reaching the desired state.

Water resilience is explored from different approaches, such as the engineering aspect (functionality, vulnerability, and resistance of water infrastructure systems [23,29–31]), the socio-ecological aspect (socio-ecological system capacity to face change and transform, creating solutions at the lowest cost and with the least environmental impact [32,33]), the ecological aspect (assessment of the ecological system's capacity to face stress [34,35]), the community capacity to face problems [36,37]), and the institutional aspect (institution or government capacity to manage, adapt to, and deal with threats related to hydric resources [38,39]). Finally, we can explore how education can help secure inclusive and resilient development around water resources, engaging students as the vector for knowledge transfer to secure water for society in a sustainable development context [40].

Several authors have used numerical methods [41,42] or the water storage variability in a period [42] to assess the resilience of groundwater systems during droughts. Peters et al. [41] evaluated the performance of groundwater systems in the event of drought using three indicators: resilience, reliability, and vulnerability. In the Pang Basin (United Kingdom), a similar study was carried out by Hugman et al. [42]. In the Querença–Silves aquifer system (Portugal), a quantitative evaluation of aquifer performance and its resilience or recovery capacity was carried out based on four sustainable performance factors: property, recharge, pumping, and distribution of wells in aquifers. Another study, on a larger scale, used remote sensing satellites to assess resilience. The study made use of NASA's Gravity and Recovery and Climate Experiment (GRACE) tool to assess groundwater resilience based on global estimates of groundwater storage and average flow subsurface net storage.

The authors defined the total groundwater stress ratio as a measure of groundwater resilience that applies to large aquifers only [34].

Water resilience must be comprehensively evaluated beyond the recharge capacity or economic impact of significant changes in the system. The analysis must include physical, environmental, economic, and social impacts.

There are many ways to assess sustainable development; indicators are among the most commonly used approaches [43]. Studies have been presented in the water context based on the development of indicators to measure the sustainability and resilience of different aspects of these systems. Some examples are the development of the water provision resilience indicator, a measure of the capacity of the water system to maintain or improve the percentage of the population with access to safe water in the water supply sector (supply, infrastructure, service provision, finance, water quality, and governance) [44]; the application of a framework of nine indicators of water resource management at the level of the watershed (water quality, water quantity, system stability, water-use efficiency, user-sector productivity, institutional preparedness, equitable water services, water-related well-being, public participation) [45]; the use of indicators of wastewater treatment systems for sustainability assessment, highlighting key indicators such as organic matter, nutrients, cost, heavy metals, and land area [46] and work proposed by Polonenko et al. [47] studying indicators within the role of institutions and communities in urban water systems, as well as indicators for various areas such as social, institutional, governance, economic, technological, and environmental, especially in such systems [48–51].

Despite the efforts made in hydric resource management, there are some areas where the water supply relies on the exploitation of the coastal aquifer. Thus, communities have experienced water scarcity and suffered inconvenience due to the demand growth and global climate impact. These cases raise the following research questions: Is it possible to assess resilience in a communal coastal aquifer system considering the Sustainable Development Goals (SDGs)? Could the community overcome those problems and show resilience to cope with climate change, population explosion, and tourism growth?

The present study aims to assess the resilience management of a communal coastal aquifer system by configuring the groundwater resilience assessment method (GRAM) matrix. The method is based on the indicators of the SDGs (Agenda 2030) related to the socio-hydrological framework [52], which, according to Brundtland [53], is based on three axes—economic, social, environmental—with the cultural axis added later [54], and will allow the development of new strategies for water sustainability.

The GRAM was applied to a rural commune in the southwestern part of Ecuador, in Santa Elena Province. The province is in the country's semi-arid zone [55], characterized by irregular rainfall influenced by marine currents and Pacific Ocean phenomena, such as the Humboldt cold current, the El Niño warm current [56–58], and the equatorial underwater current. Since this tropical region presents an arid climate throughout the year, water diversion systems such as the Chongón–San Vicente and Daule–Santa Elena transfers were implemented. In addition, groundwater pumping is used as an alternative to mitigate drought conditions in the dry season (June–November) [59] and wet season and floods (December–May) [60].

Case Study: Manglaralto

The rural parish of Manglaralto is located in the southwest of Ecuador in the far north of Santa Elena Province. It has an area of 3,690.17 km^2 and 35,000 inhabitants [61,62]. In this area, there is a shallow coastal aquifer in which 13 wells have been built to supply water to six communes (Montañita, Manglaralto, Río Chico, Cadeate, San Antonio, and Libertador Bolívar) (Figure 1) [63]. The aquifer is considered an important geosite within the Santa Elena Peninsula Geopark Project [64].

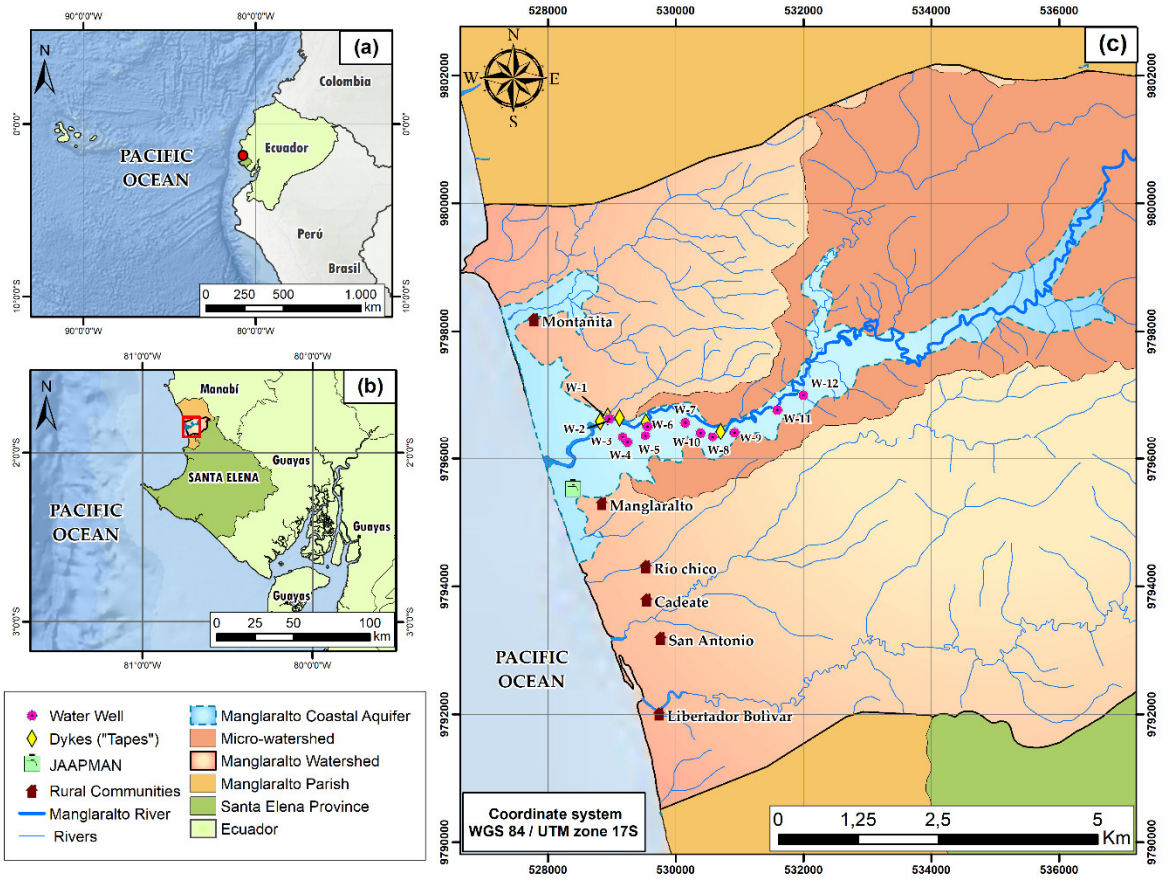

Figure 1. Location map of case study. (**a**) Location of study area in northwest of South American margin. (**b**) Manglaralto watershed location in Ecuador. (**c**) Manglaralto watershed setting and its main elements, and location of rural communities that the Manglaralto Drinking Water Board (JAAPMAN, from the Spanish) supplies with water.

