

Groundwater Potential Mapping using AHP-GIS and Geoelectrical Validation in a Semi-arid Coastal Aquifer, Entre Ríos-Ecuador

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Abstract

In semi-arid regions, identifying groundwater potential zones is essential for sustainable water management and for reducing uncertainty in well siting. The Entre Ríos community, located in southwestern Santa Elena, Ecuador, depends economically on agriculture but faces irrigation-water shortages that limit productivity and socioeconomic development. This study aimed to spatially identify groundwater potential areas by integrating Multi-Criteria Decision Analysis (MCDA) and geophysical methods to support agricultural well-drilling decisions. The groundwater potential model was developed using thematic layers, including lithology (32.44%), geomorphology (14.35%), drainage density (7.55%), land use and land cover (4.81%), slope (8.01%), topographic wetness index (10.97%), normalised vegetation index (4.75%), and soils (17.12%). The Analytic Hierarchy Process (AHP) was applied to weight these factors and generate a groundwater potential map, which was validated using Electrical Resistivity Tomography (ERT) and Vertical Electrical Soundings (VES). The highest potential zones were located in the northwestern sector of the study area. However, geophysical results showed that the saturated unit occurs mainly between 10 and 30 m depth and consists predominantly of silts and clays. Thus, AHP-GIS favourable zones may indicate water accumulation, but not necessarily productive aquifers. Integrating geophysics is therefore crucial for reducing uncertainty.

Keywords

Water management, Remote sensing, AHP, Non-invasive methods, Sustainability,

1. Introduction

According to Aranguren-Díaz et al. [1], by 2024, 2.5% of the Earth's water will be freshwater, of which approximately 30% is stored as groundwater, making it one of the main reserves of liquid freshwater [2]. In coastal regions with limited surface water availability, groundwater is a key element for the sustainability of agricultural systems and food security. Globally, approximately 70% of the extracted

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water is used in the agricultural sector, whereas approximately 30% of the water used for irrigation originates from groundwater [3].

The increase in global food demand has driven the intensification of agricultural production, particularly in rural areas, where agriculture is the primary source of livelihood [4]. However, water availability and access to irrigation systems are critical limiting factors for agricultural expansion in the region. Water scarcity can lead to production losses, increased socioeconomic vulnerability, and compromised food security [5]. Studies have indicated that global water resources can meet future food demand if managed in an integrated and efficient manner [2]. Therefore, identifying areas with groundwater potential is a key strategy for strengthening agricultural development in semi-arid and low-rainfall regions [6].

Identifying Groundwater Potential Zones (GWPZ) is crucial for mitigating water scarcity in arid and semi-arid regions [7]. When these zones exhibit optimal hydrogeological conditions, they can become strategic sources of water supply. Furthermore, their proper delineation allows the implementation of sustainable aquifer management plans, reducing risks such as saltwater intrusion in coastal environments [8]. Several methods have been used for GWPZ identification, including geophysical, GIS, and remote sensing approaches [9]. Among geophysical techniques, electrical methods are widely applied in hydrogeology due to their ability to detect resistivity contrasts related to lithology and groundwater saturation [9]. GIS-based AHP further enables the integration and weighting of factors such as slope, precipitation, drainage density, geomorphology, land use/land cover, geology, and faults to delineate groundwater potential zone [10, 11].

The integration of geophysics, remote sensing and GIS has been widely used to delineate GWPZ in arid and semi-arid regions. GIS-based spatial analysis enables rapid assessment of surface factors controlling infiltration, whereas geophysical methods provide direct subsurface evidence for model validation [12, 13]. However, AHP-GIS models rely on surface variables and expert-based weights, which may overestimate aquifer potential without field validation. In this context, geophysics is essential to verify whether areas classified as highly favourable actually contain saturated conditions [14, 15].

