International Journal of Sustainable Development and Planning
Vol. 19, No. 10, October, 2024, pp. 3793-3807
Journal homepage: http://iieta.org/journals/ijsdp

Water Use Alternatives to Proposal Agricultural Development in a Semi-Arid Zone: Ayangue Commune, Ecuador

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https://doi.org/10.18280/ijsdp.191009

Received: 17 June 2024
Revised: 14 August 2024
Accepted: 5 September 2024
Available online: 30 October 2024

Keywords:
agriculture, geoelectric, sanitation, treated wastewater use, wells, water management

ABSTRACT

The Ayangue commune in the Santa Elena province, Ecuador, has a water distribution for human consumption but lacks an endowment for agricultural use. This work aims to evaluate alternatives for water use through hydrogeological studies and monitoring the water quality of stabilisation ponds for a water management proposal for agriculture. The study includes: i) hydrogeological analysis of the study area; ii) groundwater study using vertical electrical soundings (VES) and laboratory tests (e.g., permeability and porosity); iii) assessment and influence of pretreated wastewater using physical-chemical analysis of water and fruit quality; and iv) water use strategies in agriculture using Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis. The findings determined five zones with the potential for the extraction of groundwater at depths between 20 m and 30 m, with an approximate volume of the saturated zone of 1175.6 km^3 that will allow the water resources supply for irrigation with a proposal for dikes for artificial recharge of aquifers. The analysis of treated wastewater reflects the permissible levels of contaminants that do not contaminate or harm the quality of cultivated fruits. Specifically, the success of the joint use of treated wastewater and groundwater as a sustainable water management model for irrigation is evidenced by proposals for the implementation of surface water storage techniques for aquifer recharge and the installation of tertiary purification systems, such as green filters.

1. INTRODUCTION

Globally, social, economic and environmental development depends on water availability [1]. However, the scarcity of water resources worldwide is intensifying owing to population growth [2] and the development of activities that demand large volumes of water, such as agriculture [3]. Added to this is climate change, which affects temperature and, thus, precipitation and evapotranspiration [4]. In 2050, an increase in food demand between 35% and 56% is possible [5], causing an increase in the global water requirement to 25% of the current demand [6], threatening sustainable agricultural development.

Agriculture is considered one of the activities with the highest water consumption in the world, reaching 70% of the use of the resource [7], with groundwater being its main source of supply, due to the low associated costs and its easy obtaining [8]. However, the increase in salinity as a consequence of transpiration, evaporation of the crops, and the mobilisation of salts and fertilisers accumulated in the soil that can infiltrate into the aquifers compromise the quality of the water resource [9]. In recent decades, to mitigate the problems of water depletion and its deterioration of quality, there are considerations regarding the saving and care of the resource, such as technological improvements in irrigation systems [10] and the exploration of alternative methods, such as the use of treated wastewater for irrigation [11, 12]; the use of surface water and desalinated or salted seawater [13].

Demand for the exploration of water resources has increased [14]. Evaluating groundwater potential is one of the most commonly used methods [15]. The analysis considered precipitation, geological formations, slope, land cover, geomorphology, and drainage characteristics [16]. Another effective tool for the exploration and evaluation of groundwater resources is geophysics [17], with Vertical Electrical Sounding (VES) being the most used method in water exploration, which allows the estimation of the thicknesses and depths of saturated zones considering the variations in the resistivity of the medium [18].

Due to the water stress caused in aquifers by the overexploitation of agricultural resources [19], wastewater for irrigation is an alternative in developed and developing countries, such as China and Mexico [20]. Although the opinions of its use regarding the risks associated with food security and changes in soil structure are still under debate [21, 22], this method continues to be used because of the high nutrient content beneficial for crops and their permanent access [23]. To regulate the use of treated water for agriculture, considering health risks, the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations issued guidelines to promote standards and support government regulations related to wastewater management [22, 24].

In countries with high water stress, such as Israel and Jordan, the reuse of treated wastewater is between 80% and 90%, respectively [25, 26]. In the face of scarcity, European countries like Cyprus and Malta reuse 90% and 60% of treated water [27, 28]. Australia uses 2 billion m^3 of municipal wastewater for irrigation [29]. Pakistan and India directly use raw or poorly treated wastewater for their crops [30, 31]. Mexico reuses treated water to irrigate 80,000 ha of crops in the Mezquital Valley [32]. China has used reclaimed wastewater over 789 km^2 in Beijing since 2003 [33].

In Ecuador, water collection comes from the surface (46.6%) and underground (53.4%) sources [34]. The public network mainly provides the water supply, but certain vulnerable sectors use means of supply, such as tankers, wells, rivers, or springs [35]. The 80% of the use of water resources is for agriculture; however, this activity needs an efficient water management system [36, 37]. In Santa Elena, a coastal province in Ecuador, it is possible to identify the implementation of ancestral techniques such as artificial wetland (albarradas in Spanish) and dykes (tapes in Spanish) to counteract local water scarcity [38]. However, this measure is only used during the rainy season, so the need for this vital resource has been latent for many years [39].

The drinking water supply in the province of Santa Elena depends on the transfer of water from the Guayas River basin. Only the northern part of the province is supplied with groundwater from small hydrographic basins generated in the mountainous system of Chongón Colonche. Santa Elena's hydrographic system comprises eight hydrographic basins: Manglaralto, Valdivia, Viejo, Javita, Grande, Salado, La Seca and Zapotal River. Small estuaries that develop from San Pedro, Ayangue, to the Grande River and converge in the Valdivia River form the Valdivia basin [40].

According to a study, in the commune of Ayangue, 82% of the productive activities are dedicated to agriculture and 18% to livestock [41]. Ninety-one per cent of agricultural irrigation is carried out with sewage water, which farmers consider suitable. The main crops are lemon, soursop, passion fruit, banana, and plum, mostly drip-irrigated. The main challenges are water scarcity, droughts, soil degradation, pests and diseases, which negatively affect agricultural production [42].

Considering the problems associated with the demand for water for agriculture, the following research question arises: Is the joint use of groundwater and the management of treated wastewater safe and enough for agricultural development in the Ayangue commune? This study aims to propose alternatives for water use from underground sources and pre-treated wastewater through geophysical-hydrogeological studies and analysis of the water quality of the stabilisation ponds and the quality of the fruits irrigated in this process for a water management proposal aimed at agricultural development.

1.1 Geographical-geological setting

The Ayangue commune is located to the west of Ecuador (Figure 1a) in the Colonche parish, to the north of Santa Elena province (Figure 1b), with a territorial extension of 15.25 km^2 that limits to the north with San Pedro, to the south with Palmar, to the east with Manantial de Colonche and the west with the Pacific Ocean [43]. According to the last population census, the Colonche parish has 31322 inhabitants [44]; at present, due to an internal population census of the "Junta Administradora de Agua Potable y Alcantarillado de Ayangue", it was established that the number of inhabitants of the commune ranges from 2500 to 3000 inhabitants [45]. The economic activities that stand out are fishing, tourism and agriculture, with their respective limitations due to lack of water [43].