The Manglaralto basin has an area of approximately 13,238 ha, and the coastal aquifer reaches an area of 508 ha; the aquifer is influenced by four forested areas (Chongón Colonche, Loma Alta, Cangrejal de Olón, and Esterillo Oloncito) that maintain its ecosystem. However, due to the demographic and tourist exposure of the place, a 32.30% reduction in aquifer capacity has been reported, generating concern and the need for regulatory measures that ensure the sustainability of the resource to be implemented [63].

In the community, the primary sources of income for the inhabitants are tourism, agriculture, livestock, fishing, and retail trade [33]. Despite the alternatives for economic activity, only 34.15% of the residents are economically active. Thus, most of the population has a low economic status [61]. According to Herrera [65], the availability of water in the study area is limited and does not meet the basic needs of the community and economic activity. The shortage of drinking water in the community means that 92.67% of the population receives freshwater from wells, 2.26% from rivers and "albarradas" (retention ponds to capture water during wetter periods), 2.26% from rainwater, and 3.34% from delivery trucks (tankers) [61]. Participatory community educational processes (social, economic, environmental, and cultural actions that ensure the continuity of the water supply) have generated positive changes in water management and conservation. Hence, problems have been solved based on ancestral knowledge with the contribution of academic and community work [63].

The Manglaralto commune, with approximately 2000 inhabitants and limited access to water, solved its shortage by using tanker trucks to supply low-quality water. With population growth came the construction of houses and other typical buildings. Naturally, river water was used, but since it was seasonal, the use of groundwater also began. In response to this event, the Manglaralto Drinking

Water Board (JAAPMAN, from the Spanish) was created on 29 March 1979. The objective was to obtain and distribute water to Manglaralto inhabitants by taking advantage of the existing shallow coastal aquifer. JAAPMAN's first aim was to construct a series of wells, which in many cases were unsuccessful due to a lack of knowledge about aquifer geometry. However, seven wells were successful and provided water to the population on defined schedules (one hour each in the morning and afternoon). Thus, the wells reduced the expense of tankers. Unfortunately, the El Niño and La Niña phenomena that occurred until 2005 led to drought and rapid growth of poverty in the area. Moreover, it is relevant to highlight the 1964 drought and 1982 floods as historical natural disasters that occurred in Ecuador (Figure 2) [66].

The decreased resource aquifer emerged in the well closest to the coast, which was affected by saline intrusion, leaving the well water unfit for human consumption. However, the community used ancient techniques to construct albarradas to store rainwater, which, together with the enabled wells, allow artificial recharge by pumping. In the period between 1979 and 2005, the community faced various problems, through which it improved its adaptive and recovery capacities, as reflected in Figure 2.

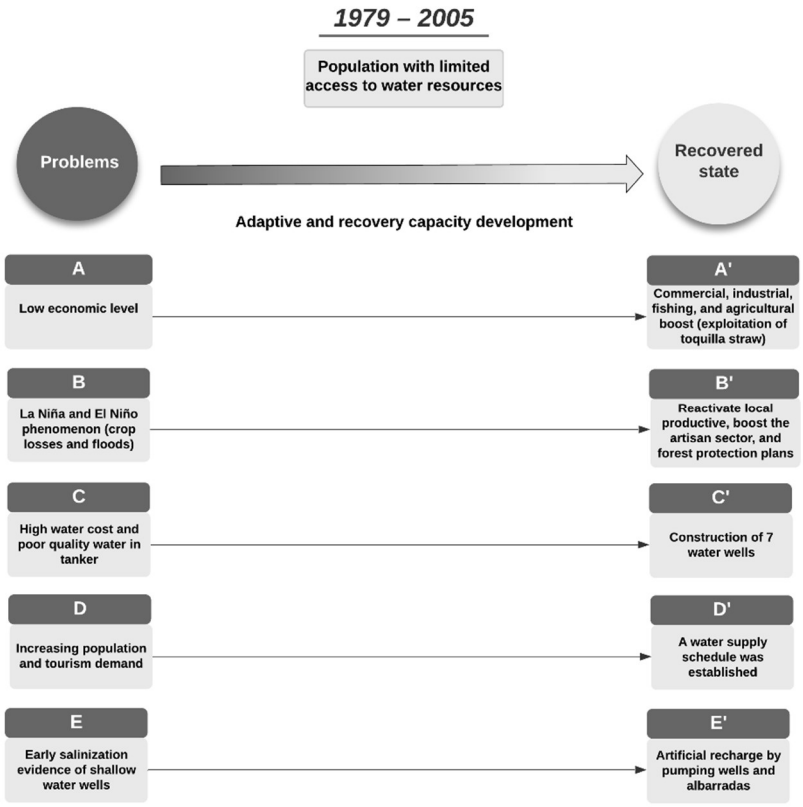

Figure 2. First resilience period, 1979–2005.

In addition to environmental problems, the growing population and tourist demand until 2005 led JAAPMAN, which only had seven wells, to have inadequate water management. The situation forced the distribution of water with tankers and the protection of nearby forests in the Loma Alta Commune Ecological Reserve.

The lack of water and socioeconomic studies in the sector led to the second resilient period, in which projects were developed from 2007 through 2011 to evaluate the water resources in the area and their quality and promote sustainable use. To find an alternative solution to improve the water situation in the area, Escuela Superior Politécnica del Litoral (ESPOL), through its Research Center of Projects, applied to the Earth Sciences Project (CIPAT, from the Spanish) for academic-scientific development in the community. This initiative generated project proposals ECU/8/041: Characterization of Coastal Aquifers in the Santa Elena Peninsula and RLA/8/026: Application of

Isotopic Tools for Integrated Management of Coastal Aquifers. The projects began in 2007, led by CIPAT-ESPOL, together with the International Atomic Energy Agency (IAEA) [63,67].

By 2009, the Manglaralto commune had seven wells that supplied water to approximately 18,000 people 24 h a day. The projects raised awareness of the importance of preserving scarce water resources. It was the excellence of the water supply that led to the growth of tourism in Montañita, a surf beach located in the area.

However, in 2011, the population increased to approximately 24,000 inhabitants, along with exponential growth of water demand. With studies by CIPAT-ESPOL with the IAEA, six new wells were built to improve the water supply. Even though there were 13 water wells, over-exploitation of the aquifer and a decrease in the water supply to two hours a day were evident. As the number of inhabitants and tourists in the area increased, problems with the oxidation ponds for wastewater treatment began. The design had limited capacity, exceeded levels of contaminants, and contaminated the environment. In 2011, supported by academics, a strategic plan was designed to address the imminent need for artificial aquifer recharge and the wastewater problem. These resilient events are summarized in Figure 3.