In the semi-arid zones of Ecuador, aquifers account for 53.4% of available water [16], and are essential for economic and social supply, such as the coastal aquifers, which are the sole sources of water for several communities [17, 18]. The Entre Ríos community (Santa Elena, Ecuador), has an economy based primarily on agriculture. However, water availability is limited to domestic consumption, restricting its use in agriculture, especially in areas far from existing infrastructure [19]. In this context, this study poses the following research question: What variables influence the delimitation of GWPZs using a Multi-Criteria Decision Analysis validated with geophysics in Lot 2 of the Entre Ríos community? This study aimed to determine the GWPZs in Entre Ríos zone by combining Multi-Criteria Decision Analysis with geophysical methods, providing a technical basis for the efficient planning of agricultural wells that will strengthen local socioeconomic development.

2. Materials and methods

The study was conducted in three phases (Figure 1). First, baseline spatial data, including a Digital Elevation Model (DEM), land use/land cover, and geological maps, were collected. Second, GIS-based Analytic Hierarchy Process (AHP) analysis was applied to integrate and weight thematic layers for groundwater potential mapping [20, 21]. Finally, 1D (VES) and 2D (ERT) geophysical surveys were used to validate the GWPZ map and identify aquifer depth, thickness, and lithological characteristics.

2.1. Phase I: Analysis of available spatial information and selection of conditioning variables

Phase I involved the analysis of available spatial information and the selection of conditioning variables. Based on previous studies in semi-arid regions, eight variables were selected according to their hydrogeological relevance and data availability (Table 1). The topographic variables were derived from a 30 m DEM for South America [22]. Lithological information was obtained from SENAGUA [23], while