The climate in the region is semi-arid and is characterised by two seasons: winter from December to May and summer from June to November, with a range of rainfall that varies between 0 and 250 mm/year [46]. The geology of the commune comprises different sedimentary sequences: the Zapotal member (Upper Oligocene) composed of intercalations of sandstones and siltstones; the Dos Bocas Unit with shales alternating with layers of siltstones and sandstones (Lower Miocene); the Tablazo Formation with calcareous sandstones, lumaquelas, and conglomerates (Pleistocene-Holocene); and different sedimentary deposits (marine, alluvial, colluvial, and alluvial colluvium) belonging to the Quaternary [46, 47] (Figure 1c).

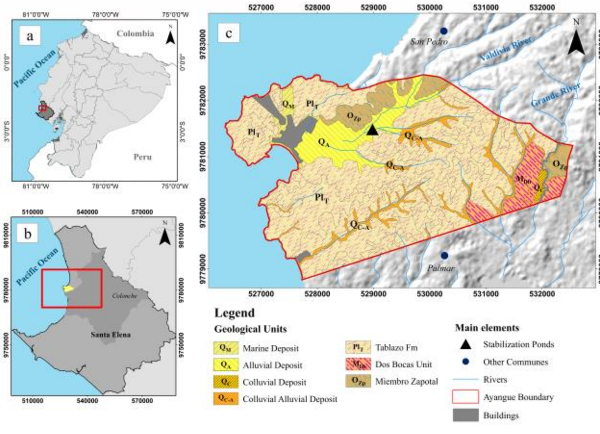

Figure 1. Location map of the study area: (a) Location of the province of Santa Elena, (b) Ayangue commune, (c) Geological formations of the Ayangue commune

2. MATERIALS AND METHODS

The methodological process involves the evaluation of two alternatives for the use of water in agricultural activities. The first alternative corresponds to groundwater use, which was analysed using historical meteorological data and geological and geophysical field works to determine aquifer zones. The second alternative to wastewater reuse has already been empirically tested in the community. According to the study [41], farmers do not continuously monitor the water quality or the treated effluent at the outlet of the stabilisation pond system. There is no register of physical, chemical and microbiological water quality for irrigation use [48], as established by environmental regulations in Ecuador [49, 50]. Therefore, it is considered that the productive activity is carried out without adequate control. This study analysed the quality of the wastewater used in irrigation and microbiological analysis of the fruits harvested using this second alternative. Based on the results and the experts' criteria, alternatives are shown for the safe and sustainable use of the two water sources (Figure 2).

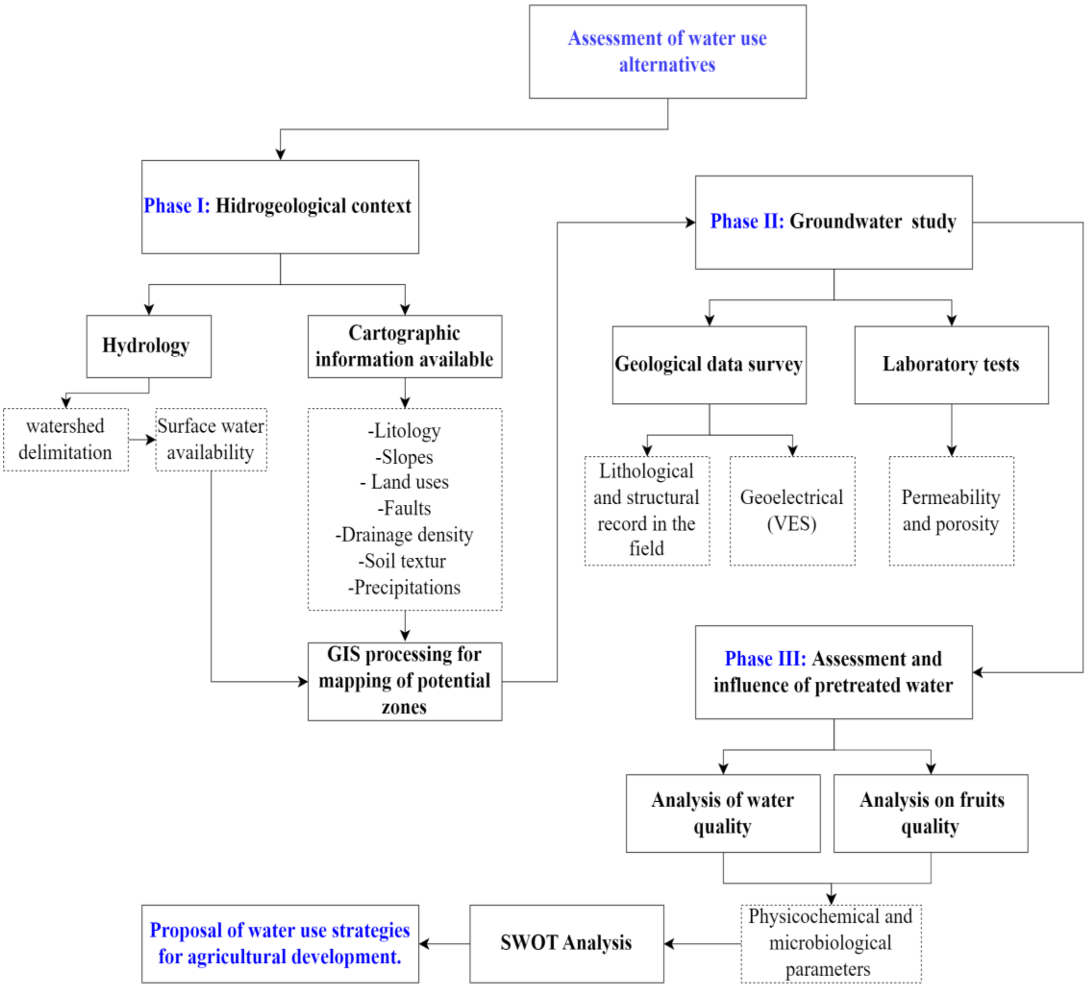

Figure 2. Methodological sequential scheme of the research process

2.1 Phase I: Hydrological context

The hydrological context analyses data on water availability in water bodies and rivers and the limits of catchment and drainage areas referred to as basins and drainage divides [46]. The basins delimitation contemplated processing in ArcMap software version 10.5 of a Digital Terrain Model (MDT) through tools such as "Flow direction" to obtain the flow direction, "Flow accumulation" to locate the points of water accumulation and "Basin" to get the micro-watersheds. In addition, the order and frequency of drainage were determined using the raster calculator, with Eqs. (1) and (2), and the tools "Stream link", "Stream Order", and "Stream to features".

$$\log_{10}(flow\_accumulation) \quad (1)$$

"With ("logarithm" >3,"logarithm")" (2)

Surface water availability was estimated considering historical data of approximately 30 years, extreme drought events ("La Niña" phenomenon) and high rainfall ("El Niño" phenomenon) to determine reserves or deficits in the study area. Potential Evapotranspiration was calculated using the Thornthwaite method [51] using Eq. (3). The data used comes from the "Colonche" meteorological station (M0780) and information available at NASA: POWER (Prediction of Worldwide Energy Resource).

$$\text{PET} = PET_{uncorrected}\left(\frac{N}{12}\right)\left(\frac{d}{30}\right) \quad (3)$$

where, PET: Potential Evapotranspiration; $PET_{uncorrected}$: Uncorrected monthly evapotranspiration; N: Maximum number of hours of sunshine at the national level; d: Number of days of the month.

