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ORIGINAL ARTICLE

Applying georadar for groundwater prospection in Sabanalamar basin, Guantánamo province

Aplicación del georradar para prospección de agua subterránea en la cuenca Sabanalamar, Guantánamo

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Abstract

Water resources deficiency in San Antonio del Sur municipality in Guantánamo province, Cuba is one of the main challenges to face by all factors of society. This study proposes favorable areas for groundwater prospection in the lower part of Sabanalamar watershed using the georadar technique. Five profiles were measured to accurately characterize the geological section and obtaining information related to stratigraphic sequence, depth of the water table and bedrock. Radargrams were interpreted and compared with data from the wells, which allowed to establish the water table depth between 3.0 m and 4.0 m. These results propose the further west located areas of the evaluated sector as potentially favorable areas for groundwater prospecting.

Keywords: georadar, groundwater, Sabanalamar hydrographic basin, water table

Resumen

El déficit de recursos hídricos en el municipio costero de San Antonio del Sur, provincia cubana de Guantánamo, es uno de los principales desafíos a enfrentar por todos los factores de la sociedad. El objetivo de esta investigación fue proponer áreas favorables para la prospección de aguas subterráneas en la parte baja de la cuenca hidrográfica de Sabanalamar mediante el empleo de la técnica del georradar. Se midieron cinco perfiles para caracterizar con precisión la sección geológica y obtener información sobre la secuencia estratigráfica, profundidad del nivel freático y del manto rocoso. Los radargramas se interpretaron y compararon con datos de pozos, lo cual permitió establecer la profundidad del nivel freático entre los 3,0 m y 4,0 m. Se proponen como áreas potencialmente favorables para la prospección de aguas subterráneas las ubicadas más al oeste del sector evaluado.

Palabras clave: georradar, agua subterránea, cuenca hidrográfica Sabanalamar, nivel freático

1. INTRODUCTION

Ground-penetrating radar (GPR) is a non-destructive and non-invasive technique aimed at studying the shallow subsurface. It is based on the capability of low-frequency radar waves (10 MHz - 2.5 GHz) to propagate through low-conductivity media. The method uses a transmitting antenna to direct short electromagnetic pulses (1 ns - 20 ns duration) into the ground. In this case, a 100 MHz antenna was used to achieve a greater depth of investigation.

Internationally, numerous studies have successfully applied the GPR method for groundwater exploration, for investigating the unsaturated soil zone in various geological environments, and for improving the performance of water networks (García *et al*., 1996; Annan, 2003; Carcione *et al*., 2003; Lapazaran, 2004; Biskup *et al*., 2005; Tavera, 2008; Hernández, 2017; Schwarck *et al*., 2020; Soldi, 2020; Ruffell & Parker, 2021; Zhang *et al*., 2022).

In eastern Cuba, this method has been applied for sand prospecting (Acosta & Dussac, 2016). Work carried out by the OSDE *Gestión Integrada de las Aguas Terrestres* (Guantánamo Water Utilization Company, 2023) for the proposed redesign of the hydrogeological network in this province has also been reported. Likewise, the method has been used in various engineering-geological studies for siting housing in the localities of El Paraíso, El Jamal, and Yumurí, located in Baracoa (Socorras *et al*., 2021a, 2021b, 2021c), and for evaluating critical points of the *La Farola* viaduct (Rosabal *et al*., 2024 a, b, c, d).

The water resource deficit in eastern Cuba has become one of the main challenges faced by government bodies and all sectors of society. This situation is particularly acute in the coastal municipality of San Antonio del Sur, in Guantánamo province, due to the adverse effects of climate change and anthropogenic actions that have disrupted the flow of surface water sources in the area.

Specifically, few geophysical investigations have been conducted in the Sabanalamar river basin, among which the work by Dussac *et al*. (2017) for the *Arena Sabanalamar* project can be mentioned.

It is well-established that the application of geophysical methods to hydrogeology resolves aspects related to the geometry of subsurface rock formations, the thickness and depth position of rock layers influencing the hydrogeological behavior of the study area, the position of the water table, and others.