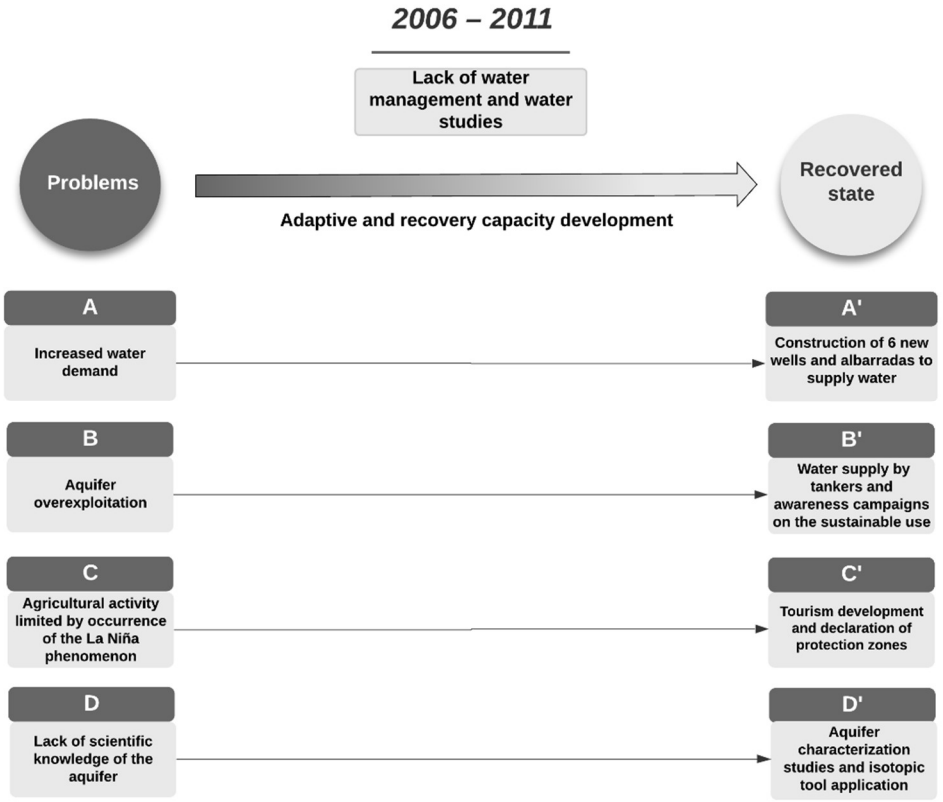

Figure 3. Second resilience period, 2006–2011.

In 2014, the third resilience period began with the technical–academic advice of ESPOL with the community and JAAPMAN, applying strategies for artificial recharge of the aquifer. The plan was to take advantage of the seasonal rivers and dam the water with so-called "tapes" (artisanal dykes), hence reviving the ancestral knowledge of the province of Santa Elena. The harvesting of water flourished along with the artisanal construction of tapes. Then, with an artisanal and technical method and some trial and error, the knowledge of past generations was revived [68]. The implementation of tapes allowed desalination of disabled wells, recharging of the aquifer, and increasing volume to an adequate supply of water for the community [69].

Currently, the harvesting of water [62,70,71] is carried out by the community. The assistance of academia has promoted the protection of the aquifer, prohibited the exploitation of construction material, and implemented reforestation campaigns in the area under study [62]. In 2017, CIPAT

began community service projects to monitor the geometry of the aquifer, the water quality, and the wastewater treatment with the application of green filters to maintain and ensure water sustainability (Figure 4) [72].

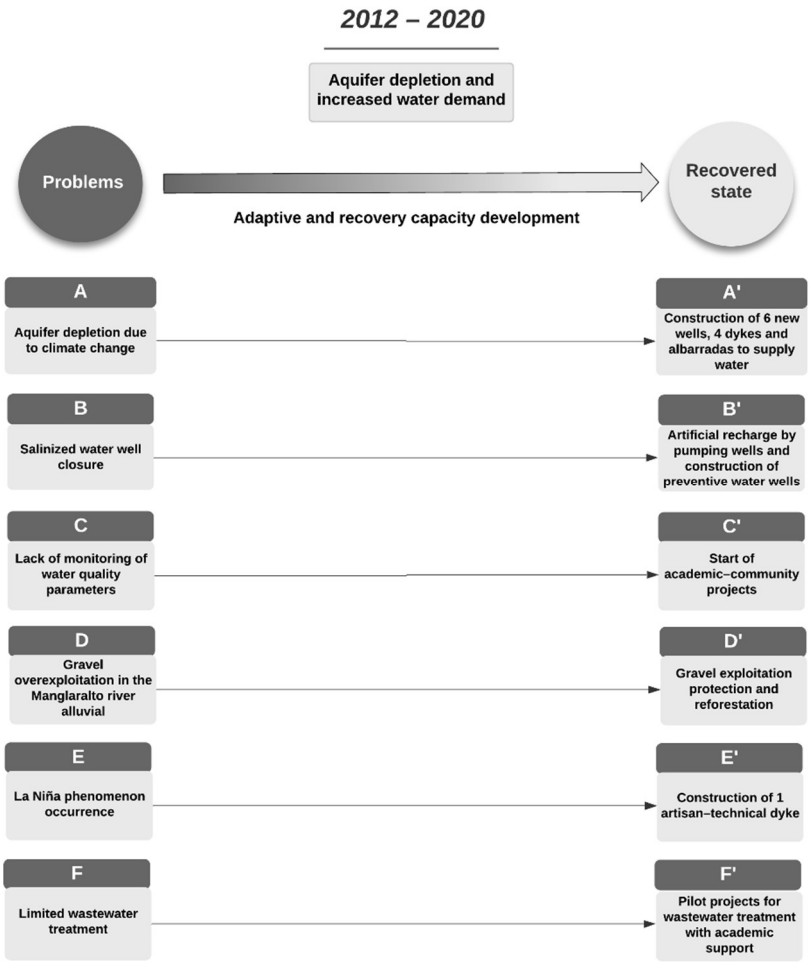

Figure 4. Third resilience period, 2012–2020.

The actions by public institutions and academia have shown that the efforts of management policies to counteract the effects of scarcity and the high demand for water in groundwater basins such as the Manglaralto basin have not been enough. This natural system has been the focus of ongoing study for more than 10 years. However, studies show that no progress has been made in determining the interaction of biophysical, social, and other factors in an integrated way [33,63,67,68,73]. These elements may affect the flow of water for anthropic activities (tourism, industry, governance, among others) and cause shortages in the water supply. However, the resilience periods (Figures 2–4) reflect the partial environmentally friendly solutions funded to face the various problems associated with the water resource.

2. Materials and Methods

The method of this study consisted of analyzing the conceptual framework of sustainability in groundwater management, which allowed us to define evaluation parameters, which led to the design of a resilience assessment matrix, establishing a resilience classification in the communal coastal aquifer system, as illustrated in Figure 5.