As part of the hydrological context, cartographic information was analysed to identify areas with potential for surface water infiltration associated with groundwater. The map of potential zones was obtained from the application of map algebra, considering the cartography available in the shape format of conditioning factors (Fc) such as lithology (L), slope (P), land cover and use (LULC), soil texture (TS), fault density (DF), drainage density (DD) [52], and the triggering factor, precipitation (F_d). For the application of map algebra, the study used Eq. (4), which resulted in using the Saaty ranking method [53] for the determining factors (F_c).

$$F_c = 0.12LULC + 0.09P + 0.24TS + 0.06DD + 0.06DF + 0.43L \tag{4}$$

The weighting values of each determining factors were reclassified using the "Reclassify" tool of the ArcMap software, with a scale from 1 to 4, where: "1" is classified as Low, "2" Medium, "3" High, and "4" Very high (Table 1). Table 2 shows an example of the classification carried out in the parameter (L), considering the litho-permeability map [54]. The potential zone (PZ) map was obtained using Eq. (5).

$$\text{ZP} = 0.60F_c + 0.40F_d \tag{5}$$

Table 1. Reclassification of conditioning and determining factors [53]

Factor	Indicator	Value Class	Classification
Slope	20 - 75%	1	Low
	12 - 20%	2	Medium
	7 - 12%	3	High
	0 - 7%	4	Very high
Land cover and use	Unproductive land, water reservoir, urban areas	1	Low
	Conservation and protection areas	2	Medium
	Agricultural areas	3	High
	Water: Rivers	4	Very high
Soil texture	Clay or clay loam	1	Low
	Loam or silt loam	2	Medium
	Sandy loam	3	High
	Sandy	4	Very high
Fault density	Extension between 0 and 0.5 km/km^2	1	Low
	Extension between 0.5 and 1.0 km/km^2	2	Medium
	Extension between 1.0 and 1.5 km/km^2	3	High
	Extension greater than 1.5 km/km^2	4	Very high
Drainage density	Drains with extensions greater than 6 km/km^2	1	Low
	Drains with extensions between 4 and 6 km/km^2	2	Medium
	Drains with extensions between 2 and 4 km/km^2	3	High
	Drains with extensions less than 2 km/km^2	4	Very high
Precipitation	Less than 250 mm/year	1	Low
	250 - 500 mm/year	2	Medium
	500 - 1000 mm/year	3	High
	1000 - 2000 mm/year	4	Very high

Table 2. Reclassification according to the type of lithology (L) considering the class values [54]

Geological Units	Type of Permeability	Permeability Class	Value Class
Alluvial deposits	Intergranular	High	3
Colluvial deposits	Intergranular	Very high	4
Alluvial colluvial deposits	Intergranular	Very high	4
Marine deposits	Intergranular	Medium	3
Tablazo Formation	Intergranular	Medium	2
Zapotal Member	Intergranular	Medium	2
Dos Bocas Member	Intergranular and cracking	Low	1

2.2 Phase II: Groundwater study

2.2.1 Geological data survey

This phase includes collecting bibliographic and field geological information (Figure 3) and acquiring subsurface data using geophysical methods. The geology and lithology were delimited according to the description of outcrops and 2m deep test pits to determine the main lithological units and correlate them with the results of the geophysical campaigns. The geophysical method consisted of 25 Vertical Electrical Soundings (VES) campaign using a Terrameter SAS 1000 to configure the electrodes according to the Schlumberger geometry [55]. This method consisted of injecting current into the ground through a pair of electrodes (A and B) and measuring the potential difference across the electrodes (M and N) to obtain the apparent resistivity of the subsurface layers.

The delimitation of the subsoil layers was obtained by correlating the VES through five sections according to the resistivity values obtained and the local geology using Surfer software.

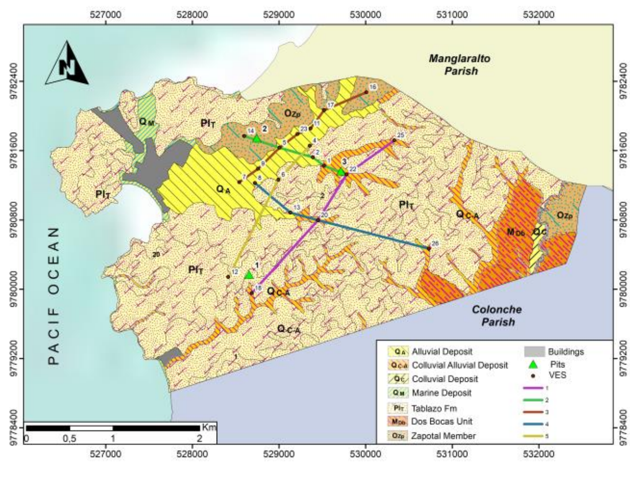

Figure 3. Map of locations of Vertical Electrical Soundings (VES) and test pits where samples were taken for laboratory testing

2.2.2 Laboratory test

The laboratory study included the classification of the soils through laboratory tests of granulometry and permeability in three samples of pits with a depth of approximately 9 m (Figure 3). The granulometric curve of the tested samples was obtained by calculating the percentage of soil that passes through the sieves (No. 10, 20, 40, 80, 100 and 200). The accumulated passing percentage was obtained using Eqs. (6)-(8), corresponding to the granulometric curve's ordinate and the sieve meshes' opening in millimetres on the abscissa [56].

$$\%\text{Retained} = 100 \times \frac{\text{Partial Weight}}{\text{Total}} \qquad (6)$$

where, Partial weight: corresponds to the weight retained in each of the sieves.

$$\%\text{Accumulated Retained} = \sum \%\, Retained\ on\ larger\ sieves \qquad (7)$$

$$\%\ \text{Accumulated Pass} = 100\% - \%\ Accumulated\ Retained \qquad (8)$$

The Uniformity Coefficient (UC) Eq. (9) and Curvature Coefficient (CC) Eq. (10) were calculated for the soil classification established by Villalaz [57].

$$U_C = \frac{D_{60}}{D_{10}} \qquad (9)$$

$$C_c = \frac{(D_{30})^2}{D_{60}(D_{10})} \qquad (10)$$

where, D_{60}: diameter of the grains, where 60% of the particles are finer and 40% coarser; D_{10}: diameter of the grains, where 10% of the particles are finer and 90% coarser; D_{30}: diameter of the grains, where 30% of the particles are finer and 70% coarser.

