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Geometric Model of a Coastal Aquifer to Promote the Sustainable Use of Water. Manglaralto, Ecuador

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Abstract: Modeling an aquifer provides significant advantages when evaluating and estimating the water resource for its sustainable use. This study focuses on the rural parish Manglaralto, a semi-arid area with a shortage of water, and without supply service by the public network. Still, it has a great demand for supply by the local and floating population (tourism). This has caused the coastal aquifer, which supplies the area's water, to show signs of overexploitation, and its natural balance is compromised. The aim is to establish a geometric model of the aquifer through geological and geophysical analysis to set sustainable water-use guidelines. The methodology includes: (i) the processing of the current technical and hydrogeological information to know the aquifer's data; (ii) geometric modeling of the aquifer through the correlation of technical information, using the GeoModeller software; (iii) proposals for the sustainable use of water in the framework of the United Nations' Agenda 2030. The geometric model results reveal that the aquifer's thickness varies from 4 m at the head of the river to 30 m at the sea's mouth. The volume of water is estimated at 13.6 Hm^3. The sustainable-use proposals ensure that more than half of the population receives the community company's service. More than 40% of the territory is a protected area, and 64% of the population has sewerage service. This geometric model is a visual contribution that allows us to know the aquifer's shape and establishes guidelines that help strengthen the water supply's development and sustainability over time.

Keywords: coastal aquifer; geometric model; sustainable management; GeoModeller

1. Introduction

As natural resources become scarce and ecosystems appear to be degrading despite all improvement measures, the constant extraction of resources is subject to broad public debate, fueled by increasing demand for resources, restrictions on their use, and climate change [1–3]. Sustainable development faces one of its most significant challenges, the increasing scarcity of water, which will grow with the increase in the world population estimated for 2030, to affect 8600 million inhabitants [4]. Added to this, the rate of climate change is intensifying [5]. Currently, a large proportion of the world's population is experiencing water stress [6]. Studies warn of the likelihood of a drinking water shortage soon. This shortage will affect all sectors and agents, mainly water supply to cities [7,8]. According to reference data from the World Health Organization, a person requires 50 L/day to cover their basic needs and reduce public health risks [9]. The global water demand is expected to grow above the current use, between 20% and 30%, until 2050 [10].

The availability of water resources is a challenge for many communities since it is a scarce resource, limiting social and economic development [11,12]. In arid and semi-arid areas, the primary sources of water are aquifers. Furthermore, coastal areas concentrate more than half of the global population [13]. Due to increasing urbanization in coastal areas, which leads to an increase in water demand, and variations in climatic conditions (extreme flooding or drought), there has been a decrease in groundwater levels, as well as its quality deterioration (due to saline intrusion) [14–18].

There is a relationship between water access and poverty, which translates into development and sustainability [19]; since groundwater exploitation is correctly programmed, it influences socio-economic development [20]. The water reserves of an aquifer are estimated for strategic planning towards development. One method used to improve groundwater reserves in aquifers is the infiltration of surface water. Therefore, artificial recharge is used to increase piezometric levels (volume increase) and enhance groundwater quality. The artificial recharge technique through surface water infiltration has been used throughout the world for more than 200 years [21]. An example of sustainable use is in Rajasthan (India) with the MARVI project (management of aquifer recharge and sustained groundwater use through interventions at the village level). They have created check dams in streams to increase recharge artificially [22]; they also plan their plantations by measuring groundwater levels [23].

Effective aquifer management is becoming an essential aspect of water resource management strategies [24]. At the global level, the United Nations' Agenda 2030 considers the sustainable development goals (SDGs) to achieve sustainability in any project [25,26]. For these fines, three-dimensional (3D) modeling methods are increasingly being used, digital representations of the object of study's characteristics in three dimensions. Software tools for 3D modeling require updates for intricate, detailed, and high-quality models [27]. One of these types of software is GeoModeller [28,29], which allows the modeling of complete formations respecting the geological characteristics by using a series of geological, hydrogeological, and geophysical data [27,30].

Geometric 3D models are essential for visualizing an aquifer's geometric relationships and understanding the influence between subsoil layers; they are based on advanced studies such as fault relationships [31] and flow models [32]. They also allow evaluation of the water resource and favorable areas for settlement or recharge [33]. They are also useful in proposing sustainable development and management policies, as is the case of the Küçük Menderes river basin, in western Turkey [34], where the units and the aquifer's geometry have been defined with a model flow. In Spain, they obtained the 3D model of the Loma de Úbeda aquifer by processing geological and geophysical data in software to model the aquifer flow [35]; a similar study was conducted in Musi, India [36]. A 3D model was set up in Australia to improve the geometric visualization and subsequent volumetric calculation of the Barwon Downs Graben aquifer [37]. In Ecuador, aquifer studies to determine management criteria occur in the Cutuchi river aquifer in the northern Andes. The aquifer was mathematically modeled to propose preventive strategies and mitigation of environmental impact [38,39].

The challenge occurs in the coastal areas of Ecuador, north of the Santa Elena province (Manglaralto river basin), where various types of studies have been carried out, such as proposals for the construction of wells for water extraction, management models, enhancements of the river–aquifer system, hydrogeological analysis of the basin, and a hydrochemical analysis of groundwater [40–42]. A next stage contemplates the geometric study, which is essential to visualize and understand the aquifer, recognize water catchment sites, sustainable use, and decision-making in managing the resource.

The water supply's biggest problems occur, especially in January to March, due to the beach season. The increase in the floating population (tourists) triggers high consumption values, especially in the Montañita, Manglaralto, and Libertador Bolívar communities [43]. The season coincides with the wet season, where there is the most significant amount of precipitation, which is the only source of recharge of the aquifer [44]. However, according to the National Institute of Meteorology and Hydrology, the maximum monthly mean precipitation of the Manglaralto watershed is 100 mm, with water deficits during all years [42]. These imply a low natural recharge of the aquifer.