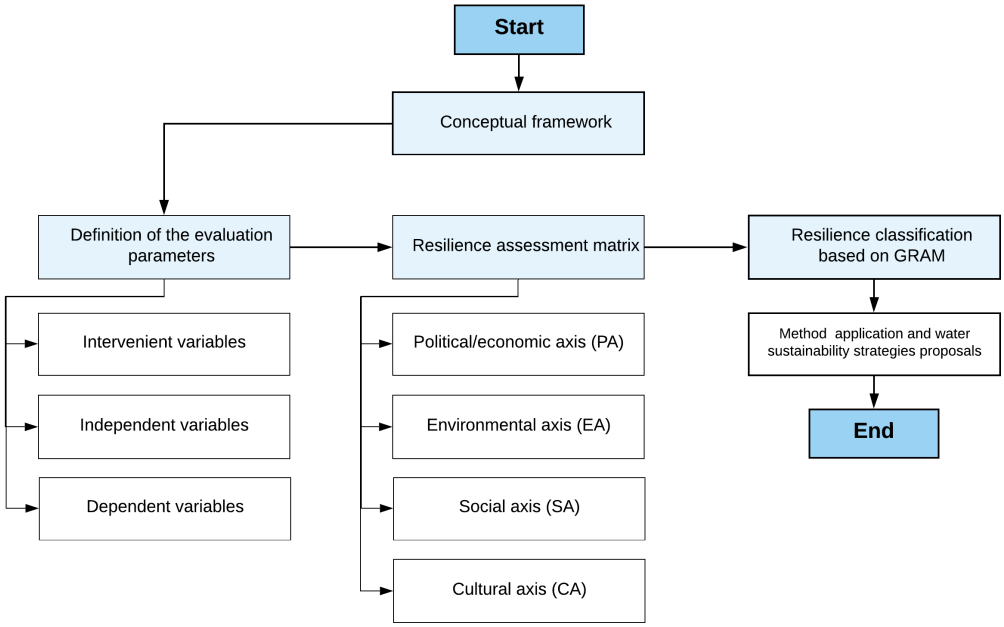

Figure 5. Groundwater resilience assessment method (GRAM) development diagram.

2.1. Conceptual Framework

Sustainable development is essential in resilience assessment methods, for which the four axes of sustainable development have been considered [54,74]. The method seeks to satisfy the current needs of the community without compromising future generations. According to Berkes et al. [75], hydric resource systems are considered to be socio-hydrological systems that integrate nature with humanity. Therefore, resilience is a crucial property in order to achieve sustainable development [75–77].

The study considers the definition of groundwater resilience given by Sharma and Sharma [16] as the "system capacity to maintain groundwater reserves despite major disturbances." Once the analysis system (socio-hydrological system [75]) is known, the main factors that influence groundwater recharge in the system are defined.

The first factor is the climate, which includes natural climate cycles (cyclical variations in the Earth's climate, interannual to decadal climate cycles such as El Niño–Southern Oscillation (ENSO), millennial climate cycles (Milankovitch cycles)) and anthropogenic climate change (accelerated global warming). The second component includes geology and topography, which consists of the aquifer type and characteristics and its geomorphology, where depressions improve infiltration and precipitation increases with elevation. The third element is land cover and uses where anthropogenic activities such as agricultural expansion and rapid urbanization exert pressure on groundwater. These three factors were brought to the sustainability groundwater concept.

Groundwater resource sustainability has been debated by Brundtland [53], the American Society of Civil Engineers [78], Loucks [78,79], Loucks [80], and Mays [81]. For Mays [81], water resource sustainability is defined as "the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life."

Thus, this is a complex process of interaction that involves political, economic, social, environmental, and even cultural aspects. Since the Anthropocene era, the need for sustainable, social, political, and environmental relationships, through management practices and the rational use of resources, has emerged [82]. When we analyze water management, use, and conservation, it is essential to assess imminent climate change [83,84] and the demographic explosion that the planet

experiences. These factors will increase freshwater consumption beyond sustainable levels in the future [85].

The political aspect is dominated by four blunt policy instruments that seek to regulate the behavior of groundwater users [86–88]: (i) direct administrative regulation, (ii) economic instruments (charges, taxes, subsidies, quotas, among others), (iii) tradable water rights through the creation of water markets, and (iv) participatory aquifer management by groundwater communities through the organization of farmers' associations with a mandate to manage aquifers on a sustainable basis. Given these factors, consideration should be given to rational and appropriate policies that adapt to changes that have occurred over time, with the possibility of reforms that extend to future changes [89].

Consequently, human regulations and policies directly influence water resource management and sustainable consumption. Human intervention can cause disturbances to systems that induce unexpected responses. Environmental, technical, and governmental problems with water cause scarcity and poor quality [84]. According to Newig et al. [90], the participation of people in charge of water policy management and formulation and the community is required.

The social aspect implicates groundwater users' behavior with local aquifer dynamics [91], representing a concept known as community-based and/or participatory management [33,87,92,93], where, through collective action, existing social capital, including trust and norms, makes the community self-regulate the use of resources more effectively [94].

The environmental framework deals with natural and human-made activities (land use) that affect the quality and quantity of subsurface water and the physiology, geology, and characteristics of the rock structure, as well as the effects of the environment, climate, and other physical and natural forces trying to alter the subsurface water source [95,96]. This context is where the environmental standards emerge, including limits on saline and other chemical intrusion from other water sources into groundwater bodies, including values for conductivity, levels (and associated limits) expressing the water balance in the groundwater body, and thresholds of impact on the ecology or status of dependent surface waters and terrestrial ecosystems [97].

The role of culture in the science of environmental decision-making is increasing across a range of disciplines [98–101]. Knowing, reconstructing, and studying the past provides guidance in resource management decision-making, as even institutions that have "generational amnesia" may not be able to account for changes over long timescales [100]. For example, structures called "qanats", sloping tunnels that tap into the groundwater without the need for pumping, have survived the test of time over millennia [101]. In addition, the revival of ancestral knowledge has provided solutions for water scarcity through a process known as "nurturing water" [102].

In addition to the four axes of sustainable development, the role of groundwater in the general assessment of the world's water resources should be taken into account; it is established that groundwater has to be seen within the broader context of the hydrological cycle and aquifers as a significant hydrological component of watersheds and basins [103]. Various unconventional methods have been implemented in order to address present and future water crises and challenges, such as desalination of seawater, recycled effluents for potable water supply, reuse of drainage water for agriculture, closed industrial water systems, and collection of rain and fog water [104–106].

In brief, this complex process of interaction involves groundwater management in its different components: the legal and economic framework (in matters of quality and treatment), monitoring (environmental, contamination detection, compliance with water quality according to standards, and performance), information/data management, groundwater source protection, aquifer artificial recharge, modeling and optimization that support decision-making, and integrated management of water sources.

2.2. Definitions of Evaluation Parameters

For the GRAM design, the authors considered measuring the dynamics of the communal coastal aquifer system in the framework of resilience, which involves the interaction of the population, the floating population (tourism), the water management organization, and the resource as the primary agents involved in the system. From this complex interaction, independent, dependent, and

intervening variables arose that allowed the problem to be defined and the research hypothesis to be proposed.

Intervening variables are actions that modify the system positively or negatively in the cause–effect relationship of independent and dependent variables, respectively, which are determining factors for resilience or scarcity scenarios. Some of the main variables present in the communal coastal aquifer system are shown in Figure 6.