The purpose of this research was to propose, based on the application of the ground-penetrating radar (GPR) technique, potentially favorable areas for groundwater prospecting in the lower part of the Sabanalamar river basin in eastern Cuba.

1.1. General Characteristics of the Study Area

The study area is located (Figure 1) within the Sabanalamar River basin in Guantánamo province, eastern Cuba. It covers an area of 3.22 km². Figure 2 shows the layout of the survey profiles, and Table 1 lists the ground-penetrating radar (GPR) lines established within the study area.

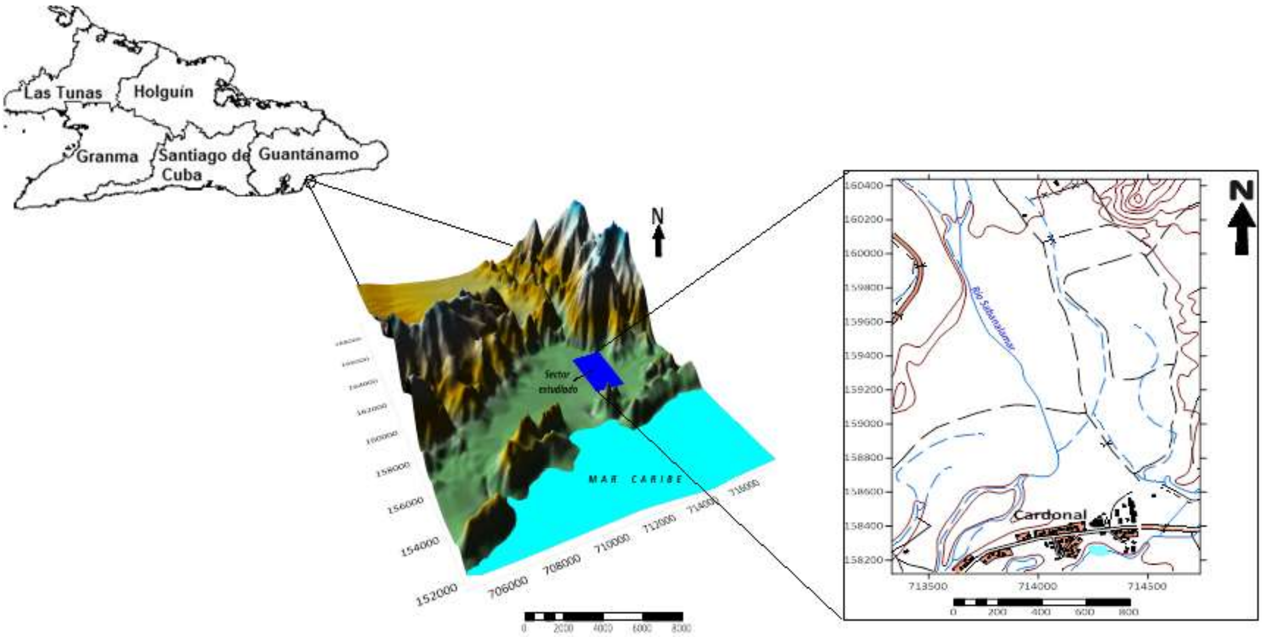

Figure 1. Geographic location of the study area within the Sabanalamar River basin, Guantánamo province, eastern Cuba.