The Study Case

Ecuador presents a high climatic variability with very rainy and other semi-arid zones, the latter being Santa Elena's province. The province comprises three municipalities (Santa Elena, La Libertad, and Salinas), of which 44.8% of the population is rural [44,45] and 42.46% is below the income poverty line [45,46]. The coastal area, north of Santa Elena, has been promoted for tourism for approximately ten years by the "Ruta del Spondylus" to improve its economic resource. This route travels along the Ecuadorian coastline, connecting coastal towns with many tourist booms [47], as is the case with the Manglaralto.

Manglaralto has 18 communes, of which six (Manglaralto, Montañita, Río Chico, Libertador Bolívar, Cadeate, and San Antonio) are supplied with water extracted from the aquifer associated with the Manglaralto River, through 12 wells administered by the Manglaralto Drinking Water Board (JAAPMAN) (Figure 1).

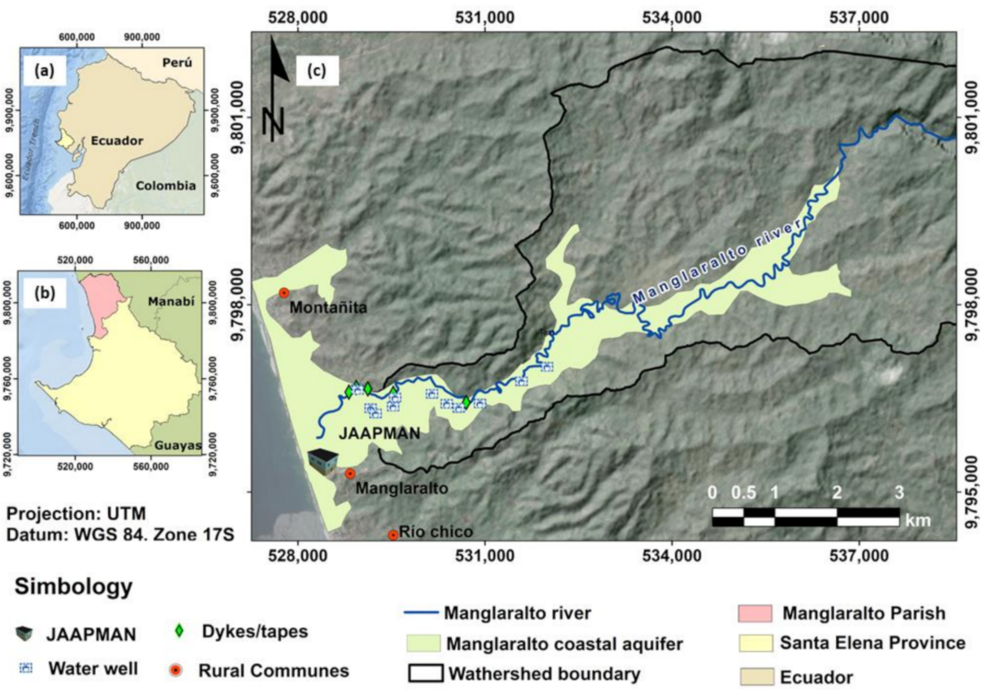

Figure 1. (**a**) Study area location in Ecuador. (**b**) Parishes of the province of Santa Elena and location of the parish of interest. (**c**) Zone of the aquifer associated with the Manglaralto River, including the design of 'tapes' (word of traditional/ancestral knowledge) or artisanal dykes.

A name used in the commune proposes to accumulate rocks and sediments in certain parts of the riverbed to try to dam the water and allow it to collect, preventing the water from escaping into the ocean. It facilitates the artificial recharge of aquifers and to establish possibilities for resilience [48,49]. Additionally, these engineering works, carried out traditionally, rescuing ancestral knowledge, generate opportunities for research and applications of geotourism based on the sector's geo-biodiversity [50–54].

Under these premises, in the case of Manglaralto, is it possible with technical, topographic, geological, and geophysical information to estimate the geometric model of the aquifer and plan its sustainable use? This study aims to establish a geometric model of the Manglaralto aquifer through geological–geophysical analysis to set sustainable water use guidelines. The aquifer's resilience capacity, in terms of planning its sustainable management, can be realized through computer tools, the rescue of ancestral knowledge, solutions based on nature, and the mitigation of environmental impacts [55–57].

2. Materials and Methods

The study was implemented using a three-phase methodology, as shown in Figure 2. In phase I, the previous information on topography, geology, geophysics, and hydrogeology was processed to plan geophysical campaigns. All this information was analyzed to visualize a conceptual model. In phase II, geological and geophysical information was correlated with the aquifer's geometry model to estimate its volume. In phase III, through the model and volume estimation, proposals for the sustainable use of the water resource were designed.