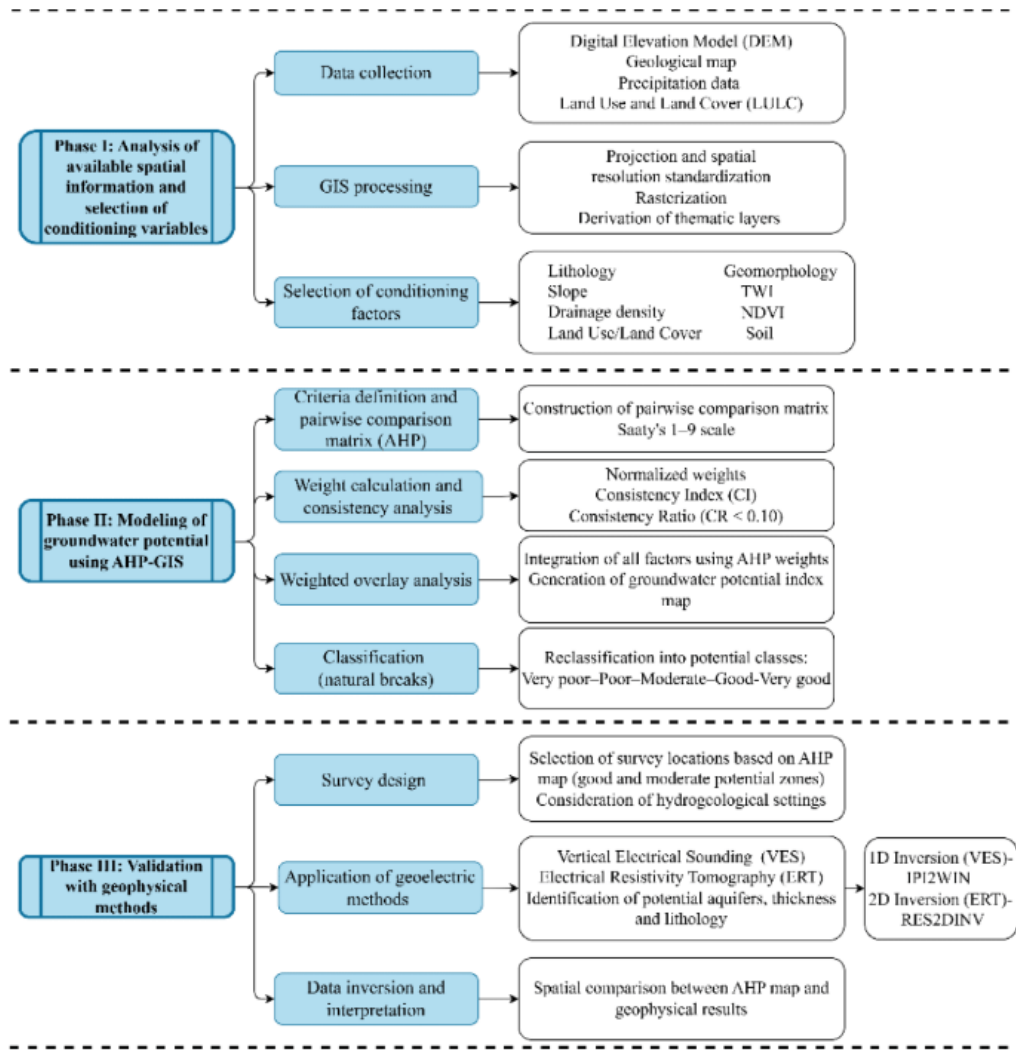


Figure 1: Methodological framework applied in this study.

geomorphological data were obtained from MAGAP [24]. The Normalised Difference Vegetation Index (NDVI) was prepared using Google Earth Engine (GEE) [25], and subsequently processed in ArcGIS Pro. All thematic layers were standardised to a 30 m spatial resolution to ensure spatial consistency. Vector layers were converted to raster format using the Feature to Raster tool in ArcGIS Pro version 3.6.3.

2.2. Phase II: Modeling of groundwater potential using AHP-GIS

Once the variables were established, the Analytic Hierarchy Process (AHP)[34] was applied to assign a weight to each criterion. The Delphi method was used to obtain a reliable consensus among five experts in geophysics, geology, civil engineering, remote sensing, and hydrogeology [35]. A paired-comparison variable was constructed using the Saaty scale (1-9) [36] (Equation 1), enabling the calculation of the normalised weights for each layer (Equation 2).

$$A = (a_{ij})_{n \times n} \begin{bmatrix} 1 & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & 1 & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & 1 \end{bmatrix} \quad (1)$$

where a_{ij} represents the relative importance of criterion i with respect to criterion j , and w_i is the normalised weight of criterion i .

Table 1

Variables selected for the determination of groundwater potential.

Variable	Description	Justification	Resolution	Source
Land Use and Land Cover (LULC)	Types of land cover and land use	Controls evapotranspiration, surface runoff and infiltration rates [26]	1:25,000	[24, 27]
Lithology	Permeability and porosity of the geological substrate	Controls the transmission and storage capacity of groundwater [28]	1:250,000	[23]
Slope	Surface runoff gradient	Low-slope areas increase surface water retention time and favour infiltration [20]	30 m	[22]
Drainage density	Concentration of the drainage network	Acts as an inverse indicator of permeability [29]	30 m	[22]
Geomorphology	Geomorphological units and landforms	Defines natural recharge and groundwater flow-transition zones [30]	1:25,000	[23]
Soil	Soil texture and water-retention capacity	Regulates the initial infiltration rate [31]	1:25,000	[23]
Topographic Wetness Index (TWI)	Estimation of terrain-controlled moisture accumulation	Identifies areas prone to prolonged moisture accumulation [32]	30 m	[22]
Normalised Difference Vegetation Index (NDVI)	Quantification of vegetation vigour and biomass density	Acts as an ecological indicator of subsurface water availability [33]	10 m	[25]

$$w_i = \frac{(\prod_{j=1}^n a_{ij})^{1/n}}{\sum_{k=1}^n (\prod_{j=1}^n a_{kj})^{1/n}} \quad (2)$$

To ensure the reliability of the model, a consistency analysis was performed by verifying that the Consistency Ratio (CR) (Equation 3) was lower than 0.10.

$$CR = \frac{CI}{RI}, \quad (3)$$

$$CI = (\lambda_{max}) / (n - 1) \quad (4)$$

where CR is the Consistency Ratio, CI is the Consistency Index (Equation 4), RI is the Random Consistency Index proposed by Saaty and λ_{max} represents the maximum eigenvalue and n is the order of the judgement matrix. A pairwise comparison matrix was constructed using Saaty's scale, based on the consensus of the expert panel (Table 2).