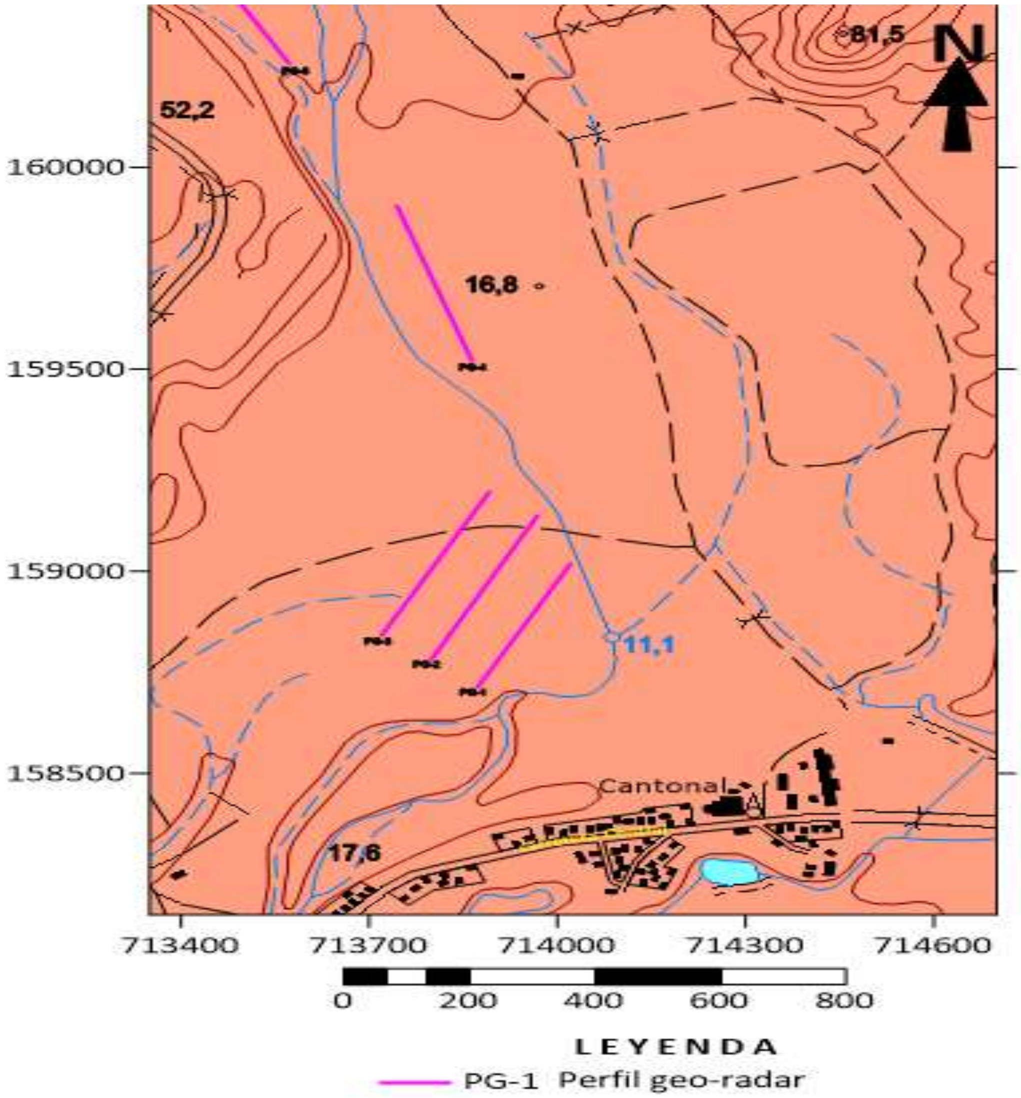

Figure 2. Layout of the ground-penetrating radar (GPR) profiles within the study area of the Sabanalamar basin, Guantánamo province, eastern Cuba.

Table 1. Ground-penetrating radar (GPR) survey lines established within the study area

Línea Georradar	Longitud (m)	Rumbo	Antena Utilizada (MHZ)
PG-1	340	SW-NE	100
PG-2	380	SW-NE	100
PG-3	400	SW-NE	100
PG-4	400	SE-NW	100
PG-5	400	SE-NW	100
TOTAL	**1920**	-	-

1.2. Geological and Hydrogeological Characteristics of the Study Area

The geological characterization of the area was based on the digital geological map (IGP, 2003) and its description (IGP, 2013):

Río Sabanalamar Formation (rsb): Composed of pebbles, occasionally weakly cemented conglomerates, with intercalations and lenses of clayey sands, gray and yellowish-gray in color. Age: Upper Pleistocene, lower part (IGP, 2013).

The hydrographic network is well-developed, with the Sabanalamar River being prominent. It originates in the Sierra El Purial and discharges its waters into Sabanalamar Bay (Caribbean Sea). During the dry season (low water period), the river's flow diminishes significantly until its waters flow subterraneously through the alluvial terraces.