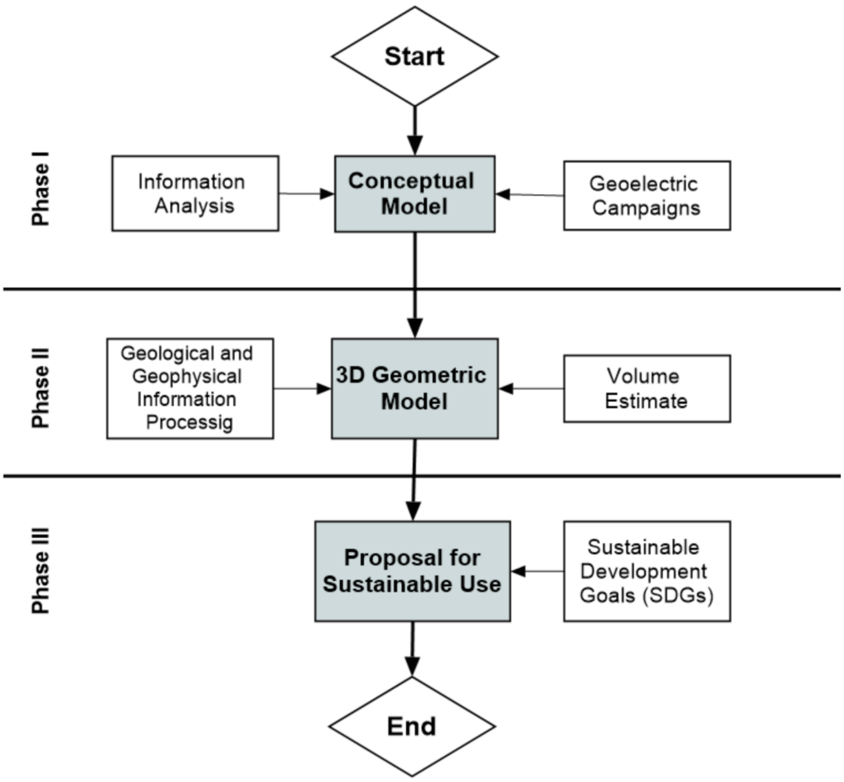

Figure 2. Scheme of the methodology of this study.

2.1. First Phase

The 3D geometric model was necessary to review the topographic, geological, geophysical, and hydrogeological information to identify the area and plan the geoelectric campaigns [41,42,58]. Forty-three Vertical Electrical Soundings (VES), whose locations are shown in Figure 3, were carried out on the riverside of the Manglaralto river, using the Schlumberger technique with the Terrameter SAS 1000 equipment, with maximum external openings (AB/2) of 215 m, and maximum internal openings (MN/2) of 20 m. With this set of information, the data was analyzed and correlated. It was also contrasted with a conceptual model to have a preliminary idea of the model according to the area's reality.

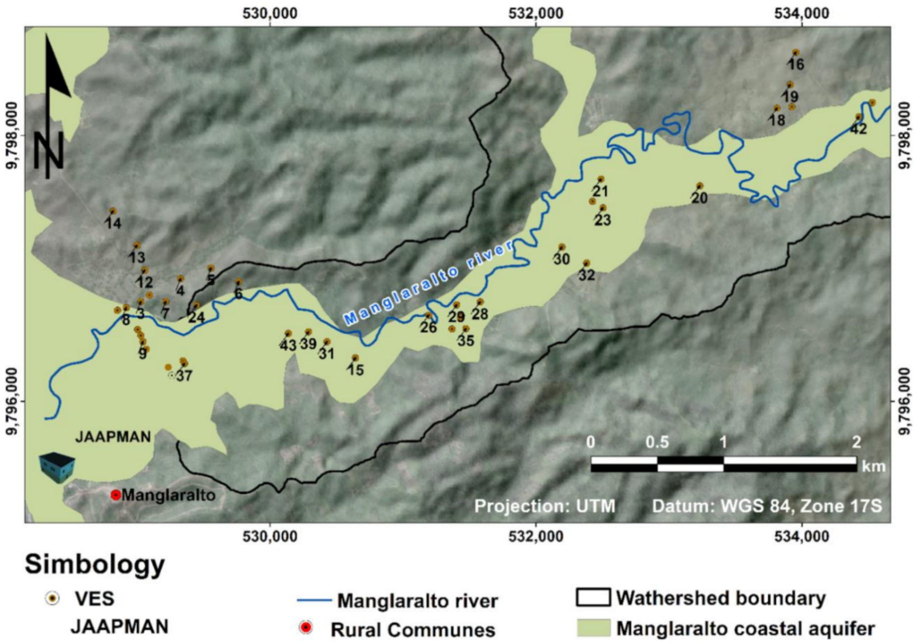

Figure 3. Locations of Vertical Electrical Soundings (VES) in the Manglaralto basin.

2.2. Second Phase

The 3D geometric model made in this study was created with GeoModeller software, which is software used for three-dimensional modeling [28,29]. The methodology is related to the applications of studies carried out in other aquifers [59–63], in which geological and geophysical information has been used to create three-dimensional models of the subsoil in the program.

The information obtained, such as the geological map or geoelectric data, must be processed before being included in the 3D GeoModeller v4.0.7 software. The input data follow the process described in Figure 4. The interpretation of the VES was carried out in the IPI2win software, and later the results were transferred to the Microsoft Office Excel 2019 program. The electrical sounding information is divided into three Excel files (with a .csv extension): the collar file contains the x, y, z coordinates of the sounding points; the survey file contains sounding depth, azimuth, and inclination data; and the geology file locates the depths at which the layers are found, relating them to the corresponding formation/lithology. The digitization of the geological contacts, of the units to be modeled, was carried out in ArcGIS 10.5. (with extension .shp). In this case, three hydrogeological units (permeable, semi-permeable, and impermeable) were modeled.

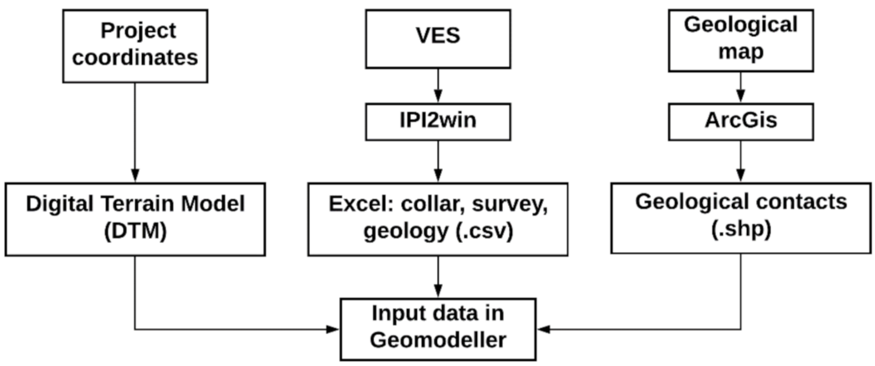

Figure 4. Input data schema in the GeoModeller software.