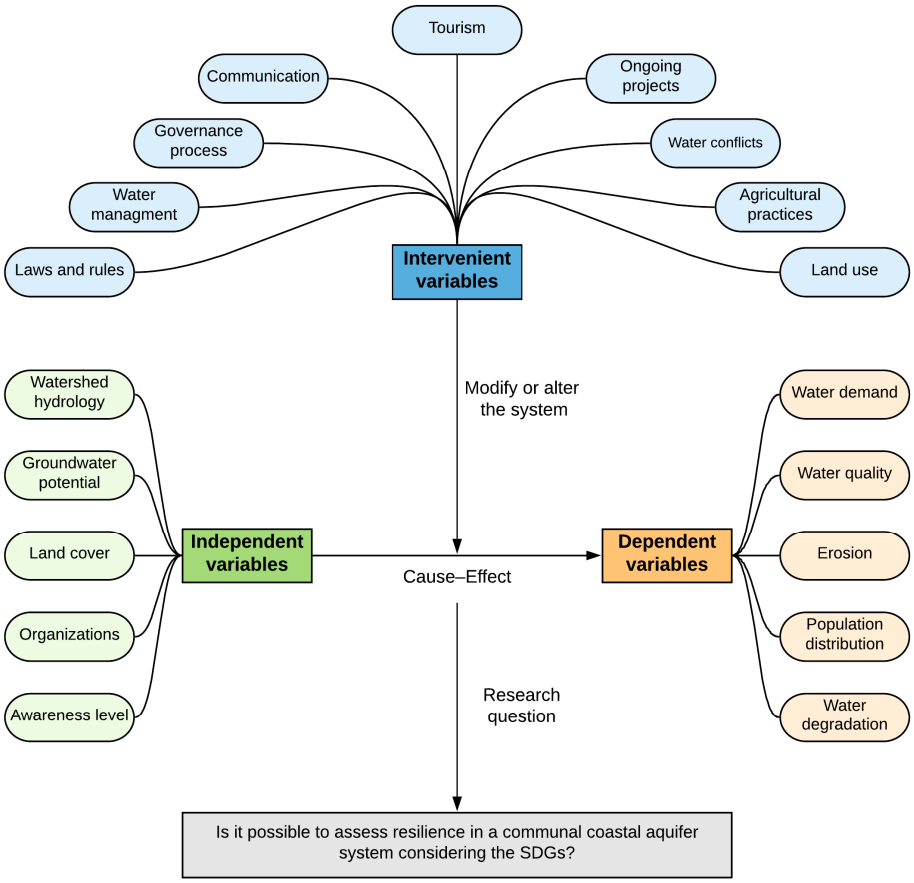

Figure 6. Principal dependent, independent, and intervening variables in communal coastal aquifer system. SDGs, Sustainable Development Goals.

Based on the analysis of variables, the authors proposed a GRAM matrix to assess the resilience in a communal coastal aquifer system, which led to proposals for plans and strategies related to sustainability. This matrix was built by defining sub-indicators based on the four axes of sustainable development—political/economic, environmental, social, and cultural [54,74]—and SDG indicators (Agenda 2030) related to the socio-hydrological framework [52]. In this study, 27 sub-indicators are proposed, which were obtained using the focus of 47 of the 232 SDG indicators, as shown in detail in the Supplementary Materials (Supplementary Material 1), grouped into the four axes of sustainable development.

The development and selection of indicators is a reflective process [107]. This process considered models of different practices and knowledge of community management in drinking water and sanitation in 13 specific rural communities (communal coastal aquifer system) of Santa Elena Province, southwest Ecuador, the result of pilot research projects carried out in the last decade. They were part of the Technical Cooperation Projects called "Characterization of Coastal Aquifers on the Santa Elena Peninsula" (ECU8026) and "Application of Isotopic Tools for Integrated Management of Coastal Aquifers" (RLA/8/041) with the IAEA [63,108], and projects on the "Unidad de Vinculación con la Sociedad" (UVS, acronym in Spanish) of ESPOL called "Hydrology and Hydrogeology Applied to the Manglaralto Coastal Aquifer (Stages I and II)", "Comprehensive Water Management

in Hydrographic Basins of the Manglaralto Parish", and "Resilience in Water Management before COVID-19, Manglaralto".

The method collects the experiences of water management experts, managers of water boards, and researchers, with the aim of sustainable development of the resource in rural coastal areas. These case studies are common in different coastal areas such as Peru, Brazil, Mexico, Chile, Bolivia, and Colombia [102].

2.3. Resilience Assessment Matrix

With the sub-indicators defined (Supplementary Material 1), Table 1 shows the number of SDGs, targets, and SDG indicators with the corresponding sub-indicators proposed in this study. The evaluation criteria for each established axis (see Tables 2–5) are rated on a scale of 1 to 4. However, any sub-indicator can be scored as zero if the communal coastal aquifer system being evaluated does not comply with minimum criteria established for the sub-indicator.

The sub-indicators are ranked in descending order from the desired level of harmony or balance for sustainability and resilience in water management. Hence, political/economic, environmental, social, and cultural aspects in the communal coastal aquifer system have specific roles.

Table 1. Criteria and indicators used for GRAM.

SDG.	Target	SDG Indicators	Axes/Sub-indicators	Score
			Political/Economic Axis (PA)	
1	**1.2**	**1.2.1**	A. Water rate	1–4
5	5.1	5.1.1	B. Management and community structure of water system	
	5.5	5.5.1		
		5.5.2		
	5.c	5.c.1		
6	6.b	6.b.1		
6	6.1	6.1.1	C. Water access	
6	6.2	6.2.1	D. Water use	
	6.4	6.4.1		
12	12.2	12.2.1		
		12.2.2		
6	6.b	6.b.1	E. Water quality	
13	13.b	13.b.1	F. Financial support	
			Environmental Axis (EA)	**Score**
2	2.4	2.4.1	A. Agriculture area	1–4
3	3.9	3.9.2	B. Freshwater quality monitoring	
6	6.3	6.3.2		
6	6.3	6.3.1	C. Wastewater management	
10	10.4	10.4.1		
11	11.6	11.6.1		
12	12.4	12.4.2		
6	6.3	6.3.2	D. Water estimation	
	6.4	6.4.1		
	6.6	6.6.1		
6	6.4	6.4.1	E. Ecosystem extent	
	6.6	6.6.1		
15	15.1	15.1.1		
	15.3	15.3.1		
6	6.4	6.4.2	F. Evapotranspiration/precipitation	
9	9.4	9.4.1	G. Monitoring of particulate matter	
11	11.6	11.6.2		
11	11.5	11.5.1	H. Population affected by natural disasters	
	11.b	11.b.2		
13	13.1	13.1.1		

		13.1.3		
14	14.5	14.5.1	I. Protection areas	
	15.1	15.1.2		
	15.2	15.2.1		
15	15.4	15.4.1		
		15.4.2		
	15.5	15.5.1		
	15.7	15.7.1		
			Social Axis (SA)	**Score**
4	4.7	4.7.1	A. Knowledge transfer	1–4
11	11.3	11.3.1		
6	6.4	6.4.2	B. Water rationing	
11	11.5	11.5.2		
6	6.a	6.a.1	C. International alliances	
17	17.6	17.6.1		
7	7.2	7.2.1	D. Energy sources	
11	11.3	11.3.2		
11	11.3	11.3.2	E. Community participation	
11	11.a	11.a.1	F. Development plans	
11	11.3	11.3.1	G. Education	
15	15.b	15.b.1	H. Academic support	
			Cultural Axis (CA)	**Score**
6	6.a	6.a.1	A. Intercultural relations	1–4
17	17.6	17.6.1		
11	11.3	11.3.2	B. Hydrological culture	
16	16.7	16.7.2	C. Cultural diversity	
16	16.7	16.7.2	D. Cultural holidays	

Note: A sub-indicator can also be ranked zero if appropriate.

2.3.1. Political/Economic Axis (PA)

Considering that the political axis is a base for the sustainable management and development of water, the aim is to assess groundwater resilience with six sub-indicators (Table 2).