The hydrogeological characteristics indicate an open basin type, with an unconfined aquifer. The depth to the groundwater table ranges from 3.0 m to 10.0 m, and the water mineralization is less than 1 g/L.

1.3. Hydrogeology

In 2021, the Valle de Caujerí station, the closest to the study area, reported 527.2 mm of rainfall, the lowest figure among the province's stations. This represents 476.9 mm below the provincial average and 601.5 mm below the national average (ONEI, 2021).

Measurements of groundwater depth allowed for the creation of a hydroisohypse map for the lower part of the basin, located north of the Central Highway leading to Imías and east of the road leading to the Valle de Caujerí (Figure 3).

The behavior of the hydroisohypses corroborates the marked influence of the topography, rivers, tributaries, and existing depressions in the area, showing a decrease in the depth to groundwater towards the south, which constitutes the discharge zone towards the Sabanalamar River.

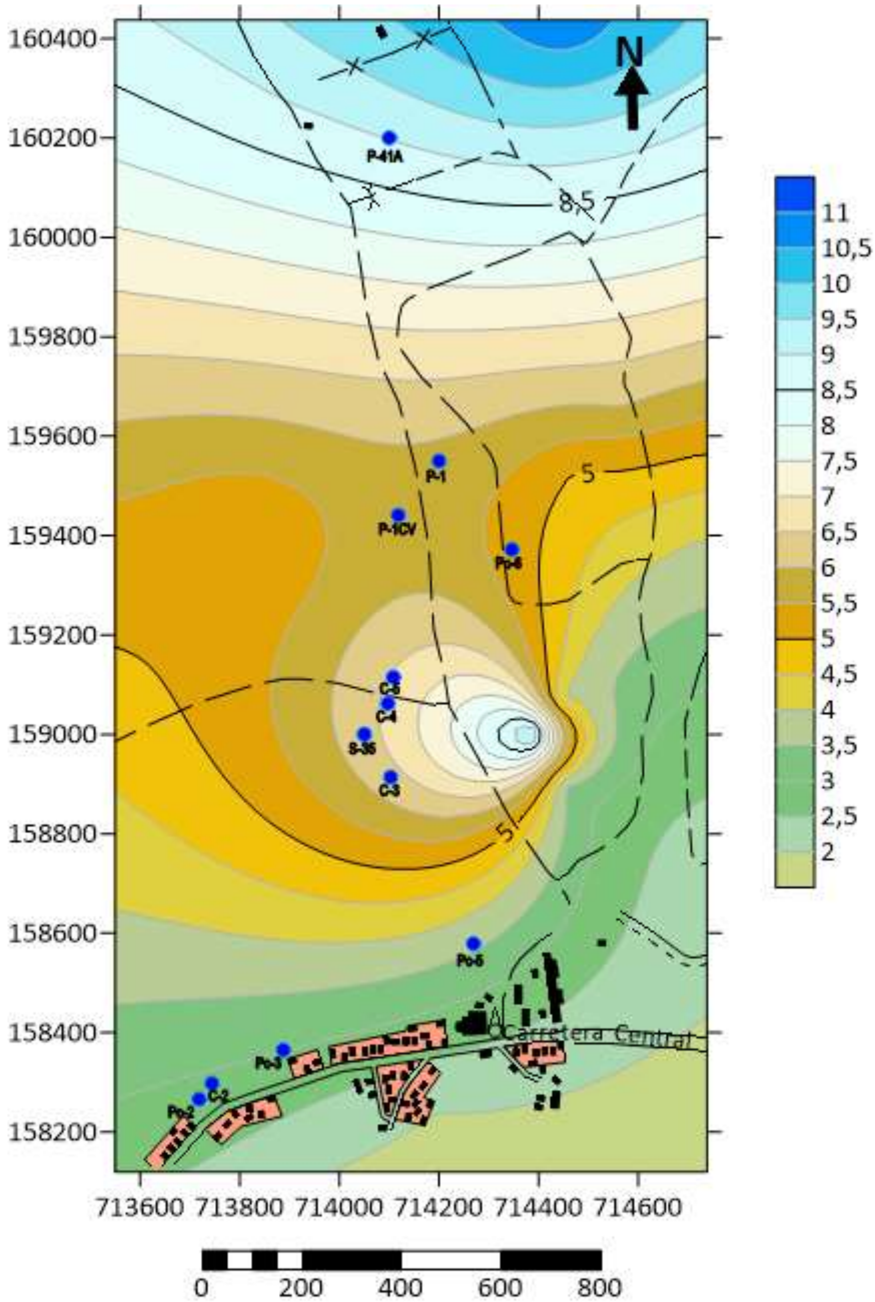

Figure 3. Hydroisohypse map showing water flow direction. The blue points represent the wells drilled in the area.

2. MATERIALS AND METHODS

The materials used included maps and results derived from preceding investigations. Initially, the available information for the area was compiled, such as the results of the geological survey of Eastern Cuba conducted by the Cuban-Hungarian brigade and its 1:100,000 scale geological map from the Cuban Institute of Geology and Paleontology (IGP); the location map of the surveyed sector; and records of superficial geological information.

Subsequently, in the field, five ground-penetrating radar (GPR) lines were deployed over the terrain to characterize the subsurface to a depth of up to 10 m and, in some cases, 15 m. Finally, during the office phase, the radargrams obtained in the field were processed, generating filtered information. Based on this, the physical characteristics of the subsurface, the geostructural conditions, and the inferred subsurface behavior could be determined.

The report on the geophysical work carried out for the *Arena Sabanalamar* project (Dussac *et al*., 2017), developed within the same basin in Guantánamo province, was consulted. This report concluded that the suite of methods employed (GPR and VES - Vertical Electrical Sounding) provided significant details to the investigation, such as the definition of strata with contrasting physical properties, which allowed for the establishment of different layers and the probable existence of sand deposits.