The creation process of the model is shown in Figure 5. The study area coordinates first entered are shown in Table 1. It was necessary to create a topographic surface to adjust the model to the topography. A digital terrain model (DTM, with .tif extension) was necessary, with which a 3D surface of the area was obtained. Next, the geoelectric models resulting from the vertical electrical soundings (VES, with extension .csv) are introduced, with their contacts and orientations. The program correlates the input data, thus obtaining a proto-three-dimensional model of the aquifer. This model was then verified with the information from the existing wells in the area, to adjust to reality.

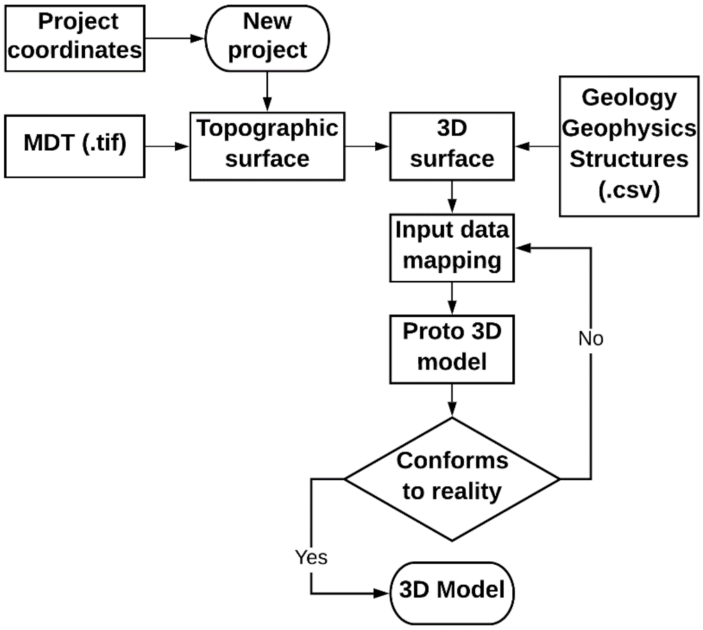

Figure 5. GeoModeller software process creation model.

Table 1. Coordinates of the study area. * UTM: Universal Transverse Mercator/WGS 84: World Geodetic System 1984.

Limits (UTM/ WGS 84 * Zone 17S)	Minimum (m)	Maximum (m)
Coordinates X	528,000	537,000
Coordinates Y	9,795,000	9,800,000

Once the model better represents the area's physical environment, an estimate of the aquifer's volume was made. To do this, by creating regular orthogonal grids in the program, a gross volume of the discretized units was calculated. In this case, they are hydrogeological units differentiated by their capacity to store water—the gross volume of the permeable unit multiplied by the stratum's porosity. The result was compared with the piezometric levels measured in the wells to estimate water volume in the aquifer.

2.3. Third Phase

Sustainable-use proposals are presented in a matrix. According to the Brundtland Commission's criteria [64], the four Environmental, Cultural, Social, and Economic factors (ECSE) should be analyzed. Each factor is related to the SDG indicators [65]. Also, the status of the indicators is detailed. The factor–indicator relationship allows us to offer proposals to strengthen the water supply's development and sustainability. It is presented in a Venn diagram that allows visualization of the critical points for the aquifer's sustainable management.

3. Results

3.1. Information Synthesis

The area's topography was obtained from the digital elevation model: ASTER Global Terrain Model (ASTGTM) with a resolution of 12.5 m; and the geological map of Ecuador. Scale 1: 100,000: Manglaralto Leaf (3488 MIV-E), in Figure S1 (Supplementary Material). The coastal aquifer's characteristics within a basin of order four can be highlighted from the hydrogeological information, with a slope towards the Pacific Ocean, as shown in Table 2.

Table 2. Aquifer data. This information is based on various investigations [40–42].

Manglaralto River Coastal Aquifer Data	
Static level (depth from the surface)	1.2 to 9.7 m
The average porosity of the gravel/sand layer	22%
Darcy's permeability ("real")	1.59–5.15 m/day
Well-extraction flow	Rainy season: 12 L/s; dry season: 5 L/s

The geoelectric campaigns comprised 43 VES, 40 that were obtained from geophysical field surveys, and another three that were taken from other campaigns [42]. They have been interpreted with the IPI2win software, and resistivity curves were adjusted to represent the strata with an error of less than 6%. In Figure 6 and Table 3, the program's interpretation of VES N°15 is shown, obtaining the number of subsoil layers, the depth, and each one's thickness. The analysis of the information, and the geological and geophysical study, reinforce the study basin's hydrogeological system's conceptual model, shown in Figure 7.

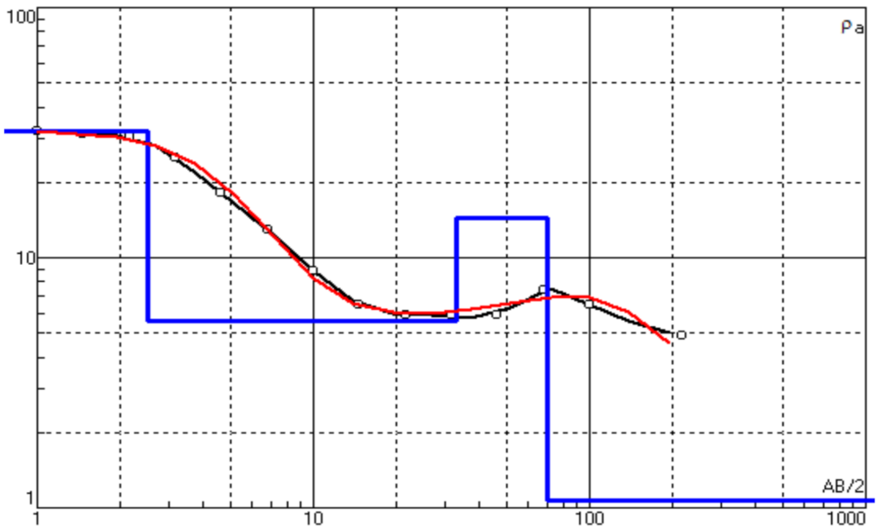

Figure 6. Value adjustment curve of VES N°15.

