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GIS Application for Groundwater Information Processing and Sustainable Use in Rural Communities

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Abstract

Assessing aquifers in semiarid rural regions offers significant social and economic benefits. The "Loma Alta" community, located northeast of Santa Elena, Ecuador, primarily depends on agriculture as its leading economic activity. However, the community requires sufficient water resources for irrigation and domestic purposes. This research aims to investigate groundwater resources in the upper Valdivia–California River basin by applying Geographic Information Systems (GIS) and hydrogeological studies to propose sustainable water resource management strategies in line with the Sustainable Development Goals (SDGs). The methodological framework is structured into three phases: i) hydrologic and hydrogeologic analysis, encompassing hydrology, geology, geophysics, and water quality assessments of wells; ii) GIS application to delineate potential areas; and iii) setting of strategies for water sustainable management. The findings indicate that the highest water extraction occurs between January and April during the dry season and extends until the end of May in the wet season. The area with the most significant extraction potential was between the "Loma Alta" and "La Unión" communities. It features a saturated layer approximately 20 m thick in sandy soil capable of retaining up to 150 mm of water. This study underscores the potential for sustainable groundwater management in Loma Alta, which could contribute to the region's socio-economic development while addressing the challenges of water scarcity.

Keywords

Aquifer, Integrated Water Resources Management, GIS, Sustainable Development Goals, Geophysic

1. Introduction

Groundwater is the world's second most vital water source, providing for approximately half of the global population [1], mainly in semi-arid areas, because of its importance for irrigation and daily activities [2]. Groundwater is naturally recharged by rainfall and nearby rivers [3]. Among the anthropogenic activities that reduce water levels are excessive pumping [4] and climate change, which leads to variations in the water level and location of recharge sites, modifying the amount stored [5]. The Sustainable Development Goals (SDG) promoted by the United Nations reflect an integrative approach to the water, agriculture, and development nexus that proposes increasing the number of jobs in the agricultural area of the country's communities (SDG 1), efficient management and distribution of water resources to avoid water scarcity (SDG 6), and contribution to the development of communities (SDG 11) [6, 7].

In recent decades, ecosystems with arid or semi-arid climates worldwide have become vulnerable to the effects of climate change, causing a greater deficit than surplus water resources [8, 9]. Low rainfall

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directly affects the natural recharge of groundwater, as does extraction due to the demand generated by growing populations, resulting in a considerable decrease in groundwater levels [10].

In coastal aquifers, reducing groundwater levels and rising sea levels are driven by climate change push the interface zone inland, increasing the risk of seawater intrusion [11, 12]. It is crucial to develop a controlled groundwater extraction plan that accounts for the volume of natural recharge to prevent groundwater depletion and marine intrusion, the discharge into the sea, and the coastal boundary within which the saline water body must be contained [13, 14].

In arid regions, rural communities rely on pumps to extract groundwater to address the scarcity of surface water, particularly during droughts [15]. Groundwater is often preferred because of its high quality and fewer pathogens and pollutants [16]. Managed Aquifer Recharge (MAR) has been implemented in rural areas to counteract the declining water tables, meet irrigation needs, and enhance irrigation water quality [17]. A notable example is the Central Valley of California (United States), one of the world's most productive agricultural regions, where MAR is applied to agricultural land (Ag-MAR) using multi-criteria decision analysis based on Geographic Information Systems (GIS) to improve groundwater supply for rural communities [18]. Similarly, in Manglaralto, a rural community in Santa Elena Province, Ecuador, water extracted from the subsoil is managed by integrating Water Sowing and Harvesting (WS&H) techniques with water-resilience practices to maintain the capacity of the exploited aquifer [19, 20, 21].

As population growth intensifies and water demand increases, it is imperative to identify new areas for resource extraction [22]. Geoelectrical methods are widely employed to assess the resistivity of groundwater sources, enabling differentiation between fresh and brackish water [23]. Techniques such as Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) are non-invasive, straightforward to implement, and cost-effective for aquifer mapping and exploration, facilitating the identification of subsurface geological layers [24, 25].

At a global level, there are multiple experiences in the benefits of using geoelectrical methods for the characterization of hydrogeological parameters, such as the delimitation of saline intrusion zones present in alluvial aquifers [23], the prevention of environmental impacts in conjunction with the strategic location of engineering works to improve the quality of water resources [26], and an increase in agricultural production in rural communities [27].

In Ecuador, there is a legal framework that recognizes the right of people to access water, in addition to its correct use in productive activities. Currently, the National Irrigation and Drainage Plan (PNRD) (2021–2026) [28], constitutes a tool for the comprehensive planning of objectives within the framework of efficiency and sustainability in the administration of the country's hydrological heritage.

In the province of Santa Elena, Ecuador, there is the Loma Alta commune, whose primary need is the supply of water to carry out activities such as agriculture, livestock, and domestic consumption. Some factors that cause this problem are population growth, increased agricultural land, and climate change, which causes droughts. The inhabitants use the surface water of the Valdivia-California River and some artisanal wells from which groundwater [29]. The MAR approach provides opportunities to transform brackish aquifers into productive resources and sustainable water management practices [4]. An integrated approach is required to identify and understand the groundwater exploitation sites within the hydrographic basins as a basis for generating future MAR projects, which allows the aquifer-man balance. In this context, the following research question is raised: What hydrogeological exploitation sites can potentially improve groundwater supply in rural communities in the upper Valdivia-California River Basin? This study aimed to explore the groundwater in the upper Valdivia-California River Basin (Ecuador) by integrating hydrology-hydrogeological studies, the use of geoelectrical methods, and the application of GIS for the proposed use of water resources within the framework of the SDGs that ensure the development and supply of rural communities. This study proposes an integrated methodology for assessing groundwater resources based on a GIS and Delphi method that combines geological-geophysical analysis, precipitation and recharge, groundwater level and quality, and hydrodynamics (flow direction).