Subsequently, the Weighted Overlay tool was applied to integrate all the conditioning variables and generate the Groundwater Potential Index (GWPI) map, as expressed in Equation 5.

$$GWPI = \sum_{i=1}^n wxr, \quad (5)$$

where w represents the normalized weight of each conditioning factor and r the suitability rank assigned to each class. The resulting map was classified into five categories (Very Poor to Very Good)

Table 2

Pairwise comparison matrix for the eight variables.

Variable	LI	SL	GM	DD	LULC	ST	TWI	NDVI
Lithology (LI)	1.00	5.35	3.02	5.28	5.10	1.60	3.06	5.24
Slope (SL)	0.19	1.00	0.53	1.95	2.15	0.41	0.70	1.02
Geomorphology (GM)	0.33	1.90	1.00	1.85	2.81	0.92	1.55	3.57
Drainage Density (DD)	0.19	0.51	0.54	1.00	2.14	0.44	0.65	2.26
Land Use and Land Cover (LULC)	0.20	0.46	0.36	0.47	1.00	0.33	0.34	1.32
Soil (ST)	0.62	2.44	1.08	2.27	3.08	1.00	1.66	3.74
Topographic Wetness Index (TWI)	0.33	1.43	0.64	1.55	2.98	0.60	1.00	2.35
Normalized Difference Vegetation Index (NDVI)	0.19	0.98	0.28	0.44	0.76	0.27	0.43	1.00

using the Jenks Natural Breaks method [37], which minimizes within-class variance and maximizes between-class differences [38]. This approach has demonstrated good performance in groundwater potential mapping and showed the best agreement with observed spring density in the Wuqi Basin, China [39]. Therefore, it was selected for the final classification of the *GWPZ* map.

2.3. Phase III: Validation with geophysical methods

Phase III validated the AHP-GIS model through a geophysical campaign conducted, where possible, in accessible sites within or near the Very Good and Moderate groundwater potential zones. Profile locations were defined by field accessibility, land access, terrain conditions and community-prioritised agricultural areas. Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) were carried out using an ABEM Terrameter LS 2 to identify saturated materials and estimate their thickness. Seven ERT profiles and four VES surveys were conducted between July and September 2025. ERT used a gradient array with 41 electrodes spaced 5 m along 200 m profiles, while VES applied the Schlumberger array with a maximum AB spacing of 200 m [40]. Data were processed in IPI2WIN (version 3.0.1) and RES2DINV (version 4.08), obtaining RMS errors below 5%. The interpretation was supported by literature-based resistivity ranges for subsurface materials (Table 3) [41, 42], allowing the AHP-GIS groundwater potential zones to be validated and refined.

Table 3

Resistivity ranges associated with subsurface materials.

Materials	Resistivity ($\Omega \cdot m$)	Materials	Resistivity ($\Omega \cdot m$)
Dry fine-grained materials	<5	Dry fine materials	20-70
Wet fine-grained materials	5-20	Dry coarse materials	>70

3. Results and discussion

3.1. Spatial assessment of conditioning factors

The study area covers 3722.38 ha in the semi-arid Entre Ríos commune, located in Atahualpa parish, Santa Elena Province, Ecuador. The climate is characterized by distinct dry (July–November) and wet (December–June) seasons, with average temperatures of 25–26 °C and annual rainfall of 200–300 mm [43]. Geologically, the area was characterised through the integrated analysis of lithology, geomorphology and soil properties (Figure 2). Lithologically, the area is mainly dominated by the Tablazo Formation

(Pleistocene), which covers 73% and consists of fine sands, calcareous sandstones and calcareous conglomeratic sands overlying the basaltic basement of the Piñón Formation. Other units include the Ancón Group (8.48%) and Quaternary surface deposits, mainly colluvial-alluvial (12.08%), alluvial (3.08%) and colluvial sediments (1.24%), distributed along channels and slopes. Geomorphologically, the area is characterised by undulating landforms, low hills, river valleys and undifferentiated terraces. River valleys and alluvial plains represent preferential zones for surface water flow, accumulation and potential recharge. Regarding soil distribution, Aridisols predominate (91.35%), whereas Entisols occur mainly in the north-western sector (5.28%), and minor Vertisol and Inceptisol areas are found towards the south-west (1.29%).