Table 3. Results for VES N°15 analyzed with IPI2win.

Resistivity (Ω·m)	Thickness (m)	Depth (m)
32.2	2.5	2.5
5.59	30.3	32.8
14.4	37.5	70.3
1.07		

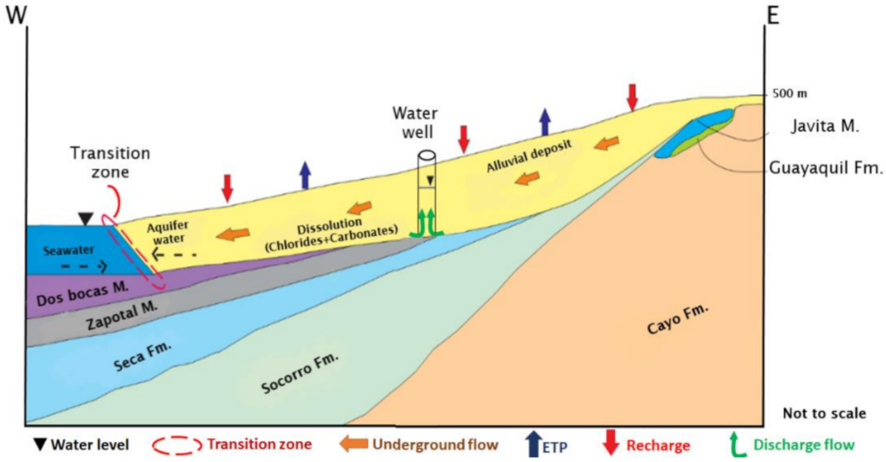

Figure 7. Alluvial conceptual model. Modified from the study [44].

The intrusion of seawater is present in the coastal aquifer. The chemical analyses carried out indicate that wells P2, P3, and P4, which are the closest to the sea, reach chloride concentrations of 34.48 mmol/L, 10.42 mmol/L, and 20.37 mmol/L, respectively. In interior wells below 3.04 mmol/L was found. This concentration indicates that the freshwater–seawater transition zone is located in this area [44].

Three hydrogeological units were modeled in the basin, shown in Figure 8: (i) unit one is the area with the highest slopes and elevations, consisting of low-permeability materials (in orange); (ii) unit two contains semi-permeable material (yellow) and has medium slopes; and (iii) unit three comprises permeable materials (light blue) and is characterized by having low slopes. The permeable unit has been verified due to the Manglaralto river channel, drilled wells, and plugs. These last structures help to retain the surface water of a river for its subsequent storage, infiltration, and recharge of the aquifer [41].

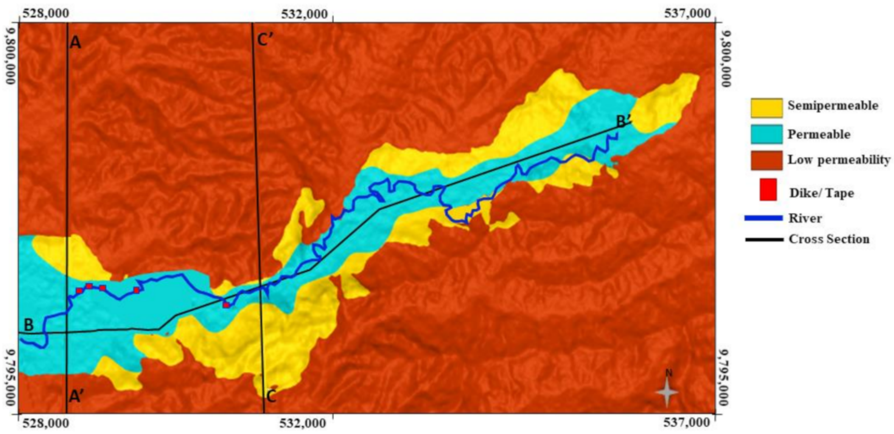

Figure 8. Plan view of the hydrogeological units modeled.

Besides this, three profiles have made, which are shown in Figure 9, to verify the above: (i) the A–A′ cross-section shows the largest and most powerful area of the aquifer; (ii) the B–B′ cross-section intersects the alluvial to show a profile of the geometry; finally, (iii) the C–C′ cross-section has been made to observe the geometry of the preferential accumulation zones that are highlighted in the B–B′ cross-section.

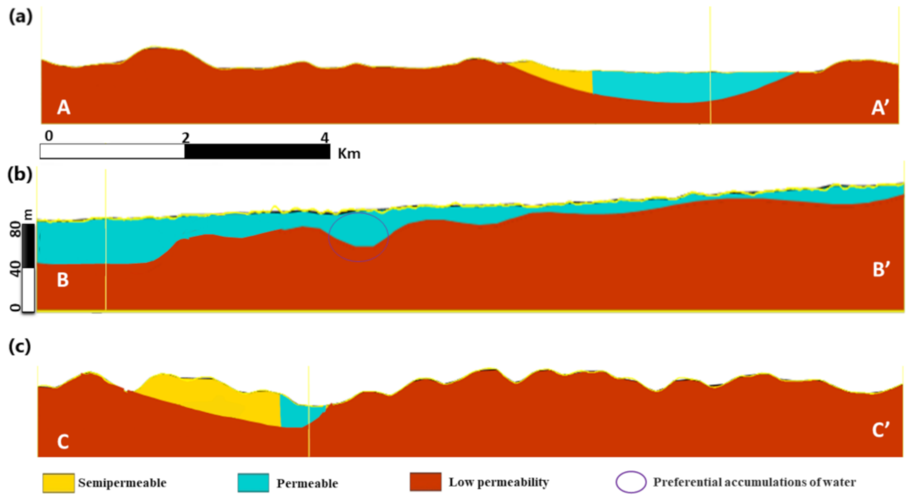

Figure 9. (**a**) A–A′ cross-section of the lower part, in the broadest area of the alluvial. (**b**) B–B′ cross-section along the permeable zone shows the water accumulations′ geometry, highlighting the preferential accumulations. (**c**) C–C′ cross-section of the geometry of the preferential accumulations of water.