The results obtained from the granulometry were classified according to the uniformity coefficient: UC>4 is Gravel, UC<6 is Sand, and CC must be between 1 and 3 for the soil to be considered well-graded. The permeability and porosity values were compared to the standard values established by Villalaz [57].

The permeability test measured the amount of water passing through the soil for a certain time and applied the direct method of variable load permeameter for fine soils [58]. The permeability was calculated by applying Eq. (11).

$$k = \frac{V \times L \times C_v}{A \times h \times t} \qquad (11)$$

where, V: volume of water discharged; L: length of the cylinder containing the sample; A: cross-sectional area of the cylinder containing the sample; h: hydraulic load; t: time of discharge; C_v: viscosity coefficient of water.

2.3 Phase III: Pretreated wastewater assessment

The final phase of the study consisted of two types of analyses: i) laboratory analysis of pretreated wastewater quality and ii) laboratory analysis of fruits. The laboratory tests to determine the quality of the pretreated wastewater included the analysis of the physicochemical and microbiological parameters of two water samples from the oxidation ponds. The microbiological parameters analysed included total coliforms, faecal coliforms, oils and fats, nitrites, sulphates, and dissolved oxygen. Physicochemical analysis recorded the concentration of parameters, such as Total Dissolved Solids, conductivity, and pH. The quality criteria established in Table 3 of the Unified Text of Secondary Environmental Legislation [49] were used to compare the microbiological parameters in the water.

In addition, the study included microbiological analysis of five fruit samples resulting from irrigation with pretreated wastewater. The parameters measured in the analysis corresponded to the total coliforms, faecal coliforms, enterobacteria, and N° aerobic mesophiles. The results obtained from the analysis were compared to the standards established in Table 3 by Health Ministry [50].

2.4 Water use strategies for agriculture development

The study ends with a qualitative analysis of the main strengths, weaknesses, opportunities, and threats (SWOT) [59] of the agricultural development potential in the study area through a focus group [60] comprising experts in groundwater management and effective reuse of treated wastewater with diagnostic workshops with the community. For the SWOT analysis, a questionnaire was administered with open questions that addressed the social, political, economic, academic, and environmental axes in relation to the sustainable management of water resources in the study area. The objective of the analysis was to propose agricultural development strategies using a combination of internal and external factors.

3. RESULTS

3.1 Hydrographic basin analysis

According to the results obtained from hydrographic processing, it is possible to define two micro-basins: i) Ayangue River micro-basin and ii) Viejo River micro-basin with an area of 8.65 km^2 and 8.56 km^2, respectively. Both micro-basins are of order three, with a northwest drainage direction (Figure 4).

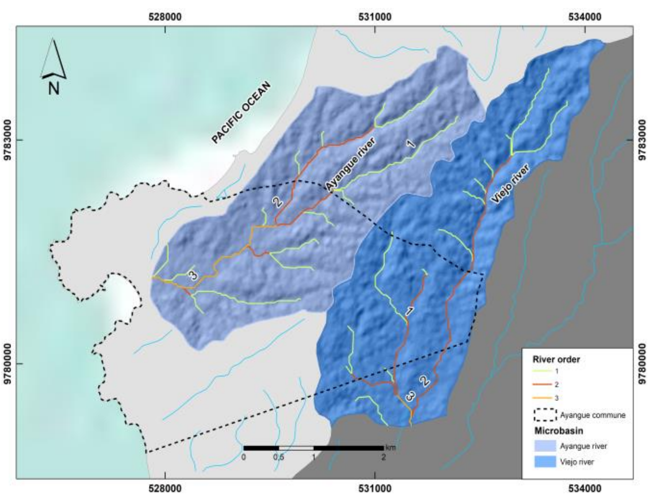

Figure 4. Micro-basins delimited for the Ayangue and Viejo rivers, in the Ayangue commune

Based on the multitemporal analysis of accumulated rainfall between 1990-2021, it is possible to identify three marked sequences: dry and rainy (Figure 5). The dry sequence occurred during the first seven years of the analysis, registering the lowest precipitation values. The rainy season covers 1996-2007, obtaining the highest accumulated precipitation values in 1998, with a maximum value of 1250 mm/year. The second dry season was identified from 2007 to 2021, with accumulated precipitation values from 0 to 25 mm/year.

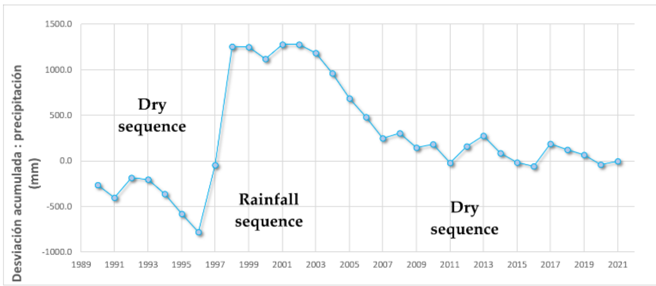

Figure 5. Multitemporal analysis for the period 1989-2021

The water balance calculation for the years 1990-2021 shows a potential annual evapotranspiration of 1357.4 mm and an average annual precipitation of 337.5 mm. For all the months analysed, it was observed that there was no reserve, the greatest deficit occurred in May, and the lowest rainfall was recorded in September. Table 3 shows rainfall was greater than 20 mm during January- May, and rainfall was below 15 mm/year for June-November.

Table 3. Water supply of the Ayangue river micro-watershed

Month	P (mm/month)	PET (mm/ month)	RET (mm)	DEF
January	47.75	128.70	47.75	80.90
February	91.60	121	91.60	29.20
March	70.71	136.02	70.71	65.31
April	50.60	130	50.60	79.70
May	20.57	124.10	20.57	103.60
June	4.28	105.60	4.28	101.40
July	4.33	98.30	4.33	93.96
August	4.18	96.37	4.18	92.19
September	2.84	96.60	2.84	93.70
October	6.97	102.40	6.97	95.40
November	13.34	102.40	13.34	89.03
December	20.30	115.77	20.30	95.46
January	47.80	129	47.80	80.90
Total	337.48	1357.40	337.48	1019.90

Note: P: Precipitation, PET: Potential Evapotranspiration, RET: Real Evapotranspiration, DEF: Deficit.

Figure 6 shows the map of the reclassified conditioning factors, in which 14.20% of the area has a very high groundwater recharge potential, 24.91% at a high potential, 54.21% of the surface has a medium potential and finally, 6.68% does not represent areas with groundwater recharge.

This results from processing through map algebra and applying Eq. (5). A map of potential groundwater zones is presented. Figure 7 shows that 6.68% of the surface had no recharge potential, 54.21% had medium conditions for groundwater recharge, and 39.11% had areas with high and very high groundwater recharge potential. These high-potential areas coincide in lithologies corresponding to alluvial and colluvial-alluvial deposits and minor drainage areas with low slopes.