The ground-penetrating radar (GPR) method was employed. This is a near-surface remote sensing and non-invasive prospection technique based on the emission of a very short-duration electromagnetic pulse (1 ns - 20 ns), characterized by a nominal frequency that can range from 10 MHz to 2.5 GHz, depending on the selected antenna. Its ultimate goal is to obtain radargrams, pseudo-images that approximate a cross-section of the subsurface beneath the antenna traverse line, similar to those obtained by classical seismic reflection methods.

In this case, a 100 MHz RTA (Rough Terrain Antenna) was used, an 'all on line' configuration where the transmitter and receiver are located on the same axis. This antenna meets the required depth of investigation (15 m), considering that higher frequencies result in a shallower investigation depth and the desired resolution, provided the geological profile characteristics are favorable, with the capability to detect objects as small as 4 cm.

To conduct the GPR measurements in the study area, a somewhat irregular survey grid was laid out according to the topographic conditions of the terrain. Five profiles were established: three with a SW-NE orientation, spaced approximately 95 m apart, and two with a SE-NW orientation.

Following the processing of the radargrams, the types of anomalies present were defined. The anomalies are represented by: hyperbolic reflectors (hyperbolic-type anomalies), which may constitute rock blocks, cavities, among others; and linear reflectors (horizontal, vertical, inclined, or curved), which correspond to interfaces between two media with different electromagnetic properties and indicate the presence of different layers, the water table, fractures, and faults. These can also indicate cavities, soil disturbances, and the stratigraphic sequence.

Data acquisition for all profiles was conducted by taking a measurement approximately every 0.50 m, which allowed for obtaining a continuous image of the subsurface with good lateral and vertical definition of the geological profile.

2.1. Parameters and Important Characteristics

2.1.1. Penetration Depth

Electromagnetic waves can penetrate a certain distance before becoming attenuated. This distance is the nominal penetration depth (1/ɑ), and at five times this value, the field is considered completely attenuated, although for practical purposes, the signal ceases to be received earlier (Cimadevila, 1994). Table 2 compiles typical values of relative permittivity, conductivity, velocity, and attenuation factor for a frequency of 100 MHz.