3.2. Geometric Model

Unit one features low-permeability material. Unit two is silt and clays. Aquifer unit three (permeable unit) is gravel and sand; however, it also combines with clay material, as shown in Figure 10. Water is contained in the aquifer unit's pores; therefore, the gross volume (2.03×10^8 m^3), shown in Table 4 is multiplied by the average porosity obtained from previous studies (0.22). As a result, a value of 45.3×10^6 m^3 has been obtained. At this value, the data's piezometric level from 12 wells in the area must be considered, with a decrease of 30%; the final result has been estimated at 13,596,000 m^3 (13.6 Hm^3). It is important to note that water cannot be drawn from the aquifer up to the maximum limit, due to the ecological balance.

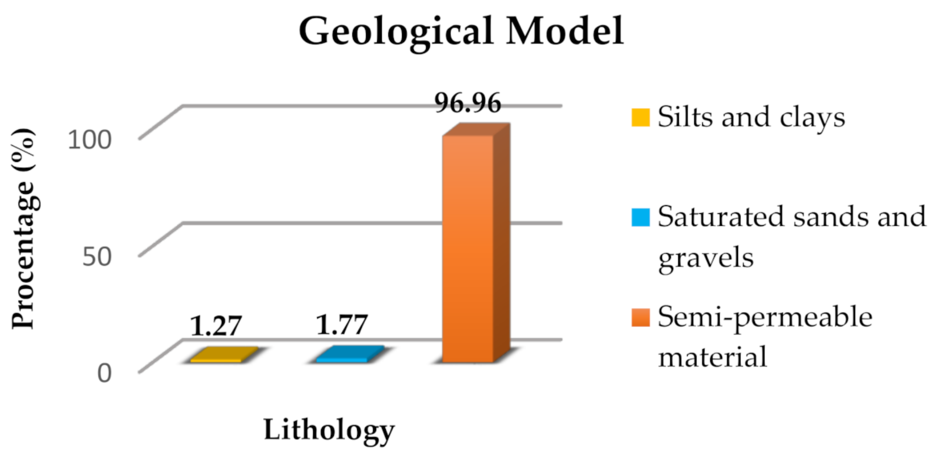

Figure 10. Volume estimation with GeoModeller software.

Table 4. Results of volume estimation with GeoModeller software.

Lithology	Volume (m^3)	Percentage (%)
Silts and clays	1.45×10^8	1.27
Saturated sands and gravels	2.03×10^8	1.77
Semi-permeable material	1.11×10^{10}	96.96

The three-dimensional model of the Manglaralto aquifer, generated with the 3D GeoModeller software, represents curves in the 2D and 3D viewers through a discretization or succession of rectilinear segments. This discretization is managed to create an excellent representation of its shape. Note that 3D GeoModeller represents surfaces and a triangulation assembly docked together. Therefore, the representation of these curves and surfaces depends on the number of segments and triangles used. Three parameters control this quality: first, 2D deflection, whose value is 0.001 m; second, 3D deflection, with 0.0001 m, and thirdly, a discretization of 1,000,000 m. Additionally, the model has an accuracy of 1 m. All the parameters described demonstrate the sensitivity of the geometric model generated. Likewise, its reliability has been evidenced, once in 2020 and early 2021, as the Manglaralto sector is under the influence of the La Niña climate phenomenon. This has produced low rainfall, and therefore the recharge to the aquifer has been minimal in relation to the last five years. Despite this, the geometric model has contributed to the geographical recognition of accumulations of water in strategic places, where the base of the river has greater depth. This detail has been used for the construction of two water wells, which have helped in this emergency situation. Additionally, the geophysical information and the location of existing wells have served to provide robustness in the input information of the geometric model.

3.3. Sustainable Use Proposals

Based on the geometric model and the estimated volume, distinguishing factors that influence the aquifer have been identified. The factors are examined against four goals (relating to water resources) of the predefined guide to the SDGs to analyze the aquifer's sustainable use.

Table 5 presents a qualitative analysis of nine indicators of Agenda 2030 concerning the four ECSE factors of the Brundtland Commission [64,65]. The indicators are related to the following SDGs: 1. Putting an end to poverty (indicator 1.4.1); 6. Guaranteeing the availability and sustainable water and sanitation (indicators 6.1.1, 6.2.1, 6.3.2, 6.4.1, 6.4.2); 13. Climate action (indicators 13.1, 13.3); and 15. Protecting, restoring and promoting the sustainable use of ecosystems (indicator 15.1.2). The goals were selected based on the following criteria:

- Goal 1: The Manglaralto sector is a rural area of poverty in Ecuador. Moreover, there is no government responsibility for water supply.
- Goal 6: Year after year, JAAPMAN has increased accessibility to essential services such as drinking water and sewerage, to the attached communities; besides which, the central socio-economic axis of the parish is the river–aquifer system.
- Goal 13: Due to changes in weather patterns, rising sea levels, and extreme weather events (droughts/floods), it is necessary to evaluate the conditions of the Manglaralto coastal aquifer.
- Goal 15: Manglaralto, because it depends economically on groundwater, is obliged to protect its basin. Reforestation projects have been undertaken throughout the basin once a year. Thanks to the Ministry of the Environment, the basin's upper part (beginning) has been named a Reserve, which guarantees protected forests that help against climate change.

Figure 11 shows the schematic relationship between the four factors for sustainable development analyzed in this study, seeking to visualize the links between the factors and their indicators better.

Table 5. Analysis matrix of indicators of the sustainable development goals (SDGs) of the Agenda 2030 for environmental, economic, cultural, and social factors.