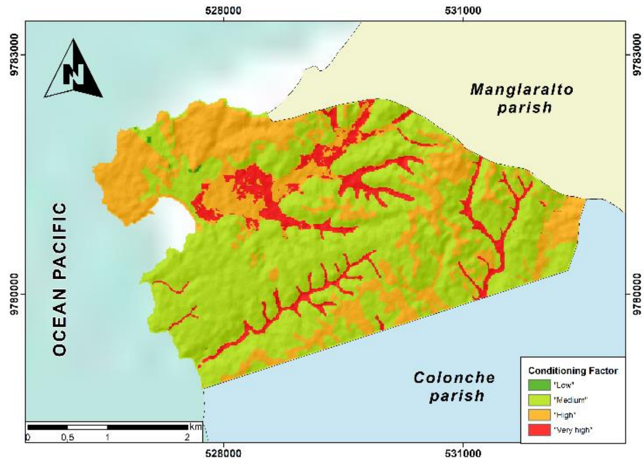

Figure 6. Map of conditioning factors for groundwater recharge

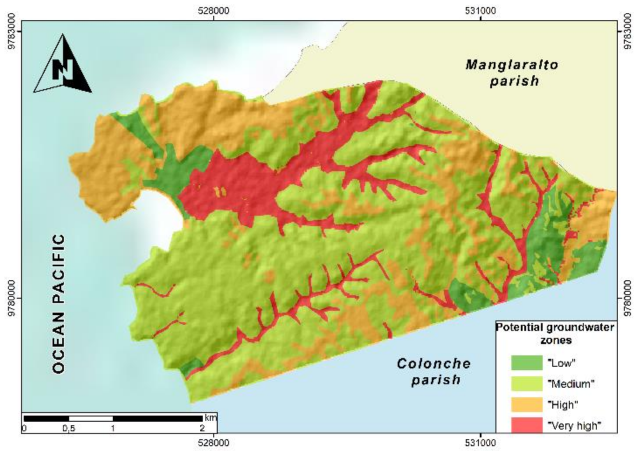

Figure 7. Map of potential groundwater zones

3.2 Groundwater alternative use

3.2.1 Geophysical data survey

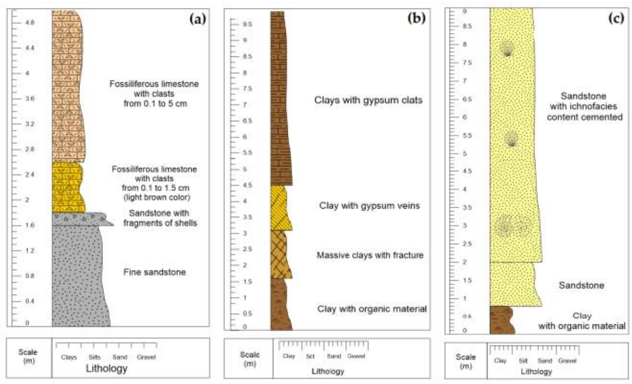

Figure 8. Description of outcrop with lithological units identified

Figure 8a shows the lithological column corresponding to pit three, where three units were identified. The first level, with a thickness of 1.80 m, corresponds to limestone, with clasts of

0.5 2 cm, well classified, and medium roundness, with bivalve content starting at 1.60 m. A second level of yellowish-brown massive fossiliferous limestone presents 80% of clasts from 0.1 to 1.5 cm, poorly sorted, subrounded, and of medium sphericity. Unit three comprises an inverse gradation of sands with clasts of size 2 to 5 cm, moderately classified and subangular, whose granulometry decreases towards the base of the outcrop.

Figure 8b shows the lithologies observed in pit two at a depth of 9 m. The first layer (1.5 m) represents clay-type soil with organic matter content. The second layer comprises light-brown compacted 2 m thick clays with small subangular quartz clasts. The last two strata correspond to clays with gypsum minerals in veinlets and clasts. This last unit is 6.5 m thick. In contrast, two strata separated by erosive contact can be observed in the lithological column of pit two (Figure 8c). The first layer is 0.70m thick and dark brown, corresponding to clay with organic material content. The second lithological unit corresponds to a light brown calcareous massive sandstone in which carbonate ichnofacies were identified. The clasts were classified as moderate.

Five geoelectric profiles of the subsoil layers were obtained due to the VES campaign. Figure 9 shows the apparent resistivities ranging from 5 to 800 Ωm in the zone. Profile one (Figure 9a) shows the behaviour of almost horizontal geoelectric layers, with apparent resistivities of up to 50 Ωm in the first layer. The resistivity values increase towards the SW in the first 20 m of the profile length, where resistivities from 750 to 1000 Ωm indicate a lithological change to more consolidated material at a depth of 30 m. Profile two (Figure 9b) shows resistivities between 0-200 Ωm, the highest resistivities, which correspond to another more consolidated lithological unit, underlie the SE of the profile. The resistivity of interest for water storage could be reflected in the geoelectric layers with resistivities of 20-30 Ωm at 200 m and 700 m length of the profile at an estimated depth of 50 m.

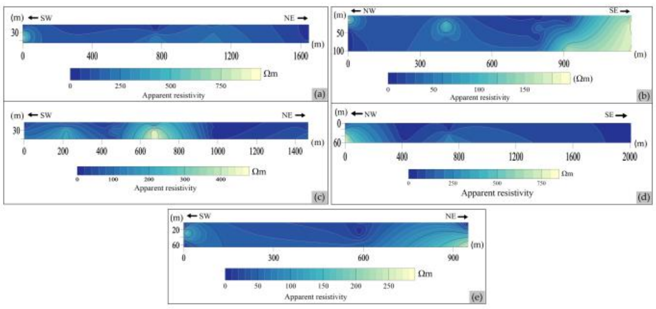

Figure 9. Geoelectrical profiles of subsoil layers

Profile three (Figure 9c) shows resistivities between 0-500 Ωm, a geological resistivity unit of 200-5000 Ωm is observed from 0 to 300 m, and from 500 to 900 m along the profile. Less resistive zones with a 40-100 Ωm potential towards the NE. Less resistive zones with the potential to store fresh water are found in the NE with resistivities of 20 a at 40-100 Ωm at 1400 m of geoelectric profile length at an approximate depth of 30-40m. The resistivities in profile four (Figure 9d) reached their highest values in the first 10 m of the profile at a depth of 25m. The distribution of the geoelectric layers shows fewer resistive layers towards the SE. The profile shows potential for freshwater saturation at 1800m SE of the profile with a resistivity of 30-50 Ωm at an approximate depth of 25m. For profile five (Figure 9e), resistivities between 0-300 Ωm are observed, and the geoelectric layers are almost horizontal; to the NE at 900 m of the profile and to the SW between 0-70 m in length, a geoelectric layer corresponding to a more consolidated lithological unit can be observed. Between 300 and 600 m in the profile, 30-40 Ωm resistivities were identified, which could correspond to groundwater potential at a depth of approximately 40 m.

As part of the alternative for groundwater use, factors to be considered include cost, benefits and environmental impacts. The costs considered in the alternative are construction, operation and maintenance, as detailed in Table 4.