2. Materials and Methods

2.1. Geographic and geological setting

The study area is located in the province of Santa Elena within the parish of Colonche, with an estimated population of 40,058 [30]. The Loma Alta Commune has an area of 6,842 ha [31] and is also home to the Loma Alta communal ecological reserve established by the same community to protect water sources and the associated ecosystem [32]. In the area, there are four rural communities (Figure 1) located approximately 90 meters above sea level (m.a.s.l.), Loma Alta, La Unión, La Ponga and El Suspiro [33]. The area's climate is arid [34]; it has an average temperature of 24.3 °C and an annual temperature range of 4.8 °C [35]. In terms of the geological setting, the area is located on a sedimentary basin with an igneous basement forearc (Piñón Formation of the Lower Cretaceous), where pelagic and volcanic sediments corresponding to the Cayo Formation (Upper Cretaceous) are superimposed [36]. The stratigraphic sequence of the Zapotal Member that crops out in a large part of the study area is composed of sandstones and siltstones, and in its basal part, it presents conglomerates and limestones with a thickness of approximately 1,000 m [37, 38].

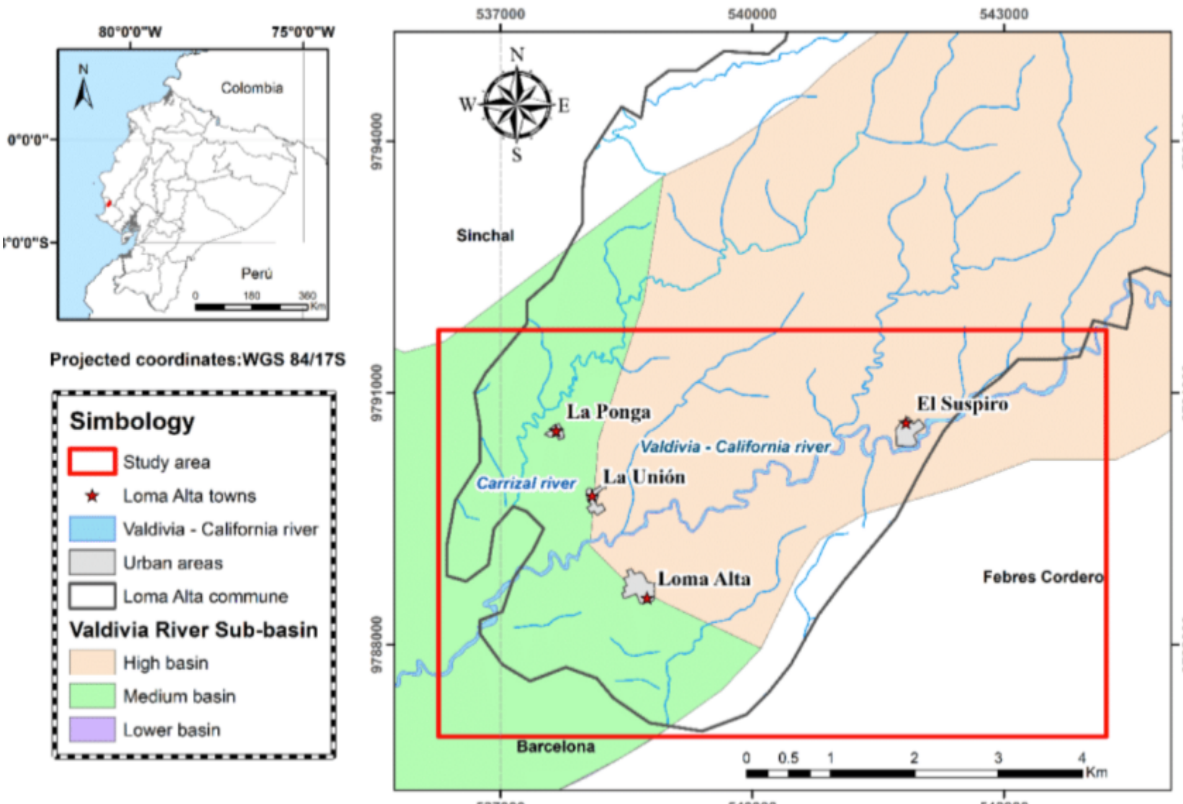


Figure 1: Location map of the study area

2.2. Methods

This study employs a multidimensional analysis that integrates geological-geophysical factors, precipitation and recharge (isohyets), hydrodynamics (flow direction), static and dynamic groundwater levels, and water quality (including physical-chemical and microbiological parameters) within a GIS framework to identify potential zones for hydrogeological utilization. Both 1D (VES) and 2D (ERT) geoelectrical methods and spatial analysis tools were utilized to generate thematic maps and establish correlations