A. Water rate: helps to identify whether the price of water the population of a municipality/place has access to is in accordance with the current poverty level; compares family income to the national average.

B. Management and community structure of the water system: identifies the entities/organizations that manage water and the degree of community participation.

C. Water access: evaluates the proportion of the population of a municipality/place that has access to safe or potable water.

D. Water use: determines the use of water extracted from the aquifer; that is, if the water is used only for basic needs or has more than one alternative use.

E. Water quality: rates the policies for quality assurance and sanitation of groundwater and wastewater, respectively.

F. Financial support: considers national and/or international financial support for hydric resource management plans to cope with climate change; relevant for measuring water resilience.

Table 2. Political axis (PA) and sub-indicators used for GRAM.

Axis/Sub-Indicators	Score
Political/Economic	
A. Water rate	
Laws/regulations for different water rates based on socioeconomic studies applied according to type of activity in the area (e.g., industry, tourism, agricultural, livestock, private residential areas, public residential area, the elderly care)	4
Two water rate laws based on socioeconomic studies: commercial and basic	3
Single basic water rate law based on socioeconomic studies	2
Single basic water tariff law that lacks socioeconomic studies (e.g., collection through barter and/or payment agreement)	1
B. Management and community structure of water system	
Water resource distribution carried out by:	
Inclusive national and private entities that involve community participation and gender equality	4
Inclusive national entities that involve community participation and gender equality	3
Inclusive private entities that involve community participation and gender equality	2
National or private entities that do not involve community participation and gender equality	1
C. Water access	
Percentage of population with access to potable water:	
75–100%	4
50–75%	3
25–50%	2
10–25%	1
D. Water use	
Freshwater extracted from aquifer is used for:	
Only basic needs (human use)	4
Basic needs and at least one alternative use	3
Basic needs and at least two alternative uses	2
Basic needs and more than three alternative uses	1
E. Water quality	
Operational policies and procedures preferably based on international standards that consider:	
All physical–chemical parameters to ensure quality and sanitation of surface water, groundwater, and wastewater, using techniques associated with sustainability (e.g., green filters, protected areas, reforestation)	4
All physical–chemical parameters to ensure quality and sanitation of surface water, groundwater, and wastewater	3
At least six of these parameters	2
At least three of these parameters	1
F. Financial support	
Direct national and international financial support for hydric resource management plans to cope with climate change	4
National or international financial support for hydric resource management plans to cope with climate change	3
National or international financial support for plans related/linked to management of hydric resources to cope with climate change	2
Limited national financial support for hydric resource management plans to cope with climate change	1

Note: A sub-indicator can also be ranked zero if appropriate.

2.3.2. Environmental Axis (EA)

This axis assesses the environmental aspect of groundwater resilience with nine main sub-indicators (Table 3).

A. Agriculture area: evaluates the type of agriculture and forestry in a municipality/place and verifies whether it meets the sustainability and resilience context.
B. Freshwater quality monitoring: measures groundwater quality based on the existence and recurrence of parameter monitoring in the municipality/place.
C. Wastewater management: rates the percentage of safely treated wastewater.
D. Water estimation: identifies whether there is an estimate of water within a defined period that allows the community to preserve and ensure water measures.
E. Ecosystem extent: evaluates the variation of the ecosystem extent over time and its impact on the resilience of a communal coastal aquifer system.
F. Evapotranspiration/precipitation: assesses water use, artificial recharge, and environmental care measures to deal with hydric deficiency in a municipality/place.
G. Monitoring of particulate matter: analyzes the implementation of clean industrial processes and technologies and the recurrence of monitoring of particulate matter to determine air pollution levels.
H. Population affected by natural disasters: rates water shortage per hour in the event of a natural disaster.
I. Protection areas: identifies areas of the ecosystem of a municipality/place where conservation and sustainable use are promoted to ensure hydric resources.

Table 3. Environmental axis (EA) and sub-indicators used for GRAM.

Axis/Sub-Indicators	Score
Environmental	
A. Agriculture area	
Percentage of agriculture and forestry area is used in a sustainable and resilient way that increases productivity, maintains ecosystems, and strengthens the ability to adapt to climate change:	
75–100%	4
50–75%	3
25–50%	2
10–25%	1
B. Freshwater quality monitoring	
Monthly	4
Quarterly	3
Semi-annual	2
Annual	2
C. Wastewater management	
Safe treatment of wastewater, by percentage:	
75–100%	4
50–75%	3
25–50%	2
10–25%	1
D. Water estimation	
Groundwater conservation estimates for:	
Next 10 years	4
Next 5 years	3
Next 3 years	2
At least 1 year	1
E. Ecosystem extent	
Extent of water-related ecosystem has:	4
Increased over time, and they have sustainable productive activities related to it	3
Increased over time	
Not changed over time	2
Decreased over time	1
F. Evapotranspiration/precipitation	
Given hydric deficit:	

Treated with measures to take advantage of groundwater, artificial recharge, and environmental awareness	4
Treated with at least two of these measures	3
Treated with at least one of these measures	2
There are proposals for environmental initiatives regarding groundwater	1
G. Particulate matter monitoring	
On-site adoption of clean and environmentally sound industrial technologies and processes and monitoring of PM10 and/or PM2.5 particulate matter:	
Monthly	4
Quarterly	3
Semi-annual	2
Annual	1
H. Population affected by natural disasters	
Water shortage for population due to natural disasters in the last decade:	
None	
Less than 24 h	4
24–48 h	3
48–94 h	2
I. Protection areas	1
Conservation and sustainable use of ecosystems rich in flora and fauna that ensure and protect freshwater, by percentage:	
75–100%	4
50–75%	3
25–50%	2
10–25%	1

Note: A sub-indicator can also be ranked zero if appropriate. Hp, hydrogen potential; TDS, total dissolved solids; BOD, biological oxygen demand; COD, chemical oxygen demand; PM10, particulate matter 10 micrometers or less in diameter; PM2.5, particulate matter 2.5 microns or less in diameter.

2.3.3. Social Axis (SA)

This axis assesses the social aspect of groundwater resilience within GRAM in eight main sub-indicators (Table 4).

- **A.** Knowledge transfer: allows knowing the percentage of institutions that include development measures, adaptation, and mitigation of climate change in their teaching plans.
- **B.** Water rationing: indicates the period when a population receives limited water service due to demographic explosion; considerably affects the SA of the municipality or place.
- **C.** National and international alliances: benefits communal coastal aquifer system resilience; projects and agreements allow the implementation of new mechanisms for the conservation and sustainable use of water.
- **D.** Energy sources: reflects the contamination level of the municipality/place in terms of the percentage of the population that implements green energy sources.
- **E.** Community participation: evaluates the interaction of the water management entity with the community to apply methods of planning, management, and conservation of hydric resources in a municipality/place.
- **F.** Development plans: evaluates projected development plans for a determined period considering demographic explosion and hydric resource demand.
- **G.** Education: analyzes whether the population of the municipality/place has a basic level of education and academic support.
- **H.** Academic support: verifies the implementation of pilot projects considering water use, sustainable conservation, and wastewater treatment with corresponding academic support.

Table 4. Social axis (SA) and sub-indicators used for GRAM.