Table 4. Costs associated with the alternative of groundwater exploitation

Activities	Costs
Construction	**$10.130,00**
1. Drilling 40m deep	$4.000,00
2. Sanitary seal	$600,00
3. Blind pipe	$3.000,00
4. Grids	$400,00
5. Gravel	$80,00
6. Bentonite	$50,00
7. Construction of a well shed	$2.000,00
Operation	**$ 6.860,00**
8. Pump	$2.000,00
9. Pumping test	$1.500,00
10. Pump installation	$1.000,00
11. Wiring for operation	$1.000,00
12. Electrical installation	$1.000,00
13. Annual Electricity Costs	$360,00
Maintenance	**$ 1.600,00**
14. Well Cleaning	$500,00
15. Pump Repair annual	$600,00
16. Parts Replacement annual	$500,00
TOTAL	**$18.590,00**

The alternative of groundwater exploitation must also consider the positive and negative effects that may be triggered in the environment. The main impacts of this alternative are presented in Table 5, thinking that it should be addressed in more detail in future studies.

Table 5. General environmental impacts for the groundwater exploitation alternative

Medium	Positive Impact	Negative Impact
Water	Reduction of pressure on surface sources, conserving rivers and lakes	Decrease in the water table, affecting aquifers
Air	Reduced evaporation compared to surface water storage, improving resource efficiency	Greenhouse gas emissions from the use of fossil fuel-powered pumps
Soil	Potential artificial recharge of aquifers that can benefit areas with salinization problems	Land subsidence (subsistence) due to over-extraction
Socioeconomics	Improved water security in communities	Inequality in access to water resources

The expected benefits of implementing this alternative include ensuring a supply that meets the demand for agriculture and alleviating and conserving nearby rivers that are exploited for crops. In addition, it is expected to provide access to all small and medium-sized farmers, stimulating the economy through this productive activity at a local level.

3.2.2 Laboratory tests

The granulometry test determined that samples 1, 2, and 3 of the pits corresponded to sand and fine-silt material with clay. Sample 1 had less than 12% of fine material, corresponding to poorly graded sand. Samples 2 and 3 contained percentages of fine material greater than 12%. The permeability and porosity values are listed in Table 6, where the samples were classified as clayey sandy soil for samples 1 and 2, and sample 3 was classified as silty sandy soil with clay content.

Table 6. Classification of soils according to their granulometry, porosity and permeability

Sample		1	2	3
Granulometry	Gavel %	0	0	0
	Sands %	36.08	17.88	19.90
	Fine %	10.26	18.59	13.00
	CU	7.43	3.71	3.61
	CC	0.48	0.90	0.72
Permeability (m/s)		7.44×10^{-8}	3.10×10^{-7}	1.54×10^{-7}
Porosity (%)		69	63	69

Note: UC: Uniformity coefficient, CC: Coefficient of curvature.

3.3 Pretreated wastewater analysis

Table 7 presents the results of the concentrations measured in the laboratory in the water samples from the stabilisation pond used for irrigation. The presence of oils and fats was evident, and faecal coliform content exceeded the permissible limit of 700 NMP/100 ml. In addition, these pre-treated waters have a dissolved salt content of 750 mg/l, which, according to the permissible limit of the Ecuadorian Environmental Regulations, already presents a moderate restriction of its use.

The microbiological analysis of fruit crops (lemon, orange, tangerine, passion fruit, and soursop) where pretreated water was used did not show faecal coliform content, and no bacterial content that may be harmful for human consumption was detected, as shown in Table 8.

Table 7. Results of the quality analysis of stabilisation ponds for agricultural irrigation water use

Parameter	Result	PL	Observations
Oils and fats	<10 mg/L	Absence	Non-compliance
Fecal coliforms (NMP/100 ml)	1700	1000	Non-compliance
Nitrites (mg/l)	0.12	0.5	Complies
Sulphates (mg/l)	83	250	Complies
Dissolved Oxygen (mg/l)	6.58	3	Complies
pH	8.40	6-9	Complies
Conductivity mmhos/cm	1.5	0.7 (no restriction) 0.7-3 (mild moderate restriction) >3 (severe restriction)	Mild moderate restriction
Total Dissolved Solids (mg/l)	750	450 (no restriction) 450-2000 (mild to moderate restriction) >2000 (severe restriction)	mild to moderate restriction

Note: PL: Permissible limit, NMP: Most practical number.

Table 8. Results of the quality analysis of stabilisation ponds for agricultural irrigation water use

Parameter	PL	L	PF	O	M	S
Total coliforms (NMP*/ gr)	<9	<1.1	<1.1	<1.1	<1.1	<1.1
Fecal coliforms (NMP*/ gr)	<3	<1.1	<1.1	<1.1	<1.1	<1.1
Enterobacteriaceae	Absence	Abs	Abs	Abs	Abs	Abs
N°. Mesophilic aerobes	20000-50000	25	0	0	70	90

Note: PL: Permissible limit, L: Lemon, PF: Passion fruit, O: Orange, M: Mandarin and S: Soursop. Abs: Absence, NMP: Most practical number.

3.4 Proposal of water use strategies for agricultural development

According to the analysis of internal and external aspects of the potential of groundwater and treated water for irrigation (Figure 10), the Ayangue area presents favourable geological conditions for storing groundwater, which can be used for human and agricultural consumption. On the other hand, according to the analysis, the purified residual water from the stabilisation ponds used in irrigation does not affect the quality of the cultivated fruit species. This favourable groundwater and pre-treated water condition primarily reflect the potential to ensure socio-economic development through sustainable agriculture. However, it is important to highlight the importance of monitoring the quality of groundwater and treated wastewater, which allows for the management of water resources by promoting the circular economy of water.

Based on the SWOT matrix (Figure 10), this study proposes different strategies that consider the social, political-economic, educational, and environmental aspects that guarantee the development of agricultural activity, considering the combination of internal and external factors:

Social aspect:

• Develop community forums/workshops to train residents in sustainable irrigation techniques.

• Develop alliances with academic institutions to conduct agricultural experimentation projects with new species

Political-economic aspect:

• Implementing public policies that promote the circular economy of water through treated wastewater.

• The national academic plan includes the teaching of nature-based solutions for the care and management of water.

• An experimental plan for the cultivation of species with the potential to be commercialised nationally and internationally.

• Implement tourist routes that promote sustainable management of water resources and represent an alternative to economic development.

Educational aspect:

• Strengthen the community-academy link through projects that support the need for water conservation and sustainable use.

• Develop campaigns to rescue ancestral water knowledge that promotes environmental awareness in current and future communities.

Environmental aspect:

• Implement drip irrigation systems and water quality control (groundwater and treated wastewater).

• Design and build NbS such as artificial wetlands and dikes during the rainy season to recharge aquifers and avoid the overexploitation of groundwater.