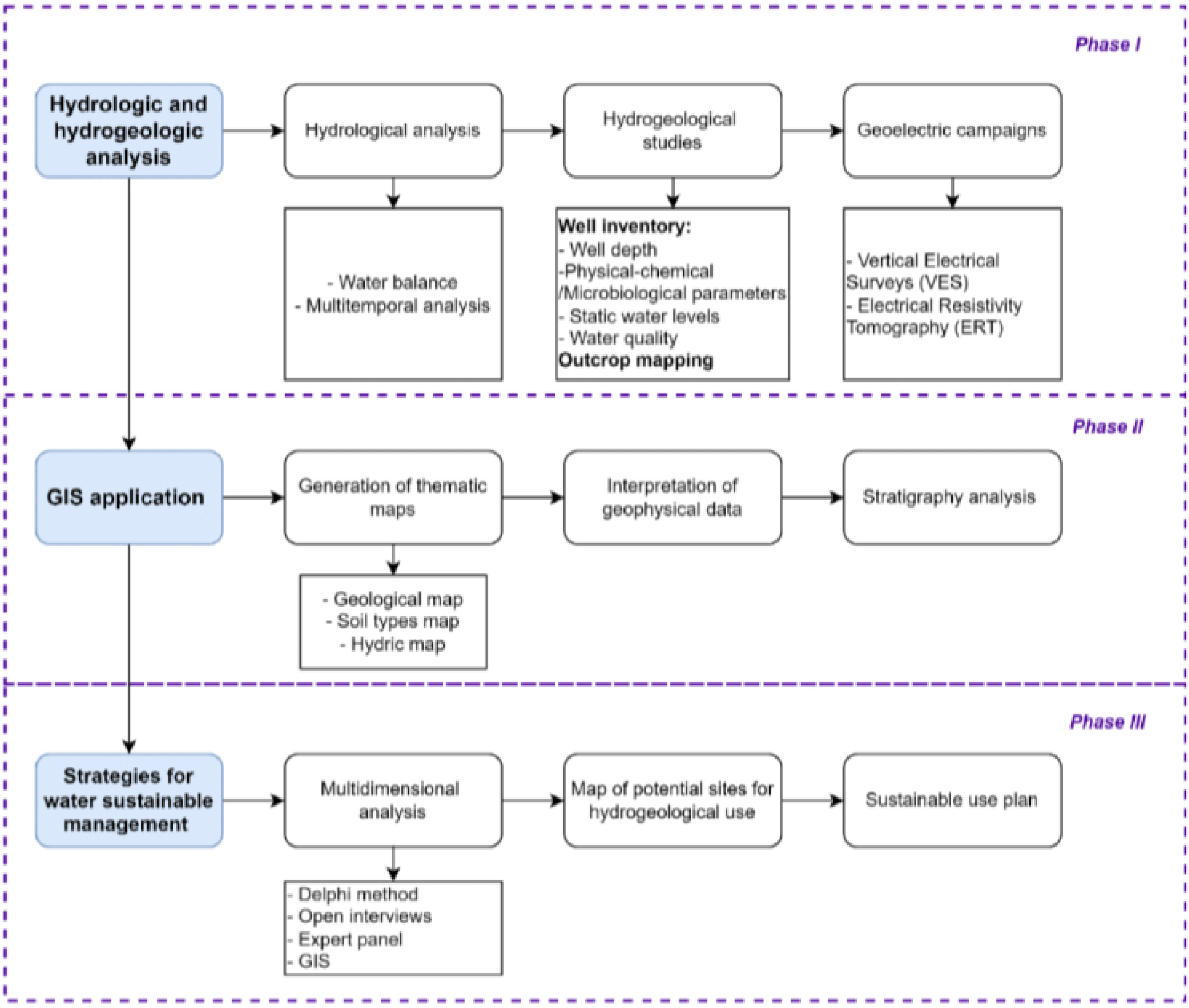


Figure 2: Workflow of this study.

between hydrological and hydrogeological factors. The phases of this study are schematically shown in Figure 2.

2.2.1. Phase I: Hydrologic and hydrogeologic analysis

Phase I involves analyzing the hydrology and hydrogeology of the study basin. The initial stage included evaluating precipitation and mean annual temperature data to perform the water balance. We obtained data from 1981 to 2020 from GeoEye-1 satellites using the 'Five-Degree Blocks of Cells' extension, the National Aeronautics and Space Administration (NASA) Satellite, Prediction Of Worldwide Energy Resources (POWER) [39], and meteorological yearbooks from the National Institute of Meteorology and Hydrology (INAMHI) [40] for the 'El Suspiro' station (M245), which includes data for 1994, 1995, 2000, 2002, and 2007.

The study gathered cartographic information on rivers, contour lines, geology, lithology, settlements, and roads from the IGM Geoportal [41]. For the three domestic water wells in the area, collected location data and conducted microbiological analysis detecting five parameters: faecal coliforms, total coliforms, Escherichia coli, Salmonella, and Shigella. We analyzed the water's chemical parameters, including pH, salinity (S), temperature (T), and Total Dissolved Solids (TDS), using the portable multiparameter WTW 3430 device. The physical parameters, conductivity (C), resistivity (R), and static level, were also measured. Then, the results of the water samples analysis were compared with national regulations, as specified in the Unified Text of Secondary Environmental Legislation (TULSMA, INEN Standard 1108) and international standards (World Health Organization, WHO) [42, 43].

In the second stage, the research conducted geophysical surveys using 16 Vertical Electrical Soundings (VES) with the Terrameter SAS 1000 equipment, employing a Schlumberger electrode array (AB/100 m and MN/10 m). Also, three Electrical Resistivity Tomography (ERT) surveys were performed using the Terraloc equipment with the Wenner method, obtaining ground resistivity and the approximate depth of layers with both methods. This combination of geophysical prospecting methods reduces exploratory costs and provides reliable information by minimizing the uncertainty generated by indirect measurement methods [44].

2.2.2. Phase II: GIS application

This phase created isohyet maps using the Kriging method of Spatial Analysis in ArcGIS Pro (version 3.2.0) to obtain the groundwater flow direction map. The VES resistivity measurements were processed in the IPI2win program (version 3.0.1), which yielded the different resistivities and apparent thicknesses of the layers or strata composing the subsoil of the area of interest. Additionally, the pseudo-sections of the ERT were generated using the RES2DINV program, producing 2D graphs of the resistivity values for each substrate and the stratigraphic columns using Strater 5 software to graph the lithology observed in the field.

2.2.3. Phase III: Strategies for water sustainable management.

Phase III involved generating a map of suitable sites for groundwater use in the upper Valdivia-California River basin. This map integrated the hydrology and hydrogeology factors from Phases I and II in a GIS and applied the Delphi method to develop guidelines and reach a consensus [45, 46]. Six experts participated in the Delphi method, including geologists, hydrogeologists, geophysicists, GIS specialists, and agriculturalists. These experts included the publication's authors, professors, researchers, and representatives from the Loma Alta community, all of whom provided informed consent.