Table 2. Wave characteristics for a frequency of 100 MHz (Milsom, 1996)

Material	ϵ_r	σ (mS/m)	v (m/ns)	∝ (dB/m)
Air	1	0	0,30	0
Ice	3-4	0,01	0,16	0,01
Fresh Water	80	0,5	0,033	0,1
Salt Water	80	3000	0,01	1000
Dry Sand	3-5	0,01	0,15	0,01
Wet Sand	20-30	0,01-1	0,06	0,03-3
Silt	5-30	1-1000	0,7	1-100
Limestone	4-8	0,5-2,0	0,12	0,4-1
Granite	4-6	0,01-1	0,13	0,01-1

For the processing and interpretation of the information obtained with the ground-penetrating radar method, the following software packages were used: Ramac GroundVision, supplied by the firm Mala Geoscience (Sweden); Reflexw2D, acquired by Geominera Oriente from Sandmeier Software (Germany); and Surfer v11.

3. RESULTS

The radargram from the 100 MHz antenna (Figures 4 and 5) clearly shows a continuous reflector at variable depth, identified as the clayey-silty and clayey-sandy contact.

In the radargram images from profiles 1 and 2 (Figures 4 and 5), two zones with well-defined and contrasting characteristics are observed. Throughout the extent of profile 1 (Figure 4), intense reflections are apparent, allowing the identification of two layers: the first is associated with clayey-silty sediments with an electromagnetic wave propagation velocity approximately equal to 0.06 m/ns, represented by blue lines; and the second layer is associated with sandy clay with gravels where the propagation velocity of these waves increases to over 0.160 m/ns, represented by red and blue lines.

In this profile, within the first 40 m; from 80 m to 120 m; and from 160 m to 200 m, hyperbolas are observed which may be related to the presence of rock fragments or coarser-grained sands.

These characteristics were depicted in the geological-geophysical interpretation profile (Figure 4), which shows two layers: the first with a variable thickness associated with the topsoil and intercalations of silts and clays, and the second layer of clay with sandy gravels, with a thickness not exceeding 3.5 m.

Numerous fractures or lithological contacts are mapped, as seen in Figure 4 with dashed lines.