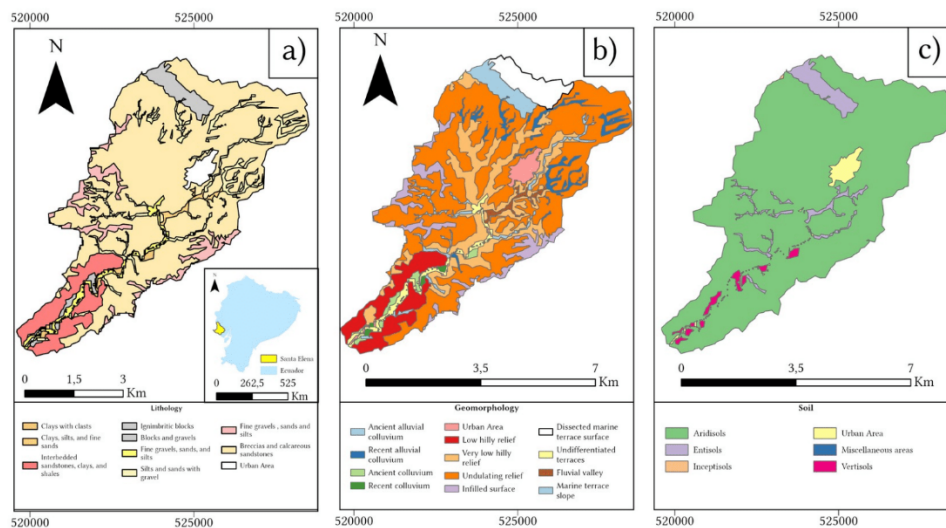


Figure 2: Geologic factors: a) Lithological map; b) Geomorphological map; c) Soil map.

Topographic and hydrological factors were used to assess surface runoff and potential infiltration conditions (Figure 3). Slope was classified into four ranges, from gentle terrain (2-5%) to steep slopes (25-40%) (Figure 3a). Drainage density ranged from 0.001 to 7.5 km/km², with higher values in steeper areas (Figure 3b). TWI values ranged from -18.27 to 12.11, with positive values indicating zones of flow convergence and prolonged moisture accumulation (Figure 3c).

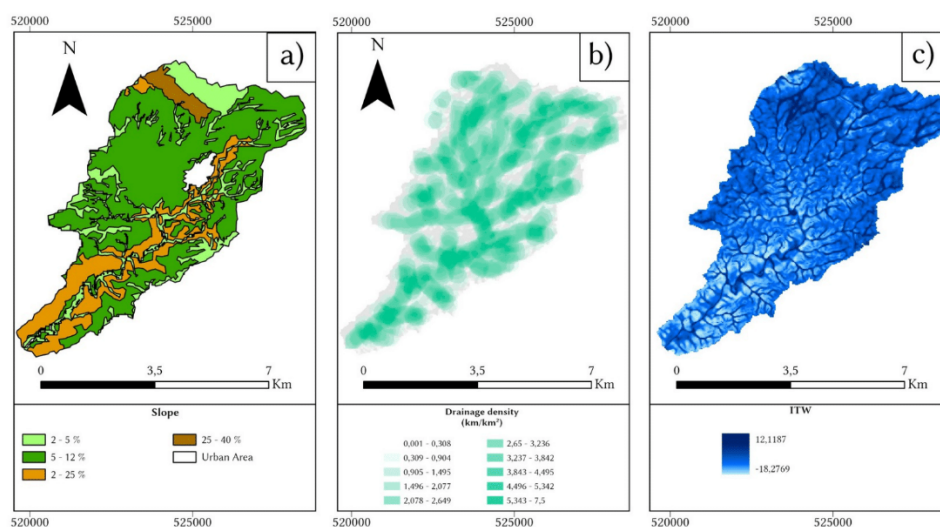


Figure 3: Topographic and hydrogeological factors: a) Slope map; b) Drainage density map; c) Topographic moisture index map.