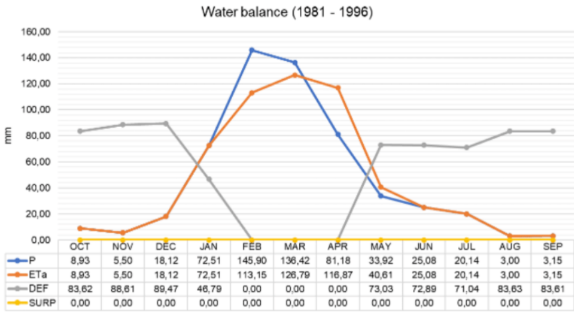
The study conducted three rounds of open interviews. In the first round, the researchers presented the maps generated in Phase II, and the experts suggested adjustments to the thematic maps. In the second round, the experts selected the primary areas for groundwater use and requested an evaluation of the geological stations and a correlation of the geophysical campaigns. The panel identified areas with the most significant water potential in the third round. It delimited the layers with the most substantial thickness and groundwater content for extraction and developing productive activities through a controlled irrigation system. During this final round, the experts formulated strategies to assess zones for the future development of Managed Aquifer Recharge (MAR) projects.

3. Interpretation of results and discussion

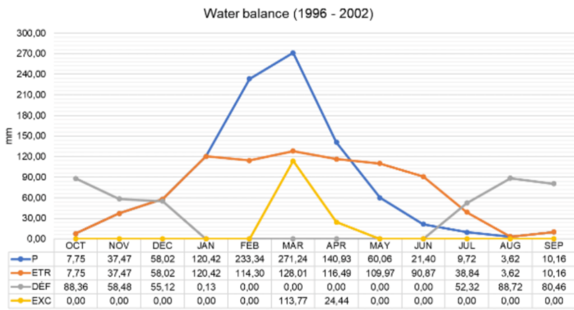
3.1. Hydrological and hydrogeological assessment

3.1.1. Water balance

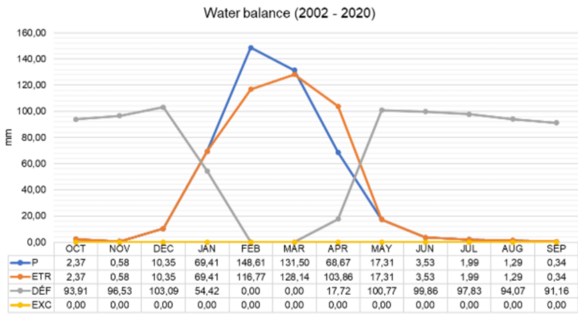
Of the two dry intervals, the one with the lowest amount of precipitation is from 2002 to 2020, with a total of 455.94 mm per year, while in the interval from 1981 to 1996, it was 553.85 mm. The humid sequence had an annual precipitation of 974.13 mm. The months of reserve recharge for all sequences begin in February and continue until March only in the dry sequences; for the humid sequence, it extends until April. In the interval from 1981-1996, the reserves were depleted in May, while in the interval from 2002-2020, the reserves were depleted in April; for the humid interval from 1996 - 2002, the reserves were depleted in July.



(a) Water balance for dry sequence of 1981 – 1996



(b) Water balance for the humid sequence of 1996 – 2002



(c) Water balance for dry sequence from 2002 to 2020

Figure 3: Water balance

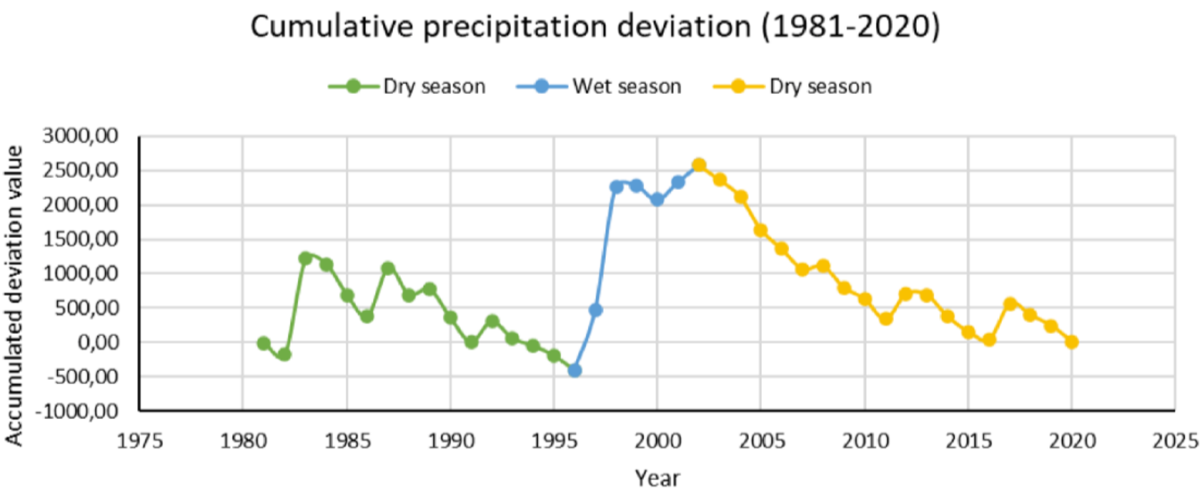


Figure 4: Cumulative precipitation deviation (1981-2020).

3.1.2. Multitemporal analysis

The precipitation analysis in the study area from 1981 to 2020 resulted in three intervals (Figure 4): the first considered a dry season from 1981 to 1996, the wet season from 1996 to 2002, and the dry season that continues until 2020. The average annual temperature for the first interval is 24.06 °C, the second interval is 24.17 °C, and the last dry season is 24.54 °C. The soil's field capacity or water retention capacity was estimated to be 148.5 mm. With the elaboration of the water balance according to the mentioned intervals, it is distinguished that for a dry season, the months with the highest rainfall are February (145.90 mm), March (136.42 mm), and April (81.18 mm), subsequent months the rainfall varies between 3.00 mm to 72.51 mm. The situation is similar during the wet season, with the difference that the months of most significant rainfall extend from February to the end of May, with rainfall of 233.34 mm to 60.06 mm. In the second dry sequence, the months of most significant rainfall are repeated concerning the first season; these range from 148.61 mm to 68.67 mm.