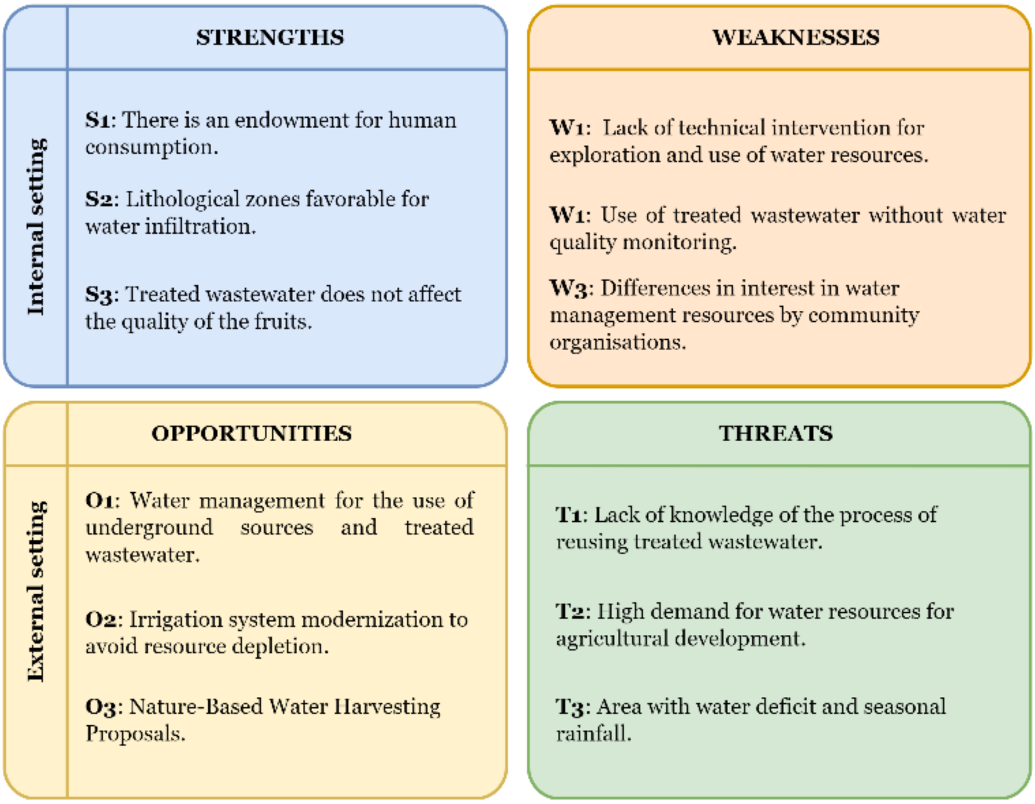

Figure 10. SWOT analysis

4. INTERPRETATION OF RESULTS AND DISCUSSION

The methodological approach used in this study integrates the evaluation of the potential of groundwater in a semi-arid zone considering the perspective of watershed management and the use of treated residual water to promote agricultural development as an alternative for community socioeconomic development. According to the hydrological analysis of the study area, there are two micro-basins (Viejo River and Ayangue River) where the recharge of the aquifers depends on the months of precipitation with an average drainage density of 1.80 km/km^2, which suggests short times of concentration of water in the subsoil, favouring the infiltration of water in areas with permeable semi-permeable lithologies (colluvial and alluvial). The shape factor of the micro-watersheds complemented this; the value obtained was 0.04, representing low runoff and higher infiltration. The area's morphological, hydrological, and meteorological characteristics show that managing surface water resources is limited, reflecting the need for alternative water sources, such as groundwater and treated wastewater.

The results of the groundwater evaluation in the community made it possible to define potential zones obtained through the multi-criteria layer process (Figure 7) that coincide with zones of low to medium drainage density, with the presence of permeable and semi-permeable materials corresponding to sandy soils and alluvial and colluvial deposits, whose slope changes are slight to moderate and allow the infiltration of surface water. Geoelectric prospecting corroborates that water storage occurs in alluvial and colluvial areas. Underlying this layer of semi-permeable materials are resistivities of 20 to 50 Ωm (Figure 9) at a depth of 20-25 m, which are interpreted as a water reserve for future exploitation.

According to the geophysical interpretation and groundwater potential map obtained through map algebra, a saturation zone of 587.7 km^2 is interpreted with a storage of approximately 1175.6 km^3 of water resources (Figure 11). This study proposes that future irrigation projects should consider carrying out five wells (Figure 11) at depths between 20 m and 30 m for the extraction of water resources combined with the implementation of Water Sowing and Harvesting (WS&H) techniques as NbS, which include the construction of five dams (Figure 11) for the use of rainwater and subsequent artificial recharge of the aquifer [61-64].

Wastewater for agricultural use is used in areas with scarce rainfall and water resources. The Ayangue commune produces 125000 l/inhabitants/day of wastewater, treated in two 65000 m^3 stabilisation ponds, with irrigation demand accounting for approximately 90% of the availability through direct irrigation. Laboratory analysis of pre-treated wastewater used in fruit crops in the study area indicates parameters that exceed the regulations; however, the fruits are not affected because the water is irrigated into the soil, which acts as a filter medium, preventing the root from absorbing nutrients that could be harmful to crops. Compared to Colombia (Resolution 1207 of

2014) [65] and Mexico (NOM-001-SEMARNAT-96) [66], which establish standards for the use of wastewater in agriculture, Ecuador also regulates this aspect under the Water Resources Law through the Water Regulation and Control Agency Directory (DIR-ARCA-004-2016) [67]. All these regulations share the requirement to comply with water quality criteria. However, Colombia limits reuse to specific crops and industrial activities, while in Ecuador, although quality criteria are established, the regulations still need more specific regulation regarding the types of crops, water and fruit quality monitoring, and soil quality after applying this practice.

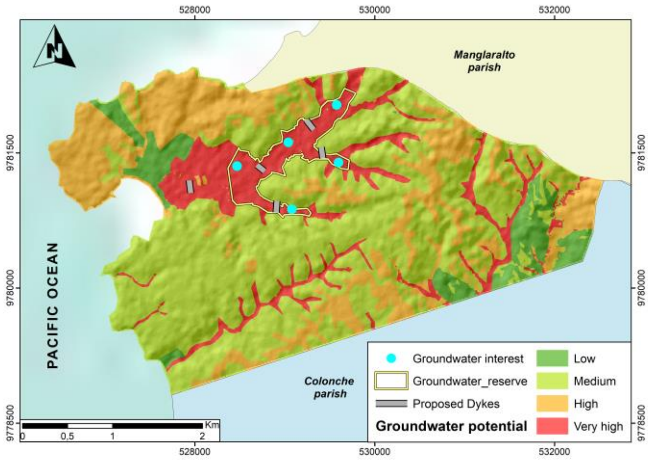

Figure 11. Location map of wells and dikes that can be implemented in the study area

Using effluents from the secondary wastewater treatment system represents a tool to meet agricultural production needs in an area with water scarcity and a considerable population growth rate [68], avoiding its direct discharge to peripheral water bodies and contributing to food security [69]. On the other hand, using wastewater to promote agriculture reduces the consumption of fertilisers and the nutrients naturally present in the wastewater, favouring the safe growth of crops and guaranteeing a closed and environmentally favourable nutrient cycle [70-72].