The NDVI thematic map (Figure 4a) shows values ranging from -0.23 to 0.92. The highest and most

positive values are found in the southeastern and central parts of the watershed. In contrast, the northern and central-eastern parts have low and negative values. Figure 4b shows a strong predominance of shrub vegetation; in the northeastern sector, there is a change in vegetation type, with herbaceous vegetation and a few small areas of infrastructure.

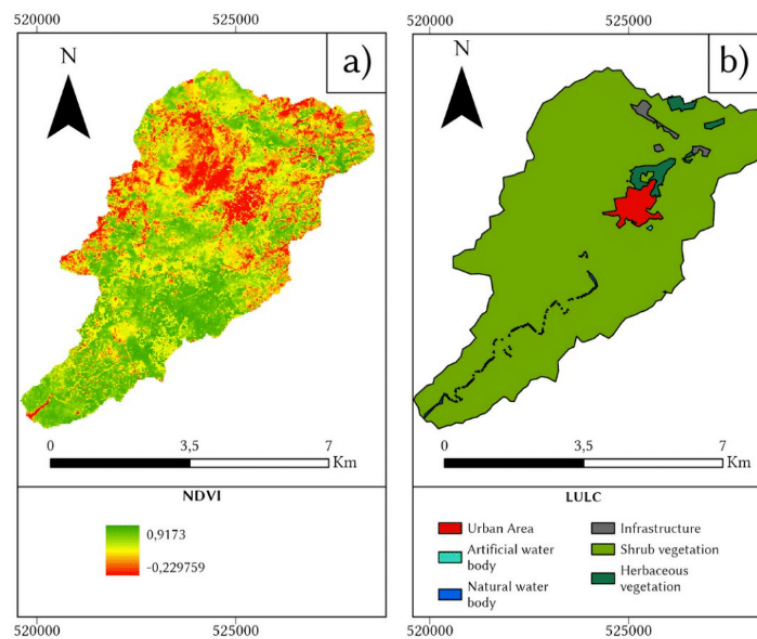


Figure 4: Environmental Factors: a) NDVI map; b) LULC map.

3.2. AHP weights and consistency analysis

The ADMC showed that lithology was the dominant factor in groundwater potential mapping, with a normalised weight of 32.44%, followed by soil type (17.12%), geomorphology (14.35%) and TWI (10.97%) (Table 4). Together, lithology, soil and geomorphology represented 63.91% of the total model weight, indicating that groundwater potential is mainly controlled by the permeability and temporary storage capacity of geological and pedological units, which regulate infiltration and runoff. In contrast, slope (8.01%), drainage density (7.55%), LULC (4.81%) and NDVI (4.75%) had a secondary influence. The expert-based judgement matrix showed strong reliability, with a Consistency Ratio (CR) of 0.018, below the acceptable threshold of 0.10.

Table 4

Matrix with normalized weights.

Criteria	Weight	Criteria	Weight
Lithology	32.44	Land Use and Land Cover	4.81
Slope	8.01	Soil	17.12
Geomorphology	14.35	Topographic Wetness Index	10.97
Drainage Density	7.55	Normalized Difference Vegetation Index	4.75
CI	0.028		
CR	0.018		

3.3. Groundwater potential zoning

The final Groundwater Potential Zones (GWPZ) map classified the study area into five categories: Very Poor, Poor, Moderate, Good and Very Good (Figure 5a). The most favourable areas, classified as Good to Very Good, are mainly located in the NW sector and along the main channels and river valleys in the central part of the basin. These zones coincide with the Tablazo Formation, recent alluvial deposits, flat valleys, Entisols and Aridisols, as well as higher TWI values, indicating favourable conditions for groundwater accumulation. In contrast, Poor and Very Poor zones dominate the southern, south-western and south-eastern sectors. These areas are associated with steeper slopes and less favourable geomorphological conditions, which promote surface runoff, reduce water retention time and limit effective aquifer recharge.