3.1.3. Physical-chemical and microbiological analysis of water-well simples

Table 1
Physical-chemical parameters of the wells in the study area. Values in red do not comply with the permissible limits according to TULSMA.

Wells	Coordinate X	Coordinate Y	Coordinate Z	Static level (m)	Well depth (m)	Conductivity ($\mu S/cm$)	Resistivity (ohm.cm)	TDS (mg/L)	Temperature (°C)	pH	Salinity (%)
1	538346	9789196	45 ± 3	4.18	8.6	1.377	1.374	358.8	24.6	7.07	359.8
2	538140	9789081	45 ± 3	0	6	5.230	359.9	1379	23.8	7.05	1459
3	538204	9789377	47 ± 3	1.48	8	1.398	1.331	373.9	25.4	6.85	370.3
4	537997	9789551	51 ± 3	0	4.85	1.886	997.5	502.2	23.4	6.91	495.1
5	542370	9790774	90 ± 3	0	2.5	843.7	2.238	223.2	23.4	7.13	216.4
6	542060	9790676	85 ± 3	0.9	3.3	1.936	996	514.4	23.6	7.34	515.9
7	541676	9790407	85 ± 3	2.47	4.85	1.261	1.477	338.2	23.9	7.21	334
8	539581	9789569	55 ± 3	2.77	5.75	1.245	1.513	330.1	23.6	7.51	325.9
9	537838	9791200	64 ± 3	0	8	4.046	468.2	1072	21.6	7.47	1113
10	538687	9789400	50 ± 3	0.58	8	1.040	1.815	275.5	23.4	7.32	268.9
11	537821	9789495	48 ± 3	0	2	3.279	576.3	869.8	23.2	6.64	878.7
12	537560	9789115	40 ± 3	0	8	1.797	1.435	349	23.5	7.06	343.1

The analysis of the physicochemical parameters carried out in the 12 wells distributed in the study area (Table 1) indicates that 9 of them have suitable conditions for use, while well-02, well-09 and well-11 presented values of conductivity (> 2500 µs/cm), TDS (> 900 mg/L) and salinities (> 800 ppm) that exceed the permissible values according to the TULSMA regulations, this is due to poor conditioning, landslides, plant decomposition and the inactivity of the wells.

The results of the microbiological analysis of the water samples are presented in Table 2 and were compared with National Regulations (TULSMA, INEN 1108 Standard) and International Regulations (World Health Organization Drinking Water Guide, 2006) and indicated the absence of Salmonella and Shigella, while the presence of Fecal Coliforms, Total Coliforms and Escherichia Coli did not exceed the permissible limits.

Table 2
Results of microbiological analysis of three wells.

Parameter	Result	Accreditation	Units
Fecal Coliforms	< 1.8	A2LA/SAE	NMP/100ml
Total Coliforms	< 1.8	A2LA/SAE	NMP/100ml
Escherichia Coli	< 1.8	A2LA/SAE	NMP/100ml
Salmonella	Absence	_	Absence/Presence
Shigella	Absence	_	Absence/Presence

A2LA: American Association for Laboratory Accreditation.
SAE: Society of Automotive Engineers.

3.1.4. Analysis of groundwater flow direction

Figure 5 shows the map of groundwater flow directions with a Northwest (NE)-Southwest (SW) trend that helps recharge the Valdivia-California River. The range of water table measurements varies from 40 to 83 (m.a.s.l.).