Factor	Indicator	Indicator Status
Environmental	Change in the efficient use of water resources over time. (6.4.1)	The geometric model provides an understanding of the aquifer's horizons and estimates to control the incidence in its use. It is a community project with its members' participation to control the quality of its waters [47].
	The proportion of good-quality water bodies. (6.3.2)	All the JAAPMAN wells (12) are currently located on the south bank of the river at less than 100 m apart. The intense exploitation and the proximity to the coastline have caused the closure of two of them, resulting in only 83% (10 wells) having extracted good-quality water.
		In two of the wells closest to the coastline, the extracted water presents high salinity due to marine intrusion caused by the coastal aquifer's overexploitation [43]. The construction of 'tapes' has helped to control this situation.
	The proportion of the population using health services' risk-free managed sanitation. (6.2.1)	According to population projections for 2020, 64% of the population attached to JAAPMAN (Montañita, Manglaralto, and Libertador Bolívar) will use the sewerage and wastewater treatment service, with oxidation pools [66,67].
	Strengthened resilience and adaptive capacity to climate-related risks and natural disasters in all countries. (13.1)	Thanks to the joint work of JAAPMAN and the Escuela Superior Politécnica del Litoral (ESPOL) universities through CIPAT-ESPOL, the construction of dykes/'tapes' has been achieved, which have helped to recharge the coastal aquifer since 2015, thereby gaining some resilience [41,48].
Cultural	Change in the efficient use of water resources over time. (6.4.1)	Through the construction of five 'tapes', shown in Figure 7, the commune's ancestral knowledge has rescued, since they involve a technical–artisan construction. These retain rainwater and benefit the aquifer recharge [41,49].
	The proportion of sites important to terrestrial and freshwater biodiversity included in protected areas. (15.1.2)	Natural areas cover 44.03% of the Manglaralto parish territory natural areas (18,673 has) [45]. This parish has protected areas such as the Chongón–Colonche protective forest, the Dos Mangas nature reserve, and the Loma Alta reserve [68]. These zones allow recharging and help balance the aquifer ecosystem [69].
	Improved education, awareness, and human and institutional capacity regarding climate change mitigation, adaptation, reduction of its effects, and early warnings. (13.3)	Socialization about the water resource's sustainability and resilience is necessary to create a parish water culture, especially for the new generations [70].
Social	The population proportion living in households with access to essential services. (1.4.1)	Of the Manglaralto parish homes, 85.6% have electricity, and 92.7% have supplied water managed by the JAAPMAN (public network) [42,70].
	Change in the efficient use of water resources over time. (6.4.1)	For the year 2017, the water boards supplied 30.8% of Ecuador's rural areas [71]. The control of the Manglaralto aquifer is given by JAAPMAN, which is a communal organization that involves the whole of society. Therefore, creating the geometric model allows them to approximate the aquifer horizons to improve management.
Economic	The proportion population using safe, managed drinking water services. (6.1.1)	JAAPMAN complies with the norm of the Ecuadorian Institute of Standardization INEN 1108 (drinking water) and has water treatment for consumption [71]. It provides safe water to approximately 54.1% of the population of the Manglaralto parish (40,000 people including locals and tourists) [72,73].
	Level of water stress: freshwater withdrawal in proportion to available freshwater resources. (6.4.2)	An aquifer volume of 13.6 Hm^3 has been estimated, with annual water extraction of approximately 685,000 m^3. An annual increase of 9% is obtained due to the native and floating population (tourism). There is a deficit in recharging in the sector due to it being a semi-arid climate zone, which projects future water stress if aquifer conservation measures have not taken.

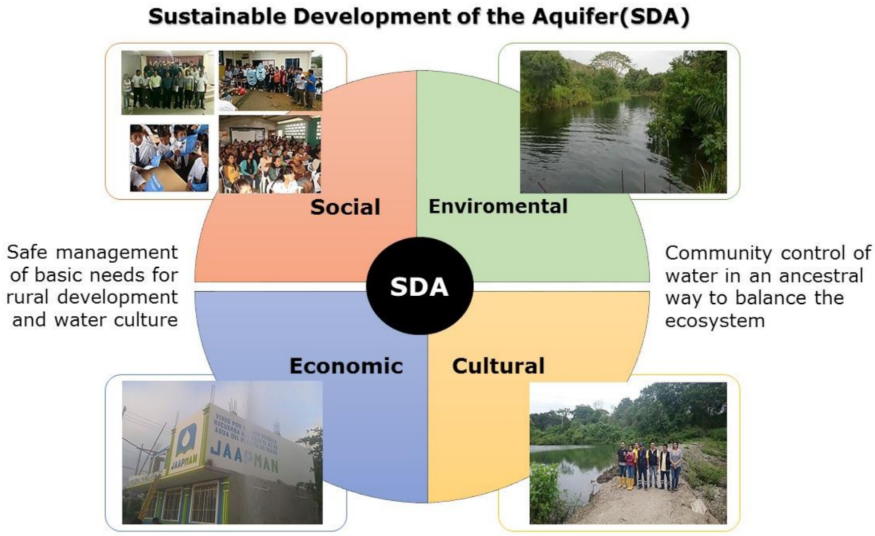

Figure 11. Relationship between environmental, economic, cultural, and social factors for the Sustainable Development of the Aquifer (DSA).

4. Discussion

The free porous coastal aquifer has been conditioned by the topography and geomorphology of the alluvial terrace. The riverbed follows the meanders in the alluvial terrace. The geometric model discerned that towards the mouth of the sea (west), the aquifer is more powerful, reaching up to 30 m of power, and that it is of lower power towards the high areas (4 m), as shown in Figure 12.