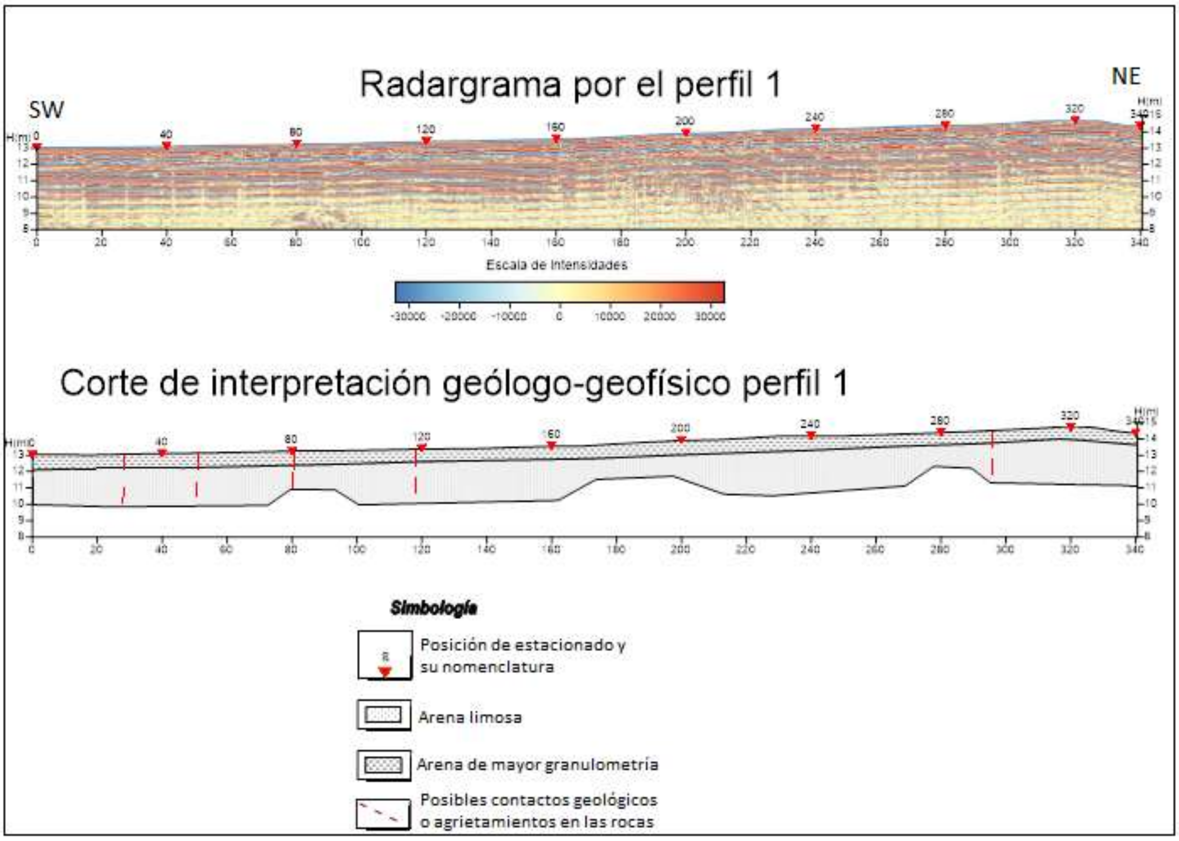

Figure 4. Radargrams and geological-geophysical interpretation of Profile 1.

Profile 2 (Figure 5) exhibits the same characteristics as Profile 1. Throughout the entire profile, the radargram shows intense reflections separating two layers. The boundary between these two layers is represented in blue. The first stratum is associated with silty-sandy sediments, where the electromagnetic wave propagation velocity is approximately 0.06 m/ns. Beneath this layer, characterized by less intense reflections and electromagnetic wave velocities greater than 0.160 m/ns, a stratum associated with gravelly silty sand is defined, represented by red and blue zones. In this profile, from 130 m to 240 m, hyperbolas are observed, which may be related to the presence of rock fragments or gravelly silty sand with a larger grain size.

Profiles 3, 4, and 5, conducted within the study area of the Sabanalamar basin, present the same characteristics as the previous two.