Axis/Sub-indicators	Score
Social	
A. Knowledge transfer	
Percentage of local educational institutions that incorporate development, adaptation, and mitigation techniques for effects produced by climate change related to water in their teaching plans:	
75–100%	4
50–75%	3
25–50%	2
10–25%	1
B. Water rationing	
There is population growth, hydric resource reports water rationing, and:	
Service is already restored	4
Rationing remains until the middle of the dry season	3
Rationing remains throughout the dry season	2
Rationing remains to date	1
C. National and international alliances	
Participation of water management body in international and national alliance projects/agreements in the last decade:	
At least four of both	4
At least two of both	3
At least one of both	2
At least one international	1
D. Energy sources	
Percentage of population with green energy sources that reduce environmental pollution:	
75–100%	4
50–75%	3
25–50%	2
10–25%	1
E. Community participation	
Water management body, which operates on a regular and democratic basis:	1
Uses participatory methods with the community in planning, management, and conservation of resources	2
Communicates efficiently with the community in planning, management, and conservation of resources.	3
Does not involve community in planning and management of resources	4
F. Development plans	
Site implements development plans that integrate demographic projections and water resource needs for:	
Next 10 years	4
Next 5 years	3
Next 3 years	2
At least 1 year	1
G. Education	
Education level of users and administration is:	
Basic and strengthened with academic scientific support	4
Basic and they have permanent technical training about water	3
Basic and they have sporadic technical training about water	2
Basic	1
H. Academic support	
Academic support and pilot projects consider:	
At least sustainable water use, water conservation, and wastewater treatment	4
At least two of these aspects	3
At least one of these aspects	2
Academic support and pilot projects are proposed as initiatives	1

Note: A sub-indicator can also be ranked zero if appropriate.

2.3.4. Cultural Axis (CA)

This axis assesses the cultural aspect of groundwater resilience in four main sub-indicators (Table 5).

A. Intercultural relationships: based on attendance to events related to water and evaluates if a municipality/place has established national or international alliances.

B. Hydrological culture: based on the application of ancestral knowledge and provides solutions to problems of water shortages without overexploiting the resource, or if the community has help from the academy.

C. Cultural diversity: analyzes the importance of solving water problems using awareness methods, with participation by the community, the water management body, and academia**.**

D. Cultural holidays: evaluates the recurrence of holidays in a municipality/place; holidays with cultural basis in water are one of the main ways to raise public awareness of use, management, and conservation of water.

Table 5. Cultural axis (CA) and sub-indicators used for GRAM.

Axis/Sub-indicators Cultural	Score
A. Intercultural relationships	
Number of annual intercultural events on water and environment the water management body and community have participated in that allowed them to establish national and international alliances:	
More than two	4
Two	3
At least one	2
At least one that allowed them to establish national alliances	1
B. Hydrological culture	
Within the population, ancestral knowledge techniques implemented for water storage and recharging of the aquifer:	4
Provided a solution to overexploitation of the resource and water shortage; initiative was strengthened by technical design of academic counsel	3
Provided a solution to overexploitation of the resource and water shortage Partially solved overexploitation and water shortage	2
There is knowledge of ancestral techniques for storing water and recharging the aquifer; implementation of pilot projects reduced overexploitation and water shortage	1
C. Cultural diversity	
Solving water-related problems involves the following as pillars of awareness and application of participatory and educational methods for capacity development:	
Intercultural dialogue, water management body, and academia	4
Intercultural dialogue, water management body, or academia	3
Only intercultural dialogue	2
Eventual intercultural dialogue for awareness	1
D. Cultural holidays	
Number of annual holidays with cultural roots based on water and environment involving participation of the population and tourists:	
More than two	4
Two	3
At least one	2
No such holidays, but water assemblies held with inhabitants	1

Note: A sub-indicator can also be ranked zero if appropriate.

2.4. Resilience Classification Based on GRAM

Once the scores for the sub-indicators of each axis have been established, as shown in Tables 2–5, the following calculations can be made. The resilience value (R) is a weighted sum of the four axes (PA, EA, SA, CA), as expressed in Equation (1), where N is the addition of the maximum value for

each sub-indicator of each axis (in this case, 4), and the value 4 in the denominator is the number of axes. Substituting the N value for each axis, the R-value can be expressed in compact form, as shown in Equation (2), and is classified according to the statistical criterion by quartiles (Table 6).

$$R(\%) = \frac{\sum_{i=1}^{n} \frac{S_{Pi}}{N} + \sum_{i=1}^{n} \frac{S_{Ei}}{N} + \sum_{i=1}^{n} \frac{S_{Si}}{N} + \sum_{i=1}^{n} \frac{S_{Ci}}{N}}{4} \times 100\,, \quad (1)$$

$$R(\%) = \frac{(12\sum_{i=1}^{n} S_{Pi}) + (8\sum_{i=1}^{n} S_{Ei}) + (9\sum_{i=1}^{n} S_{Si}) + (18\sum_{i=1}^{n} S_{Ci})}{1152} \times 100\,, \quad (2)$$

where R is resilience; S_P represents sub-indicators of the political/economic axis; S_E represents sub-indicators of the environmental axis; S_S represents sub-indicators of the social axis; S_C represents sub-indicators of the cultural axis; n is the number of sub-indicators for each axis; and N is the sum of the maximum value (4) for each sub-indicator of each axis (PA, EA, SA, CA).

The GRAM classifies resilience into four categories (Table 6), based on the total percentage of each sub-indicator of the axes considered. A communal coastal aquifer system has a maximum classification in Table 6 (scores of 75–100%) when most of the sub-indicators that include actions or practices, cultural heritage, natural characteristics, and community management demonstrate resilience capacity in each axis of sustainability. Although this score does not indicate the absence of problems, it signals a higher level of consciousness and willingness to face difficulties.

Scores between 50% and 75% indicate limitations in water management that could affect the balance. Scores between 25% and 50% refer to places with partial resilience. Thus, improvement opportunities are identified.

If the site scores below 25%, it requires special attention, since according to the criteria related to these sub-indicators, there could be a reduction in the level of access to aquifer water in the long term. It could also indicate environmental, social, cultural, and political/economic limitations.

Table 6. Resilience classification using GRAM.

Resilience Classification	Score
Very high resilience	75–100
High resilience	50–75
Resilience	25–50
Low resilience	0–25

3. Results

Based on the proposed GRAM, the assessment of the communal coastal aquifer system of the Manglaralto parish was carried out considering the criteria of five evaluators with knowledge of the area (two experts, one academic, one director of the water board, and one user). The results obtained show a high average assessment value in the four axes—AP: 15/24 points; EA: 20/36 points; SA: 21/32 points; and CA: 13/16 points (Table 7). The system obtains a value of 62.33%, using Equation (2) and Table 6, for the proposed GRAM resilience rating, which ranks it within the high resilience range (Table 8).

Table 7. Results obtained for GRAM in the study case.

Axis/Sub-Indicators	Score				
Political/Economic	**E1**	**E2**	**E3**	**E4**	**E5**
A. Water rates	3	3	3	3	3
B. Management and community structure of water system	2	2	2	2	2
C. Access to drinking water	3	4	3	4	2
D. Water use	3	1	3	1	4
E. Water quality	3	4	3	4	3
F. Financial support	1	1	1	1	1
Avg/24	**15**				
Environmental	**Score**				
A. Agriculture area	2	3	1	3	2
B. Freshwater quality monitoring	4	4	4	4	4

C. Wastewater management	2	3	3	2	1
D. Water estimation	1	1	1	1	1
E. Ecosystem extent	4	4	4	4	3
F. Evapotranspiration/precipitation	4	3	4	4	3
G. Particulate matter monitoring	1	1	1	1	1
H. Population affected by natural disasters	1	1	1	1	1
I. Protection areas	1	2	1	1	1
Avg/36			**20**		
Social			**Score**		
A. Knowledge transfer	2	2	2	3	3
B. Water rationing	1	1	1	1	1
C. International alliances	3	3	3	3	3
D. Energy sources	2	1	1	3	1
E. Community participation	4	4	4	4	3
F. Development plans	1	1	1	2	1
G. Education	4	4	4	4	4
H. Academic support	4	4	4	4	4
Avg/32			**21**		
Cultural			**Score**		
A. Intercultural relationships	3	4	3	3	3
B. Hydrological culture	4	4	4	4	4
C. Cultural diversity	4	4	4	4	4
D. Cultural holidays	2	1	2	2	2
Avg/16			**13**		
E1–E5, evaluators 1–5.					