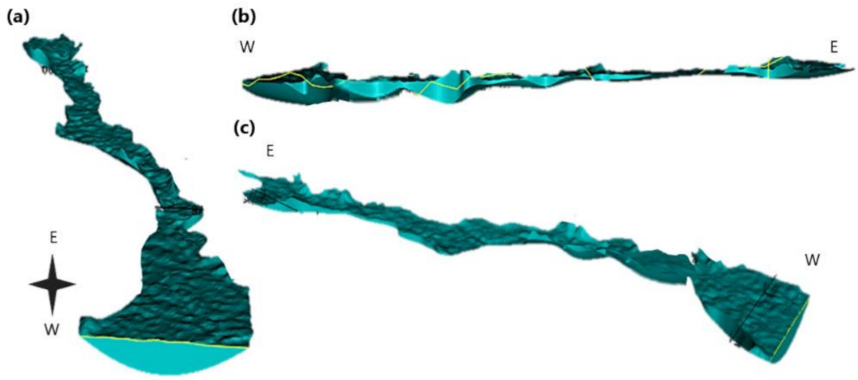

Figure 12. Different views of the aquifer geometric model. (**a**) Front west–east view direction. (**b**) South side view in a west–east direction; (**c**) north side view in an east–west direction.

The turbulence of the river in the upper zone transports the sediments deposited mainly towards the sea's mouth, in comparison with the VES correlation performed by Valencia [42], which indicates an average power of the water layer of 17 m to the west with a decrease of up to 3 m to the east. Studies show that there are apparent zones of preferential accumulation of sediments due to meanders. With this study, a more significant number of SEVs were used and a greater depth reached. The three-dimensional visualization detects the peculiarities of the terrain and the shapes of the alluvial terrace. There are strategic areas with greater depths in the terraces and, therefore, the aquifer, which has been protected for conservation, so the community has declared them a natural reserve to favor the aquifer's recharge.

The area of the basin associated with the Manglaralto River covers 5400 hectares. Using the GeoModeller software, an aquifer water volume has been estimated at 13.6 Hm^3.

However, other authors, such as Valencia J., estimate the value at 9.9 Hm^3 [42], but it should have been noted that their study was carried out in the dry season, recovering from an intense drought in the area. Furthermore, Herrera G. [40] indicates an approximate value of 8.5 Hm^3 with a methodology similar to that of Valencia, simplifying the surface's calculation multiplied by the average depth. In comparison, the program's volume is a more accurate estimate because it considers the aquifer geometry's details. Another factor may be the use of 'tapes' in the river bed since this helps to recharge the aquifer, as has been done in other places, such as Spain [74] and Cuba [75]. In other places, the rescue of ancestral knowledge has been applied to accumulate rainwater in areas with scarcity [76,77].

The methodology used in the GeoModeller software for geometric modeling is like that of studies carried out in aquifers in Colombia [57], Spain [58,59], and Australia [60]. They incorporate input data such as topography, geology, and geophysics in the software results in a three-dimensional model that allows us to understand the aquifer's geometry. For the present study, the model has contrasted with information from the wells drilled in the area and, in general, the model shows a good coupling with reality.

Modeling is the first step to analyze an aquifer from different factors, as in this case, which examines its impact on its sustainable use through an analysis matrix that we call ECSE, where the indicators of the SDG Agenda 2030 are linked to four factors created by the Brundtland Commission [62,63], for a compilation of critical sustainable development links concerning the aquifer. These essential links have been reorganized into a Venn diagram, which allows a synthetic and holistic vision for sustainable aquifer management, which is effected through community engagement and scientific advice from academia. It allows us to note that the factors are closely linked to each other, and that a comprehensive vision is required for sustainable water use over time. In comparison, other studies also indicate that water plays a role in the economy and the environment [78–80]. To ensure sustainable management, effective social participation and community ownership of the source care is necessary [81].

5. Conclusions

The three-dimensional model generated by the geophysical surveys correlated with topography and geology allow us to know the aquifer's geometry. The Manglaralto River transports the sediments that make up the aquifer. They have the properties of being porous and permeable, associated with gravel and sand, with intercalations of silts and clays. The volume of water in this layer was estimated by the GeoModeller software in 13.6 Hm^3. The model estimates that the most significant thicknesses are those closest to the coast (west) with approximate thicknesses of up to 30 m and up to 4 m near the Dos Mangas sector (east). Besides this, there are places with preferential materials for accumulating water with an approximate thickness of up to 40 m due to meanders, which have served wells' locations and construction.

The ECSE analysis, based on the SDG Agenda 2030 indicators, shows that the aquifer has an essential impact on the hydrographic basin and its natural resources. The inhabitants and their culture have contributed some sustainability aspects to the area, such as the aquifer's recharge, through the rescue of ancestral knowledge applied to the river and aquifer management. Also, it reflects matters to attend to, since the aquifer presents a danger of contamination due to the intense water extraction. For this reason, the distribution of future wells should improve and more 'tapes' should be built to help artificially recharge the aquifer and allow an environmental balance. This social connection allows community water management to supply to rural communities safely. However, lately, they have to face a new influence regarding climate change; the La Niña phenomenon associated with a drought period brings new challenges.

The modeling had limitations, such as the amount of VES and the location of these. Since there is less information, this lack can create blind areas. It could be improved by locating the VES in a mesh. However, in this study, the terrain characteristics did not allow this type of spacing. Thus, the model has been generated using geoelectric profiles, contrasted with the information of water wells drilled in the area to ascertain whether the model had a good connection with reality. However, introducing a more significant amount of reliable information would generate higher quality model validation.

For this reason, it would also be essential to carry out studies of structural faults, and gain information on drilling cores and seismic profiles in the area. Notably, this study is a first approximation of the aquifer's shape and is the first of its kind, carried out in the Ecuadorian coast's semi-desert area. Still, its most significant importance lies in the fact that the rural population that inhabits the area establishes the aquifer management through social, cultural, economic, and environmental axes, whose synchronization occurs through the knowledge of what they have through studies of the geometric model.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13070923/s1, Figure S1: Map of the geology of the area, in which the location of the VES carried out is detailed.

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