3.4. Geophysical validation of groundwater potential zone

In-situ geoelectrical validation was used to reduce the uncertainty of the AHP-GIS model, which is mainly based on surface variables and expert-derived weights. The geophysical campaign was carried out in Lot 2, an area prioritised by the local community because of its agricultural importance (Figure 5; Table 5). Owing to operational constraints, land access and field accessibility, the surveys did not cover the entire study area. Nevertheless, ERT and VES data confirmed the presence of saturated units in areas classified as “Poor”, “Moderate” and “Good” by the AHP-GIS model.

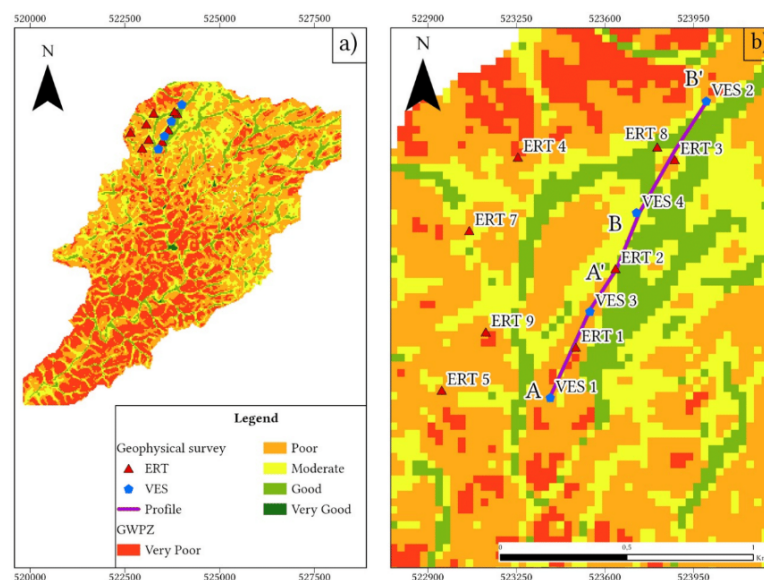


Figure 5: a) Groundwater potential map in the study commune; b) Location of geophysical survey.

The integrated SW–NE geoelectrical profile, with a length of 1,316 m and a maximum investigation depth of 40 m, revealed a shallow unsaturated layer from the surface to approximately 10 m depth. In the first section of the profile, from 0 to 750 m, dry fine materials and localised coarse deposits were identified above a continuous low-resistivity unit (Figure 6a). This unit occurs mainly between 10 and 30 m depth and shows resistivity values generally below $7 \Omega \cdot m$, suggesting saturated fine-grained materials, mainly silts and clays.

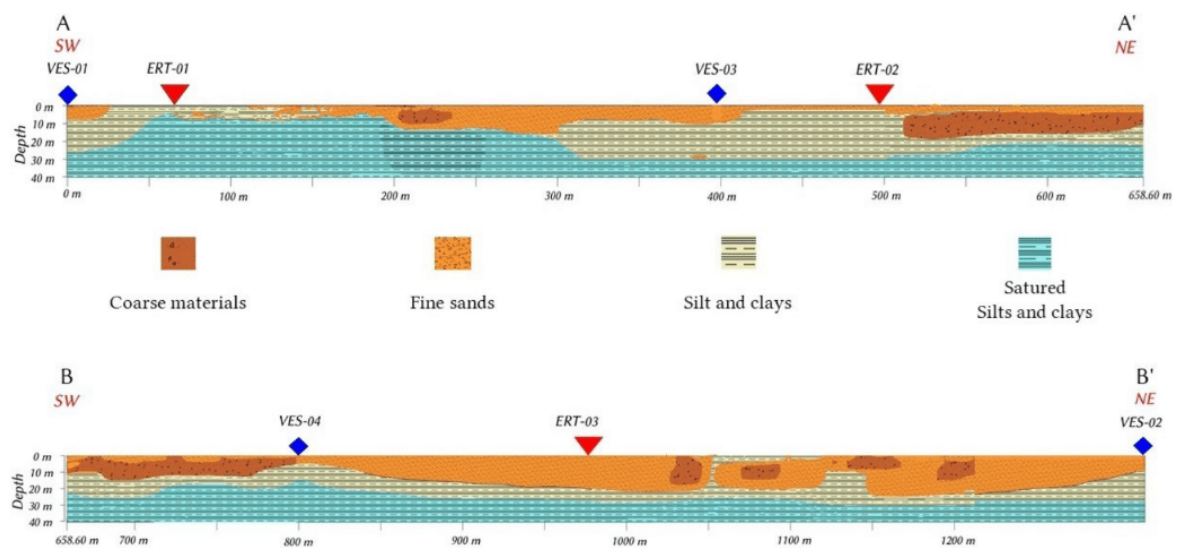
In the second section, from 658.60 to 1,316 m, coarse materials and fine sands were identified near the surface, followed by a continuous fine-grained layer and a deeper saturated unit (Figure 6b). This saturated layer occurs at variable depths of approximately 15–30 m and has a thickness greater than 20 m in some sectors. Overall, both sections indicate the presence of saturated materials beneath the superficial dry deposits, but the dominant lithology is mainly fine-grained.