Table 8. Summary of results obtained for each axis of GRAM in the case study.

Axis	Score
A. Political/Economic	15
B. Environmental	20
C. Social	21
D. Cultural	13
$R(\%) = \frac{(12\sum_{i=1}^{n} S_{P_i}) + (8\sum_{i=1}^{n} S_{E_i}) + (9\sum_{i=1}^{n} S_{S_i}) + (18\sum_{i=1}^{n} S_{C_i})}{1152} \times 100$	62.33

4. Discussion

The GRAM is a quasi-quantitative assessment at the communal coastal aquifer system scale. It is a pragmatic and comprehensive assessment of water resource management based on the indicators of the socio-hydrological framework of the SDGs (Agenda 2030) [52] and the four axes of sustainable development [54,74]. This method determines the characteristics that require special attention or that can negatively influence the balance of a system. The GRAM identifies the vital links as well as the weak ones (political/economic, environmental, social, and cultural) that can be strengthened in water management. Therefore, recovery processes are possible with the implementation of strategies for socio-hydrological planning and organization

The methodological approach proposes six sub-indicators within the political axis, nine within the environmental axis, eight within the social axis, and four within the cultural axis. The geological aspects are found indirectly in the environmental axis, in the sub-indicators water estimation and evapotranspiration/precipitation, because the general work scheme is to meet the SDGs. These sub-indicators are intended to measure the capacity of the system in order to preserve or improve access to the water resource through environmental measurement practices and water estimation studies, which measure the percentage of ground and surface water with regard to total available water. The sub-indicators of this study assess resilience in the different strategic sectors of water: resource management bodies, consumption policies, water quality, supply, associated ecosystems, community participation, and hydrological culture.

The GRAM applied to Manglaralto revealed high resilience, as shown in Table 6, and the detailed values for the case study are shown in Tables 7 and 8, based on the strengths in the cultural

aspect followed by social, political/economic, and environmental aspects. Hence the relevance of JAAPMAN, as the community management entity, which has overcome problems and demonstrated socio-hydrological resilience (Figures 2–4). JAAPMAN has maintained the water supply despite climate change and the growing demand of the domestic and floating population linked to tourist activity.

Resilience is the product of several factors. The community is the central axis, but it requires political–economic, social, and environmental concurrence to promote it. The GRAM application in Manglaralto reflects a communal coastal aquifer system with problems maintaining water service. However, since the creation of JAAPMAN, the success factors have been community participation based on ancestral knowledge [62], the interaction between the academy and the community, and the ability to make alliances reflected in technical cooperation projects with national and international organizations [63,67]. In addition, the key factors are projects with practices based on sustainability, such as treating wastewater through green filters and promoting reforestation, thus, expanding the social responsibility of supplying water to the population by attending to wastewater and integrating it into the water cycle (Figures 2–4) [72]. Ultimately, the sum of all these elements allows the community in its specific territory to participate in solutions and have resilience.

Some of the examples of measuring resilience capacity in groundwater are essentially based on estimating the volume of water entering and leaving the system, that is, they provide an understanding of the states of flux in the aquifer [34,41,42]. These methods are essential in the sustainability of groundwater; however, it is necessary to increase resilience, and this is possible through the comprehensive management of the factors involved in the system, considering the four axes proposed in GRAM, whose parameters can be applied on a communal coastal aquifer system scale in areas that experience the most significant effects produced by climate change.

The quasi-quantitative assessment of resilience in the Manglaralto commune has revealed weak points in each axis. Based on the results, the researchers propose general and specific strategies to improve the situation, generate development plans, and enhance resilience.

- Strengthen the political–economic system of the community through alliances between the private entity in charge of the management and distribution of water and government entities at the local, regional, national, and international levels. This cooperation could generate economic support for management plans to cope with climate change and depletion of the aquifer.
- Promote the development of sustainable agriculture through the implementation of drip irrigation or intelligent solar irrigation systems to significantly reduce the amount of freshwater used and improve the management of the aquifer.
- Based on the success of pilot projects for the treatment of wastewater using green filters, it is essential to develop a large-scale project that enables the treatment of more than 50% of wastewater from Manglaralto, reduces pollution, and promotes its alternative use for the irrigation of specific species.
- Establish water conservation plans with estimates of at least 10 years to promote the application of ancestral knowledge and avoid salinization of the aquifer or a shortage of the resource for more than two days.
- Promote international alliances to raise funds for reforestation plans and establishment of protection zones to ensure the sustainability of ecosystems rich in flora and fauna and protect freshwater.
- Incorporate sustainable development and climate change adaptation and mitigation techniques in the educational system to boost the use of green energy and reduce pollution.
- Promote the resilient and sustainable practices of JAAPMAN and possibly replicate them in communities with similar situations.
- Maintain and strengthen the relationship between the community and academia through community awareness and participation in activities of projects that generate knowledge, management, and conservation techniques of the aquifer.

5. Conclusions

For groundwater sustainability, it is essential to know the factors that influence recharge: (i) climate, (ii) geology and topography, and (iii) land cover and use, adapting them to the four axes of sustainability: (i) political and economic, (ii) environmental, (iii) social, and (iv) cultural. The positive interaction of all these aspects makes the socio-hydrological system resilient, satisfying the demand for water in the face of demographic explosion and climate change.

Due to the importance of resilience in sustainability for a communal coastal aquifer system, a comprehensive pathway, GRAM, was designed which identifies strengths and weaknesses in order to recommend plans and strategies related to socio-hydrological sustainability. The method offers a variety of application opportunities in areas with similar natural conditions, and can be used by organizations that manage groundwater. Furthermore, it shows how culture facilitates and is the engine of the economic, social, and environmental dimensions of sustainable development of the Brundtland Commission.

Based on the application of the GRAM to the coastal communal coastal aquifer system in Manglaralto, a resilient system with an average score of 62.33/100 was obtained (Tables 7 and 8). The score of the cultural axis (13/16; Table 7) reflects the resilience capacity of the community with the support of the university. Currently, in a small hydrographic basin where wells have been implemented, with the revival of ancestral knowledge (techniques for harvesting water), the design and construction of tapes (dykes) that recharge the aquifer have stopped saline intrusion and provided water to the population. The environmental axis presents the lowest valuation due to the influence of factors such as climate change combined with the growing demand for the resource, and the community and its management of the construction of tapes; it needs to expand to more recharge sectors, which would require more labor and a larger budget.

Resilience can be taught and improved if there is a methodology that benchmarks, measures, and indicates its strengths, good practices, and acute problems. Therefore, it will be possible to implement long-term measures that solve system problems.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/12/19/8290/s1, Supplementary Material 1: Goal, target, and indicators of sustainable development which are the basis for the sub-indicators used in the groundwater resilience assessment method (GRAM).

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