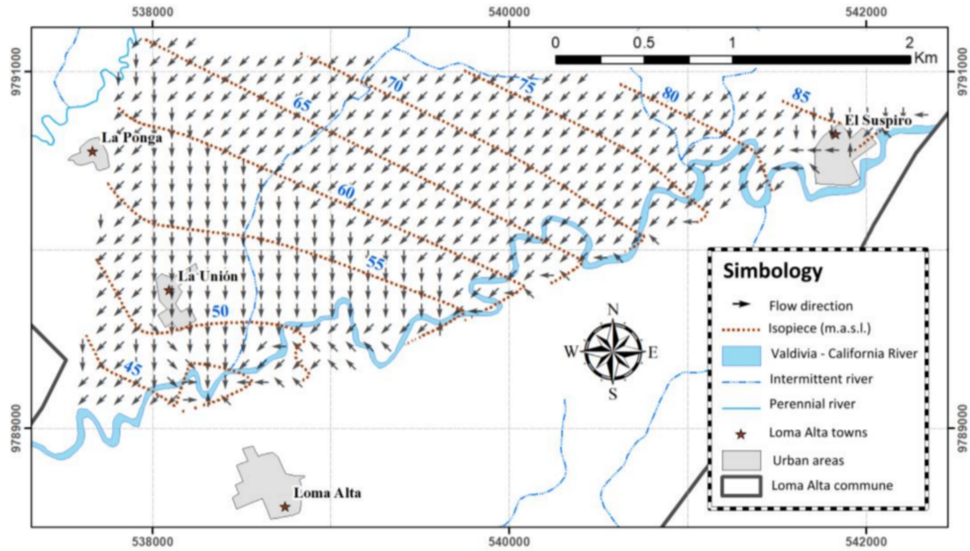


Figure 5: Groundwater flow map

3.1.5. Geological outcrop stations and geoelectrical campaign correlation

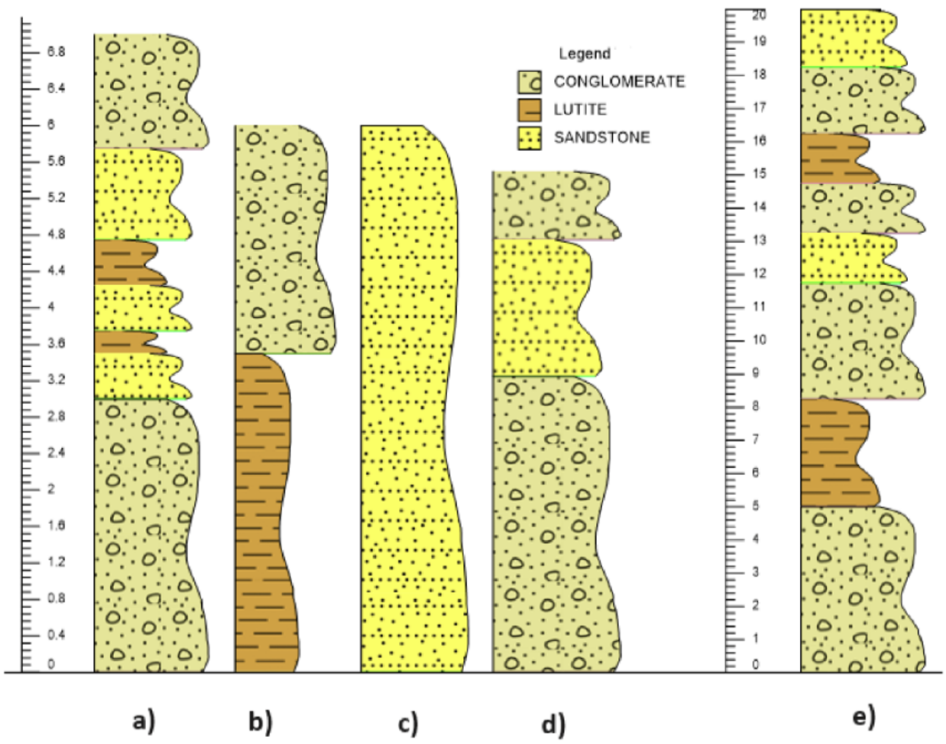


Figure 6: Mesoscale description of the four geologic outcrops: a) Outcrop O_LA1, b) Outcrop O_LA2, c) Outcrop O_LA3, d) Outcrop O_LA4_1, e) Outcrop O_LA4_2.

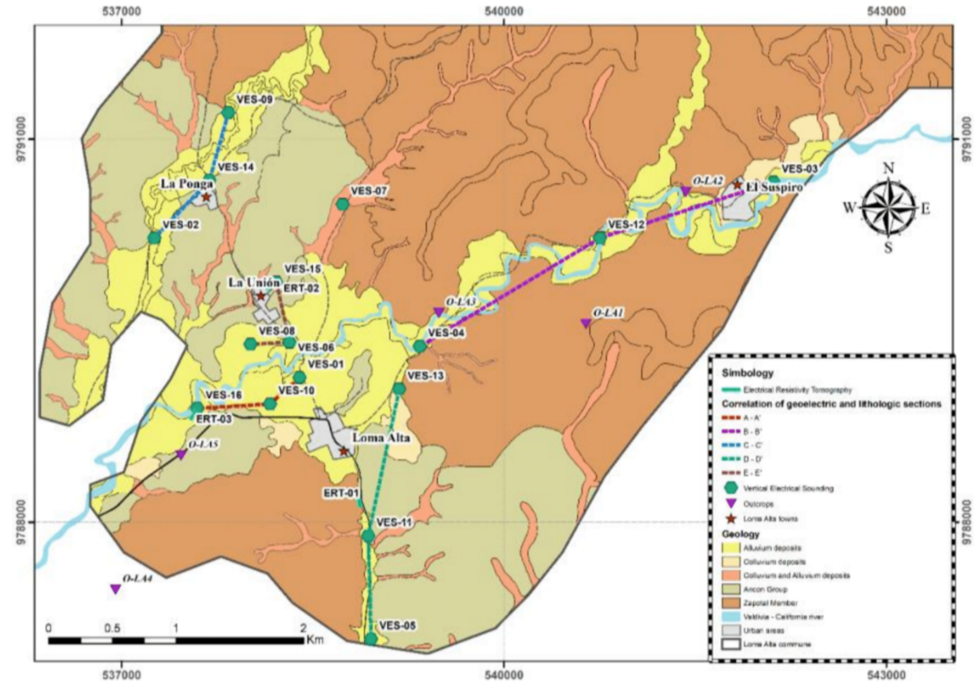


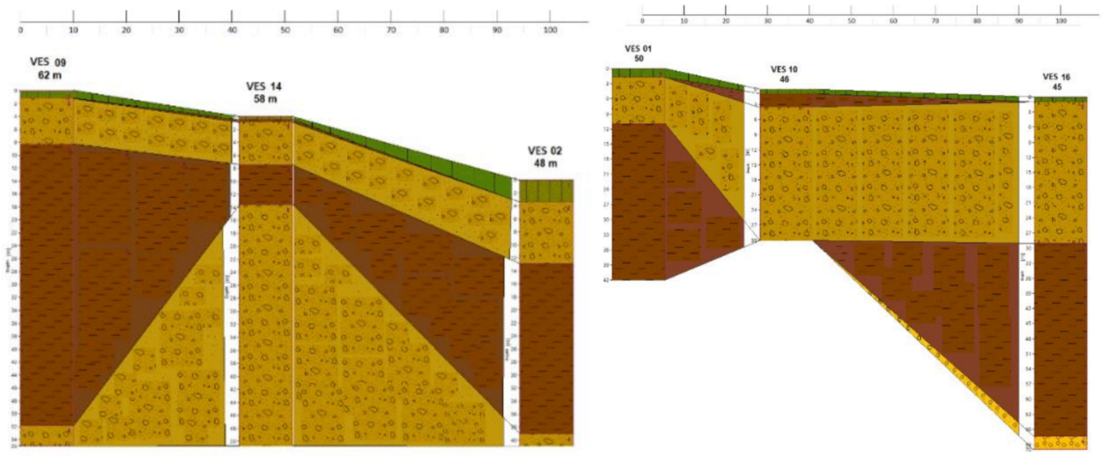
Figure 7: Location of VES, ERT, and geologic outcrops in the study area.