Although the AHP-GIS model identified favourable zones based on lithology, soil type, geomorphology and TWI, the geophysical results show that groundwater accumulation does not necessarily imply high

Table 5

Geophysical interpretation identifying the saturated zone.

Geophysical survey	Class AHP-GIS	Resistivity ($\Omega \cdot m$)	Depth (m)	Interpretation
ERT-01	Poor	<7	10-30	Saturated fine material (silts and clays)
ERT-02	Moderate-Good		20-30	
ERT-03	Poor-Good		20	
VES-01	Poor		25	
VES-02	Moderate		30	
VES-03	Poor		30	
VES-04	Moderate		15	

**Figure 6:** Section a) and b) of the geoelectric profile.

aquifer productivity. The predominance of the Tablazo Formation explains the high weight assigned to lithology in the model; however, the ERT and VES interpretation indicates that the saturated unit is mainly composed of silts and clays, which may reduce hydraulic conductivity and transmissivity. Similar studies have shown that the dominant AHP factor varies according to the local hydrogeological context; for example, geology has been reported as the main factor in some semi-arid regions, whereas LULC, drainage density or lineament density may dominate in others [32, 44].

The very low resistivity values recorded in the geoelectrical models are consistent with the conductive behaviour of saturated silts and clays. In clay-rich materials, low resistivity may result not only from water content, but also from surface conduction along clay minerals. Therefore, these low-resistivity zones should be interpreted with caution, as they may behave more like an aquitard or aquiclude than a productive aquifer [45]. This finding highlights the importance of distinguishing between groundwater accumulation potential and groundwater productivity. The main limitation of this study is the restricted spatial coverage of the geophysical campaign, which was conditioned by accessibility and community priorities. Future work should expand ERT and VES surveys towards Good and Very Good zones and include exploratory drilling, lithological logs, pumping tests and hydrochemical analyses to confirm aquifer productivity and groundwater quality.

4. Conclusion

The AHP-GIS model identified the north-western sector of the Entre Ríos commune as the most favourable area for groundwater occurrence. This pattern was mainly controlled by lithology, soil type, geomorphology and TWI. The Very Good, Good, and Moderate classes accounted for 0.28%, 7.88%, and 21.23% of the study area, respectively, while the Poor and Very Poor zones dominated most of the territory. ERT and VES surveys confirmed the presence of saturated units between 10 and 30 m depth. Nevertheless, the very low resistivity values indicate that these units are mainly composed of saturated silts and clays, suggesting limited hydraulic conductivity and low expected productivity. Therefore, the AHP-GIS map should be interpreted as a groundwater accumulation potential map rather than a direct indicator of well productivity.

The main contribution of this study is the integration of spatial modelling and geophysical validation to reduce uncertainty in groundwater exploration. Future work should include exploratory drilling, pumping tests and hydrochemical analyses before defining productive agricultural wells.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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