According to the current irrigation techniques in the area (hoses), the resource has not been optimised and is not used by other farmers because of the lack of a collection and distribution system and the implementation of new irrigation techniques. The findings of this study suggest the implementation of medium- and large-scale green filter projects as tertiary purification systems [73-75], in which the use of soil as a filter medium allows for higher levels of water purification and contributes to reforestation plans for endemic species [76]. This type of NbS would contribute to the well-being of the ecosystem, guarantee higher-quality fruit products, and promote the cultivation of plant species. Several studies have promoted the use of treated wastewater in agriculture [77-80], making it possible to meet the demand for existing water in crops and generate successful results without affecting the growth of fruits or vegetables in the context of the circular economy of water. However, some research points out disadvantages, mainly in the soil, such as increased salinity and organic content, and higher concentrations of heavy metals that compromise the health of the ecosystem and human beings [81, 82].

In semiarid areas, such as the study area, Pedrero et al. [83] evaluated the behaviour of crops and vegetation irrigated with wastewater and determined that the recorded variations are not only associated with the quality of the wastewater but also with the habits of people and the type of cultivated species. On the other hand, pilot projects or regional projects have been developed worldwide, such as in semiarid areas of Italy [84], Africa [85], and Chile [86].

Although present findings suggest the benefits of using treated wastewater in agriculture, such as reduced fertilization costs, improved crop production, and decreased water overexploitation, the potential disadvantages of this practice should also be mentioned [87]. Among the primary medium- and long-term disadvantages, soil salinization, crop toxicity due to double fertilization, exposure of crops and farmers to pathogens, and increased microbial activity should be considered [82]. Studies in olives and other crops have reviewed these long-term effects and concluded that these disadvantages could be mitigated by implementing appropriate treatment technologies, soil and water quality control, and proper irrigation procedures to reduce the dangers of increased soil salinity and human health problems [81].

The analysis of the agricultural potential using treated wastewater and groundwater for the Ayangue community through the SWOT analysis made it possible to identify three main aspects: i) the environmental contribution and community security provided by the effective reuse of treated wastewater in fruit crops, avoiding direct discharge into bodies of surface water, ii) the potential to exploit groundwater resources to complement the demand for water in irrigation, and iii) the importance of NbS in the integration of residual and groundwater for crop irrigation, in which irrigation systems, tertiary purifiers, and water planting and harvesting techniques guarantee sustainable management and a circular economy of water. It is important to highlight that community participation strengthened by academia, government entities, and companies is key to promoting rural socioeconomic development. This is reflected in the strategies proposed in this study, which consider the interaction of environmental, social, educational, and political-economic systems that consider the use of groundwater and treated wastewater as a model of community water management in rural areas with scarcity, contributing to the fulfilment of the Sustainable Development Goals (SDG).

Among the limitations of this research is the need to include other types of geophysical studies, such as electrical tomography or electromagnetic soundings, to validate the groundwater studies conducted. Likewise, to further explore the use of treated wastewater for crop irrigation, future research should consider measuring the physicochemical parameters of water more frequently and include the study of heavy metal concentrations and their possible influence on crop quality. This study contributes to the research related to sustainable agricultural development in semi-arid areas with scarce water resources. Within this area, the management of surface water, groundwater, and treated wastewater plays an important role in the socioeconomic development of rural communities [88-90]. However, more community interaction is needed to maintain the success of water management models in rural areas [91-94], where ancestral knowledge represents a complementary and viable alternative to solving social and environmental problems [94-97].

5. CONCLUSIONS

Water scarcity is a global problem threatening ecosystems and human life, generating concern for society, researchers, and public and private organisations. Agriculture worldwide represents one of the most important water sources, making it necessary to search for alternative irrigation sources that guarantee food security. This study provides a vision of the potential for the joint use of treated wastewater and groundwater as a sustainable system for the agricultural strengthening of a rural community in a semi-arid area of Ecuador. Although the Ayangue commune already has a water supply for human consumption, resources are necessary to promote local agriculture and empower the socioeconomic sector, which depends exclusively on tourism.

The study findings revealed that 14.2% of the study area has a very high potential for water exploitation to supply water for crop irrigation. Based on the processing and interpretation of geophysical data, the construction of five water extraction wells in the interpreted saturation zone was proposed. These wells would represent an approximate volume of 4702.4 km^3 of water at depths between 20 m and 30 m. Considering the possibility of overexploitation of the resource, this study proposes the implementation of five dams for seasonal water storage and artificial aquifer recharge. On the other hand, laboratory analyses on treated water and fruit species cultivated to date have demonstrated the success of water reuse in agriculture, avoiding discharge into rivers and minimising the use of fertilisers.

The integration of qualitative analysis through experts made it possible to establish strategies to guarantee sustainable agricultural development, including the implementation of NbS for artificial recharge of aquifers, tertiary purification systems to achieve greater removal of pollutants, modernisation of irrigation systems, and the inclusion of educational plans for the circular economy of water. The interaction between the community, academia, business and government entities is key in improving the inhabitants' quality of life, guaranteeing food security and the conservation of ecosystems.

The methodological approach presented two main limitations: i) applying a type of geophysical test (VES) and ii) the analysis of physical-chemical parameters of water in a specific climatic station. Future research studies on the joint use of conventional (groundwater) and non-conventional (treated wastewater) waters may include electromagnetic soundings that allow for more accurate determination of deep groundwater. Additionally, a multitemporal analysis of physicochemical parameters in treated wastewater will allow for more detailed knowledge of the level of pollutant removal from the existing treatment system.

The methodological approach proposed in this study represents a replicable tool for semi-arid regions with water stress. This study contributes to sustainable water resource management goals with NbS for recharge aquifers and the subsequent use of groundwater and treated wastewater for agriculture within a circular economic framework. Additionally, this study highlights the need to strengthen the country's legal framework for water resources, which guarantees the exploration, exploitation, supply, and purification of freshwater and residual water with environmentally and economically sustainable systems.

Wastewater reuse is positioned as an innovative, sustainable, and effective practice that addresses water scarcity in agriculture. Irrigation Boards in the province of Santa Elena could adopt this strategy to revitalize agricultural production, which has declined due to the lack of water resources. Implementing this solution would not only improve productivity but would also contribute to long-term sustainability in the region.

ACKNOWLEDGMENT

This work is supported by ESPOL Polytechnic University research project "Registro de sitios de interés geológicos del Ecuador para estrategias de desarrollo sostenible." (Register of geological sites of interest in Ecuador for sustainable development strategies), with code No. CIPAT-002-2023. Additionally, this study thanks the Ayangue commune and the "Ayangue Potable Water and Sewerage Management Board" for their participation and support during the execution of the research work. Additionally, this study thanks to the outreach project "Water sowing, harvesting and reuse water for sustainability strategies" with code No. PG13-PY24-07.

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NOMENCLATURE

km^3	Cubic kilometers
km^2	Square kilometers
mm/year	Millimeters per year
m	Meter
cm	Centimeters
Ωm	Omio meters
ml	Milliliters
mg/L	Milligrams per liter