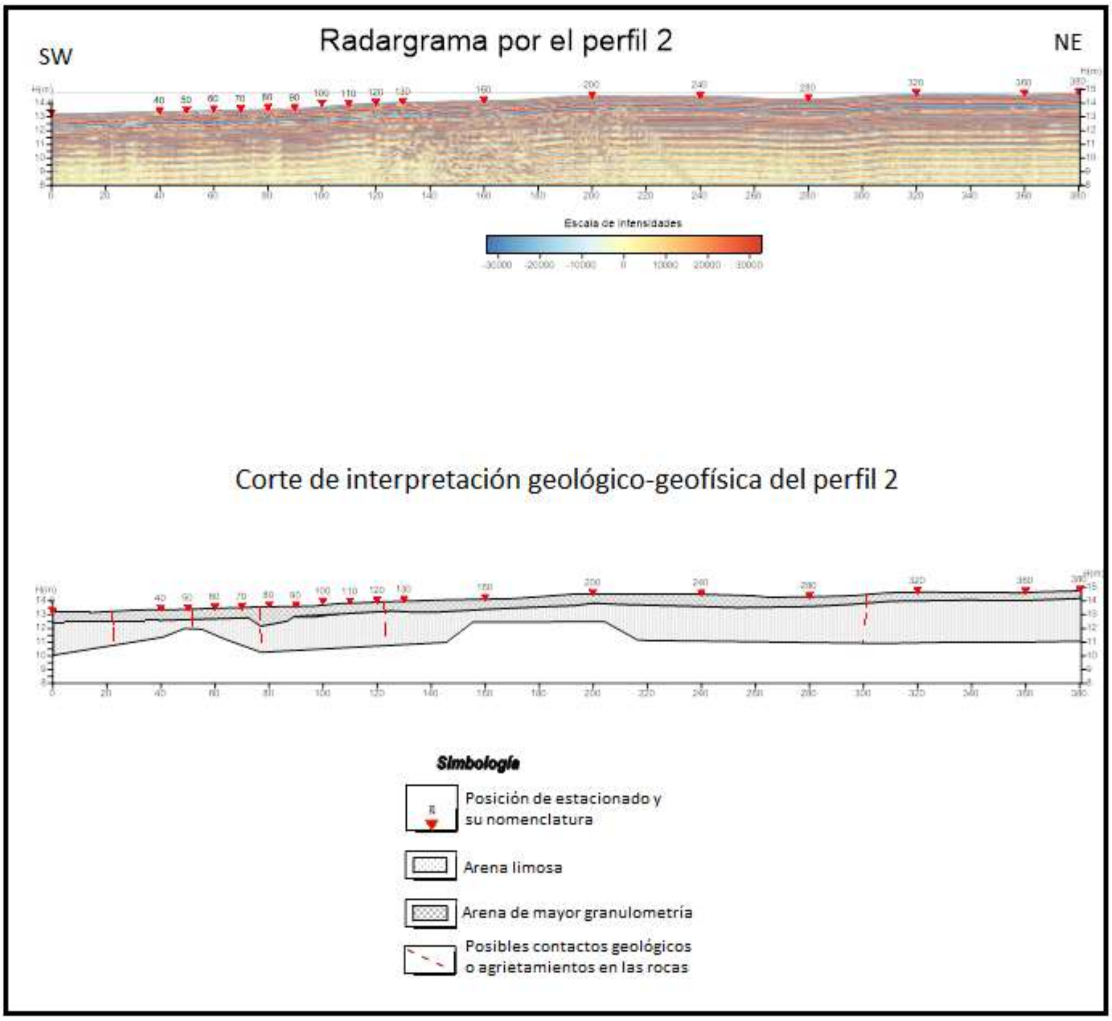

Figure 5. Radargrams and geological-geophysical interpretation sections for Profile 2.

4. DISCUSSION

In the Sabanalamar river basin, the use of the ground-penetrating radar (GPR) method successfully addressed hydrogeological tasks within the coastal sandy environments. This included providing information on the stratigraphic sequence, as well as detecting and determining the depth to the water table and the bedrock. The 100 MHz antenna achieved greater penetration to define the interfaces between clayey-silty and coarser-grained clayey-sandy materials; it also allowed for determining the thickness of each layer. The water table is visible in the radargrams due to the high porosity of the clayey-sandy volume with a higher percentage of gravels.

By comparing the GPR results with measurements taken to determine the water table level in some existing wells in the area, it was established that the depth to the water table ranges between 3.0 m and 4.0 m.

The execution of additional geophysical investigations (such as Electrical Tomography, Seismic Refraction, and parametric Vertical Electrical Sounding in wells) is necessary to determine the extent of seawater intrusion.

When conducting GPR measurements, it is essential to remain outside the influence of seawater, as its presence drastically alters the electromagnetic properties of the soil, leading to the complete attenuation of the signal.

5. CONCLUSIONS

- The variation in the electromagnetic wave and its velocity may be related to the variation of the dielectric constant in the area, influenced by the moisture and porosity of the material present in the zone, particularly at the boundary between clayey-silt and coarser-grained clayey-sandy gravels, where an increase in electromagnetic wave velocity is observed.
- Data acquisition with ground-penetrating radar allows for the characterization of the geological section with high precision, providing information on the stratigraphic sequence, as well as the detection and depth of the water table and the bedrock.
- Comparing the results from the radargrams with water table measurements from some wells in the area determines that the depth to the water table ranges between 3.0 m and 4.0 m.
- The areas furthest to the west of the studied sector are proposed as potentially favorable for groundwater prospecting.

6. ACKNOWLEDGMENTS

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Additional Information

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

JIMH: Data interpretation, writing, review, preparation of GPR profiles, design of GPR profiles, approval of the final version.

JMC: Data processing and interpretation.

SRD: Writing and editing of the report.

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