A geological field survey was conducted in four outcrops distributed in the study area (Figure 6). In the outcrop O_LA1 (Figure 6a) we found diaclases, sedimentary structures such as cross-stratification, fine-grained beige sandstones without compacting, some layers contained subrounded grains of pebble size of poor classification, shale layers containing clay particles, and the presence of fine-grained silt of grayish to dark brown color. In outcrop O_LA2 (Figure 6b) laminar layering of ortho conglomerates with pebble-sized clasts, layers of grayish-white shales weathering to yellow and gypsum-filled reverse faults were identified. In outcrop O_LA3 (Figure 6c), yellowish-white fine sandstones, cross-stratification, erosion, and gypsum layers were observed. The description of outcrop 4 is divided into 2, the lower part which is the O_LA4_1 (Figure 6d) that corresponds to the flank of a syncline with dip 15° and strike 50° SE, it was identified as a collapse of layers by gravity, thick brownish yellow sandstones, silicified shale intercalations and a layer of matrix-supported conglomerate with pebble size clasts with good classification; the middle and upper part of the outcrop called O_LA4_2 (Figure 6e) is the other flank of the syncline with strike 82° SW and dip 20° also shows gravity landslides, thick brownish-yellow sandstones, intercalation of silicified shales and layers of matrix-supported conglomerates with pebble size clasts were observed.

The correlation of the data obtained by the VES together with the geological survey allowed the identification of the saturated layers associated with a potential aquifer present resistivities associated with clasts with a sandy matrix (30-50 Ωm) (Table 3) at depths ranging from 3 to 40.5 m, and the impermeable layers are associated with a lithology of compact clays (0-5 Ωm).

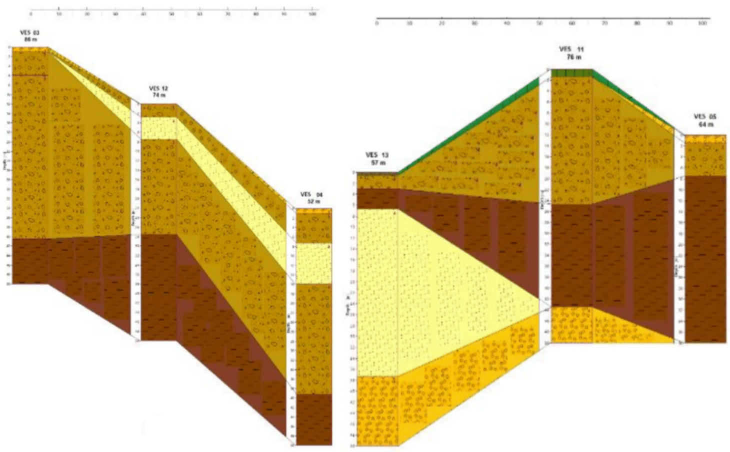
By correlating geoelectric profiles (Figure 7), layers of water interest were located in sections A-A', B-B', C-C', D-D', E-E' (Figure 8, 9, 10), where it is inferred that the saturated layers (clasts with sandy matrix) are approximately 10-12 m thick at shallow depths (no deeper than 3 m).

Within the three ERTs a layer of interest was located in ERT-01 (Figure 11a), with resistivity values associated with saturated sandstones (2.45 Ωm) at a depth of approximately 5 m, this profile reached an error of 3.9% in its processing, being the highest among the three profiles. In ERT-02 (Figure 11b) the sandstone layer (5.0 Ωm) is found from 15 m with an undefined thickness covered by a layer of saturated silty sands. Profile ERT-03 (Figure 11c) is similar to profile ERT-01 with the difference that the saturated sandstone layer (15.8 Ωm) is located from 2.30 m reaching 23.5 m depth.



(a) C-C' Section (VES 02, 09 y 14) (b) A-A' Section (VES 01, 10 y 16)

Figure 8: C-C' and A-A' Sections



(a) B-B' Section (VES 03, 04 y 12) (b) D-D' Section (VES 05, 11 y 13)

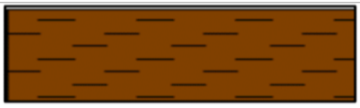
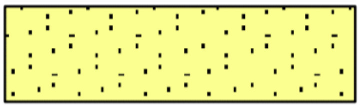
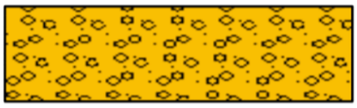
Figure 9: B-B' and D-D' Sections

3.2. Suitable sites for groundwater use in the upper Valdivia-California River basin

The interest area of a groundwater well was between the towns of "Loma Alta" and "La Unión" (Figure 12), with thicknesses varying between the categories "Excellent" (30-35 m) and "Highly recommended" (25-30 m). The thickness in the "Very good" range continues toward the river towards the SW. The study highlighted the possible existence of a semi-confined or confined aquifer at variable distances between 15 and 40 m below the Quaternary aquifer. A panel of experts developed strategies for the sustainable use of underground resources, grouped into four pillars:

1. Establish continuous monitoring networks that record the quantity and quality of the groundwater.
2. Integrate the "Map of potential hydrogeological exploitation sites" into land use and cover planning.
3. Community participation must include water boards, local communities, and farmers in the decision-making and implementation of aquifer recharge strategies.
4. Future studies are essential to identify MAR project areas to take advantage of resources during the wet period. A multicriteria decision analysis based on remote sensing and GIS of the river basin is recommended, combining the factors established in this study with biophysical, hydrological, and socio-ecological data usually applied in similar environments [47, 48]. This study will allow

Table 3
Range of resistivities with their lithological interpretation for VES.

Resistivity (Ωm)	Lithology	Legend
0-5	Compacted clays	
5-20	Sandstones	
20-30	Sands with silts	
30-50	Clasts with sandy matrix	
> 50	Gravels with sand	

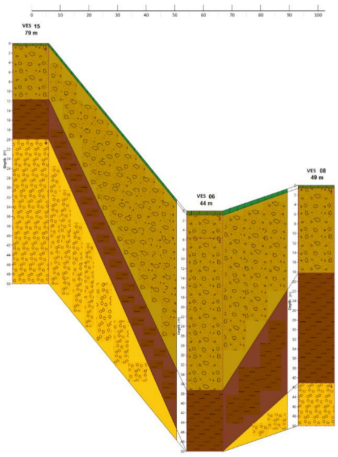
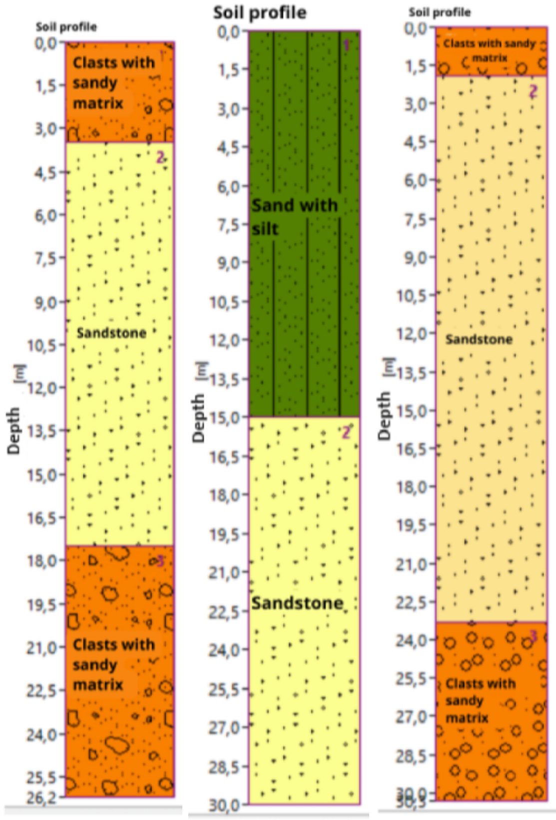


Figure 10: E-E' Section

for the design of management strategies that consider future climate change, ecosystem needs, and population growth.

4. Conclusion

The study identified groundwater use sites between the communities of "Loma Alta" and "La Unión", consisting of a saturated layer approximately 20 meters thick in sandy soil, capable of retaining up to 150 mm of water. Generally, the thickness of the saturated layers ranges from 15 to 31 meters, associated with clasts in a sandy matrix, while the impermeable layers consist of compact clays. The water balance analysis revealed that the months of highest precipitation occur from January through June, during which the soil regains moisture, benefitting agriculture, livestock, and domestic consumption through aquifer recharge. The analysis of physicochemical and microbiological parameters indicated



(a) ERT-01 (b) ERT-02 (c) ERT-03

Figure 11: Description of geoelectric profiles.

that 75% of the wells have good water quality; however, wells 2, 9, and 11 exhibited elevated levels of dissolved solids and conductivity, attributed to neglect and poor maintenance of the hydraulic structures.

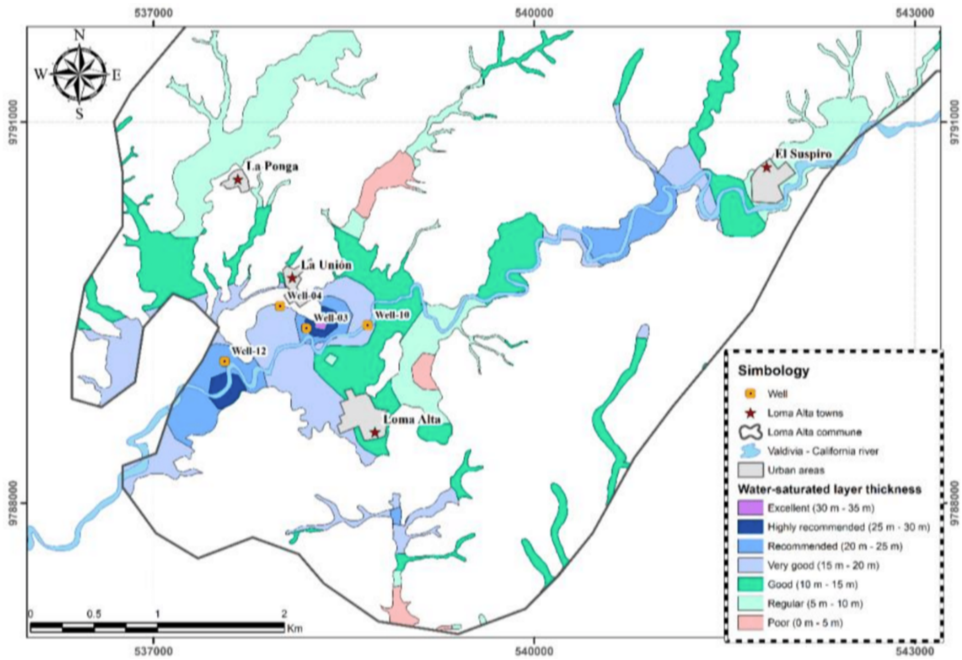


Figure 12: Map of potential hydrogeological exploitation sites.

Future research should focus on identifying recharge areas to comply with environmental and water management regulations, thereby facilitating the planning of climate change adaptation measures for the associated communities and ecosystems.

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